William S. Bainbridge
Mihail C. Roco
Editors

Handbook of Science and Technology Convergence

Springer Reference

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With 127 Figures and 29 Tables

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Editors
William Sims Bainbridge
Cyber-Human Systems Program
Division of Information and
Intelligent Systems
National Science Foundation
Arlington, VA, USA

Mihail C. Roco
National Science Foundation and National
Nanotechnology Initiative
Arlington, VA, USA

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Preface

Convergence of science and technology means more than simply the creation of multidisciplinary teams to address hard problems, in which effective communication takes place across distinct fields. Importantly, it also requires development of new concepts and new methodologies for research, design, and collaboration that bridge across fields in time while preserving their distinctive characters and aims at overarching goals. Especially in engineering and the development of new technologies, but also even in areas considered pure science, convergence must integrate ethical analysis and social science concerning both the intended and potential unintended consequences of the work and seeking the best means to integrate new ideas into human culture. Thus convergence not only brings together all the fields of science and technology but also unites them with society.

This handbook is the culmination of 15 years of conferences and publications, including several book-length reports, to which literally hundreds of scientists, engineers, and societal leaders from around the world contributed. The editors and the authors of the 74 chapters owe a great debt to the many other people who contributed their time and wisdom to the development of the convergence vision and the specific innovations needed to achieve it.

The initial vision focused on the four "NBIC" fields: Nanotechnology, Biotechnology, Information technology, and new technologies based on Cognitive science. As the meetings progressed, the importance of the related pure sciences and the human implications received increasing attention. This handbook became both possible and necessary, after the work of so many contributors developed a comprehensive perspective on the centrality of science and engineering in the human future, with many of the specific technical and social components required for significant accomplishment. While this handbook was designed as an integrated unity, to maximize its clarity and utility the chapters are arranged in six sections, each with an introductory chapter that primarily identifies key concepts, rather than summarizing the topical chapters that follow:

1. Concepts and Methods: This first section examines several ways of conceptualizing science, technology, and society as complex, dynamic, interacting systems.
2. Foundational Technologies Platform: Here the NBIC heritage is central, with an emphasis on how specific sets of fields converge with each other.

3. Human-Scale Platform: This section emphasizes partnerships between individual human beings, emerging technologies, and advancement of the scientific enterprise.
4. Earth-Scale Platform: Preserving Earth as the unified home of humanity requires many kinds of international, cross-cultural, and large-scale environmental collaboration.
5. Societal-Scale Platform: The emergence of global society requires understanding the ways in which all people may collaborate positively through the wise application of science and technology.
6. Convergence in Education: Innovative training of professional scientists and engineers within higher education is essential, but consideration is also given to how schools and informal educational activities of many kinds can play their most valuable roles.

The concepts and methods come first, in order to provide a roadmap of the tools needed to render convergence both possible and beneficial. Then the four "platforms" cover the territory in relatively coherent regions, each much larger than the four original NBIC fields, but in a similar manner interacting with each other, even while they can be distinguished for the sake of clarity. The concluding section then considers the needs and opportunities for progressive innovation in education broadly defined.

Since this handbook is a reference work, each chapter is self-contained and can be understood separately from the others, but all of them harmonize with each other and are most valuable together. Thus the chapters themselves exemplify convergence and its dynamic relationship to creative divergence. This handbook is a conceptual toolkit the reader may use to contribute in new ways to human progress.

Contents

Editors

William Sims Bainbridge works at the convergence of social and information sciences, as well as in research areas relating to the history of technology and culture. He earned his doctorate in sociology from Harvard University with a dissertation analyzing the history of the spaceflight social movement, including observation of the last human launch to the Moon in 1972, and resulting in his first book, *The Spaceflight Revolution* (1976). Other related books include *Dimensions of Science Fiction* (1986), *Goals in Space* (1991), *The Virtual Future* (2011), and *The Meaning and Value of Spaceflight* (2015). He owned his first computer game in 1956, a Geniac, and recently published extensively about online gameworlds, including *The Warcraft Civilization: Social Science in a Virtual World* (2010) and *eGods: Faith Versus Fantasy in Computer Gaming* (2013). A series of studies examining real-world religious movements employed convergence of social, cognitive, and information sciences, using methods that included analysis of historical documents, ethnographic field observation, questionnaire surveys, computer simulations, and logical deduction.

Since his family had been involved with information technology innovations for a century, he naturally learned to program personal computers as soon as they were available and began to publish textbook-software packages: *Experiments in Psychology* (1986), *Sociology Laboratory* (1987), *Survey Research: A Computer-Assisted Introduction* (1989), and *Social Research Methods and Statistics* (1992). He joined the National Science Foundation in 1992 to manage the sociology program, represented the social sciences in the Digital Library Initiative throughout the 1990s, and then moved in the year 2000 to NSF's computer science directorate. Some of his recent research has been at the intersection of computer science and social psychology, for example, *Personality Capture and Emulation* (2014), which includes results of a 200-item questionnaire study of the traditional Big Five personality dimensions, but conducted through innovative distribution of an Android app that garnered over 3,200 valid responses within a week.

His first experience as a reference work editor was as a member of the large team of specialists that compiled *The Encyclopedia of Language and Linguistics* (1994), writing 19 of the essays himself and recruiting authors for 22 others. In addition to collaborating in editing nanotechnology and converging technology books, he was solo editor of *Encyclopedia of Human-Computer Interaction* (2004), *Online Worlds* (2010), and *Leadership in Science and Engineering* (2012). In addition to involvement with traditional scientific organizations, he has been especially active in the Association of Religion Data Archives and the Institute for Ethics and Emerging Technologies, both of which seek a future in which technology will serve humanistic goals. It has been a great honor to serve the unification of science, engineering, and society, through helping to organize and edit the results of the forward-looking conferences that formed the intellectual basis for *Handbook of Science and Technology Convergence*.

Mihail C. Roco
Senior Advisor for Science
and Engineering
National Science Foundation
and U.S. National Nanotechnology
Initiative
Arlington, VA, USA

Mihail C. Roco is the founding chair of the U.S. National Science and Technology Council's subcommittee on Nanoscale Science, Engineering, and Technology (NSET) and the Senior Advisor for Science and Engineering at the National Science Foundation (NSF). Prior to joining NSF, he was a professor of mechanical engineering at the University of Kentucky (1981–1995) and held professorships at the California Institute of Technology (1988–1989), Tohoku University (1989), Johns Hopkins University (1993–1995), and Delft University of Technology (1997–1998).

Roco is credited with 13 inventions and has contributed over 250 articles and 21 books on multiphase systems, laser visualization, computer simulations, nanoparticles and nanosystems, trends in emerging technologies, and societal implications. These include *Particulate Two-Phase Flow* (1993), *Converging Technologies for Improving Human Performance* (2003), *Managing Nano-Bio-Info-Cogno Innovations* (2007), and *Mapping Nanotechnology Knowledge and Innovation* (2009). Recent books include *Nanotechnology Research Directions for Societal Needs in 2020* (2011) and *Convergence of Knowledge, Technology and Society* (2013).

Roco initiated the first Federal Government program with focus on nanoscale science and engineering (on synthesis and processing of nanoparticles) at NSF in 1991. He formally proposed NNI in a presentation at White House/OSTP, Committee on Technology, on March 11, 1999. Roco is a key architect of the National Nanotechnology Initiative (NNI), and he coordinated the preparation of the U.S. National Science and Technology Council (NSTC) reports *National*

Nanotechnology Initiative (NSTC, 1999) and *National Nanotechnology Initiative* (NSTC 2000).

Roco is a Correspondent Member of the Swiss Academy of Engineering Sciences, an Honorary Member of the Romanian Academy, a Fellow of the American Society of Mechanical Engineers, a Fellow of the Institute of Physics, and a Fellow of the American Institute of Chemical Engineers. He has been cofounder and Chair of the AIChE Particle Technology Forum and of the International Multiphase Flow Council. He has served as Editor for the *Journal of Fluids Engineering* and *Journal of Measurement Science and Technology* and is Editor-in-Chief of the *Journal of Nanoparticle Research*. He has been a member of several research boards in Americas, Europe, and Asia including the S&T Council of the International Risk Governance Council in Geneva.

Roco was honored as recipient of the Carl Duisberg Award in Germany, "Burgers Professorship Award" in the Netherlands, and the "University Research Professorship" award in the USA. He was named the "Engineer of the Year" in 1999 and again in 2004 by the U.S. National Society of Professional Engineers and NSF. In 2002, he received the first "Best of Small Tech Awards" ("Leader of the American nanotech revolution"), and Scientific American named him in 2004 as one of top 50 technology leaders. He received the "Semiconductor Research Association Award for Nanoelectronics," the "ChinaNano Award" from the Chinese Academy of Sciences, "Doctor Honoris Causa" from Polytechnic University Bucharest, and "Outstanding Service and Vision for Sustainable Nanotechnology" from the Sustainable Nanotechnology Organization. Roco is the 2005 recipient of the AIChE Forum Award "for leadership and service to the national science and engineering community through initiating and bringing to fruition the National Nanotechnology Initiative." He was awarded the National Materials Advancement Award from the Federation of Materials Societies at the U.S. National Press Club in 2007 "as the individual most responsible for support and investment in nanotechnology by government, industry, and academia worldwide." He received the inaugural award of the International Union of Materials Research Societies' "Global Leadership and Service Award" at the European Union Parliament in 2015 for "vision and dedicated leadership . . .that has made major impact to all citizens around the world."

Contributors

Catalina Achim Carnegie Mellon University, Pittsburgh, PA, USA

Robert Amant Department of Computer Science, North Carolina State University, Raleigh, NC, USA

Chunli Bai The Chinese Academy of Sciences, Beijing, China

William Sims Bainbridge Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA

Larry Bell Museum of Science, Boston, MA, USA

David M. Berube Department of Communication, North Carolina State University, Raleigh, NC, USA

Magdalena Bielenia-Grajewska Intercultural Communication and Neurolinguistics Laboratory, Department of Translation Studies, University of Gdansk, Gdansk, Poland

Dragana Brzakovic Science and Technology Centers, Office of Integrative Activities, National Science Foundation, Arlington, VA, USA

Jian Cao Department of Mechanical Engineering, McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL, USA

R. P. H. Chang Materials Research Institute, Materials Science and Engineering, Northwestern University, Evanston, IL, USA

Hongda Chen NIFA/USDA, Washington, DC, USA

Hyo-Jick Choi Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB, Canada

Ingenuity Lab, Edmonton, AB, Canada

Claudio Cioffi-Revilla Computational Social Science Program, Center for Social Complexity, Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA, USA

Terry Nichols Clark Department of Sociology, University of Chicago, Chicago, IL, USA

John H. Cozzens Division of Computing and Communication Foundation, National Science Foundation, Arlington, VA, USA

Kevin Crowston School of Information Studies, Syracuse University, Syracuse, NY, USA

Christopher L. Cummings Nanyang Technological University, Singapore, Singapore

Gregorio D'Agostino ENEA, Centro Ricerche Casaccia, Rome, Italy

Kornel F. Ehmann Department of Mechanical Engineering, McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL, USA

Yasmine El-glaly Faculty of Science, Port Said University, Port Said, Egypt

College of Computers and Information Technology, Taif University, Taif, Saudi Arabia

David Feldman Department of Planning, Policy, and Design, School of Social Ecology, University of California, Irvine, Irvine, CA, USA

Jing Feng Department of Psychology, North Carolina State University, Raleigh, NC, USA

Douglas H. Fisher Vanderbilt Institute for Digital Learning, Vanderbilt University, Nashville, TN, USA

Jane E. Fountain Political Science and Public Policy, University of Massachusetts, Amherst, MA, USA

Batya Friedman Information School, University of Washington, Seattle, WA, USA

Robert Geraci Department of Religious Studies, Manhattan College, Riverdale, NY, USA

James K. Gimzewski Department of Chemistry and Biochemistry, University of California-Los Angeles, Los Angeles, CA, USA

California NanoSystems Institute (CNSI), University of California-Los Angeles, Los Angeles, CA, USA

WPI Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science, Tsukuba, Japan

Viktoria Gisladottir Risk and Decision Science Team, US Army Engineer Research and Development Center, Concord, MA, USA

Department of Mechanical and Aerospace Engineering, University of California, San Diego, CA, USA

Jerome C. Glenn The Millennium Project, Washington, DC, USA

Michael E. Gorman Science, Technology and Society Program, University of Virginia, Charlottesville, VA, USA

Piotr Grodzinski Office of Cancer Nanotechnology Research, National Cancer Institute, Bethesda, MD, USA

Albert A. Harrison University of California, Davis, CA, USA

Barbara Herr Harthorn NSF Center for Nanotechnology in Society and Department of Anthropology, University of California, Santa Barbara, Santa Barbara, CA, USA

Christopher Hartshorn Office of Cancer Nanotechnology Research, National Cancer Institute, Bethesda, MD, USA

Beth Hawkins Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Thomas E. Horton Department of Computer Science, North Carolina State University, Raleigh, NC, USA

Matthew Hsu Materials Research Institute, Materials Science and Engineering, Northwestern University, Evanston, IL, USA

Shiv Kapoor Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Champaign, IL, USA

George Khushf Department of Philosophy and Center for Bioethics, University of South Carolina, Columbia, SC, USA

Moonkyung Mark Kim School of Electrical and Computer Engineering, Cornell University, Ithaca, NY, USA

Janet L. Kolodner School of Interactive Computing, Georgia Institute of Technology, Atlanta, GA, USA

Joyce Koo Science and Technology Innovation Program, Woodrow Wilson International Center for Scholars, Washington, DC, USA

Roger D. Launius Division of Space History, Smithsonian Institution, National Air and Space Museum, Washington, DC, USA

Jo-Won Lee Department of Convergence Nanoscience, Hanyang University, Seoul, South Korea

Michael Lesk Library and Information Science, School of Communication and Information, Rutgers University, New Brunswick, NJ, USA

Igor Linkov Risk and Decision Science Team, US Army Engineer Research and Development Center, Concord, MA, USA

Zack Lynch Neurotechnology Industry Organization, San Francisco, CA, USA

Robert M. Mason Social Media Lab, The Information School, University of Washington, Seattle, WA, USA

Michael Mateas Center for Games and Playable Media, University of California, Santa Cruz, Santa Cruz, CA, USA

Anne Collins McLaughlin Department of Psychology, North Carolina State University, Raleigh, NC, USA

Andy Miah Chair in Science Communication and Future Media, School of Environment and Life Sciences, University of Salford, Manchester, UK

Pietro Michelucci Human Computation Institute, Fairfax, VA, USA

Carlo D. Montemagno Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB, Canada

Ingenuity Lab, Edmonton, AB, Canada

James Murday Office of Research Advancement, University of Southern California, Washington, DC, USA

J. Tinsley Oden Institute for Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX, USA

James L. Olds Department of Molecular Neuroscience, Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA, USA

Aude Oliva Computer Science and Artificial Intelligence Laboratory (CSAIL), Massachusetts Institute of Technology, Cambridge, MA, USA

Francisco Oliveira Ceara State University, Fortaleza, Brazil

Gary M. Olson Department of Informatics, University of California, Irvine, Donald Bren School of Information and Computer Sciences, Irvine, CA, USA

Angela Page U.S. Environmental Protection Agency, Washington, DC, USA

Richard Pak Department of Psychology, Clemson University, Clemson, SC, USA

Y. Eugene Pak Advanced Institutes of Convergence Technology, Seoul National University, Suwon, South Korea

Jim Pass Astrosociology Research Institute, Huntington Beach, CA, USA

Eleonore Pauwels Science and Technology Innovation Program, Woodrow Wilson International Center for Scholars, Washington, DC, USA

Jonathan C. Peck Institute for Alternative Futures, Alexandria, VA, USA

Francis Quek Department of Visualization, Texas A&M University, College Station, TX, USA

David Rejeski Science and Technology Innovation Program, Woodrow Wilson International Center for Scholars, Washington, DC, USA

Ortwin Renn Environmental Sociology and Technology Assessment, Universität Stuttgart, Institut für Sozialwissenschaften, Abteilung für Technik- und Umweltsoziologie, Stuttgart, Germany

Wonjong Rhee Graduate School of Convergence Science and Technology, Seoul National University, Suwon, South Korea

Katherine Richardson Sustainability Science Centre, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark

Mihail C. Roco National Science Foundation and National Nanotechnology Initiative, Arlington, VA, USA

Erin Rose Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Nora Savage Office of Research and Development, Environmental Protection Agency, Washington, DC, USA

Walt Scacchi Institute for Software Research, Institute for Virtual Environments and Computer Games, University of California, Irvine, Irvine, CA, USA

Antonio Scala CNR-ISC, UoS "Sapienza", Rome, Italy

Brian Scassellati Department of Computer Science, Yale University, New Haven, CT, USA

Robin Schoen Board on Agriculture and Natural Resources, NRC, Washington, DC, USA

Norman R. Scott Biological and Environmental Engineering, Cornell University, Ithaca, NY, USA

Ullica Segerstrale Social Sciences, Illinois Institute of Technology, Chicago, IL, USA

Jennifer Shanahan Materials Research Institute, Materials Science and Engineering, Northwestern University, Evanston, IL, USA

Susan Rundell Singer Biology and Cognitive Science, Carleton College, Northfield, MN, USA

Andrew J. Spakowitz Department of Chemical Engineering, Stanford University, Stanford, CA, USA

Biophysics Program, Stanford University, Stanford, CA, USA

Department of Applied Physics, Stanford University, Stanford, CA, USA

Department of Materials Science and Engineering, Stanford University, Stanford, CA, USA

Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Jim Spohrer IBM Almaden Research Center, San Jose, CA, USA

Will Steffen Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

Fenner School of Environment and Society, The Australian National University, Canberra, ACT, Australia

Dorian Stiefel Baker Center for Public Policy, University of Tennessee, Knoxville, Knoxville, TN, USA

Adam Z. Stieg California NanoSystems Institute (CNSI), University of California-Los Angeles, Los Angeles, CA, USA

WPI Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science, Tsukuba, Japan

George O. Strawn Federal Networking and Information Technology Research and Development National Coordination Office, Arlington, VA, USA

Anita Street United States Government, Washington, DC, USA

Santani Teng Computer Science and Artificial Intelligence Laboratory (CSAIL), Massachusetts Institute of Technology, Cambridge, MA, USA

Bruce Tonn Department of Political Science, University of Tennessee, Knoxville, Knoxville, TN, USA

Katherine M. Tsui Department of Computer Science, Yale University, New Haven, CT, USA

Carol J. Van Hartesveldt National Science Foundation, Arlington, VA, USA

Victoria Vesna Art|Sci Center, Department of Design Media Arts, University of California-Los Angeles, Los Angeles, CA, USA

Program in Empowerment Informatics, School of Integrative and Global Majors, University of Tsukuba, Tsukuba, Japan

Chen Wang National Center for Nanoscience and Technology, Beijing, China

Noah Wardrip-Fruin Center for Games and Playable Media, University of California, Santa Cruz, Santa Cruz, CA, USA

Matthew D. Wood Risk and Decision Science Team, US Army Engineer Research and Development Center, Concord, MA, USA

The Era of Convergence

William Sims Bainbridge and Mihail C. Roco

Contents

Abstract

For more than a decade, hundreds of scientists and engineers debated in conferences and contributed to books exploring the need and value of convergence across their fields and with society. Convergence advances an integrative approach across human dimensions, is based on the material unity of nature, and is best facilitated by a holistic approach with shared methodologies, theories, and goals. Convergence seeks to transcend existing human conflicts to achieve vastly improved conditions for work, learning, aging, and physical and cognitive wellness and to achieve shared human goals. Seven theories offer different perspectives on this complex dynamic and suggest why this century may be the Era of Convergence: (1) Economic Growth, (2) Specialization Network, (3) Reverse Salient, (4) Fundamental Principles, (5) Progress Asymptote, (6) Exogenous Revolution, and (7) Social Problems. Science and technology should serve the needs of human beings, and innovation is a complex social

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

M.C. Roco
National Science Foundation and National Nanotechnology Initiative, Arlington, VA, USA
e-mail: mroco@nsf.gov

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enterprise. Thus, convergence must include transformative tools, ethics, the social sciences, political diversity, the arts, and humanities. For the sake of clarity and comparison, the chapters of this handbook are organized in six sections: (1) Concepts and Methods, (2) Foundational Technologies Platform, (3) Human-Scale Platform, (4) Earth-Scale Platform, (5) Societal-Scale Platform, and (6) Convergence in Education.

Introduction

This handbook catalogs all the ways in which scientific and technical fields can combine far more effectively than in previous times, in the service of humanity. Scientists and engineers have long been aware of the tension between narrow specialization and multidisciplinary cooperation, between bottom-up and top-down approaches, between short-term and long-term perspectives, and between individual and collective effects, but now a major transformation is in process. Nature is a single coherent system, and diverse methods of scientific and engineering investigations should reflect this interlinked and dynamic unity. Accordingly, general concepts and ideas should be developed systematically in interdependence, with cause-and-effect pathways, for improved outcomes in knowledge, technology, and applications. At the same time, industrial and social applications rely on integration of disciplines and unification of knowledge. Thus, convergence is both a fundamental principle of nature and a timely opportunity for human progress.

What Is Convergence?

The initial framework developed in over a decade of professional conferences established connections between nanotechnology, biotechnology, information technology, and new technologies based on cognitive science (Roco and Bainbridge 2003; Roco and Montemagno 2004; Bainbridge and Roco 2006a, b). Subsequently, emphasis was given to the social and ethical implications of scientific research and engineering development and thus the convergence of all technical fields with society itself (Roco et al. 2013). The core ideas are that convergence:

- Advances an integrative approach across human dimensions, encompassing value systems, operating at societal and global scales, while remaining valuable for each individual person
- Is based on the material unity at the nanoscale, integrated systems, and information universes, connected via human behavior and other integrators
- Is best facilitated by a holistic approach with shared methodologies, theories, and goals, which is quite different from traditional forms of collaboration in which a division of labor separates disciplines from each other

- Renews the focus on people's capabilities and human outcomes, rather than allowing decisions to be technology driven, and seeks to transcend existing human conflicts to achieve vastly improved conditions for work, learning, aging, and physical and cognitive wellness and to achieve shared human goals

Convergence is more than simply multidisciplinary collaboration. Yes we can learn something about how a shark swims through collaboration between an oceanographer and a biologist who divide the questions into two distinct areas, outside the skin of the shark and inside. But the shark is part of the larger system comprising the ocean in which it swims, including the other fish it chases after, and the dissolved oxygen that keeps it alive from moment to moment. So one way of conceptualizing convergence is in terms of complex systems that are the subjects of scientific study or engineering design. But as with the shark and the ocean, there are also two kinds of systems involved, the second being the social system of human beings who seek knowledge about the life of a shark, composed of scientists, engineers, students, and the general public.

Convergence includes all relevant areas of human and machine capability that enable each other to allow society to answer questions and to resolve problems that isolated capabilities cannot, as well as to create new competencies, knowledge, technologies, and products on that basis. Principles and methods to facilitate convergence are based on the interdependence between various domains of nature and human activity and their evolution in time as summarized in another chapter in this volume (Roco 2015). At the core of science and technology convergence in the first part of the twenty-first century is the convergence and emergence of four foundational and transformational S&T fields, briefly called nano-bio-information-cognitive technologies (NBIC).

Whenever it is valuable to do so, sciences and fields of engineering should share their concepts, research tools, information resources, and connections with the wider economic and social system. When one field borrows from another, the result is often a surge of creativity, as ideas combine and methods provide leverage for each other. But this does not mean that convergence should be homogenization. A tragic example of what must be avoided was Lysenkoism in the Soviet Union that suppressed progress for decades (Medvedev 1969). Perhaps because Darwinian theories of biological evolution by natural selection from random variation were associated in many people's minds with the struggle for wealth and power in capitalist societies, a Marxist society was ready for the perhaps more optimistic theory that biological characteristics were easily acquired. One practical result was degradation of the seed stocks for agricultural crops, for example, varieties of wheat that grew better in different parts of the vast nation, as seeds that were adapted for different climates were mixed together. More generally, progress in biology was retarded. Any orthodoxy can retard progress to some degree, and merging science and politics is risky in many ways. Lysenkoism is certainly not an example of what this handbook means by *convergence*.

Yet many of the chapters express hopes that science and engineering can merge in positive ways with society, allowing more people to understand the emerging truths about nature and participate actively in creating the technology of tomorrow. Throughout history, progress has resulted in progressive differentiation of society into an ever more complex system of somewhat separate social institutions, professions, and social groups (Spencer 1896). Yet this need not contradict convergence, if we conceptualize dynamic systems as following successive processes of *convergence and divergence*. This coherence process has been identified first in science and engineering progress (Roco 2002). Yes, a complex system consists of many parts, but they are integrated, ideally harmonizing but certainly influencing each other. Such a dynamic system cannot be understood in terms of a single idea but in terms of a system of ideas. One approach is to identify separate theories of convergence, prior to any attempt to integrate them, with special attention to the possibility that they define the present day as a revolutionary watershed requiring convergence if human progress is to continue.

General Theories of the Era

Many factors are active at the present time that encourage convergence, and several nagging problems might be solved by intensive collaboration between people in separate disciplines. The modern situation is so complex and dynamic that we need multiple ideas to understand it, yet too much detail generates unintelligibility. Therefore it is reasonable to consider briefly seven different but compatible theories, each of which could explain why the present time is the Era of Convergence. Each can be seen as an agenda for future research, as well as a likely factor encouraging convergence.

The *Economic Growth Theory* emphasizes that we can afford bigger and more complex research projects, paying the salaries and research expenses of ever larger numbers of scientists and engineers who work together in an increasingly complex division of labor. The classic example is the Apollo program that took the first human beings to the moon in 1968–1972. The fact that wealth has accumulated does not immediately imply it will be invested in science or engineering, of course, and advocates may need to organize a social movement to convince influential groups in society that their own interests suggest the project should be supported (Bainbridge 1976). Economic growth has an impact at every stage in the emergence of new projects, including years before in the training of experts who will do the necessary work. Many kinds of research will directly or indirectly increase the economy, thus producing a positive feedback loop. Over four decades ago, a computer simulation study called *The Limits to Growth* (Meadows et al. 1972) modeled such negative consequences as environmental pollution and resource depletion, and over two centuries ago Thomas Malthus (1798) argued that human population growth would end in a grim conflict beset by starvation, disease, and war over limited resources. Thus one of the key scientific and technological questions for humanity is why Apollo did not lead to human colonization of the solar system and ultimately exploitation of all the resources of the universe. One possible answer might be that progress in the future will consist of ever-increasing scientific knowledge, technology progress, and cultural productivity, with a stable human population assured everlasting well-being here on Earth by sustainable technologies.

The *Specialization Network Theory* notes that the opportunities for connections (C) between pairs of fields increase not merely at the same rate as the number (N) of fields but following the formula $C = N(N-1)/2$, thus exponentially. In his presidential address to the American Sociological Association, Douglas Massey (2002) argued that this formula drove the prehistoric increase in human intelligence, as the populations of social groups increased, and he postulated that today we have reached a new evolutionary threshold as primitive tribes vanish and cities become the residences of the majority of humans. Increase in the possible combinations of innovations is one of the ways in which divergence creates conditions conducive for convergence, a general principle mentioned in several chapters of this handbook. By analogy, the extensive rigorous research on social networks can illuminate the present situation, in which the connectivity of the network is incomplete (Burt 2004; Granovetter 2005). If scientists and engineers in several adjacent fields invest time and energy organizing convergence within their limited territory, a dense local network of connections can be most effective. However, this inward focus can insulate them from innovative ideas generated in distant fields that are not yet participating in the local convergence. As they evolved over the nineteenth and twentieth centuries, distinct sciences and fields of engineering emerged in the organizational structures of educational institutions and industries Ziman (2003). The really creative potential for convergence now may be the greatest in what could be described as long-distance chains of network connections, linking previously unconnected areas of human endeavor, even dynamic in pulsing between convergence and divergence.

The *Reverse Salient Theory* uses a military metaphor to highlight the fact that some areas of science and engineering may lag behind as others advance. Traditionally, a *salient* was an intrusion by one combatant on a battlefield into territory held by the other, and a reverse salient was a sector that failed to advance when those on either side were doing so. Thomas P. Hughes (1983) introduced this concept to the analysis of technological development in a study of a highly convergent and significant example, the development of the electric power and appliance industries in 1880–1930. More than a mere metaphor, the concept of reverse salient covers several kinds of problems that can arise, especially concerning how the existence of a reverse salient can retard progress all across the line of advance. A key example Hughes offered was the problem that earlier electric utilities had in transmitting power to customers, because they generated direct current (DC) rather than the alternating current (AC) that proved more efficient for power transmission. Progress required switching from DC to AC, yet that transition proved difficult politically as well as technically, although progress in the development of a wide range of electrical appliances depended upon it. The very rapid advances of recent decades in foundational emerging fields such as information technology, nanotechnology, and biotechnology imply that many other areas have been left behind, becoming effectively reverse salients.

The *Fundamental Principles Theory* begins with the observation that many sciences have progressed historically from rather superficial documentation of facts to ever deeper explanations of a more profound and abstract character. Most obviously, many statements of scientific laws take the form of mathematical equations, and some of those formalisms may be similar across fields. A less technical kind of example is the use of metaphors, such as saying that a political campaign has momentum or that one person is attracted to another. We may have reached a point in history when many fields of discovery and invention have developed abstractions that now can be compared, linked, and combined across traditional disciplines using multidomain higher level languages. One example would be computerized gene sequencing in which molecular biology has developed a model of the structure of DNA and tools for measuring variation within a conceptual system that is very amenable to computer analysis. The four nucleobases of DNA are isomorphic conceptually with two bits of computer memory: 00, 01, 10, and 11. The fact that it takes much more memory to represent the structure of each base, of each base pair, and of an entire strand of DNA illustrates the necessity of connecting two intellectual disciplines at the level of abstraction appropriate for one's goal. There are several examples in which a concept from one of the natural sciences facilitated progress in social science, notably the emergence of *human ecology* a century ago, conceptualizing cities in terms derived from ecology in biology (Gaziano 1996), and transfer of concepts from semiconductor physics to analysis of human professional career paths (White 1970).

The *Progress Asymptote Theory* assumes that discovery and invention have natural limits, and as fields of science or engineering approach their own limits, much of the last progress they can achieve is through cooperation with other fields (Horgan 1996). A well-known potential example is the science fiction dream of colonizing the galaxy. If humans can expand beyond the solar system, then there may be no limits to what they can achieve. Yet the laws of physics prevent travel faster than the speed of light, and the energy required to accelerate to even a large fraction of that velocity would exceed that achievable even by nuclear fusion engines, which we seem very far from being able to build. Limits to human progress are not precisely defined by natural laws, because there also are issues of economics. In this example, it is not entirely implausible that colonizing fleets of spaceships could reach nearby stars, if they were like cities with self-contained economies that could travel for thousands of years and generations of human passengers. The question then becomes one for the social sciences to answer: What could motivate people to make the astronomically costly investments required to achieve galactic colonization by such means? The proper response may however be to change the terms of the debate, admit that humans cannot fly across immensity to the stars, and seek gratification in much more limited but intellectually consequential activities, such as exploration of the solar system by means of robot vehicles (Vertesi 2015).

The *Exogenous Revolution Theory* holds that radical shifts in other areas of society can trigger paradigm shifts in science and engineering. The classical theory of scientific paradigms offered by Thomas Kuhn (1962) can be summarized in terms of three possible conditions a science may be in: (1) pre-paradigmatic science, in which no overarching set of principles has yet been established, (2) normal science in which a set of principles has been established and works well to achieve incremental progress, and (3) revolutionary science in which a paradigm shift occurs. The usual model of a paradigm shift assumes only very modest *cultural lag* (Ogburn 1922), because data accumulate that imply the existing paradigm needs to be changed and the younger generation of scientists are ready to promote that needed change. However, Kuhn's work was based on historical study of scientific revolutions that actually occurred, missing the possibility that some failed to happen or were unnaturally delayed. A fourth possibility may already have happened in sciences that today seem to be progressing unusually slowly, a form of paralysis, perhaps because data that might disconfirm the old paradigm have been ignored or members of the younger generation are too well indoctrinated in their educations to the old ways of thinking (cf. Shwed and Bearman 2010; Malamud 2011). At this point Arnold Toynbee's (1947–1957) challenge-and-response theory enters the picture. He argued that a stable society is led by an elite that deserves its high status because it has solved the major social problems. But stability can be dysfunctional, and elites are occasionally tested by how well they respond to external challenges. If some areas of science and technology are too comfortable today in their stability, they may face unexpected challenges from the wider society that break the chains of convention and motivate innovation.

The *Social Problems Theory* notes that innovation has often been motivated by the desire to overcome some disadvantage shared by many people, such as infectious disease or the difficulty of long-distance transportation. Thus some of the most unfortunate current trends may be clouds with the silver linings of innovation that will in the future outweigh the current harm. A current example is the uncertainty about whether information technology is aggravating unemployment, as some thoughtful critics and research studies warn (Brynjolfsson and McAfee 2011; Frey and Osborne 2013), or could increase human job opportunities if adequate education programs existed to prepare workers for progress. Some evidence suggests that the decreased wealth and security of working class people in advanced nations may result not from information technology but from increased exploitation by societal elites and outsourcing of jobs to other nations (Elsby et al. 2013). Exactly what kinds of technological innovation would be the best responses to this complex problem cannot be predicted here, although clearly convergence would be central to any serious solution. International trade is itself a form of convergence, facilitated by convergence by information technology with the fields on which many industries are based. By their very definition, social problems place humans at the center of concern, and a better future may therefore require convergence of science with the social sciences and humanities.

Humane Sciences

As technology provides the material basis for human life and science provides the best route to achieve correct understanding of the nature of human existence, both should serve the needs of human beings. From the very beginning of the series of

Converging Technologies conferences and book-length reports, it has been obvious that this meant cognitive science needed to be included as a coequal partner and also serious attention needed to be devoted to ethical issues. A large number and diversity of scientists and engineers contributed to this effort, creating an implicit convergence society that was generating a convergence culture. Thus the social sciences became a coequal partner as well, both examining how convergence functions within science and engineering and examining the implications for humanity of these revolutionary developments (Bainbridge 2007).

Two related criticisms have frequently been raised against the social sciences. First, research in many of these fields does not seem to lead to definite conclusions, as studies in physics, chemistry, and biology often do (Bendix 1970; Shapin 1995). Second, political conservatives sense that a disproportionate number of social scientists are biased against conservatism and serve as support troops in a culture war to expand the powers of government, investment in social welfare programs, and secularization (Larsen 1992). Certainly, we could cite many counterexamples, such as the fact that demographers are able to measure birth and death rates accurately and many economists seem supportive of capitalism or free markets. Yet there is some truth in both accusations, and they reinforce each other in generating widespread doubts about whether the social sciences are really sciences. However, this dissonance between political conservatism and social science may be merely a reflection of the convergence-divergence dynamic considered in several chapters of this handbook and thus may be historically contingent rather than necessary. Indeed, the current dissatisfaction with government leaders and institutions may reflect a natural stage in the Era of Convergence, at which increasing numbers of people are ready for a change that does not require turning left or right but ascending upwards.

To the extent that the social sciences really are inexact, they share this defect with several of the natural sciences, paleontology, for example, in which human judgment is required to make sense of very complex realities. The laws of social behavior could be described as probabilistic or contingent. For instance, it has long been known that crime rates are especially high in neighborhoods of a city where migration rates are high and formal community organizations are weak. This has been framed in terms of *control theory*, which holds that individuals will tend to stray from the norms of the society unless they receive considerable influence from other members to conform (Hirschi 1969). However, this theory cannot predict exactly which individuals will perform which crimes. That depends not only upon random events but also upon complex factors that shape the economic geography of cities, the vitality of formal organizations like schools and churches, and the legal system itself that defines the norms.

Social scientists have long accepted the fact that much of human reality is created by human beings themselves and thus has a relativistic quality. The so-called Thomas theorem states: “If men define situations as real, they are real in their consequences” (Thomas and Thomas 1928, 572). In the turbulent 1960s, it became popular to say that reality was a *social construction* (Berger and Luckmann 1966). However, *construct* has two very different meanings: to build or to construe. Yes, societal institutions are created by humans, and thus they are historically contingent with somewhat arbitrary and unstable consequences. But especially in legalistic language, a *construction* is an interpretation of reality, which according to the Thomas theorem can have consequences even if it is not objective. In 1970, Alvin Gouldner predicted that social science was headed for a major crisis, precisely because it could never be wholly objective, but still was absolutely essential to the future well-being of humanity. Truth about human realities is *reflexive*, only partially objective, reflecting very much the position of the particular scientist in society.

Political critics of social science, who often accuse it of being merely a rhetorical instrument for left-wing ideologies, may not have the historical perspective to realize that some social sciences were politically more diverse in past decades, especially prior to the 1960s. As this was the case, then potentially social science could become politically more diverse again in the future, which would seem beneficial. One of many prominent examples was Pitirim Sorokin (1937–1941), who offered a comprehensive theory of the rise and fall of civilizations that would be very much in harmony with today's conservative perspectives. A civilization is born during a period of extreme crisis, as a social movement coalesces around a somewhat arbitrary set of cultural assumptions, such as a messianic religion, and conquers territory, often through bloody conflict against other movements that are less well organized. At birth, a civilization therefore is *ideational*, setting goals that are spiritual or transcendent. Over time, given peace and prosperity, the civilization will seemingly become ever more significant but actually begin to decline, as its faith is eroded and individual action becomes self-serving rather than self-sacrificing. That is, the civilization becomes *sensate* or hedonistic and enters an inexorable course of decline and fall. Sorokin was nearly killed by the Marxists during the Russian Revolution, so when he founded the sociology department at Harvard, he did not base it on left-wing principles.

A theory of very large-scale human institutions, like Sorokin's model of the rise and fall of civilizations, is very hard to test. He had his students classify works of art over the course of centuries, finding the predicted shift from ideational to sensate, but critics were not convinced their methods were rigorous. Clearly, we cannot use experimental methods to test a theory like this, for example, setting up a thousand civilizations with only half of them beginning with a strong ideology. Today, some leading conservative intellectuals apply similar ideas to the malaise of postindustrial societies (sensate perhaps) versus the chaos of the Middle East (ideational if any faction wins the conflict). Sorokin's theory is not only right-wing but pessimistic, yet can be framed in terms of convergence-divergence. A civilization is born in a massive cultural and social convergence and dies in an unlimited divergence. Yet, perhaps civilization need not fail if there is a properly dynamic convergence, such as a mutually respectful partnership between right-wing and left-wing politics, and a divergence network of new industries, societal institutions, and even forms of culture. Success in this difficult combination of convergence and divergence may require a modular form of social theory, in which a vast inventory of sub-theories can be combined in different ways to explain and enhance a variety of human phenomena (Markovsky 2010).

A political convergence in collaboration with social science could be extremely beneficial for society and achievable, given the widespread consensus that politics in advanced postindustrial nations has become dysfunctional. Exactly why this is happening remains open to debate, and more attention seems to be given to the symptoms rather than the causes. In 1973, sociologist Daniel Bell offered the most profound analysis of postindustrial society, arguing that scientists and engineers should play central roles in government decision-making, thus advocating convergence of all forms of expertise at the highest levels of society. One interesting empirical piece of data about Bell's analysis is that his work can be conceptualized either as left wing or right wing or something above and beyond them both. Bell liked to think of himself as a socialist, as he was prior to his university education when he belonged to a radical group. Yet as a mature adult, he played very significant roles in the formation of the orientation called neoconservatism. Prior to writing *The Coming of Post-Industrial Society*, he had written *The End of Ideology* which did not predict that ideology would necessarily vanish, but would cease to play valuable functions in society (Bell 1960). Thus his highly respected works were a prelude for political convergence, even as he acknowledged that the transition might be difficult.

Convergence need not result in uniformity. When the right quantities of steam and ice combine, the result is water at an intermediate uniform temperature. But convergence in both the social sciences and societal governance could preserve diversity, as people with different expertise and ideologies would value each other in a division of human intellectual labor, in which each specialization contributes distinctive benefits to the well-being of all. Indeed, the result could be a new kind of civilization, rendering Sorokin's theory obsolete if it was ever true. Integration of science into society could even benefit those most human of creations, the expressive arts and humanities (Snow 1959).

Consider how music, among the most universal forms of human artistic expression, can be fully understood only through the convergence of mathematics, natural science, technology, social science, and the humanities. A musical tone is a vibration in the air at a specific frequency, and essentially every stringed musical instrument embodies the fact that two tones an octave apart have wavelengths in the ratio 2:1. Remarkably, human hearing covers a range of ten octaves, and the sensed quality of any musical tone is shaped by the overtone series of higher pitches that have wavelengths integral fractions of the fundamental tone. The consonance or dissonance between two tones is a reflection of the ratio of their frequencies, and melodies often exploit the fact that intervals with complex ratios tend to produce an emotion of strain, while simple ratios can resolve that tension. A simple melody or a complex symphony arouses in the listener a sense of expectation for what sound should be heard next, and the dynamism of music results from an interplay between expectations that are violated or satisfied (Meyer 1956). These expectations are largely defined by the culture to which musicians and audience belong, even the subculture of enthusiasts for the particular musical genre, and a symphony performance is social in that performers interact with each other and that the orchestra and the audience interact in their shared consciousness even before the obvious response of applause. All of the arts employ technologies, from oil paints to ballet shoes to poetry books, but musicology may be among the most scientific of the humanities.

Globalization entails internationalization of science and engineering, and it is interesting to compare how different nations have organized their support for research. Admittedly with some debate, in the US government, support for the social sciences was significantly performed through the same agency as that supported physics, biology, and engineering: The National Science Foundation. Yet in neighboring Canada, a nation at an identical level of scientific development and a similar history, support for the social sciences is led by the same agency as support for the humanities: The Social Sciences and Humanities Research Council. As described on its website in June 2015, it seeks to achieve goals that require integration of social sciences and humanities:

> We build knowledge. We develop talent. The Social Sciences and Humanities Research Council of Canada (SSHRC) is the federal research funding agency that promotes and supports postsecondary-based research and training in the humanities and social sciences. By focusing on developing Talent, generating Insights and forging Connections across campuses and communities, SSHRC strategically supports world-leading initiatives that reflect a commitment to ensuring a better future for Canada and the world.
>
> SSHRC-supported research in the social sciences and humanities enhances our understanding of modern social, cultural, technological, environmental, economic, and wellness issues.
>
> It raises profound questions about who we are as human beings, what we need in order to thrive in complex and challenging times, and where we are headed in the new millennium.
>
> The work SSHRC supports encourages the deepest levels of inquiry.
>
> It spurs innovative researchers to learn from one another's disciplines, delve into multiparty collaborations and achieve common goals for the betterment of Canadian society.
>
> Research outcomes are shared with communities, businesses and governments, who use this new knowledge to innovate and improve people's lives.

A common principle shared by democratic societies is that government requires the "consent of the governed." In part this is accomplished by organizing politics around competing interest groups that serve the common good by behaving somewhat selfishly. That is, each faction seeks benefits for its own constituency; voters shift their allegiances as they assess their own personal interest, and the result is the greater good through a dynamic majority. But there is a very different way to conceptualize democratic systems, not as fierce competitions between teams seeking selfish benefits but as friendly debates among peoples who have different perspectives on life. In science, a perspective is literally a location from which to observe reality, potentially equal in value to every other perspective, but incomplete. Only by *triangulation*, by combining information from very different viewpoints, do we gain a complete picture of the truth. Thus, convergence of science with society could transform politics from a battle to collaboration, in which people with diverse needs and perspectives work together to discover the best possible future for humanity.

Conclusion

The handbook is organized in six sections, beginning with chapters on the concepts and methods that facilitate convergence between previously separate fields of science and engineering. The main sections are (1) Concepts and Methods, (2) Foundational Technologies Platform, (3) Human-Scale Platform, (4) Earth-Scale Platform, (5) Societal-Scale Platform, and (6) Convergence in Education. The concepts and methods provide the ideas and analytical tools that are of value across all four platforms described in sections (2) to (5), while the concluding education section surveys how all the other materials can be taught to students and will enhance the way both professional training and societal progress can be achieved.

The division into four *platforms* unfolds the dense system of scientific and technological topics into groups of chapters that have affinity with each other, thus representing conceptual divergence in a system designed around convergence. We might have called these four *stages*, in that they are like theater stages on which different scenes of a drama will be presented. But *stage* often implies a period in a process of maturation, while these four are equally advanced and with equal significance for the future. *Platform* can mean a plan of action as well as the physical location that supports an activity.

The intellectual contributions of literally hundreds of scientists and engineers made this handbook possible, involving far more than the authors and editors, also certainly the other participants around the world at 15 years of conferences, and the authors of all the literature cited here. Indeed, one way to conceptualize the handbook is a gateway to a coherent world of science and engineering, which is to say the world in which we all live. The handbook invites readers to consider a vast number of research methods and analytical principles that could unite disparate fields, but the greater hope is to use them as vehicles for uniting humanity. The importance of those goals is increasing in time as the human activity domains and their complexity and networking are expanding. The culmination will be convergence of knowledge and technology for the benefit of society, defined as the escalating and transformative interactions among seemingly different disciplines, technologies, communities, and domains of human activity to achieve mutual compatibility, synergism, and integration.

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Part I

Concepts and Methods

Principles and Methods That Facilitate Convergence

Mihail C. Roco

Contents

Abstract

The main benefits of science and technology convergence are increasing creativity, innovation, and productivity. Various methods to improve and expedite convergence aim at adding value in the convergence process and enabling people to more readily use new convergence-enabled competencies. These methods are based on applying five general principles of convergence:

1. *Exploiting interdependence among domains*: Convergence methods associated with this principle include integrating originally distinct domains and databases of science and technology; forming efficient science and production networks and ecosystems; changing local interactions and guided self-organization in systems to encourage, enable, and reward desired outcomes and governance improvements; supporting system science and team science; and advancing S&T dedicated social networking, holistic management, and interpersonal and intrapersonal education.

M.C. Roco (✉)
National Science Foundation and National Nanotechnology Initiative, Arlington, VA, USA
e-mail: mroco@nsf.gov

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2. *Improving the convergence–divergence evolutionary cycle*: Convergence methods associated with this principle include balancing support for the creative, integration, innovation, and spin-off phases of the process; supporting the cross-domain spiral of innovation; facilitating open collaboration and innovation; combining knowledge and technology pushes from the convergence stage with societal pulls from the divergence stage; and scaling up knowledge and technology diffusion in the divergence stage.
3. *System-logic deductive decision making and problem solving*: Convergence methods associated with this principle include a holistic approach to problem solving in complex systems; combining deduction with induction, lateral, and time evolution approaches in decision making; balancing bottom-up research with top-down vision; and using knowledge mapping, network visualization, and fractal analysis to identify the relevant cause-and-effect system patterns.
4. *Creating and applying high-level cross-domain languages to facilitate transfer of knowledge and new solutions*: Convergence methods associated with this principle include using universal languages such as mathematical abstractization, music, and general system architectures and focusing on essential aspects through "simplicity"; promoting technology integrators and benchmarking to facilitate introduction of emerging technologies in multiple areas; and creating and sharing large multidomain databases and trading zones between areas of research and education in distinct areas.
5. *Using "vision-inspired" basic research to address long-term challenges*: Convergence methods associated with this principle include forecasting and scenario development; promoting a culture of convergence based on common goals; anticipatory measures for preparing people, tools, organizations, and infrastructure; and reverse mapping and planning.

S&T convergence has the potential to transform the education, research, and production ecosystems. A challenge in proactively guiding the convergence process is to deliberately encourage public and private efforts that currently contribute to the *unguided* convergence of knowledge and technology to use a *systematic approach* to convergence that may amplify the most beneficial endeavors in the knowledge society. Illustrations of applying the methods for convergence to research, development, and education governance are discussed.

Introduction

This chapter presents methods to implement and facilitate a more effective and more rapid process of convergence across scientific and technological fields or domains. The term convergence as applied to science and technology (S&T) encompasses the full breadth of human activity:

> Convergence includes all relevant areas of human and machine capability that enable each other to allow society to answer questions and to resolve problems that isolated capabilities

> cannot, as well as to create new competencies, knowledge, technologies, and products on that basis. The convergence process consists of the escalating and transformative interaction of seemingly different disciplines, technologies, and communities to (a) achieve mutual compatibility, synergism, and integration, and (b) create added value (generate new things, with faster outcomes), to meet shared goals. The convergence process is evolutionary and non-uniform. It requires a preliminary degree of development in each domain; it begins with achieving reciprocal compatibility [between fields of study] such as in communication and knowledge exchange, and it leads to changes in the system in terms of its assembly, functions, and outcomes. The initial interactions between fields of study may be either coincidental or deliberate. (Roco et al. 2013, pp 139–140)

In the history of scientific and technological development, it is typical that a convergence process is followed and enhanced by a process of *divergence* where new knowledge gained in the convergence process begins to be applied creatively in entirely new activities and situations. The ultimate value of this *convergence–-divergence cycle* is that it leads to unanticipated scientific and technological applications and solutions (Fig. 1). This process conceptually goes beyond the convergence of disciplines. In brief, "convergence is an approach to problem solving that cuts across disciplinary boundaries" (NRC 2014a, p. 1) and in that process provides disruptive opportunities for expanding, enriching, and benefiting the human experience.

Convergence trends have been inherent in natural and human development since the formation of assemblies of atoms in the material world and the earliest group interactions in tribal life. What is new in the early decades of the twenty-first century is the increasing importance of convergence as a means of both comprehending and harnessing the fundamentally new and rapid scientific and technological advances of our time in our more crowded and interactive world. Despite the distinct benefits of breaking down the long-established boundaries between traditional S&T domains and disciplines, fostering convergence is not a straightforward process. To date, the research and development (R&D) focus for converging technologies has remained reactive (or "coincidental") to various opportunities for collaboration rather than being driven by a holistic, systematic, proactive approach. There is a need for a *methodology* of convergence to help people understand, guide, and expedite the convergence process to best achieve its added value and visionary outcomes. As noted in the 2013 National Academy of Sciences Workshop on Key Challenges in the Implementation of Convergence, "Organizations and practitioners wishing to undertake convergence face a lack of practical guidance in how to do it" (NRC 2014a, p. 34). Ideally, a "science of convergence" will emerge to provide the necessary guidance.

The possible scope of convergence applications is diverse and broadly practical, encompassing improving the "innovation chain," digital and distributed manufacturing, individualized and integrated healthcare and education, understanding the human cognitive process, empowering individuals and groups through broadening and expanding education, and farsighted governance of science and technology development.

S&T convergence concepts in a broad sense began to be introduced late in the twentieth century by E.O. Wilson (1999) and Ray Kurzweil (1999), among others.

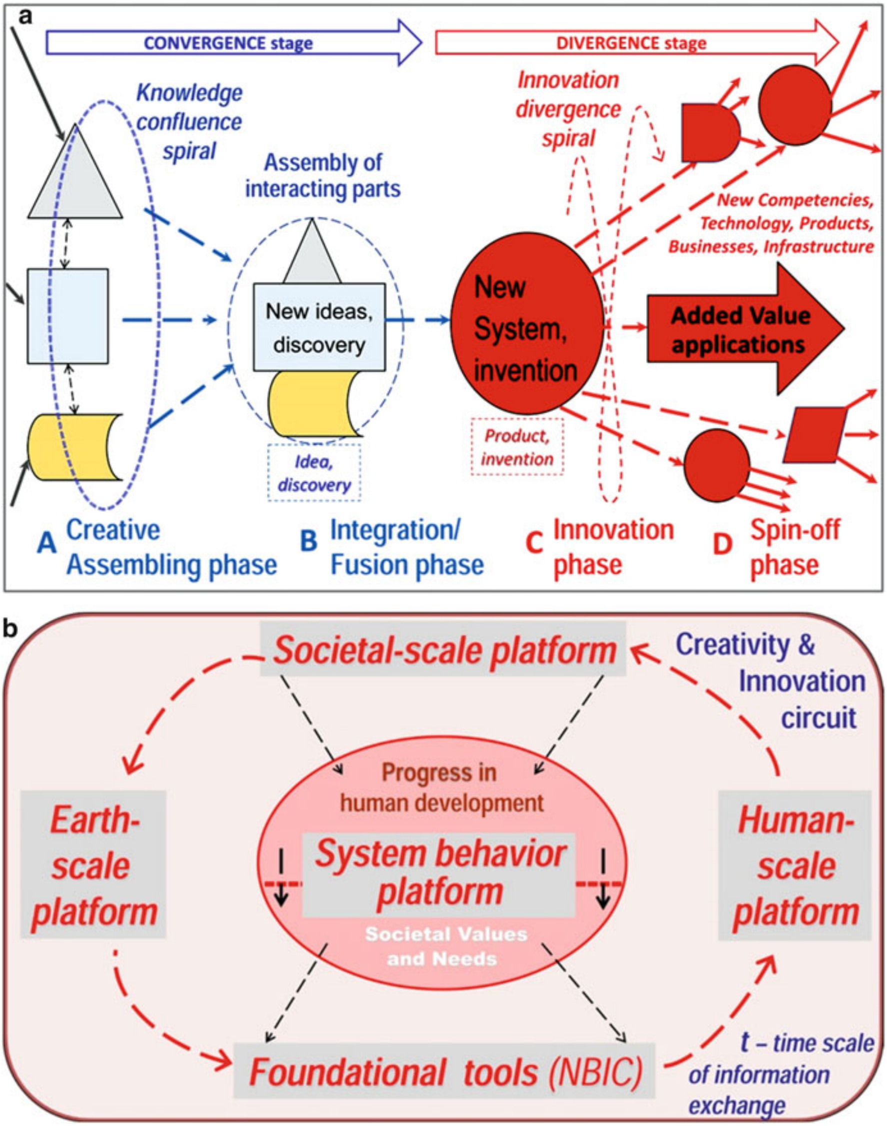

Fig. 1 The evolutionary convergence–divergence cycle of processes in the human activity system: (a) the convergence–divergence cycle with its four phases, creative, integration, innovation, and spin-off, and (b) the human activity system with its five essential convergence platforms, system behavior, foundational tools, and human-scale, Earth-scale, and societal-scale platforms (Modified from Roco et al. 2013, p. 141, Fig. 4.1)

Although the general public has not become fully conversant with the term *convergence*, the significance of convergence to continuing progress in science and technology – as well as to resolving national and international medical, social, economic, environmental, and security issues – is widely appreciated within scientific and academic communities. A number of US universities such as Arizona State University, Harvard, MIT (Sharp et al. 2011; Sharp and Langer 2011), Stanford, State University of New York at Albany, and University of Wisconsin–Madison have in the past decade undertaken efforts to foster convergence in some specific areas (Roco et al. 2013). Convergence also is becoming increasingly visible in policy arenas. Targeted convergence efforts have been initiated by the European Union (EU), Korea, Russia, Japan, and China, among others. An example in EU is the project Knowledge Politics and New Converging Technologies; A Social Science Perspective, funded by the European Commission under Priority 7 of the 6th Framework Programme. Several national and EU science and technology multiyear plans are beginning to use components of the convergence approach within their own political contexts and requirements. Korea has set up a Future Convergence Research Policy Division at the Korea Institute of Science and Technology (http://eng.kist.re.kr/kist_eng/?sub_num=540). An example in Russia is the Kurchatov Institute Centre of Nano-, Bio-, Info-, and Cognitive Sciences and Technologies in Moscow (http://www.kiae.ru/e/nbic.html). The Kurchatov Institute is Russia's National Research Centre. An illustration in China is the program "NBIC–New Opportunity for China" at the National Natural Science Foundation of China. In the United States, one policy example is the initiation of NBIC research efforts in several agencies about 2001 (Roco and Bainbridge 2003). In another example, the National Cancer Institute at the National Institutes of Health has set up a series of Physical Sciences-Oncology Cancer Centers to support the convergence of biology with physical sciences and engineering in the fight against cancer.

Proactively applying S&T convergence principles aims at transforming the culture for setting integrated and visionary education, research, and production projects. Corresponding "*governance*" practices change relationships in a societal system, in a way that is fundamentally different from top-down "*governing*." Besides the format in which relationships are brought together in the S&T development ecosystem, convergence in governance also includes setting the goals and evaluating the results of the convergence process. S&T convergence may be implemented (1) horizontally between various domains of basic research, applied research, or applications, (2) translationally from basic research to applications, or (3) evolutionarily between various ecosystem states over time.

A carefully developed convergence infrastructure that includes a portfolio of methods and/or expert system platforms can help organizations and practitioners to select the most valuable methods of integration and domains of application. This chapter proposes methods for R&D performing and funding organizations and individuals to proactively, thoughtfully, and ethically manage convergence of the revolutionary advances taking place in scientific knowledge and technological know-how in order to achieve maximum benefit to society. The proposed methods are grouped within the context of five general principles that underpin them: (1) exploiting interdependence among domains, (2) improving the convergence–divergence evolutionary cycle, (3) system-logic(-based) deductive decision making and problem solving, (4) creating and applying high-level cross-domain languages, and (5) using "vision-inspired" basic research to address long-term challenges.

Exploiting Interdependence Among Domains

The principle of interdependence among domains observes that all aspects of both natural and human activity systems constitute a holistic unit. Applying the interdependence principle to S&T convergence endeavors produces coherence among individual processes through network structuring, transformation, and interactions between processes. It then generates changes in the system – changing the links, nodes, and overall system over time. This leads to evolutionary hierarchical structures – polycentric systems, new knowledge convection and diffusion patterns, to name those most relevant – which together determine the long-term evolution of the system.

Key methods to facilitate convergence based on exploiting (*and cultivating*) *the interdependence among S&T domains* take various forms, including (a) identifying the essential convergence platforms; (b) integrating originally distinct domains of science and technology; (c) establishing large multi-topic sets of databases and expert systems; (d) forming efficient science and production networks and ecosystems; and (e) introducing system science, team science, open learning, social networking, linking of diverse cultural environments, and other methods that take advantage of interdependence.

Identifying the essential convergence platforms can best take place after common concepts, tools, players, and network architecture are evaluated. Five general convergence platforms were identified for the entire human activity system by Roco and Bainbridge (2013; also see Fig. 1) based on the main players, unifying tools, and goals. They are (1) foundational science and technology tools, (2) human-scale and quality-of-life systems, (3) Earth-scale systems, (4) societal-scale systems, and (5) system behavior platform. Within each of these five platforms, other hierarchical platforms may be identified at a lower level.

Integrating originally distinct domains of science and technology is a way to exploit the benefits of interdependence and synergism in large systems. An approach in S&T is using technology "*integrators*" such as nanotechnology or information technology across multiple application areas. *Partnerships between distinct disciplines and sectors* are another mechanism to stimulate convergence and increase collaboration among academic, industry, and government sectors. As industry has reduced its investment in internal basic research, it has looked to the academic community for research discovery. As an illustration, the semiconductor industry has formed several extended partnerships with federal and state governments to co-fund use-inspired basic research pertinent to its interests: the Semiconductor Research Corporation's (SRC) Nanoelectronics Research Initiative (http://src.org/program/nri/) is co-funded by industry, the National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST); and the SRC's Focus Center Research Program (http://www.src.org/

program/fcrp/) is funded by roughly 50/50 cost sharing with government. Another illustration is international partnerships under international organizations such as the Organisation of Economic Co-operation and Development (OECD) where a convergence group has been created with a focus on biotechnology and nanotechnology.

Establishing large multi-topic sets of databases and expert systems from distinct domains using informatics and computer simulations that cross between topics is a way to increase interdependence and interaction between potentially synergistic areas.

Forming efficient science and production networks and ecosystems can be accomplished by changing local interactions, node functions, or network structures to produce desired outcomes. A specific approach based on understanding system dynamics (Meadows 2008) is self-organization in large complex systems *triggered by local interaction mechanisms* (as observed in studies such as those by Robinson et al. 2014). Creation of ecosystems can be illustrated by converging knowledge and technology supporting personalized medicine – rooted in the integration of medicine, electronics, robotics, bionics, and data handling – leading to an increase in average life expectancy. Another illustration is personalized online education – rooted in advances in neuroscience, communication, psychology, and understanding of learning – for both formal and informal lifelong learning.

Various researcher network systems have been connected to institutional data via websites systems such as VIVO (the "Facebook for researchers," http://vivoweb.org), Harvard Catalyst Profiles (http://profiles.catalyst.harvard.edu), Stanford CAP Network (http://med.stanford.edu/profiles), Academia.edu (the "Linked In for academics"), and Elsevier SciVal Experts (http://www.scival.com/experts). Since these systems function primarily as profiling services where members can find expert members in the systems, they currently lack the opportunities created by open-communication functionality and resource sharing; collaboration has to be done through email outside the systems. HUBzero® (http://hubzero.org/) has taken this web-based researcher network concept further by providing an online space for sharing resources and collaborating; however, it is still limited to members only, and each hub is only available for a specified expertise group. For example, nanoHUB (http://nanohub.org/) is for nanoscience researchers and the C3Bio hub (http://c3bio.org/) is for researchers involved in energy and carbon efficiencies of biofuel production.

Introducing system science and team science concepts into R&D procedures allows researchers to take advantage of interdependence and synergism in a systematic way (Boardman and Ponomariov 2014). Convergence methods that support system science include specific tools such as neural networking and logic models that underlie system interactions, as evident in evolutionary biology (Carroll et al. 2014) and evolutionary computational design for system convergence (e.g., the BEACON project website http://beacon-center.org/; Goodman 2014). The science of team science (Wildman and Bedwell 2013; Vogel et al. 2013) is an approach that has evolved to the point of establishing a professional organization (http://scienceofteamscience.org/). Locking together hard and social sciences in system sciences and particularly in large socioeconomic projects has to be done from the beginning in convergence programs.

There are other possible methods to support convergence based on interdependence of domains:

- Advancing interpersonal and intrapersonal education and implementing holistic management are specific methods to adapt to today's increasingly networked and diverse working environments. Creating S&T dedicated social networking is a relatively recent development with growing ramifications.
- Convergence in the investigation of natural phenomena (analogous to convergence in the unifying definition of forces of matter) will accelerate and underpin the technological effectiveness of society.
- Open learning systems (e.g., the Khan Academy for large groups, NSF's Integrative Graduate Education and Research Traineeship (IGERT) program, and many others) promote more integrated and interactive education that can bolster convergence.
- Meditation is an approach to making connections between close and distant (in space or time) events.
- An overall goal of convergence is to support a *culture* (NRC 2014b) that is guided by principles of interdependence and connectivity.

Open science is a key approach for the creative and innovation phase of convergence, and it has already begun to change the knowledge and technology culture. Open science primarily consists of "collaboratories" and "citizen science" where collaborations are almost entirely virtual. Already, scientists are beginning to talk about open science as an approach in which specialists, nonspecialist scientists, and nonscientists can fruitfully collaborate via new Internet-based means of communication and novel research methodologies (Woelfle et al. 2011). Several important information technology developments are expected to converge in the near future, with marvelous benefits for the unification of the sciences:

- The evolution of scientific data archives into digital libraries in the 1990s and into *virtual organization collaboratories* in the 2000s. Prominent examples include the Protein Data Bank (http://rcsb.org/pdb/; Berman 2012), the Computer tomography virtual organization (Tapia et al. 2012), and a computer-based archives network shared by astronomers (Djorgovski 2012).
- The emergence of *online citizen science* over the past decade, which began by using ordinary people as volunteer workers to collect and classify data, but which is beginning to include volunteers from a variety of technical backgrounds as actual collaborators. One example of using an innovative information technology approach to unite biology with nanoscience is the Foldit project (http://fold.it/portal/info/science), in which nonscientist volunteers collectively have been able to solve difficult problems in protein folding through an online game (Khatib et al. 2011). Another example is the 2010 Oregon Citizens' Initiative Review – a "citizens' jury" that deliberated the state's medical marijuana ballot

initiative and afterward shared their findings with the public prior to the statewide vote on the initiative (Gastil and Knobloch 2010).

- There will be an increased focus on *communities defining their own needs* for using convergence processes to address major issues affecting them, on an as-needed and/or as-requested basis, relying on self-regulation (through professional societies, nongovernmental organizations, etc.) in a manner that is less paternalistic than that of current systems.

Changes in business and manufacturing also are expected. Interdependence among domains and better communication means already have allowed vertical and large enterprises to be more distributed and specialized using information technology and advanced computing-enabled connectivity.

Changes in research and education governance will be reflected in new measures being taken in both R&D performing and funding organizations:

- Cross-disciplinary, cross-sector, cross-cultural, and international sharing of organizations, projects, and models in R&D endeavors needs to be encouraged based on mutual interests. An example is creating an information system on funding opportunities and compatible mechanisms of collaboration for all funding agencies within a region (such as the Americas or the EU).
- One approach is to support broader multidomain topics in R&D program solicitations, with reviews done by experts with diverse expertise. Examples are two National Science Foundation (NSF) programs, Nanoscale Interdisciplinary Research Team (NIRT, 2000–2008) where coprincipal investigators from at least three different departments must be involved and the Integrated NSF Support Promoting Interdisciplinary Research and Education (INSPIRE, 2012–2014) program where a project has to co-funded by at least two intellectually distinct NSF divisions or disciplinary programs. (Both program descriptions are available on http://www.nsf.gov.)
- Another approach is to establish or enlarge multidisciplinary, multidomain research and education units to create better ecosystems of collaboration. Such ecosystems begin with common goals and the distribution of spaces and schedules for shared research activities. Examples are the many university combinations of academic departments such as biochemistry and various engineering specializations. The Center for Nanoscale Science and Engineering in Albany has brought together disciplines ranging from basic sciences, to cutting-edge R&D in fields such as power electronics and extreme ultraviolet lithography, to commercialization of innovative businesses in partnerships with government and industry, all under the shared goal of educating and promoting a future pioneering workforce in nanoscale science and engineering.
- Changing the recognition system for researchers and faculty to support rigorous interdisciplinary work may include giving them credit for alternate research output such as research at multidomain boundaries, accomplishments within cross-domain centers, or other collaborations outside of their home units.

- Graduate students, similarly, may be encouraged to have advisors from at least two different departments. The NSF's IGERT program (2004–2014) is an example where funds are given to students who work under at least three different topic advisors.
- R&D funding and policy organizations may be encouraged to increase funding for new research and education networks and for creating support to enhance existing networking among scientists. An example is the open-source, open-access simulation, computation, and education network nanoHUB supported by NSF (2012–2014), where there were over 300,000 academic, industry, and government users worldwide from August 2013 to July 2014 (https://nanohub.org/usage).
- Corresponding coordinated changes are needed in organizational structures, strategic research planning, decision analysis, and measures to support multidomain R&D evaluation, decision making, and conflict resolution. Government organizational structures and regulations will need to be reexamined and updated to allow the convergence processes to be more effective and provide increased benefits to society. An example is establishing evaluation and networking organizations, such as the OECD's Working Party on Biotechnology, Nanotechnology and Converging Technologies formed in 2014 (OECD 2014). Another example is the formation of the Directorate of Convergence Research in the Korean National Research Council of Science and Technology in 2014. Including convergence of undergraduate education programs through the requirements of the college degree accreditation organizations (such as ABET in the United States) is another approach. The US nonprofit State Science and Technology Institute (http://ssti.org/) is an organization that interfaces between usually fragmented regional, state, and national S&T innovation and commercialization programs.

Improving the Convergence–Divergence Evolutionary Cycle

The principle of improving the convergence–divergence evolutionary cycle aims at taking advantage of the sequence in natural human problem-solving processes to realize outcomes in response to today's rapidly changing scientific, social, and ecological circumstances. The convergence–divergence cycle in science and technology development stems from human brain reasoning for reaching goals: first people focus on assembling and integrating information, implementing the action and then on applying the information to new scenarios. A typical S&T evolutionary process begins with people gathering knowledge from various fields and assembling it in new ways to reach an integrated outcome (the convergence stage) and then continues when that knowledge is disseminated to new areas through innovation and creation of new expertise, industries, businesses, and technology areas (the divergence stage) (Fig. 1a).

Convergence generates discovery and invention; divergence generates innovation and spin-offs that spur development of entirely new concepts and products. Both convergence and divergence are integral to the process of advancing knowledge and addressing societal dilemmas. The convergence–divergence process was first identified for large R&D programs (Roco 2002). The challenge for society is to improve and accelerate the processes of this convergence–divergence cycle to achieve optimal outcomes.

Key methods to facilitate convergence based on improving the convergence–divergence cycle necessarily depend on providing balanced support for the entire cycle, including its convergence and divergence phases. In the past, the divergence phases have not been fully considered in analysis. The convergence and divergence phases (see Fig. 1a) are (A) creative phase, (B) integration phase, (C) innovation phase with its spiral of innovation, and (D) outcome/spin-off phase. In addition, there is an evaluation and connectivity stage at the end of each cycle and before future cycles that leads to a Darwinian selection or efficiency in the evolution of research. R&D planning and governance for the full cycle must combine knowledge and technology pushes (typically from the convergence stages) with acknowledgment of societal pulls (typically from the divergence stages). Facilitating open access, collaboration, and innovation between key players is essential for interaction among the phases of the same cycle and among cycles. Improving knowledge and technology diffusion and scaling is essential in the divergence stage.

From an analysis of the spiral of innovation, it was determined that the innovation outcomes increase in direct proportion with the square of size of the convergence domain that can be configured for a selected project as part of human activity system (sketched in Fig. 1b) and in inverse proportion with the cube speed of the cycle (Roco et al. 2013). Accordingly, crucial factors for improving convergence are increasing the domain size and speed of interactions from the creative phase to the spin-off phase (A to D in Fig. 1a).

A method for improving *the creative/assembling phase* (A in Fig. 1a) is providing support for interdisciplinary interactivity among scientists and engineers from different traditional disciplines. Such support already is increasing. Recent research describes creativity as being spurred by real physical environments where people and ideas converge and synergies arise (e.g., in the books *Imagine* by Jonah Lehrer [2012] and *inGenius*: *A Crash Course on Creativity* by Tina Seelig [2012]). In a number of large companies such as 3M and IBM, scientists are rotated from one department to the next, regardless of their training, to spur synergistic and creative thinking. In several universities such as Cornell University and MIT, PhD students are rotated through various laboratories during the course of their studies. Creation of multidisciplinary campus spaces for faculty and students is a reality in an increasing number of campuses such as University of California, Los Angeles, and Seoul National University. One could imagine routinely rotating professors from department to department. Such practices need to be systematized and expanded.

Several methods for improving *the integration/fusion phase* (B in Fig. 1a) of the convergence–divergence cycle are:

- Mining broad-based S&T platforms that offer more integration opportunities. Such platforms may be formed by combining or working at the intersection of

the five general S&T platforms (foundational tools, human-scale, Earth-scale, societal-scale platforms, and system behavior platform), shown in Fig. 1b.
- Using multidisciplinary design methods, such as combining electronic, optical, fluid mechanics, thermal, and mechanical design approaches in optoelectronics.
- Making various manufacturing methods and phases of production compatible and synergistic by process integration, co-location, and common simulation of manufacturing systems and by developing advanced mind–cyber–physical systems.

Several methods for improving *the innovation phase* (C in Fig. 1a) of the convergence–divergence cycle are:

- Cultivating user-driven approaches such as use-inspired basic research
- Promoting open innovation and diffusion of innovation (NRC 2013)
- Pursuing participatory design and governance, such as designing and scaling up innovation for optimal divergence effects, and pursuing methods for distributed and hybrid manufacturing
- Using specialized software that provides conceptual alternatives for decision making

Several methods for improving and evaluating *the outcomes/spin-off phase* (D in Fig. 1a) of the convergence–divergence cycle are:

- Cultivating vision-inspired research.
- Identifying and pursuing high-priority common values and goals.
- Supporting foresight studies, including use of trend analysis, Delphi processes, scenario writing techniques, exploring downstream activities for identifying S&T integrators, and virtual reality methods.
- Increasing long-term planning and citizen participation. An example is reevaluating and taking steps to realign criteria for success in society by adding – besides economic output (such as GDP) – criteria such as accumulations in knowledge and technology, preparation for the future, and changes in education and infrastructure. Another example is sponsoring self-regulating convergence in self-reliant communities to support environmental sustainability.

Possibilities for improving R&D governance are notable in S&T planning in terms of allowing all four phases of the convergence–divergence cycle to contribute, using different methods in different phases of the cycle, ensuring smooth transitions between phases and between cycles, and paying particular attention to the divergence phase to anticipate where new and scalable competencies, products, and industries might be created. “Open innovation” (Chesbrough 2003) and evolutionary approaches (Carroll et al. 2014) should play an increased role in connecting the four phases A–D of the cycle and particularly those in the divergence stage (C and D). Chesbrough (2003) defined open innovation as an R&D paradigm that involves an R&D organization searching for and exploiting any and all internal and external forms of collaboration to create new S&T intellectual property as well as novel means of using and distributing that intellectual property. NSF's Innovation Corps (I-Corps 2014) funding program is an example of instituting means to systematically facilitate networking at the interface between research community and business community, between phases B and C in the cycle (Fig. 1a).

System-Logic Deductive Decision Making and Problem Solving

The principle of applying system-logic deduction to decision making and problem solving observes that optimal outcomes in complex S&T systems often arise from researchers considering the big picture and multiple approaches. Human activities are all interdependent through an evolutionary system that frames the decisions and solutions that are undertaken (Fig. 2 schematic). Considering the interactions throughout the entire system and selecting the best tools available from different fields are challenges for decision making and problem solving.

Key methods to facilitate convergence based on system logic and deductive decision making include (a) adopting a holistic deductive approach by considering multiple interaction pathways in complex systems; (b) combining top-down, bottom-up, interdisciplinary horizontal, and evolutionary approaches to decision making and problem solving; (c) facilitating human–computer and machine–communication network collaboration; and (d) using knowledge mapping, network visualization, and fractal analysis to identify the relevant cause-and-effect system patterns.

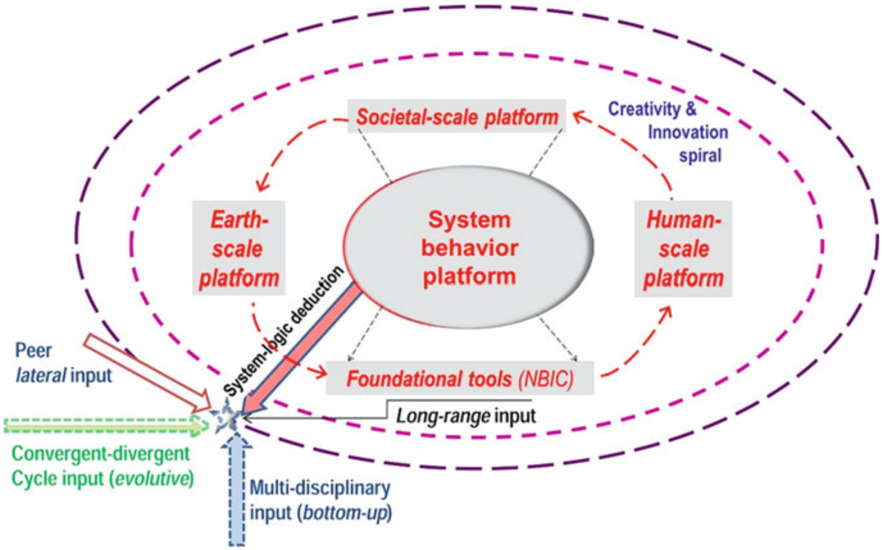

Fig. 2 System-logic deduction in decision making and problem solving. Results are better for larger systems with faster information circulations

The holistic deductive approach considers all system components and their causal evolution, using a combination of human, computer, and network capabilities. The applicability of the holistic approach is a function of how well the hierarchical structure of the respective system is known and whether the bottom-up, top-down, interdisciplinary horizontal, and longer-range links and processes are well understood. An example is Maslow's hierarchy of needs (Lester 2013) where important deductive decisions in life, depending on one's age, can be taken on five hierarchical levels: health, wellness (both physical and mental), social connections (e.g., friends and communications), independence (e.g., in transportation and decision making), and self-actualization (e.g., achievement, identity, and legacy). In another framework, a solution for energy conversion depends on the hierarchical context, and it is different depending on whether only a technology platform is considered (such as the most efficient gas-burning technology) or higher-level hierarchical societal goals are considered (such as using renewable energy in cities).

Combining top-down, *bottom-up*, *and other methods to decision making and problem solving* is a beneficial approach. It combines induction (e.g., bottom-up, from nanoscale analysis to macroscale findings), system hierarchical deduction (e.g., top-down, societal goal-driven science and technology), peer lateral interactions (between events at the same level or in other domains in a particular hierarchical structure), and the convergent–divergent time evolution (Fig. 2). The top-down deductive approach is essential in convergence to reach globally beneficial decisions. The results are improved as compared to coincidental collaborations or interdisciplinary work, where the collaborating parts and approaches are defined a priori. Also, the decisions and solutions for identical problems are different as a function of the size of the complex system under consideration. For example, renewable energy solutions may be limited to available resources in a given technology domain or geographical area.

Developing technologies for *facilitating human–computer network collaboration* entail using neuroscience, software engineering, sensing technologies, neuromorphic engineering, and other inputs. Combining human–machine–network enabling capabilities (NRC 2014a) is a trend in decision making. As an illustration, the factors influencing the effectiveness of transdisciplinary science initiatives are interpersonal (such as team cohesiveness) and intrapersonal (such as attitudes toward collaboration) and involve issues related to the physical environment (such as the spatial proximity of team workplaces) and to policies (organizational, technological, societal, and science policies) (Stokols et al. 2008).

Knowledge mapping, *network visualization techniques*, *and fractal analysis* are methods for identifying large patterns in the knowledge, technology, and societal systems, as well as related work going on in other disciplinary communities and other hierarchical levels that might benefit from collaboration.

Various R&D governance bodies may consider particular system-logic methods:

- Making decisions to balance the funding for emerging and converging technologies between bottom-up discovery-driven programs (the so-called "core" funding) and top-down vision or grand challenge-driven programs (the

so-called "initiatives" funding). This also means balancing funding between supply modes (grants and contracts to research units lead by principal investigators) and demand models (fellowships and awards to students and postdoctoral scholars and researchers). A system-logic approach also is needed to accelerate progress in penetration of foundational research in the nano-, bio-, information, and cognitive (NBIC) sciences in the economy and to create new industries and jobs at their frontiers and interfaces.
- Creating hierarchical logic systems for decision making in R&D funding programs. For example, for regulatory aspects of emerging technologies, governance functions apply to four levels of governance: (a) adapting existing regulation and organizations; (b) establishing new programs, regulations, and organizations; (c) building capacity for addressing these issues in national polices and institutions; and (d) advancing international agreements and partnerships (Roco 2008).
- Using informatics and decision-making approaches based on multiple sources, criteria for evaluation, and hierarchical levels.
- Using informal methods for addressing new situations typical in emerging technologies but not fully recognized by bureaucratic systems and for receiving long-range input.
- Using voluntary regulatory measures where there are overly complex and time-consuming formal regulatory approval systems.

Creating and Applying High-Level Cross-Domain Languages

The principle of creating and applying high-level, *cross-domain languages* observes that when the vocabularies of different domains become too narrow and specific, they obstruct understanding by practitioners in other domains, and conversely, when common vocabularies and syntaxes can be established between domains, all benefit through resulting cross-fertilization of ideas. By "convergence language" we mean the common concepts, nomenclature, network relationships, and methodologies used in the multiple domains of science, technology, and society. Languages evolve over time. Each scientific discipline and technology area has a specific language. An effective convergence process across an overarching science and technology platform will require a dedicated effort to create a comprehensive language for more facile communication and synergism among its disciplines, areas of relevance, and stakeholders or cultures. This will allow for better integration of the components and faster spirals of creativity and innovation. Establishing multidomain convergent (or higher-level) languages depends on finding what is common and essential across domains and determining words, idioms, and syntactical rules that are suitable to all those involved. Cultivation of higher-level languages is important in supporting "essential" thinking and fruitful transfer and application of new knowledge.

Key methods to facilitate convergence based on creating and applying high-level, cross-domain languages include (a) finding other domains that have common traits and goals, (b) using existing convergence languages, (c) creating and sharing large multidomain databases toward a universal language database, (d) creating "trading zones" between areas of research and education with common traits in distinct application areas, and (e) performing multidomain benchmarking.

Finding various domains that have common traits and goals (e.g., traits such as unifying physical, chemical, and biological concepts and theories or unifying goals for different technologies) is most fruitful after researchers' work initially in a single domain, so that experience may be used to generate cross-domain concepts, theoretical and technology integrators, and transformative methods. An approach to establishing a convergence platform and its suitable convergence language is to identify the knowledge and technology integrators describing the essential features of the platform. A higher level of generality of a convergence platform and its language is reached when the respective integrators are applicable for larger domains and with faster information exchanges.

Three successive phases of convergence have been reached by using integrators in successively higher-level languages: nanotechnology in 2000 (the National Nanotechnology Initiative; Roco et al. 2000); foundational and converging technology tools (nanotechnology, biotechnology, information technology, and cognitive science, NBIC) in 2002 (Roco and Bainbridge 2003); and convergence of knowledge, technology, and society (CKTS) in 2012 (Roco et al. 2013). Each phase has gradually expanded the breadth and reach of shared S&T languages:

- The nanotechnology phase led to integration of knowledge and disciplines for all sectors of the material world beginning at the nanoscale.
- The NBIC phase led to integration of foundational and emerging technologies from elemental features (atoms, bits, DNA, and synapses) into larger-scale systems with interconnected computer architecture models.
- The CKTS phase is leading to integration of essential convergence platforms in human activities, including knowledge, technology, human behavior, and society, driven by societal values and needs.

Using existing convergence languages includes using universal languages such as mathematical abstractization, music, general system architectures, and a "simplicity" approach for addressing the essential language aspects needed for productive communication:

- *Mathematical abstractization* is an existing convergence language that relies on recognizing and using patterns in various areas of relevance, as well as simulation of various areas in the knowledge society, and connecting them through formulation of a mathematical model. A convergence language that is currently in development is one that will support understanding, reasoning, and decision analysis with respect to unstructured data, patterns, and methods. Such a language will allow generalizations across apparently unrelated fields, novel solutions, and new mathematical concepts.

- *Music* is an existing communication tool (language) that can help bridge cultural divides at the human and societal scales. Throughout human history – probably before word-driven language – music has been used to create a common mood, bringing people together during important social events, from tribal meetings to funerals and military parades; it is a universal means of communication. Music education can contribute to development of the human personality, be used as therapy in difficult life situations, and be a means of communication and mutual understanding between different cultures in problem-solving processes.
- *Development of higher-level convergence languages* needs to be based on system architectures, shared concepts, relationships, and methods in order to allow integration of components from the distinct language levels for particular topics. That will facilitate integration into and among essential platforms, and that in turn will facilitate innovation (confluence of streams), improved manufacturing (hybrid NBIC methods and mind–cyber–physical systems), and advances in all emerging technologies. For example, the unified theory of physicochemical forces provides a higher-level language than the language for investigating individual mechanical forces, and concepts of converging technologies have a higher degree of generality than concepts for a specific technology such as biotechnology. Using higher-level convergence languages will enhance comprehension of surrounding complex systems and understanding of how knowledge is generated over time and crosses multiple fields using logic models (patterns). Cultural anthropologists will help make this transition.
- *A "simplicity" approach* considers only essential aspects in problem description and decision making for a complicated system with relatively complex goals. The purpose is to reach essential and asymptotic conclusions with a relatively small effort rather than consider all aspects.

Creating and sharing large multidomain databases are steps toward creating a universal language database. Using shared databases to connect computer simulations and evaluation methods for the various convergence platforms (such as NBIC tools or Earth-scale R&D) is an example of a process to establish convergent languages. Creating common large databases is a way to bring information from one field to another almost instantly and uncover new qualitative trends. This facilitates interactions and broad principles of optimization. A "universal" database and an expert system could be established to select the methods of convergence in given situations to accelerate unprecedented discovery and innovation.

Creating "trading zones" between areas of research and education with common traits in distinct areas of application is a metaphor for working together or with similar rules and languages in different disciplines, technologies, groups, or organizations (Gorman 2003). Trading zones may span a range of options from a hierarchical trading zone governed by a top-down mandate to a shared mental trading zone based on mutual understanding of what must be accomplished.

Performing multidomain benchmarking (comparative metrics for two or more domains) is an approach for relating distinct complex systems using higher-level comparative criteria valid across disciplines, technologies, and application domains.

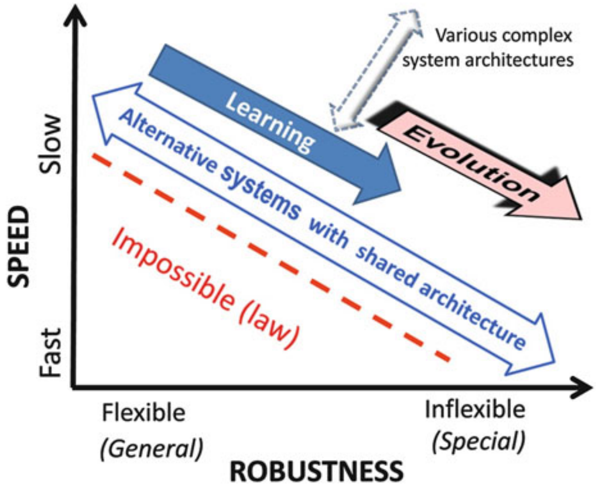

Fig. 3 Robustness versus speed in complex system architectures (based on concepts suggested by Doyle and Csete 2011)

Benchmarking is a form of higher-level language relevant to both knowledge and technology areas. It can be used in both the creative (A in Fig. 1a) and divergent (C and D) phases of cycle. It may help to identify where to focus efforts, steer interests and efforts to broader goals, spotlight key areas for creativity and innovation, and better communicate across fields. One such comparative criterion for benchmarking is the general correlation between robustness and speed as a function of possible complex system architectures in different areas of relevance. A mathematical framework for complex systems is presented by Doyle and Csete (2011; Fig. 3).

Another example for using benchmarking for a specific domain of application (e.g., device performance for semiconductors) is using the correlation between the dissipated energy and delay of response of the device (Nikonov and Young 2013). Adopting science standards in education institutions through benchmarking requires identifying essential aspects of relevance to teaching and learning in various environments and levels of education (NRC 2014c). Another straightforward example is using the correlation between patent quality (mean citation per patent) and R&D project cost (average funding) as an indicator for the rate of invention (Kalutkiewicz and Ehman 2014).

In R&D governance related to development and use of unifying languages, a balance must be sought between support for discipline-specific and multidomain research and education approach (the so-called “T” approach). In the academic R&D environment, the need is to focus on core foundational concepts using both disciplinary and general languages and to reduce the fragmentation within colleges and departments by enlarging the domains covered by each unit. Several opportunities are to:

- Focus education on core fundamental aspects and on using unifying approaches.
- Use multidomain benchmarking in selection of future R&D solutions. An example is the selection by generalized benchmarking of the new devices for

electronic devices to replace silicon CMOS technology under the US Nanoelectronics Research Initiative.
- Adopt the right system architectures for R&D programs corresponding to societal requirements for robustness and speed (Fig. 3).
- Adopt high-level principles in governance: responsibility, innovation for transformative outcomes, inclusion, and vision.

Using Vision-Inspired Basic Research to Address Long-Term Challenges

The principle of vision-inspired research leading to new fields and grand challenges observes that unique results and new application areas can be gained from conceiving research that combines inspiration and forecasting by attempting to see into the future to determine what kinds of research might best address emerging needs. One of the most influential conceptual frameworks for thinking about the goals of research was proposed in 1997 by Donald Stokes, who advocated focusing research in what he called “Pasteur’s quadrant” for conducting basic research for a known use. This is defined as research motivated in such a way that both of the following questions are answered in the affirmative: “Are considerations of the practical utility of the results crucial?” and “Is the research a quest for fundamental understanding?” The “vision-inspired basic research” concept proposed in 2013 by Roco et al. may also meet both of these criteria but also requires that two other questions be answered in the affirmative: “Is the research leading to emerging uses beyond known applications?” and “Is the work transformative in the sense that entirely new ideas are being explored and invented?”

Conceiving a long-term vision for science, technology, and society grand challenges requires going beyond known concepts and application areas and requires a specific methodology. Specific convergence methods may be used to set up the connections between long-term science and technology visions and basic research activities. As shown in Fig. 4, the proposed “vision-inspired basic research” domain will expand the existing four domains of the Stokes diagram to include a new dedication to basic research for emerging applications inspired by a vision of future needs.

Key methods to facilitate convergence based on using vision-driven basic research to address long-term societal challenges include (a) forecasting and scenario development; (b) promoting a culture of convergence based on common goals; (c) anticipatory measures for preparing people, tools, organizations, and infrastructure; and (d) reverse mapping and planning.

Using forecasting, *scenario development*, *early signs of change*, *and other approaches*, it is possible to establish a credible vision for what is desired in the longer term for a knowledge and technology field. Then, a recommended approach is to work backward from the vision to investigate intermediate research steps and approaches. This approach was used in researching and writing two seminal nanotechnology research directions reports (Roco et al. 1999, 2011).

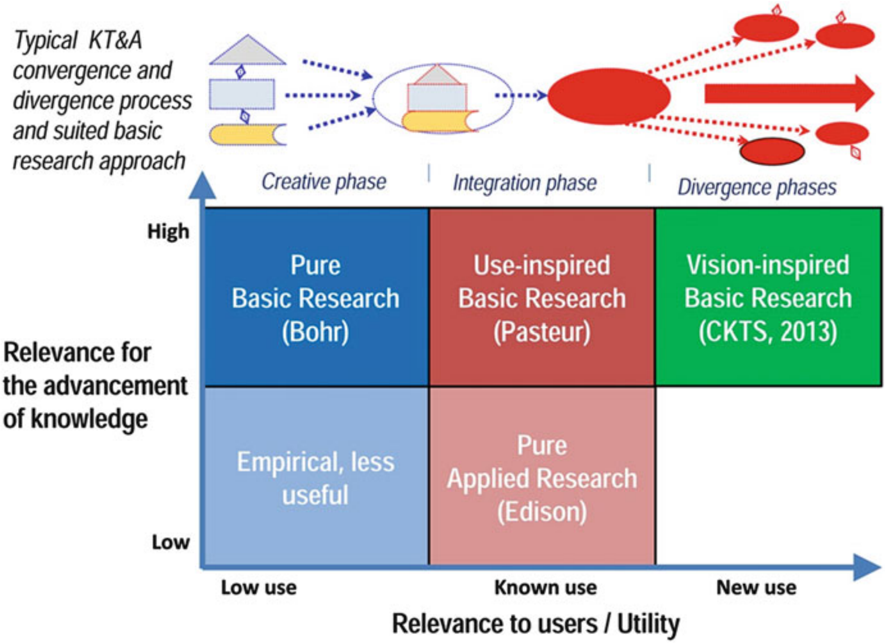

Fig. 4 Schematic for a "vision-inspired basic research" quadrangle in the modified Stokes diagram: three basic research approaches (pure, use-inspired, and vision-inspired) are suggested as a function of the phase (creative, integration, or divergence) in the science and technology convergence–divergence process (Modified from Stokes 1997, Roco et al. 2013)

Forecasting is closely tied to the vision-inspired basic research imperative proposed above. A typical knowledge and technology convergence–divergence process (Fig. 1a) has the four phases addressed earlier (creative assembling, system integration for known uses, innovation, and outcomes that lead to emerging new uses); the research approach has to adapt to the corresponding phase of the process. Various convergence methods can provide connections between the long-term knowledge and technology vision and basic research activities in each phase. The added vision-inspired basic research quadrangle addresses new and emerging areas of research and applications. To efficiently and responsibly achieve the benefits of research in new areas, the convergence processes need to be used to identify the vision and its corresponding strategic basic research areas, changing priorities periodically as interdependencies change, old goals are achieved, and new ones come within reach. Applying forecasting, scenario development and research can uncover potential open issues that may be "invisible" at the beginning of societal planning.

Promoting a culture of convergence based on common goals and anticipatory governance is a follow-up approach after setting the visionary targets (for an illustration see Klein 2010). Anticipatory, participatory, and adaptive technology assessments and decision making are means to help prepare people, tools, organizations, and infrastructure for responsibly guided innovation and change. The idea of anticipatory technology evaluation for CKTS fits within a larger national and global movement toward achieving sustainability in chemical, material, and product development and use. As an example, work on public responses to nanotechnology has included fine-grained comparative work with other contemporary merging/converging technologies like neurology and synthetic biology and with past technologies and risk controversies such as biotechnology and nuclear power. A key aim of risk perception and mental models research is to create an empirical basis for linking risk and benefit perception to risk and benefit communication. Anticipatory technology evaluation will require a reflexive approach to the development of science and technology convergence processes. That is, it will be necessary to look critically at technology itself in terms of impacts as well as benefits.

Reverse mapping and planning. In an R&D environment, vision-inspired basic research can make the difference between satisfactory and great programs with positive impact on education, technology, and the economy. Developing a ten-year technology roadmap is desirable because it takes ten years or so to go from basic scientific discoveries to industrial applications, and so signs of change can be estimated earlier. Once the long-term (say, ten-year) goals are set, one may estimate what is needed and plan backward to realize the targets.

The concept of vision-inspired basic research has important implications in:

- Long-term R&D planning for grand challenges and managing respective programs. For illustration, the National Nanotechnology Initiative (NNI) has been guided by a 20–30 year vision (pursuing systematic control at the nanoscale will lead to a technology revolution for societal benefit), and reverse mapping and planning was used to set up the goals of vision-inspired basic research at the beginning of the initiative (Roco et al. 2011).
- Supporting S&T mapping and forecasting methods and organizations.
- Supporting risk governance of science and technology that could not be developed without scenarios about future events and their probability of occurrence.

The importance of vision-inspired research is only increasing with the acceleration of S&T development on a quasi-exponential path and with significantly more complex interdependencies.

Closing Remarks

The S&T convergence process is a collaborative governance process that is different from top-down governing or just advancing multidisciplinary research or networking. Effective convergence includes a suitable culture of interaction with transformative solutions and longitudinal evaluation in a purpose-driven process in the increasingly larger, multidisciplinary, and interactive S&T communities in academia, industry, and government. This is a means to achieve greater creativity, innovation, and productivity in society, ultimately to enable people to solve both local and global problems that otherwise seem to defy solution.

Implications of *convergence methodologies for science and technology* may be broad, such as creating a suitable research and education ecosystem with visionary goals and a new culture, or more narrow and specific, such as in devising specific kinds of convergence education programs or including convergence criteria in evaluations of R&D projects. Innovation is a beneficial link from scientific discoveries and technology inventions to commercialization and societal acceptance. A system that focused only on innovation would be unsustainable in only few years. Several immediate opportunities for convergence ideas are in distributed manufacturing, integrated sustainability, S&T planning, investment policies, education, and decision analysis. This chapter outlines a portfolio of methods to enable and accelerate knowledge and technology convergence that are applicable in governance of science and technology.

An *infrastructure* to effectively achieve integration and synergy in S&T convergence is required across existing and emerging knowledge and technology domains. The priorities for infrastructure are:

- Creating specialized networks and tools for communication where the contributions of participating people and communities can be integrated *to form efficient ecosystems*. Horizontal information systems in academic, industry, and government organizations will have an increased focus on building integrated knowledge versus simply conveying information. Building convergence-driven culture and collaboration spaces should be freed from geographical boundaries, organizational constraints, and single-domain restrictions.
- Developing methods and tools for advancing convergence in planning, decision analysis, forecasting, investment policy, and other areas *to establish a science of convergence*. Developing information systems should include finding experts and partners from different domains across the world and providing communication spaces by adopting functionality from existing professional and social applications.
- *Enabling the sharing of resources* and exchange of knowledge by designing a knowledge profiling service with well-defined resources such as data, software, source code, communication spaces, documentation with standardized formats, publications, laboratories, etc. This includes providing tools or services for analyzing and visualizing trends, networks, project progress, and discussion topics. Important spaces of communication that need improvement for promoting convergence are the publication and patent systems, as well as the mode of operation of professional societies and the models used in partnerships.
- *Addressing responsible innovation including evaluation of benefits and the risks of S&T convergence* has to be done by including social sciences and social scientists from the beginning in all convergence-driven projects. Otherwise, major specific risks are inevitable, associated with realization of more powerful and transforming tools that may be dual use, that lead to nonuniform development of various world regions and changes in their relative economic power, that

have undesirable consequences due to poorly considered repurposing of solutions from one socioeconomic platform to another, and that expose tensions between bottom-up research and top-down vision in R&D providing and funding organizations.

Using the above principles and methods to facilitate convergence has the potential to change or create more efficient S&T ecosystems with inspiring goals in response to a more demanding, faster, and more interactive world.

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Biocognitive Evolution

Jonathan C. Peck

Contents

Abstract

Scientific cultures are shifting, and we can anticipate the results based on a pattern of developmental stages characterized in psychology. The major shift will be from competitive achievement of individuals in disciplines to collaborative success in networks of interdisciplinary teams linked with advanced intelligence agents. Such shifts occur by transcending while including previous cultures. So individual competition and distinct fields of study will continue as a facet while the mainstream of scientific culture shifts to include:

- The embrace of the complex over the simple
- New theory that encompasses worldviews from East and West
- Attention to personality as a facet of team success
- Tools that reshape human interaction

J.C. Peck (✉)
Institute for Alternative Futures, Alexandria, VA, USA
e-mail: jpeck@altfutures.org

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The convergence of all these factors has begun. The major scientific questions of our day have already gathered answers from large networks using computers to integrate the work of scientists around the world. This happened in the sequencing of genomes and the creation of climate models to learn about global warming. As the twenty-first century problems emerge for a population growing from 7 billion to perhaps 10 billion people, surprises will appear as crises. Solutions will need to come quickly, and networks of people using knowledge tools are likely to bring the fastest, best answers by working across the many domains that have divided science over centuries into distinct fields and disciplines.

Introduction

Science is not what it was, nor should it be. This chapter describes the culture of science progressing along a path that will pass through the integration of heretofore distinct disciplines on its way to describing the universe in terms that most scientists have yet to comprehend. This forecast is based on the premise that culture recapitulates psyche in a pattern foretelling what will likely emerge next. If true, then theories and findings from psychology can contribute to an understanding of the stages through which the culture of science will come to a larger understanding of ourselves both individually and collectively. One of the major intersections in the culture of science comes where East meets West. This fertile area for integrating different views has both cultural and intellectual implications coming as more scientists from Asian cultures contribute to new ways of thinking about old theories.

New Thinking in Biology

Biology offers especially fertile soil for new thinking. The central theory Darwin proposed almost a hundred and fifty years ago can combine with the quantum physics from a hundred years ago to reach a new theory in quantum biology. The remarkable constructs that have propelled molecular biology over decades past have yet to integrate quantum ideas such as complementarity and entanglement. Much of the excitement over genes and proteins as "building blocks of life" presumed that biology conformed to engineering disciplines which only needed the physics of Newton to explain how biology works. Yet epigenetics that has shown biology holds more complexity. Many questions got ignored or brushed aside by those who were certain that simple causal models of molecular and cellular phenomenon would explain disease, aging, and consciousness. Such questions address the nature of healing, mindfulness, placebo effects, and unusual but nonrandom phenomenon. They also invite new theory.

A decade ago futurists working on *The 2029* Project interviewed dozens of scientists across multiple disciplines focused on biomedical research and development. The project used forecasts to characterize the major developments over 25 years, including a new theory for biology (Institute for Alternative Futures 2005). Subsequently, futurists and physicists began to anticipate that the new theory may emerge from the nascent field called quantum biology along with the more established field of chaos and complexity science. Conventional biology has focused on upward causation in which lower-order molecular change affects cells, tissues, organs, and organisms. Yet biology is more complex, extending into ecosystems which show how downward causation can be as important to understand. In his lyrical book *The Music of Life*, Denis Noble explains "there is no privileged level of causality in biological systems" (Noble 2006).

Complexity in Science and Culture

Complexity science offers a useful language for understanding both biology and the pattern of culture change coming to science as it seeks to explain the larger world through which our species evolves. This evolution includes both incremental change and phase transitions through which rapid cascades lead to larger magnitude leaps as systems evolve. Historically science entered a period of rapid differentiation into multiple disciplines followed by a long period of incremental growth in knowledge. The coming period in science could bring a rapid integration of the many distinct fields that have broken knowledge into many subcultures with distinct vocabularies that form a modern-day Tower of Babel. Edward O. Wilson foresaw this integration as consilience – the jumping together of facts and theories from different disciplines (Wilson 1998). This intellectual integration also brings together the subcultures formed around disciplines. Such subcultures create central tendencies for physicists, biologists, chemists, and environmental scientists which have been reinforced by the jargons each discipline have created as both an intellectual shorthand for shared ideas and a cultural identity that distinguishes insiders and outsiders for each field.

The great challenge those overseeing research describe is how to get teams of scientists from different disciplines to work effectively together on innovation. Part of this is intellectual and another part interpersonal. The intellectual blending is an established trend evident in the many hyphenated forms of expertise, bioengineering, pharmacoeconomics, etc. As experts bring knowledge from one domain to another, they often open up new areas for innovation. Yet the ability to bring an innovation to life depends greatly on the capacity of teams to work together effectively with interpersonal understanding to draw on the strengths of each individual.

Personality Preferences and the Evolution of Science and Culture

The Myers-Briggs Type Indicator (MBTI) can help teams chart the personality differences that draw people together or tear them apart. The MBTI was initially developed to test and popularize Carl Jung's theory of personality (Jung 1971).

Over the decades the MBTI became a popular instrument for identifying the careers that the sixteen different types are most drawn to and which kinds of jobs are dominated by which personality type. For example, the data on physicians show psychiatrists score most highly on the more future-oriented form of perceiving which Jung called intuition, while pathologists score most highly on opposing form of perception grounded in actual facts which Jung called sensing. Go to any hospital and ask about the stereotypes for physicians, such as surgeons having the "personality of the knife" and see the extent to which professions attract people with distinct personality preferences. Many human resource managers use the MBTI and recognize it can mitigate personality conflicts on teams and between divisions of companies. Yet the MBTI also may prove important for understanding the deeper cultural tendencies which form in the different scientific disciplines that will need to be brought together for consilience in the twenty-first century.

The culture of science must evolve within the context of human evolution. The book *Spiritual Evolution* supports the thesis that evolution for humans is now more a cultural than biological process (Vaillant 2008). Cultural evolution can occur rapidly; so for science to fulfill its potential to help humanity meet the challenges of the twenty-first century, its will needs to be part of the emergence of a new and more collaborative culture. The key to collaboration might be called "spiritual intelligence" – the capacity to share love, joy, faith, and awe – which forms the basis for human cooperation. These are highly subjective intelligences, which in Carl Jung's theory of personality would be associated with the "feeling" forms of judgment which ties cognition into the limbic system. Jung called the complementary opposite form of judgment "thinking." Scientific cultures tend to be associated with the more dispassionate and objective forms of judgment associated with thinking rather than feeling. In contrast religious cultures are recognizably affiliated with the passion and subjectivity of the feeling function. After centuries of subservience to the church, science gained its freedom and over the past few centuries took the dominant role in reshaping culture. Now human evolution may demand that science reintegrate the function and inspiration of religion to reach a higher value proposition.

Human evolution is a process "moving inexorably toward higher and higher complexity" which Jonas Salk identified as "Epoch B" for our species (Salk 1973). To make this transition we need a wisdom which looks forward, anticipating the ability to respond to prospective challenges rather than just react to change. The climate change models created by a global network of scientists show this ability. This work develops foresight that affects decisions made today, which will be an increasingly important facet of global science over the coming decades. Yet scientific studies also show that there may be other routes to foresight. The human capacity for presentiment is described by some researchers as "feeling the future" (Mossbridge et al. 2014). Our species may have capacities long recognized in mystics and prophets that can be better understood through science. As Salk foresaw we will have to "learn how to join feeling and reason, nonverbal and verbal, as well as subjective and objective sources of information and problem solving." After hundreds of years differentiating from religion, science needs to come to an understanding of how inspiration and revelation work to change human cultures in a changing world.

The Culture Change Challenge

The ability to change culture rapidly is now a crucial concern in our society. Leaders from government, business, and nonprofits understand that the culture we have is not the culture we need. Risa Lavizzo-Mourey, President of the Robert Wood Johnson Foundation, describes this as a vision “to create a culture of health” (Lavizzo-Mourey 2014). This vision aligns with the realization that came to federal leaders in a futures meeting held in 2010. Health is the strategic priority for our nation and the focus on health care which dominated national attention was missing that point. With this shared insight came the realization that the original vision for our country was the aspiration for life, liberty, and pursuit of happiness. No health, no happiness. Those who have looked deeply into the meaning of health understand this to be true because there are multiple domains through which our health can be addressed to achieve well-being. The US military, for example, pictures a “Shield of Health” that addresses the environmental, physical, social, behavioral, psychological, nutritional, and spiritual dimensions, along with the medical domain (Jonas et al. 2010). This broader understanding of health, wellness, and well-being takes us from the simpler model of causality that medical science found so successful in confronting infectious disease in the twentieth century to the more complex models that are needed to address chronic illness through a vision of health and well-being.

E.O. Wilson questioned whether complexity science will offer a factual basis that science needs. Yet he knew the old foundation of logical positivism with its assurance of an objective truth had foundered even if that dream lives on for some. Today’s post-positivist position goes beyond simple causal models to recognize the potential for scientific understanding that accounts for randomness and nonlocal relationships that may explain areas such as consciousness and the mind. While many neuroscientists set out from the logical positivist camp to explain the material connections in the brain, another camp seeks to show that nonlocal consciousness also plays a role in our minds. Some, such as author Larry Dossey, M.D., contend that despite all of the divisions we perceive, there is a “unitary domain of intelligence” in which we all can partake (Dossey 2013).

The transition from the simpler assumption of an objective reality fully understood through cause and effect reasoning will likely take a decade or more until the number of scientists who transcend their disciplines has increased. While including causal reasoning the next generation of scientists will move to incorporate the complexity of a stochastic realm in which the highly improbable synchronicities reveal the subtlety of mind beyond the workings of the brain. Carl Jung and many quantum physicists long ago laid the groundwork for this shift when they explored phenomenon outside the causal realm (Jung 1960). While most Western scientists (including social scientists) restricted their studies to areas in which causation or high levels of correlation support explanation, Jung explored meaningful coincidences that occur with sufficient frequency to be more than random but too rarely to fit neatly into the dominant scientific worldview. Yet the Eastern worldview could accommodate the phenomenon Jung described as synchronicity in which the mind interacts with matter, which Jung acknowledged when he wrote a Foreword to the first translation of the I Ching to reach the West. More recently, Chinese Zen master Huai-Chin Nan told an interviewer "There's only one issue in the world. It's the reintegration of mind and matter" (Scharmer and Kaufer 2013). In effect this will bring a fusion of the subjective and objective views that will bring together a new scientific culture beyond the divides. Quantum physicists showed that the scientist is part of the experiment when they determined that light could be measured as either waves or packets depending on the experiment chosen; the old view that a fully objective description of the universe was all need gave way to a more subtle position. Only by embracing both objective and subjective views will science expand both intellectually and culturally to more fully comprehend life in the universe. This cultural evolution emerges as a fulcrum which can be regarded as both spiritual and psychological, and we have maps for exploring the cultural territory before us.

Stages of Development

Psychological development occurs through stages that also describe cultural development. Psychologist Clare Graves contended in his "Emerging Cyclic Levels of Existence Theory" that this development oscillates upward through a spiral that moves between ever larger constructs of "me" and more inclusive versions of a larger "we" (Cowan and Todorovic 2005). Many other psychologists have shown the human psyche to develop through such stages, but Graves studied how groups operating from the different stages solved problems. He noted that the groups operating at three conventional stages – the first more "we" oriented, second more "me," and third a larger, more holistic "we" – arrived at an increasing number of better solutions to given problems. So the solution sets became more complex, and when he observed the most highly advanced group of problem solvers, he recognized that there was a nonlinear progression, a leap in terms of the number and complexity of solutions. He also foresaw that a growing number of highly educated people will advance to stages at which they work with great effectiveness on highly complex solutions.

Within scientific cultures the three conventional stages and less evident post-conventional mindsets show up differently. We might characterize the early conventional scientist as taking a "conformist we" view that believes in the knowledge of experts at the top of the hierarchy of scientists and are willing to be self-sacrificing because the long-term endeavor of science will find the answers humanity needs. The number of these early conventional scientists is relatively low in our scientific organizations compared to those at the next stage of "competitive me" with an even larger number who align with the late conventional "holistic we" stage. The strength of the "competitive me" scientist became evident after the

Bayh-Dole Act of 1980 offered incentives which converted academic science from a stereotype of collegiality into a hotbed of entrepreneurial holders of intellectual capital competing for venture funds to strike it big through business start-ups. These scientist entrepreneurs still seek to reap fast fortunes, notably by providing targeted cancer treatments with soaring prices to the growing number of aged who will be diagnosed over the next decade.

However, the growing number of people, including scientists, who express the "holistic we" values are likely to create new limits on the wealth accumulated by scientists seeking to sell these expensive medicines, especially to elderly patients whose life expectancy is measured in a small number of weeks, months, or even years. A growing number of leaders are seeking to bring more value from science by supporting health rather than expending ever more resources on health care. Early signs that this cultural shift would come came from Europe, where Responsible Research and Innovation has taken hold. Over two decades ago, companies such as the Swiss Ciba-Geigy recognized that success needed to be more than financial and include social and ecological improvement in a "triple bottom line." Since then more companies, especially in Europe, have recognized that a higher ethic calls them to assure that science serves more than just corporate profits. Science-based industries, such as pharmaceutical companies, face a growing unease from within as more employees become sensitive to the ways in which their practices compromise public interests, recognizing that the social contract with business is in question.

A far smaller number of intriguing scientists represent the stage which might be called "authentic me." Clare Graves' research showed that teams working at this stage came up with far more solutions than all the teams from conventional stages put together, faster and with higher quality. The way these teams worked was strikingly different with a fluid shift of leadership to the person with the greatest knowledge or most innovative idea. This presages a cultural change for how scientists work together. While the conventional "competitive me" teams struggle to achieve the pinnacle of a hierarchy and the "holistic we" teams create a matrix to draw in all expertise on a level playing field, the "authentic me" moves people rapidly in and out of the center of group attention to bring expertise and creativity to bear. Graves did not have the benefit of research done since which may hold the key to understanding what makes post-conventional teams so amazing. His focus was on the cognitive strength (using IQ measurement) because emotional intelligence had not been recognized and studied. He noted the contagious laughter in the post-conventional teams, but at that time there was no understanding that teams have "interpersonal limbic regulation" that underlies outstanding team performance (Goleman et al. 2002).

The shift that Graves saw many decades ago has been more recently characterized by psychologists who see in postmodernism a new order of thinking. The import of this change for science has only begun to come into view. Psychologist Robert Kegan contends "postmodernism is not just a *different* way of thinking, it is identifiable on the continuum on the evolution of consciousness" (Kegan 1994). While most of today's population is coming to terms with modernism, a smaller number of people are engaging the more complex challenges of postmodernism. Thus many of today's younger scientists are confronting the need to differentiate themselves and stand out as experts in their field, but a smaller number are working on the more complex task of a larger, "postmodern" integration in the culture of science. What will emerge will be an environment that stimulates more people to develop a more complex view of the world. This will come in part because the demographic trend toward older and more educated populations brings more people into the postmodernist view, but also because this view will create more complex and compelling explanations and solutions in a world where simpler ideas no longer suffice.

Forecast for the Next Phase in Science

A larger proportion of the global population trained in science will be maturing into the post-conventional mindsets which share holistic views and seek out dynamic complexity in order to design for humanity's future. This larger view of both the "me in the we" and the responsibility beyond individual life spans will redirect science. The conventional mind-set will still play an important role in propelling individual achievement, especially among younger scientists dreaming of fame and fortune, as well as in the bonds from belonging to the established scientific community and its many subcultures. Yet increasingly we will see groups of genius scientists who make great leaps rather than just strides by thinking in larger terms to explain mysteries that others passed by or shrugged off. Much of the creativity that will be fostered may be symbolized by standout individuals to the world still captivated by heroes, such as Einstein. Yet the great leaps will truly be the result of groups who "think" together in new ways. What will be new is that the thinking will be knowingly more than just cognitive processing as it encompasses emotional and spiritual intelligence that gets amplified through group interactions. Within two generations we will be designing environments to bring more of these groups into being and to make the flow of knowledge flowing from different disciplines turn into a flood plain.

While psychologists offer maps that reveal the potential for a new cultural landscape for the twenty-first century science, the shift to new tools spread through global systems also supports the transformational forecast for science. The major change underway is from centralized hierarchies to networks and then learning ecosystems (Scharmer 2009). From the dawn of human society networks were the vital form for organizing work, primarily through kinship networks. Then as the scope and scale of work grew with the human population and organization of empires and then states, central bureaucracies became the more powerful way to get work done. Bureaucracies had more endurance over time and greater reach through larger space than kinship networks. Then came the Internet which started to enable global networks reaching far beyond centralized bureaucracies.

In the 1980s the power of the Internet was viewed primarily in terms of an information revolution with global reach, but the decades since made it clear that information overload means we need a knowledge revolution. Scientists now anticipate: “An Integrated Knowledge Network [with] new paradigms of hardware and software architecture...to enable the free flow of knowledge and wisdom, culminating in a ‘global brain’ which linked a vast neural network of sensors and devices to massive computational capacities that could make sense of human and machine systems” (Institute for Alternative Futures 2013). The software used by networks will become more humanlike, adept at sharing knowledge and appearing to have personalities (Bainbridge 2012). The result of using such software may even accelerate the movement through developmental stages of the users of programs that mirror their personality. With scientists using natural language systems in 24/7 global learning networks, knowledge propulsion through society could make both individual and collective learning rates increase beyond anytime in human history.

More people are likely to be drawn into the scientific endeavor as well. Citizen science has already taken hold with signs that it may spread more widely. The activism of HIV groups in the 1980s brought many motivated people to learn rapidly about pharmaceutical sciences. This was replicated by many cancer patients who connected online to play key roles in bringing therapies to market. Community-based participatory action research has invited yet more people to join in research endeavors around questions that might not be studied if science did not open its culture to people outside the academic setting. Now community labs are springing up inviting people to use equipment similar to academic and commercial labs but with an open source approach in a space where people power combines with scientific knowledge. With massively open online courses (MOOCs) also opening the academic world to more people, the potential for high-quality citizen science can continue growing. The spread of computer games can further draw people into scientific endeavors, such as when Foldit gamers model protein structures. Making science fun, meaningful, and accessible to a wider population will bring more people from outside historic boundaries into science, and that will help bring the cultural changes in the next phase of science.

Conclusion

We are going to need both the advanced tools and the wider public participation in science during the coming decades because we face a great planetary challenge. Climate change and population growth foretell an environment in which the cities where most of humanity will live may depend on brittle systems that grew heedless of the ecology. The need for new energy sources and water to sustain the larger number of people may grow acute suddenly if evidence shows we have depleted half the world’s oil. With billions of people in need, the pressures will grow for solutions that make the best of science. Whether that will mean geoengineering and public acceptance of potential downside risks, widespread introduction of genetically modified organisms or dramatic new regimens for living more simply is an open question.

To find the sources of food and energy needed for the earth's population while sustaining an ecology in which people flourish in all the dimensions of humanity, we will need all that science can offer. Yet this offer must come with a spiritual intelligence that finds and shares awe in nature and make the quest for understanding a joy shared by more of the population. Twenty-first century science can join all disciplines in the shared quest for a unity of knowledge around a shared purpose that brings the public into the endeavor. This will be the larger purpose of life that reshapes the culture of science in the twenty-first century as the planet goes through changes we must foresee rather than react to or else.

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Collective Intelligence Systems

Jerome C. Glenn

Contents

Abstract

Accelerating growth of scientific knowledge, technological advances, and their convergence makes it increasingly difficult for scientists, politicians, and the public to keep track of such changes and make informed decisions. Collective intelligence systems provide an alternative to relational databases, email networks, conventional websites, and social media. There are several definitions for "collective intelligence" and its applications. I define collective intelligence as an emergent property from synergies among three elements: (1) data/information/knowledge, (2) software/hardware, and (3) experts and others with insight that continually learns from feedback to produce just-in-time knowledge for better decisions than any of these elements acting alone. In addition to a brief

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J.C. Glenn (✉)
The Millennium Project, Washington, DC, USA
e-mail: Jerome.Glenn@Millennium-Project.org

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overview of collective intelligence systems and why they are needed, this article will explain how The Millennium Project (MP) is creating its own collective intelligence system and how it can help scientists, politicians, and the public better understand change and participate in building and improving collective intelligence for S&T convergence.

Introduction to Collective Intelligence

The term "intelligence" is used in this article to mean knowledge or information that informs action and as used in the sequence of understanding leading to wisdom: data, information, knowledge, intelligence, and wisdom (Tuomi 1999).

In the past, leaders would often gather wise elders and favorite consultants to discuss a problem until a solution was found. Then along came the Internet and Google, allowing leaders to have staff search through vast sources of information and distill these to provide intelligence for a decision. Meanwhile, the mathematically inclined might say, "give me your data and I will build a model to help you make the right decision." All of these approaches have their value, so why not integrate them all into a system?

A collective intelligence system involves these three approaches, enabling each to improve the other in an ongoing feedback improvement system. I define collective intelligence as:

> an emergent property from synergies among three elements: 1) data/info/knowledge; 2) software/hardware; and 3) experts and others with insight that continually learns from feedback to produce just-in-time knowledge for better decisions than any of these elements acting alone (Glenn 2009a)

Hence, collective intelligence can be thought of as continually emerging from changing synergies among its elements, as illustrated in Fig. 1.

A useful and efficient collective intelligence system should connect these three elements into a single interoperable platform so that each of these elements can change the others. Participants should be able to comment on any information or software or computer model in the system. These comments read by reviewers and editors can then lead to changes in the system. For example, new insights from a person in an online group discussion can lead to changes or edits in the text of some part of the information in the system. This change of text might illustrate the need for new decision-making software or changes in one of the online computer models or the requirement to add a link to a new online computer model. Running the new model could produce results that, when given to the appropriate discussion group, could stimulate additional discussions leading to better insight that would lead to new edits in a situation chart. Decision support software like Delphi could add to the mix and result in changes in the information in the system and help identify new experts to add to the discussion groups. These changes in turn can lead to new questions in a Delphi, which in turn can change the text of information in the system.

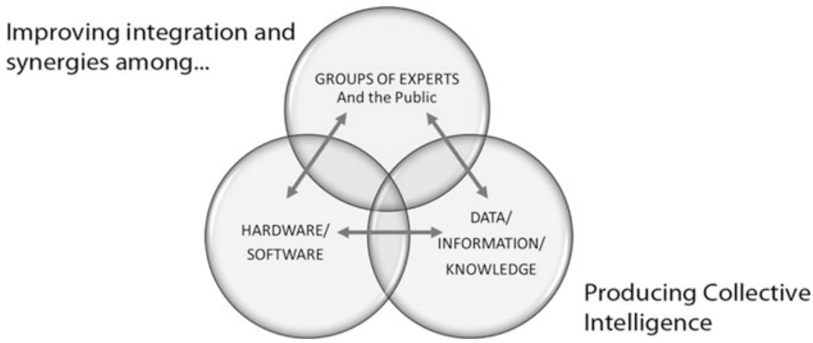

Fig. 1 Graphic illustration of three interactive elements of collective intelligence

Many of the features of a collective intelligence system (CIS) have existed before, but their integration into one platform creates a different experience, just as telephones and computers existed separately before email, but once integrated, the email experience was unique. The elements of the European opera existed before, but their integration into one experience is quite different than experiencing its different elements separately. A CIS can be thought of as a common platform of interlinked systems of people, information, and software each able to change due to feedback from the others.

Collective intelligence could be the next big thing in information technology (Glenn 2009a). CISs are relatively new developments within the ICT world, and hence, alternative approaches for creating them are more often described online than in professional journals (http://cci.mit.edu/, http://www.igi-global.com/journal/international-journal-organizational-collective-intelligence/1140, http://www-935.ibm.com/services/us/gbs/thoughtleadership/ibv-collective-intelligence.html, http://scripts.mit.edu/~cci/HCI/index.php?title=Main_Page, http://en.wikipedia.org/wiki/Collective_intelligence, http://shop.oreilly.com/product/9780596529321.do, http://www.dougengelbart.org/about/collective-iq.html). Nevertheless, there are already many different approaches to this subject. Here are a few. Pierre Levy of France focuses on the universal distribution of intelligence as the key element in *Collective Intelligence: Mankind's Emerging World in Cyberspace* (Levey 1994). Anita Williams Woolley et al. explored the psychological factors that improve collective intelligence in groups in Evidence for a *Collective Intelligence Factor in the Performance of Human Groups* (Woolley et al. 2010). Francis Heylighen of Belgium has developed collective intelligence concepts to help the emergence of a "Global Brain" or "Global Brains" from the Internet (Heylighen 1999, 2008, 2013). He leads an international network to explore how to build a global brain at gbrain@listserv.vub.ac.be. MIT's Center for Collective Intelligence has created the *Handbook of Collective Intelligence* as a wiki for an evolving conversation of the theory of collective intelligence (MIT Wiki). This center stresses the "peopleware" element of collective intelligence, looking at what characteristics are important in forming groups to best enhance their collective intelligence. The

National Endowment for Science, Technology and the Arts in London has created a working draft discussion paper on collective intelligence as a Google Doc (Mulgan et al. 2011). Even the United Nations has been considered as a future center for global collective intelligence through a series of meetings and papers (Ekpe 2009).

Although one could consider Wikipedia, Google, crowdsourcing (Howe 2006), averaging expert judgments (Gordon 2009b), swarm intelligence (Kaiser et al. 2010), and prediction markets (Wolfers and Zitzewitz 2009) as examples of collective intelligence systems, these examples would not be a CIS by the definition offered in this article. They do produce information and in some cases, conclusions from a group, but they do not – so far – include feedback on a systematic, *ongoing basis* among the three elements to permit the continual emergence of new insights which then can affect other parts of their systems. They do not produce a continuous emergent intelligence, but only give a slice in time, whereas a CIS, like the mind, continually emerges and changes from the ongoing interaction of brain, experience, and environmental stimuli.

Some Historical Roots of Collective Intelligence Systems

Many efforts have been made to develop CIS over the years (Engelbart 2008). In the 1960s, Doug Engelbart at SRI created software and hardware to augment collaborative decision-making (Engelbart 1962). The Delphi method was developed at the RAND Corporation in the early 1960s and has subsequently been used by many organizations (Gordon 2009b). The SYNCON was developed in the early 1970s by The Committee for the Future which integrated discussion groups, video, and computer conferencing (Glenn 2009b). Murray Turoff's pioneering Electronic Information Exchange System (EIES), also in the 1970s, paved the way for new thinking about collective intelligence (Hiltz and Turoff 1993) and in the author's judgment provided the best example of a collective intelligence system at that time. The Wikipedia was created in 2001 (http://en.wikipedia.org/wiki/Wikipedia:About) and has grown to become the world's most successful – if not the first truly global – participatory information and knowledge system with more than 76,000 active contributors working on over 31,000,000 articles in 285 languages as of August 2014. All of these make it seem that the emergence of Pierre Teilhard de Chardin's Omega Point (de Chardin's 1961) (integrated complexity and consciousness able to direct our evolution) and his popularization of Vladimir Vernadsky's Noosphere seem inevitable.

Thomas Malone defined collective intelligence at the opening of the MIT Center for Collective Intelligence in 2006 as "groups of individuals doing things collectively that seem intelligent" (http://cci.mit.edu/about/MaloneLaunchRemarks.html). Subsequently, the Center's website now lists its mission as: "How can people and computers be connected so that—collectively—they act more intelligently than any individuals, groups, or computers have ever done before (The MIT Center for Collective Intelligence) (Malone et al. 2010)." Thomas Malone and the MIT center continue to develop scholarly research on collective intelligence.

The Millennium Project has created collective intelligence systems for the Kuwait Oil Company (2003), the Climate Change Situation Room for Gimcheon, South Korea (2009), the Early Warning System for the Prime Minister's Office of Kuwait (2010), its own Global Futures Integration System (2012) and is now creating E-ISIS (Egypt's Integrated Synergetic Information System) for the Egyptian Academy of Scientific Research and Technology, which would be the first national CIS open to the public.

Collective Intelligence Systems Can Provide Support to Science and Technology Convergence

The accelerating complexity and the volume of change, with exponential increases in technological capacities and scientific knowledge, along with emerging interdependencies of economies, politics, and Internet-based groups, make it almost impossible for decision-makers and the public to gather and understand the information required to anticipate potential convergences among scientific knowledge and technologies to make and implement optimal or sufficiently robust decisions (Glenn 2008).

Because of such changes, the environmental, social, and security consequences of poorly informed decisions will have greater impacts tomorrow than they did yesterday. Hence, new systems for identification, analysis, assessment, feedback, and synthesis are urgently needed to inform decision-making. We need a more advanced system to think together about the future in some organized fashion so as to improve our collective prospects. We need a system to help us understand the global situation and prospects for the future that lets us interact with that information, discuss with colleagues, and use support software as need.

One approach to help identify potential future technological convergences is the combination of a modified cross-impact analysis (Gordon 2009c) and real-time Delphi (Gordon 2009a) within a CIS. For example, Table 1 below illustrates how experts could be invited to assess the future impact of one technology on another technology and the potential convergences.

Table 1 Technology convergence table

Column items impact on rows	Nano-technology	Synthetic biology	AI and robotics	Internet of things	Computa-tional science	3D printing
Nanotechnology	X					
Synthetic biology	A	X				
AI and robotics			X			
Internet of things				X		
Computational science					X	
3D printing						X

Each cell (without the x) could be the subject of an ongoing Delphi, e.g., what are the impacts, convergent possibilities, etc. of nanotechnology on synthetic biology? As experts answer these questions, and feedback is given and responded to online, a collective intelligence would begin to emerge on the potentials of convergences and impacts. Information in each cell would be hyperlinked for better visual, user-friendly access.

One could also imagine the matrix above with hyperlinked submatrixes within each cell. For example, if there were five major approaches to nanotechnology, then a cross-impact matrix of five by five could be hyperlinked in the first cell with the X. One could further imagine a sub-five by five matrixes in Cell "A" inviting participants to cross-impact five nanotechnology approaches with five synthetic biology approaches. This could be a complex, but visually managed by online hyperlinking. In this way, the general public could see – and potentially comment on – the main impacts, and the more advance scientists and engineers could hyperlink into greater detail in the sub-cells of the matrix. As a result, vast and complex information would be available in an organized, user- friendly way for both the public and the professional.

We lack systems that make it easy to see and update a situation as a whole, including current conditions and forecasts, desired situation with a range of views, and alternative policies to address the gap between what is and what ought to be. Instead, analysts often use the Internet to go from one source to other, becoming stressed by information overload (Blair 2013).

It is wise to get all the relevant information before assessing potential future S&T integration or making any informed decision, but it is increasingly difficult to organize all the positions, priorities, and strategies, in a way that brings more satisfactory coherence to our thinking and decision-making. Or as Leon Fuerth put it in *Anticipatory Governance*:

> There are many sources of foresight available to decisionmakers originating both within and outside of the U.S. Government, but foresight is not methodical, continuous, or structured in a form that is useful for decisionmakers... A simple collective intelligence system (CIS) would manage content, organize expertise, track comments and changes in documents, and support prioritization. (Fuerth and Faber 2012, pp 19 and 51)

Since everyone faces similar problems of managing complexity and change, we can expect to see the increased creation and customization of collective intelligence systems by governments, corporations, NGOs, universities, associations, and individuals. It has also been suggested that a collective intelligence system could provide continuity from one government administration to the next, "by making it easier to retain and transfer institutional knowledge that is essential for long-term strategic coherence, regardless of changes in policy or political philosophy (Fuerth and Faber 2012, pp 51)."

Collective intelligence systems can also focus on specific issues such as climate change or industries like agribusiness. Just as spreadsheets have become a general tool that any organization or individual can use, so too, CIS could become a general tool adapted for an individual or organization, or a country, as in the case of Egypt to help "bring it all together" (The Millennium Project).

An Example of a Collective Intelligence System Used to Support Global Future Research

The Global Futures Intelligence System (GFIS) was created by The Millennium Project and launched at the Woodrow Wilson International Center for Scholars in Washington, D.C., in January 2013 (Video of the launch of GFIS). It is available at www.themp.org (Fig. 2).

Using the GFIS platform alone, one can track and anticipate global change within the framework of 15 Global Challenges, review specific global futures research on a variety of topics, and access internationally peer-reviewed chapters on 37 futures research methods. Questions can be addressed and discussed with experts on the challenges, research, and methods. For example, if one wanted to explore the convergence of computational science and the Internet of things, one could discuss which methods to use, identify potential participants in the database, and send invitations to each participant. If a real-time Delphi is chosen, then it can be collaboratively designed, managed, results analyzed, and report finalized for downloading, all on one integrated platform.

GFIS is an example of the next generation of interactive technology to support those exploring global change and potential futures for humanity. It began by integrating all of The Millennium Project's 10,000+ pages of futures research obtained over the past 16 years from the annual *State of the Future* reports, plus information from expert listserv groups and its 50 Nodes (groups of individuals and institutions that connect local and global research and perspectives) around the

Fig. 2 Front page of the Global Futures Intelligence System at www.themp.org

world. It also includes the *Futures Research Methodology version 3.0* with 39 chapters totaling more than 1,300 pages of internationally peer-reviewed methods for exploring the future (37 chapters on specific methods plus an introductory chapter and a concluding chapter). All of this, plus its software, are integrated in one platform so that users can participate to update and improve any element of this online collective intelligence system.

The most commonly used section is the 15 Global Challenges that helps see the potential convergence of science and technology but also its relationships and integration of other areas (Table 2).

One of the greatest values of GFIS is that it serves as an interactive decision support dashboard, rather than just another source of information. It offers more than just new software tools – a vast body of intelligence/knowledge/data and access to experts; it is also an evolving system for producing synergies among the

Table 2 Menu options for each of the 15 Global Challenges

Menu option	Function or explanation of the options
Situation chart	Current situation, desired situation, and policies to address the gap
Report	A short executive summary followed by more detailed information with access to relevant information, programs, and other related information and sources
News	Latest news items from RSS feeds automatically entered into the system with sources identified and with the ability for users to do keyword searches to reorder the sequence, to comment in a variety of ways, and to rate the relevance of each news item
Scanning	Important information added by users from the Internet and other sources with the ability for users to annotate and comment on their significance. Bookmarklet software added to one's browser can be used for this
Real-time Delphi	To collect both expert judgment and crowdsourcing opinions on each challenge. Questions may be added at any time. When a pattern of response is clear, the question can be deleted and the answers added to a situation chart and challenge reports
Questions	A blog-like area where the public and expert reviewers discuss questions they would like to explore, with the new ability for participants to reedit their prior comments
Comments	The comment icon appears throughout the system, allowing anyone to add a comment, whether it is an item in the situation chart, challenge overview, resources, etc. These are organized by time, and people can comment on other's comments
Models	Interactive computer models, mathematical as well as rules based and conceptual
Digest	Dashboard of recent scanning items, discussions, new resources, and edits to the challenge by day, week, month, and year
Updates	Latest edits to the situation charts and reports, with sources that triggered them within each challenge, and an update option for recent content additions in the whole system is available from the homepage
Resources	List links to websites, books, videos, presentations, and papers/articles

Fig. 3 Example of a situation chart: Global Challenge 1. How can sustainable development be achieved for all while addressing global climate change?

three elements of collective intelligence (people, information, and software) that have greater value than the sum of their separate, individual values.

Figure 3 below shows an example of a "situation chart" for organizing information to reflect the present and desirable situations related to a specific challenge, as well as polices to address the gaps between what is and what ought to be. As with other elements of GFIS, the situation charts are continuously updated based on feedback and new information gathered throughout GFIS.

Everything in GFIS can be commented on by anyone who accesses the system. Substantive edits, updates, and improvements can be made in real time by experts and the public via a rapid review process. GFIS reviewers will be notified automatically of any suggested edits within their expertise. Since reviewers are very busy, not expert in every detail of a challenge, and might not have seen the suggestion, it is assumed that of the 100 reviewers per challenge, at least three will give their review of the suggestion to the relevant challenge within 24 h. These reviews go to the GFIS editors who then make the edit (Table 3).

Examples of How One Might Use GFIS to Better Understand and Anticipate Science and Technology Convergence to Benefit Society

- **Select "Updates" of the whole system from the front page.** This gives all recent changes in scanning items, edits to reports and situation charts, RSS news aggregator, comments, discussions, questions, web resources, books, papers, and models. The results are displayed in an executive dashboard allowing one to go into further detail on any category and any item in a category. This can help one to see how their interest fits into the larger whole. A specific term can be entered that returns the most recent matches.

Table 3 The types of participants, their roles, and how they are selected

Types of participants	Access and roles	How selected
1. Administrators	Can edit text directly anywhere	GFIS staff
2. Editors	Can edit in selected challenges directly determined by permissions set by Administrators Receives reviewers' recommendations for edits	GFIS staff Additional editors selected by monitoring GFIS activity
3. Reviewers Ideally about 100 per challenge (Why so many reviewers? To make sure at least three review a suggestion within a day. The reviewers are very busy, are not expert in every detail of a challenge, and might not have seen the suggestion. Also, the reviewers are part of the discussion groups, RT Delphi panels, and other parts of GFIS to continually update and improve the collective intelligence)	Receives edit suggestions from the public and other reviewers Reviews/approves potential changes, sends recommendations, or comments to editors	Invited by GFIS staff, who will also notice excellent contributors and invite new potential reviewers
4. The public	Can access all information Make text and data suggestions Add comments anywhere in GFIS Participate in real-time Delphi's and discussion groups	Self-selected, anyone

- **Pose questions.** Results from the search can lead to new questions that can be posed in the relevant discussion groups or added as a structured question in a real-time Delphi setting-specific demographic categories for analyzing the results. The categories could be from nonscientist or non-engineer as well to get a broader range of views helping to anticipate potential convergences.
- **Conduct searches in specific challenges that might not seem related to a specific S&T item.** One could search within the global challenge on organized crime and find connections to S&T not previously considered. One can search by expert reviewers' inputs versus nonexpert inputs to the system. These searches might bring up an important question that can be submitted to the discussion areas to obtain broader feedback and new insights from the group to the relevant challenge group. The discussion might generate several suggestions for updating or improving the text of the challenge's short overview. These suggestions are

automatically sent to the reviewers of the challenge and then, if accepted and/or amended, are entered into the regular text of the challenge.
- **Create a technology converge table to help anticipate S&T converges via integration of cross-impact analysis and Delphi.** One example is explained above in Table 1. Technology convergence table gives another way to gain new insights that might not have been known before.

GFIS is constantly evolving. Its collective intelligence will increase with the number of users, review and improvement of information, new software and models, and better integration of all these elements of a collective intelligence system.

Conclusion

CIS can be a new tool for both the advanced scientist and the general public to help anticipate S&T convergence to benefit society. Expert judgment and public option can be organized to increase our collective intelligence about increasingly complex issues on one platform. Agreements about S&T policy can be identified and strategies developed in an open, transparent fashion. This is also a potential new source to improve media coverage of S&T issues to make our public dialogues more informed that the current fragmented information systems.

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Consilience

Ullica Segerstrale

Contents

Abstract

Consilience is a concept coined in 1998 by E. O. Wilson in his book with that name. Having borrowed the term from the English scientist William Whewell, for whom it meant the increased certainty that a scientist feels when an explanation in one field of science gets support from developments in an unrelated field, Wilson extended it to mean instead the convergence between different areas of knowledge. His aim was the unification of the great realms of learning, more specifically the Two Cultures, through a web of cause-and-effect explanation. He hoped consiliently educated synthesizers would help solve urgent global problems. Wilson's call for consilience legitimized interdisciplinarity and encouraged bold scientific collaborations and the sharing of tools across fields. While Wilson restricted himself to science and was ambivalent about technology, technology was in its own way attempting to unify knowledge, with artificial intelligence playing a major role. With the increase of computational power and proliferation of new strategies enabled by evolutionary algorithms and network research, innovative problem solving in one domain can quickly

U. Segerstrale (✉)
Social Sciences, Illinois Institute of Technology, Chicago, IL, USA
e-mail: segerstrale@iit.edu

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affect others. Big Data and machine analysis present new opportunities and challenges. Contentious issues include the relationship between explanation and understanding, facts and values, the nature and status of moral beliefs, and the meaning of consilience in a world of accelerating technology with superintelligence on the horizon.

The Drive for Unification

Consilience is a term that has recently come into more general use, popularized by Edward O. Wilson, the famous Harvard biologist, in the title of his 1998 book which became a national best seller. Consilience is a word originally used by the English nineteenth-century scientist William Whewell to describe the informal process by which scientists become convinced about the reality of a new scientific principle or phenomenon. The name refers to the apparent convergence of independent observations from different realms of science – the principle needs to hold up, say, in physics, chemistry, geology, and astronomy. The more support it gets from different scientific fields, the more the observations "jump together," the stronger the conviction will be that the phenomenon is indeed real. (Consilience means literally "jumping together.")

For Wilson, however, this concept refers to the unification of knowledge, especially the natural and the social sciences, which he sees as connected to one another by "a web of cause-and-effect explanation." Sometimes it seems that consilience has to do with the subject matter itself, implying some kind of ontological identity. This chapter provides an overview of Wilson's discussion as well as some criticisms, introduces some possible applications, and considers whether Wilson's idea could be extended to include also hybrid or technological achievements, resulting in a more encompassing view of consilience.

The unification of knowledge has been a long-standing agenda of Wilson's. His career has been a continuing attempt to synthesize knowledge, from *The Theory of Island Biogeography* (MacArthur and Wilson 1967) to *Sociobiology: the New Synthesis* (1975) to *Genes, Mind, and Culture* (Lumsden and Wilson 1981) and finally to *Consilience*. *Sociobiology* was, in fact, intended as a provocative invitation to the social sciences to take biology seriously, but triggered the sociobiology controversy instead (see Segerstrale 2000).

Wilson views himself as a worker in the general tradition of the Enlightenment. Among his heroes looms especially Francis Bacon, whose *New Atlantis* laid out a plan for a unified scientific enterprise, where scientists from different fields worked together for the benefit of mankind. Wilson identifies especially with Bacon's wish to extend scientific investigation also to the social realm and his unfailing belief that just as nature is guided by laws, so is society. Among other important Enlightenment figures identified by Wilson are Hobbes, Hume, Locke, and Newton in England, Descartes and the *philosophes* around Voltaire in France, Kant and Leibniz in Germany, Grotius in Holland, and Galileo in Italy (Wilson 1998a, p. 22).

Later the logical positivists' attempt to unify science failed, notes Wilson. They approached objective truth as philosophers, while the point would have been to "track material phenomena of the outer world through the labyrinth of causal processes in the inner mental world, and thus precisely map outer phenomena onto the inner material phenomena of conscious activity" (Wilson 1998b, p. 27). Wilson in fact seems to conceive of truth as direct correspondence, a belief which philosophers classify as "physicalism."

Why is there a need for consilience? Wilson points to trust in consilience as the foundation of the natural sciences and the reason for their success. Also, it is the kind of project that satisfies both our intellectual and emotional needs. And importantly, consilience is also the natural way to solve global problems. These are part of both social and natural science: unchecked population explosion, irreversible environmental degradation, and our potential manipulation of the evolutionary process. We need synthesizers, broadly trained individuals! Core curricula in undergraduate education need to be built on the consilient approach (Wilson 1998a, pp. 126, 269–270). Within science, he identifies the spaces with the greatest potential for consilient exploration as "the final unification of physics, the reconstruction of living cells, the assembly of ecosystems, the coevolution of genes and culture, the physical basis of mind, and the deep origins of ethics and religion" (1998a, p. 268).

But Wilson's particular interpretation of the Enlightenment quest has also received criticism. The philosopher Richard Rorty, for instance, asked why Wilson's equated the Enlightenment quest with the unification of knowledge. Rorty thought the Two Cultures had a natural division of labor:

> [W]hen we know what we want but don't know how to get it, we look to the natural sciences for help. We look to the humanities and arts when we are not sure what we should want. This traditional division of labor has worked pretty well. So it is not clear why we need the further consilience which is Wilson's goal. (Rorty 1998)

He also wondered why Wilson believed that a seamless causal web needed to go together with a seamless explanatory web. Academic disciplines are not supposed to be reflections of the real world; rather, they have different vocabularies and provide different ways of doing things.

Jerry Fodor, too, was puzzled as to why Wilson would assume that a view of the unity of explanation should entail the view of a unity of reality, too. There was a difference between epistemology and metaphysics. We do not have to assume that everything has to be reducible to physics, Fodor protested; a view of scientific realism is quite compatible with a view of reality as made up of different levels of organization of the world (Fodor 1998).

Finally, an indirect critic would be the German social theorist Jürgen Habermas. His longtime concern has been that scientific rationality would come to dominate the humanities' and social sciences' important discussion about desirable social values and goals. In contrast with Wilson, Habermas sees the Enlightenment quest as being about the nature of a rational society. A rational society doesn't imply a scientifically or technologically managed society – rather, it is a society whose goals and values are settled in a process of rational discourse. Therefore it is important that free rational discourse be supported and protected from domination or takeover by other types of discourse (Habermas 1970).

Defying the Two Cultures

The central theme of *Consilience* is the overcoming of the divide between the Two Cultures. Wilson offers various suggestions for the unification of the arts and the sciences. His scenarios have partly to do with the idea of gene-culture coevolution and partly with his faith in neuroscience. He realizes, however, that the biggest challenges for his project will be presented by morality, ethics, and religion.

Ever since the decline of the Enlightenment, Wilson noted, the social sciences and humanities had been treated as intellectually independent, with different categories of truth and autonomous ways of knowing. But there was a way to unite the great branches of learning and end the culture wars:

> It is to view the boundary between the scientific and literary cultures not as a territorial line but as a broad and mostly unexplored terrain awaiting cooperative entry from both sides. The misunderstandings arise from ignorance of the terrain, not from a fundamental difference in mentality. . . . What, in final analysis, joins the deep, mostly genetic history of the species as a whole to the more recent cultural histories of its far-flung societies? That, in my opinion, is the nub of the relationship between the two cultures. It can be stated as a problem to be solved, the central problem of the social sciences and the humanities, and simultaneously one of the great remaining problems of the natural sciences. (1998a, p. 126)

Later in his book Wilson answered the question about the connection between the genetic and cultural histories of our species, as he identified the core of consilience to be the idea of gene-culture coevolution – the general model that he and Charles Lumsden introduced in *Genes, Mind, and Culture*. That model suggested the existence of the so-called epigenetic rules that bias our minds toward particular cultural choices. A leading example of an epigenetic rule was incest avoidance. Here they relied heavily on the so-called Westermarck effect, named after the nineteenth-century Swedish-Finnish sociologist and anthropologist Edward Westermarck, who discovered that unrelated children who grew up together were later unwilling to marry or mate. In *Consilience* the Westermarck effect was to serve as Wilson's exemplar for the unification of the natural and human sciences.

But how were the arts to be integrated in the consilience project? Wilson had a clear answer: The arts, too, are pursuing truth, because they "embrace not only all physically possible worlds but also all conceivable worlds innately interesting and congenial to the nervous system and thus, in the uniquely human sense, true" (p. 268). And what about meaning? "What we call meaning is the linkage among the neural networks created by the spreading excitation that enlarges imagery and engages emotion" (p. 268).

A direct celebration of Wilsonian-type consilience between science and literature is *The Literary Animal*, edited by Jonathan Gottschall and David Sloan Wilson in 2005. Wilson wrote the preface for this book, which includes chapters from both sides of the cultural divide. (For a comprehensive review, see Pinker 2007).

In regard to art, in *Consilience* Wilson is interested mostly in its effects. He examines cave art and contemplates its rationale and impact, he looks at a painting by Mondrian and analyzes how the painter achieved the effects he wanted by using various special techniques, and he discusses Ellen Dissanayake's point that art is used to make something special, to set something apart from everyday life. (See Kandel 2013 for a further examination of art from a neuroscientific perspective.) In regard to our aesthetic preferences, Wilson presents these as connected with particular epigenetic rules, one of which is biophilia, our innate love for nature. Wilson also discusses music and the special emotional effects deliberately attained by changes in tempo or sound quality.

Let's take a closer look at neuroscience, the discipline Wilson regards as especially well poised for connecting fields across the traditional divide between the sciences and the humanities.

The beginning of the twenty-first century saw a great increase in scientific cross-fertilization led by experts who have ventured out of their traditional specialties and achieved important new insights into the biological foundation of thought processes. This has given rise to new hybrid fields, such as neuroeconomics. An article in *Science* called "Neuroeconomics: The Consilience of Brain and Decision" notes that "economics, psychology and neuroscience are now converging into a single unified field aimed at providing a theory of human behavior. In this enterprise the method and the standard set by neuroscience is the final goal: a reconstruction of the process and mechanism that goes from a stimulus presented to the subject to his final action in response." The subject decides among various options based on desirability, realized as a neural signal in the brain (Glimcher and Rustichini 2004). Another example of interdisciplinary research that addresses the connection between higher brain functions and behavior is a study on cognitive memory aiming at integrating molecular, cellular, electrophysiological, and functional imaging data connected with encoding and retrieval of episodic memory. The growing international field of neuroethology investigates how the brain controls behavior within the great diversity of animal species (Stern et al. 2004).

Despite high hopes, however, some experts agree about the great difficulties in establishing a link between biology and behavior in humans. Better methods are needed. Currently it is possible to study one neuron at a time, or one part of the brain without knowing which electrode does what. Critics point out that the pictures generated in brain scans do not represent ongoing cognitive activity: "Brain scans are empathetically *not* images of cognition in process, as the neural activity of interest occurs on a time scale orders of magnitude faster than hemodynamic response"[the proxy for neural activity measured by fMRI] (Crawford 2008). Moreover, most complex psychological or behavioral concepts do not map into a single center in the brain. At the same time, however, neuroimaging has great charismatic value. A study at Yale showed that otherwise rational people are willing to accept an incorrect conclusion as long as it is accompanied by a picture of a brain scan saying "brain scans indicate" (Crawford 2008).

What about morality, ethics, and religion? According to Wilson, "[i]n no other domain of the humanities is a union with the natural sciences more urgently needed" (1998a, pp. 277–278). He contrasts the transcendentalist thinkers, who believe that moral guidelines exist outside the human mind, with the empiricists, who see them as products of the mind. Among transcendentalists can be found both religious believers and scholars in the humanities and social sciences. Wilson champions the empiricist argument, which according to him suggests that we will be able to explore the biological roots of moral behavior through research into the deeper processes of human thought. In this way "we should be able to fashion a wiser and more enduring ethical consensus than has gone before" (p. 262). (Note that here Wilson is much more radical than the original Enlightenment thinkers, with whom he otherwise identifies. In fact, almost all of these thinkers believed in God and many were actually devout Christians, p. 265.) Meanwhile Wilson points to the backside of religion in its connection to tribalism and the resulting encouragement of in-group-out-group opposition. In contrast, he states, science favors a democratic and global culture (p. 269).

Wilson even takes on the naturalistic fallacy – which, according to him, is not a fallacy at all if we just look at the objective meaning of ethical precepts, which are not likely to be independent truths. "From the consilient perspective of the natural sciences, they are no more than . . .behavioral codes that members of a society fervently wish others to follow and are willing to accept themselves for the common good" (p. 273). Therefore, Wilson argues, "ought" is simply the translation of the public will, a description of what society first chose to do and after that codified.

For Wilson, ethical precepts and religious belief are material products of the human mind. They increased the survival of those who adhered to the tribal faith. The epigenetic rules responsible for the moral and religious sentiments evolved over more than 1000 generations; indoctrinability became an instinct. He sees no reason why the brain sciences cannot eventually provide "a material account of the emotions and ratiocination that compose spiritual thought" (pp. 269–270).

But here consilience will be needed. Wilson hopes for the convergence of different approaches across the cultural divide: definition of the moral sentiments, analysis of the underlying neural and endocrine responses, measurement of the heritability of the psychology and physiology of ethical behavior as well as identification of the underlying genes, histories of ethical systems and individual cognitive development in different cultures, and finally the basic explanation ("deep history") of the existence of the moral sentiments (p. 179). In this way, Wilson believes, we may discover "the true origin and meaning of ethical behavior" (p. 179). (Note that he here interprets "meaning" as equivalent with "evolutionary rationale.")

But consilience can only go so far. There is no chance of convergence between science and religion as such, argues Wilson. These two beliefs are not "factually compatible" because they represent different stages of the development of the human brain. Religion developed in its proto-form already during the pre-Paleolithic stage, but science only in modern times (p. 286). And despite the attempts to solve this problem by theologians – e.g., Spinoza's "Deus sive natura" (God or nature as interchangeable) or process theology that sees God manifest in everything or efforts by scientists (e.g., Stephen Hawking's suggestion that the final theory of everything in physics would allow us to know the mind of God) – the problem remains. This is because "[t]he human mind evolved to believe in the gods. It did not evolve to believe in biology" (p. 286).

So what to do? Wilson has the answer: Derive the sacred narrative instead from the material history of the universe and the human species! Present the "evolutionary epic" as the requisite myth! Meanwhile he recommends respectful coexistence. Science will continue to "uncover the bedrock" of the moral and religious sentiments, while religion would need to update itself with science in order to retain credibility and moral leadership. Eventually, he envisions, the outcome of the competition will be "the secularization of the human epic and religion itself" (p. 286).

Integration in the Human Sciences

After considerable resistance, the evolutionary paradigm is slowly gaining influence in the social sciences. Sociobiology made itself unpopular with its explicit suggestion to cannibalize social science. While it was rejected by cultural anthropology (e.g., Sahlins 1976), it supported the emergence of evolutionary anthropology (Chagnon and Irons 1979). Biosocial anthropology had already earlier been established by Lionel Tiger and Robin Fox (e.g., 1971). In the 1980s models of gene-culture coevolution (Durham 1978, 1991; Lumsden and Wilson 1981) or "dual inheritance" (Boyd and Richerson 1985) were developed.

Later evolutionary psychology was offered as a unifying perspective (Barkow et al. 1992). Segerstrale and Molnar (1997) strove to bring the social sciences and life sciences together around the field of nonverbal communication. Barkow (2006) saw the urgent need to familiarize social scientists with useful applications of an evolutionary perspective, while Gintis (2009) attempted the unification of the social sciences around game theory and Mesoudi (2011) around a new science of cultural evolution. Comparing the social sciences with evolutionary biology, he emphasized the obvious possibility for vertical integration in the social sciences, now prevented by the existence of fields with independent explanatory strategies (see p. 211).

In the early twenty-first century, the two important foci of multidisciplinary research are the evolution of human cognition and the rise of large-scale societies. New research on human cognition is moving away from evolutionary psychology toward an integration of recent findings in anthropology, archeology, evolutionary biology, linguistics, neuroscience, and psychology. This view sees the evolution of human cognition as having taken place in a gradual manner, with new forms of cognition – causal reasoning, imitation, theory of mind, and language – emerging through gene-culture coevolution, aided by the coevolution of technology (cf. Heyes 2012).

A central theory here is that it was a particular cognitive and behavioral complex, which included forms of cooperation, egalitarianism, theory of mind, language, and cultural transmission ("a sociocognitive niche") that made it possible for a group of small hominins to hunt large mammals, acting as a group-level predatory organism. This could be the explanation for the tripling in human brain size during the past two million years (Whiten and Erdal 2012). The idea of the cooperative core of the sociocognitive niche goes directly against recent theories of competition, deception, and selfishness – those have now been superseded by arguments about the fitness benefits to be gained by contributing to group-level goods, they note (p. 2121). It also challenges earlier views of the importance of factors such as environmental change for the evolution of human cognition.

In a parallel development researchers have tackled another remaining puzzle when it comes to humans: the evolution of large-scale cooperation. Handling the challenge of unrelated strangers in large societies would require going beyond kin selection and reciprocity. This has led some researchers to take a closer look at group selection – or rather multilevel selection – since humans typically form hierarchically organized larger entities. The "group extinction" required by selection working on groups can take place in several ways. Some authors refer to the killing of a defeated group (e.g., Bowles 2006; Wilson 2012). However, alternatively the group may get absorbed by the winner and learn their culture by resocialization (Boyd and Richerson 2009). There is evidence for both views. Genomic data will help clarify issues, including the timing of genetic changes, human population sizes, and migration patterns.

Unlike genetic variation cultural variation does not require intergroup competition or group extinction. The human propensity for cooperation may have arisen through gene-culture coevolution, with *culture* as the driver. Culture can quickly create a new environment for adaptation, putting pressure on the genes and speeding up evolution. It can also quickly generate the requisite behavioral variation between groups (Boyd and Richerson 2005, 2009). Alternatively, innate propensities to cooperate could have evolved through gene-culture coevolution. Cultural rules for cooperation alone could have created a selection pressure for genotypes that obey such rules and similarly selection against genes for antisocial behavior (Bell et al. 2009).

Shared Tools for Discovery and Problem Solving

This section looks at consilience in two ways that go beyond Wilson's original conception. The first, network analysis, involves different fields coming together and sharing findings as part of an integrative, exploratory science. The second actively brings professionals from different fields together with the objective of finding simple algorithms and rules. Rather than aiming at a scientific explanation, this effort has a practical goal. The idea is to mimic nature to later use the results for human planning. Nature often finds different and simpler solutions than the human brain.

Networks represent a simple model that allows tracking the spread of things, be it ideas, diseases, or innovations, which makes network science useful in all kinds of fields, be it social science, medicine, biology, economics, computer science, or physics. A network's links (ties) and nodes may represent people, genes, viruses, etc. As these grow in number, the resulting network can become extremely complex. At the same time, because of the rules that underlie network behavior, findings in one field can be readily transferred to other fields, making the science of networks an important integrative science.

In their book *Connected: The Surprising Power of Our Social Networks and How They Shape Our Lives* (2009), physician and medical sociologist Nicholas Christakis and political scientist James Fowler demonstrate actual commonalities between social sciences, medicine, evolutionary biology, and mathematics. They are dealing with physical models of a "web of life" and the effect that one part of the network has on other parts of it. Knowing about the paths of spreading of information – and also emotion – as well as the roles of various communicators in the web is crucial for such things as potential interventions into a population's health.

Network analysis has made inroads in many fields. It is extremely useful since observations about network properties that have been reached in one field can be immediately transferred to another. Network analysis has also become a standard tool for calculating the shortest route between points. Here living organisms can be excellent problem solvers. When it came to finding the shortest way through a maze or planning a railway system, a slime mold was able to beat the experts (Gudrais 2010, pp. 44–50).

Mimicking ant collaboration, again, can teach humans how teamwork can emerge from an unstructured mass of individuals. This has been explored in detail in a collaborative project involving biologists, computer scientists, and engineers. The biologists study how ants solve various problems, such as finding the shortest path to a food source or when to send off workers to search for more food for the colony. After this the computer specialists use agent-based modeling to simulate the situation and find simple algorithms and rules behind the ants' behavior. An important principle here is to aim for an acceptable ("good") solution rather than for the best solution.

When it comes to the shortest path to the food source, some researchers have come up with a path optimization method which "electronically" mimics the trail of pheromones that a swarm of real ants leave behind as they use a particular pathway. As more ants use the path, the scent gets fortified, while unused trails lose their scent. It was shown that with repetition, artificial ant agents learn to follow increasingly shorter routes. (This is a practical answer to the famous traveling salesman problem, which quickly becomes mathematically unwieldy.) Ant algorithms have also been used for solving congestion problems in communication networks. Artificial ant agents are sent out to report about delays, and this information allows the network's switching stations to quickly adjust the routing tables and respond to local breakdowns.

A further simulation of ant behavior involves sending out swarms of miniature robots in groups to "forage" for "food" and bring it back to the "nest." It was found that when the colony's total "energy level" (measured in the amount of food brought in by the food scouts vs. the energy they expend) fell below a certain level, one or more robots would leave the nest and start foraging. Finally, ant algorithms come in handy when designing robots for lifting heavy objects and moving them up slopes. They are also useful for sorting data, since ants appear to follow a rule of placing an object with similar size objects (e.g., larvae with larvae and eggs with eggs). They may even be useful for the design of office buildings (Peterson 2000).

A View to the Future: Big Data and Superintelligence

The massive data that is available and can be collected online has invited a new type of data-driven science, Big Data, which has affected the way research is done in many fields. In network research, for example, all kinds of data are being routinely collected: digital, genetic, and other kinds. The aim is to identify different types of patterns, which will then be more closely interpreted and related to human social behavior.

With the arrival of a new "computational social science" or "Big Data" social science, the social sciences are becoming more quantified. New methods provide social scientists with easily accessible electronic data (e.g., from social media), which can then be analyzed with the help of powerful computer programs. This type of social science is able to conduct massive data collection and analysis at an unprecedented scale, breadth, and depth. Will existing social science theories based on much more limited research be challenged by the conclusions coming from new data-rich research? Also, there are new possibilities for testing existing theories of human behavior. Meanwhile, using portable "sociometers" and mobile phones, one might track moment-by-moment interactions and locations of people in real time. Virtual worlds, too, could be used for a variety of experiments (see Lazer et al. 2009).

But what is the scientific status of this new massive data-driven activity? Does it represent "a would-be methodological commonality of different fields of learning, which is de facto harking back to the massive inductivism of the Father of the Scientific Method, Francis Bacon" (Gudrais 2010)? And does this make it a consilient science in the Wilsonian sense? What are the epistemological implications of Big Data research? (See Kitchin 2014 for a serious overview.) These questions are particularly relevant in regard to "culturomics," an approach which has opened new possibilities for research in the humanities.

"Culturomics" analyzes massive data derived from digitized books in order to detect trends and patterns over long time spans. (The books have been collected and digitized by Google.) The method is based on big interdisciplinary team collaboration and has generated some intriguing results. Studies that have been made include tracking the frequency of the use of certain words in the English language over time to identify cultural trends, measuring the attention that different famous people have got in media at different times (e.g., Darwin has by now overtaken Freud), or identifying cases of non-mention, indicating potential political suppression. The data is so massive, however, that it cannot be read by a human in a lifetime, only by a computer. Also, nobody is actually reading these books – the analysts are processing a single, massive database of frequency of words and their contexts over time (Michel et al. 2011; Bohannon 2010).

But are we actually looking for scientific explanations or are we just identifying trends? And in what sense is this science, since this whole thing is data driven rather than theory driven? What does it mean in practice that the data cannot be read by a human, only by a computer? This brings us to further questions about the relationship between consilience and technology.

Can consilience accommodate rapidly accelerating technology? An extreme line of current optimism argues that as technological power all the time increases (Moore's Law), we will soon reach a point where it will be possible to "upload" a person in a computer (Kurzweil 2005). Others see a lifelike direction in technological progress, suggesting that technology "wants" to evolve (Kelly 2010). Therefore, it would be natural for technology also to "want" to transcend humans – we are just its temporary vehicles.

Some believe with Kurzweil that a sudden transition to singularity is inevitable. At this point human intelligence is expected to merge with machine intelligence, preparing a person's digitalized personality for preservation and access in the future, achieving a sort of immortality. "We ordinary humans are supposedly staying the same ... while our technology is an autonomous, self-transforming supercreature," writes techno-guru turned techno-critic Jaron Lanier. "In the blink of an eye we will become obsolete" (Lanier 2013).

A counter-scenario to these types of deterministic views emphasizes instead human choice and the need for humans to take charge. This is also Wilson's stance. In *Consilience* he made clear that he is not a friend of "prostheses" of various kinds or of human enhancement. It is best to keep it natural. Although sympathetic to energy-saving and small-scale technology, Wilson does not believe that humans should colonize space. "The earth is our home" is his position, and we'd better take care of it.

Others think we have to take concrete measures. One suggestion is for humans to become more adequately equipped to meet the challenge. In *Unfit for the Future: The Need for Moral Enhancement*, Persson and Savulescu (2012) argue that our current morality doesn't measure up to future challenges. We need radical technology-aided moral enhancement in order to attain the required moral capabilities to protect our survival as a civilization.

The most encompassing view in regard to the future is probably Oxford professor Nick Bostrom's *Superintelligence* (2014) which documents the state of the art of AI, which is already now outperforming human intelligence in many domains. He notes that much of the recent progress in machine learning has derived from formal results developed in other fields. A common research focus on Bayesian statistics, for example, has made it easy to pool findings from the fields of machine learning, statistical physics, bioinformatics, combinatorial optimization, and communication theory. In this way improved algorithms for Bayesian inference in one field can feed back and improve other fields. But rather than subscribing to the millenarian singularity idea, Bostrom calmly considers alternative technical and normative strategies to prepare for a probable future "intelligence explosion" and discusses alternative criteria for choosing between them in a state of uncertainty.

Conclusion

Consilience has been a stimulating concept which has invited fruitful developments in a number of areas. With his advocacy and eloquence, Wilson has helped legitimize an active striving for consilience in science, even between quite disparate fields, and at the same time interpretations of consilience that go beyond his own aim for integration of the sciences. It has become more generally accepted to advocate transcending disciplinary boundaries. Thus, for instance, a central theme of a number of NSF-organized conferences has been the convergence of cognitive science, information science, robotics, and nanotechnology. Meanwhile (as predicted by Wilson) neuroscience has become the common focus of interest of many sciences and given rise to new hybrid fields, such as neuroeconomics, neuroaesthetics, and neuroethics.

The two sides of the supposed Two Cultures divide have increasingly found common ground in such initiatives as *The Literary Animal* and even actual academic programs aimed at synthesizing the sciences and humanities, such as D. S. Wilson's experimental programs at SUNY, Binghamton, the EVoS and The Neighborhood Project. Meanwhile research in human origins engages researchers in evolutionary biology, animal studies, social sciences, anthropology, archeology, ecology, linguistics, psychology, philosophy, and ethics. Ecological and climatological models give valuable insights into human prehistory. Human genomics is becoming a new source of data on ancestral populations. A new picture is emerging, where the focus is on the role of both cultural and social factors for human evolution (including the evolution of our big brains). New models of cooperation have been developed to explain the evolution of large-scale societies. And as the social sciences are becoming more willing to consider the biological basis of social behavior, sociological and cultural factors are increasingly brought into sociobiological reasoning. We may be witnessing an incipient consilience between sociobiology and the social sciences.

With his insistence on the possibility and urgency of consilience, Wilson has achieved a number of personal goals. He has satisfied his long-standing ambition to unite the natural and social sciences. He has been able to put his favorite model of gene-culture coevolution in central position by using the epigenetic rules as a connecting link. He has continued to urge the social sciences to become more scientific by adopting evolutionary biology as their founding theory and philosophy to pay more attention to science. At the same time, however, he has been actively pursuing a number of practical goals: protecting the environment, increasing scientific literacy, supporting better science teaching, and improving college curricula – not waiting for consilience to accomplish this.

Ultimately, though, Wilson's real concern is the survival of mankind, which he sees as reaching a dangerous bottleneck. The important thing is to bring population into balance while leaving sufficient space for nature. Here we would indeed need all kinds of experts working together for the good of humanity within a Baconian-type New Atlantis of consilient research. But Wilson's consilience is even superseding the Enlightenment quest. His "total" consilience goal aims not only to explain all human and social phenomena but also to provide an adequate replacement for religion. Since the human mind is programmed for myth, a satisfactory alternative has to be provided, and Wilson offers us what he calls the "evolutionary epic" as the best myth we will ever have.

Since Wilson wrote his book, however, it looks as if the most exciting developments have been happening in fields outside traditional academia. New forms of knowledge are explored by network analysis and widespread applications of evolutionary algorithms. Massively increased computer power and Big Data invite knowledge gathering at an unprecedented speed, scale, and breadth. Meanwhile there is the rapidly accelerating field of information technology and AI. And here we can let Wilson have the last word, in fact his final warning in *Consilience*:

> What does it all mean? This is what it all means. To the extent that we depend on prosthetic devices to keep ourselves and the biosphere alive, we will render everything fragile. To the extent that we banish the rest of life, we will impoverish our own species for all time. And if we should surrender our genetic nature to machine-aided ratiocination, and out ethics and art and our very meaning to a habit of careless discursion in the name of progress, imagining ourselves godlike and absolved from our ancient heritage, we will become nothing. (1998a, p. 298)

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Convergence-Divergence Process

Mihail C. Roco

Contents

Abstract

Scientific discovery and technological innovation in various areas evolve in coherence but in a nonuniform manner. This process leads to domains of scientific convergence, technology integration, and divergence of knowledge and applications into new fields. This cycle brings about synergism, which stimulates further discovery and innovation. The convergence–divergence cycle is a typical process in science and technology (S&T) development. It consists of four phases: (A) creative assembling of contributions from multiple fields leading to new concepts or ideas, (B) system integration leading to a new assembly or invention for known uses, (C) technological innovation outputs leading to new products and applications, and (D) spin-off outcomes that lead to solutions not possible before and that produce new competencies, tools, and applications. Each cycle and each phase generally follow each other in a quasi-exponential growth pattern. This cyclic process originates organically from human brain functions for problem-solving and serves an intrinsic human need to pursue intellectual advancement and achieve material progress.

M.C. Roco (✉)
National Science Foundation and National Nanotechnology Initiative, Arlington, VA, USA
e-mail: mroco@nsf.gov

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Understanding and facilitating the full convergence cycle in various S&T areas have increased in importance in today's densely populated, globally networked, and richly interactive society as means of addressing the world's increasingly complex and interrelated social, economic, environmental, and political needs. Recommendations are given for how the convergence–divergence cycle can be considered in governance of science and technology.

Introduction

The convergence process has been defined as the escalating and transformative interactions among seemingly different disciplines, technologies, and communities to achieve mutual compatibility, synergism, and integration and thus to create added value to meet shared goals (Roco et al. 2013). This definition expands on the definition of the convergence–divergence cycle first proposed for science and engineering megatrends (Roco 2002) by applying it broadly to convergence of knowledge, technology, and society. There are numerous implications, as recently illustrated for physical sciences–engineering–biomedical convergence (NRC 2014), industrial convergence (see the chapter in this volume by Pak and Rhee, "▶ Convergence Science and Technology at Seoul National University"), and evolution of the human mind within a social framework (Dunbar 2003; Dunbar and Shultz 2007). The convergence–divergence cycle is a key modular structure in the general evolving architecture of science and technology development. The interaction between such cycles, characterized by various convergence domains and cycle time intervals, determines the evolution of the entire system.

A General Process for Progress

The convergence–divergence cycle is a core mechanism in the evolution of science and technology (S&T), driven by human needs for achieving progress. Its implications are profound for decision-making and problem-solving in terms of transformation of knowledge, technology, and applications. Within the two main stages of the convergence–divergence cycle there are four phases of interconnected activities, as shown in Fig. 1 and described below.

The convergence stage comprises the creative assembly and unification of knowledge and technology across traditionally distinct disciplines, sectors, and levels of abstractization and organization. It consists of analysis, making connections between disparate ideas and integration of the new "connections" into advanced scientific concepts and technological competencies. The convergence stage includes two phases (Fig. 1):

A. *The creative phase* where contributions are assembled from multiple fields, leading to new ideas and discoveries through a knowledge confluence spiral

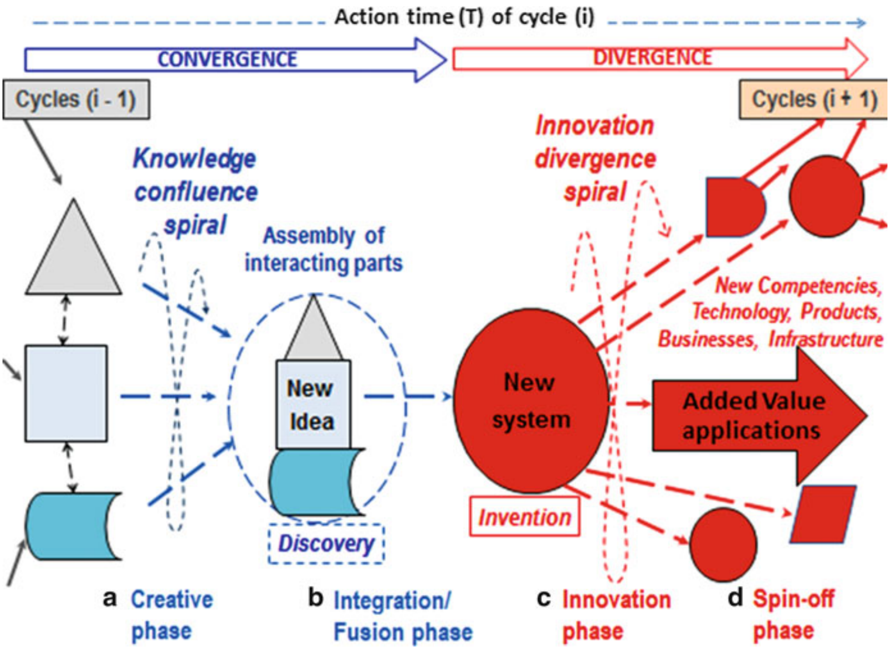

Fig. 1 A convergence–diverge cycle (i) has (**a**) creative, (**b**) integration, (**c**) innovation, and (**d**) spin-off phases. The cycle (i) receives input from previous cycles (series i-1) and affects future cycles (series i+1). The action time (T) is that taken by the evolution of the process from **a** to **d** (Modified from Roco et al. 2013, p. 141, Fig. 4.1)

B. *The system integration*, *or fusion*, *phase* where newly gained knowledge is applied, leading to inventions and newly designed products for the uses prescribed at the beginning of the cycle

The divergence stage starts after the formation of the new system that emerges from the confluence and expansion of new ideas and tools in the convergence stage. The knowledge and technology of the new system are diffused to new areas of relevance through a spiral of innovation; this in turn leads to entirely new products, tools, and competencies, all evolving rapidly through successive changes and recombinations. The divergence stage applies the systems assembled at the end of convergence stage to conceptual formation of:

C. The technology and business *innovation phase*
D. *The spin-off phase* where the products of innovation lead to emerging new competencies, tools, and uses and possibly new business and infrastructure

An evaluation and connectivity stage at the end of each cycle (i) provides solutions to be linked as input to future cycles (i + 1). A Darwinian selection of S&T solutions should occur where only the most effective solutions are used in the future cycles.

There are numerous separate studies describing individual parts of this cycle, in particular for the creative phase (e.g., how we create, Lehrer 2012), for the integration phase (e.g., using an evolutionary approach, Goodman 2014), and for the innovation phase (e.g., the innovation environment, NRC 2012) – that is, for phases A–C of the cycle. There is less understanding and there are fewer models of the spin-off phase (D) of the divergence stage (one example is on diffusion of knowledge in networks, Liu et al. 2014). Also, information is scarce regarding the *global picture* of coherent evolution in science and technology incorporating multiple cycles, as well as regarding the deliberate use of new information and management tools to improve the outcomes of a full convergence–divergence cycle.

Several illustrations of convergence–divergence cycles are given below:

- People encounter convergence–divergence cycles in their daily lives. When a challenge arises for individuals or organizations, the individuals or organization leaders usually begin by collecting and analyzing information about the problem and creatively assembling the data and proposing new ideas through discovery (creative phase A in Fig. 1); they then make a decision to solve the problem through integration, inventions, and new system design (B); they further apply the results to realize the new systems and manufacturing various products for the initially targeted area (C); and then, on that basis, they expand their attention to new areas not initially considered and develop new competencies, capabilities, and as applicable, businesses, in spin-off areas (D).
- The biological life cycle follows a convergence–divergence pattern for individual events and for species, for example, beginning with a new gene combination (Phase A) that is followed by formation of new cell biosystems (B) that grow into tissue (C), where mutations or new combinations of DNA thereafter cause divergence trends in the structure of the cells and, in turn, in the species (D).
- A tree has roots that support growth of a tree body (Phase A) that forms branches (B) that produce fruits and make seeds (C) that can spread by wind to grow into new tree generations and can combine with other plants or be subject to other biological interference mechanisms (D).
- Development of many new S&T fields, such as synthetic biology, metamaterials, quantum communications, and neuromorphic engineering, have begun with a stage of defining converging concepts and methods (Phase A), realizing a prototype (B), followed by applications in related areas (C) and an open-ended series of discoveries and development of novel technology platforms promising broad changes in society (D). The integration of biomedicine with physics and engineering (phases A and B) is already effecting transformations in human healthcare systems (C) and promises fundamentally new solutions in molecular medicine and individualized care (D).
- Economic and civilization cycles begin with a new knowledge and tool/technology base (Phase A) that leads to a new ecosystem (B), that helps increase production and other societal outputs (C), and that thereafter diverges into

various other application areas and socioeconomic projects that overall are able to sustain economic growth rates and societal progress (D).

- Individual or group learning of various scientific disciplines (Phase A), followed by practice or apprenticeship in selected technology domains (B), leads to gaining of employment in areas of preparation (C) and, then together with other factors, to creation of new businesses and competencies and completely new job descriptions (D).
- The R&D programs addressing "grand challenges" in research funding and performing agencies typically originate from a critical confluence of various disciplines. This confluence leads to new ideas and discoveries (Phase A) that further produce concepts and inventions for the given grand challenge (B), bringing significant transformative value to applications through innovation (C), and therefore generate unforeseen spin-off areas of expertise, technologies, and businesses (D). Several examples are the US grand challenges on space exploration, nuclear energy production, information technology, and nanotechnology, as further described later in this chapter.

Successive waves of innovation are delimited by "ages of transitions" (Gingrich 2003) from the end of one S&T maturing field to a new wave of innovation (that is, a new convergence–divergence cycle). Each cycle for an important change in S&T is characterized by an S-curve of cumulative outcomes (in the vertical coordinate) versus technical change or time (in the horizontal coordinate) as it will be illustrated for NASA's Apollo space exploration program in Fig. 4: (a) The scientific preparation in the slowly rising section of the S-curve is characterized by exponential increase in scientific articles and corresponds to the creative phase A; (b) the section before the inflection point is characterized by exponential increases in patents and corresponds to the integration phase B; (c) the high slope section of the S-curve corresponds to expanding the outcomes during the innovation phase C; and (d) the last section corresponds to creation of new scientific fields and technology and application domains as spin-off (phase D) of the original cycle (here originate the new wave cycles with their respective spin-off S-curves). Gingrich predicted that the convergence of nanotechnology, biotechnology, and information technology would bring about the wave of innovation that we are experiencing in the early decades of this century.

Preparing for the new economy after an initial phase of scientific and nano-, bio-, information, and cognitive technology/neurotechnology (NBIC) convergence (phases A and B) has been discussed by Cantor (2003). The implications for the future in terms of emerging technologies and enhancement of quality of life and human potential suggest a need for a larger investment in the divergence stage (phases C and D) than the initial effort dedicated to the convergence stage.

Table 1 shows how the modes of research and key players change as the convergence–divergence cycle advances through its four phases. In practice, the process is not linear, and there is a good deal of overlap between the creative, integration, innovation, and spin-off phases of a cycle and between various cycles.

Table 1 Convergence–divergence cycle: modes of research, communities, typical approaches, and improvement methods as a function of the phase of the cycle

	Convergence stage		Divergence stage	
	A. Creative phase	B. Integration phase	C. Innovation phase	D. Spin-off phase
Modes of research and outcome	Basic research for new ideas and discoveries	Use-inspired research to create systems and inventions	Technology and business diffusion, innovation for production	Vision-inspired efforts for new uses, commercialization, and acceptance
Main community	Academic, industry researchers	Concept, design, and manufacturing	Entrepreneurs, marketing	Markets, NGOs, and new user groups
Key approach	Exploratory and application-driven investigations	Problem-solving and system design	Exploratory outreach, implementation after invention	Revolutionary, unplanned directions, branching out
Key improvements	Larger domains and speed of exchange	Dedicated ecosystems	Open innovation and speed in decisions	Diversification, vision-inspired

The Apollo space exploration program, platforms for unmanned vehicles, and the international research program on fundamental particles (Higgs et al.) are all examples of coincidentally multidisciplinary projects driven by a common goal. Other examples of coincidental, rapidly evolving, and valuable convergences in knowledge, technology, and society can be seen in pairs of technologies sharing resources, joint databases of complementary fields, human–machine interfaces, cloud computing, and human–robotics systems. Because of the rapidity and magnitude of the convergence–divergence knowledge and innovation spirals taking place in science and technology today, as well as the broad scale of the potential consequences of these activities, it is critical to start formulating a *systematic and anticipatory approach* to improving the outcomes of convergence–divergence cycles and to replacing coincidental convergence with proactive and anticipatory measures for systematic convergence.

Wilson (1999) advanced a systematic approach for the unity of knowledge in the convergence stage (phases A and B in Fig. 1). Roco and Bainbridge (2003) proposed a systematic framework for convergence–divergence stages in the development of emerging and converging NBIC technologies: nanotechnology, biotechnology, information technology, and cognitive and neurotechnologies. The 2003 study introduced divergence (phases C and D) in several ways: by incorporating human dimensions in the development of emerging technologies such as brain research and neurotechnology, in new vision-inspired research targets such as universal databases and mind–cyber–physical systems, and in research to improve human performance in daily activities.

In 2013, Roco et al. proposed five principles that can be used to systematically facilitate convergence for all areas of knowledge, technology, and society in (1) exploiting the interdependence among domains, (2) improving the convergence–divergence cycle, (3) applying system-logic deduction to decision-making and problem-solving, (4) creating and applying higher-level multidomain languages, and (5) using vision-inspired research to address long-term challenges. These methods are further described in the chapter in this volume entitled "▶ Principles and Methods that Facilitate Convergence." To guide developments in S&T to most effectively meet society's needs, it will be necessary to identify, plan for, and manage future convergence–divergence processes, using these five methods to improve and accelerate convergence.

One specific illustration of the convergence–divergence process is the cell phone platform, which began with the creative assembling of a wide range of technologies and cognitive and human–computer interface sciences, all of which converged to create the "smart phone" about a decade ago (*phases A and B* in Fig. 1). With almost 7 billion subscriptions in 2014 (ITU 2014), cell phones are now owned by a majority of all people worldwide (ITU 2014). In addition to the technologies that enable imagers, gyroscopes, microelectromechanical devices, speakers, and microphones and the immensely complex set of technologies (including satellite technologies) that enable geolocation and instant mapping, cell phones and smart phones rely on convergence of "high-frequency communications technologies and packet switching protocols; materials science and nanoelectronics for logic units, data storage, touch screens, antennas, etc.; and cognitive science and human–computer interface technologies" (Roco et al. 2013, p. 154) that contribute to usability design and appeal. Mobile phone platforms are now diverging into thousands of applications scarcely imagined 10 years ago, with far-reaching "cascade" implications on areas as diverse as national security, education, healthcare, and cognitive science. Besides the myriad direct applications of mobile phone and broadband mobile phone development (in *phase C*), there are also unanticipated spin-off technology developments (in *phase D*) that are beginning to appear. Examples include Google Glass, wearable round-the-clock networked personal health monitoring devices, and mechanisms to connect automobiles to smart transportation grids in various ways. Without doubt there are yet-unimagined downstream applications still to come. The many indirect consequences (all placed in phase D) include societal impacts such as escalating privacy concerns in Europe and the United States; rapidly growing access in developing nations to telephony, phone-based banking, and computing; and rapidly expanding global economic and cultural interactions.

A Process that Reflects Human Brain Functions

The cyclical *convergence–divergence process* in decision-making and problem-solving originates organically from brain functions and indirectly from other domains of the global human activity system. The convergence–divergence cycle

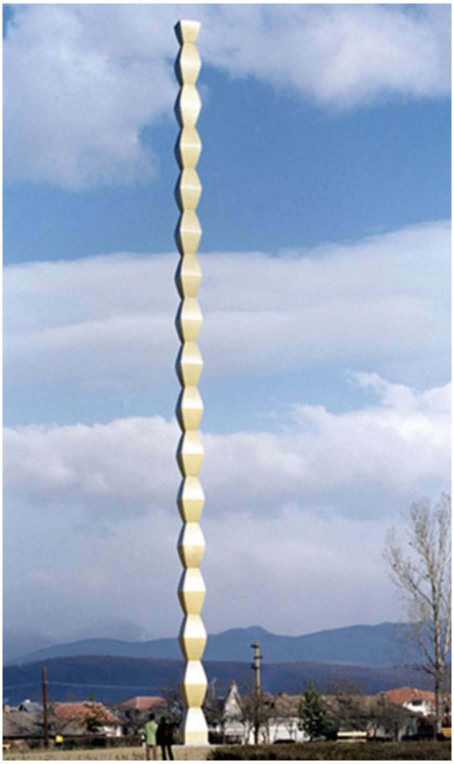

Fig. 2 The convergence–divergence cycle in human thinking as reflected in art: "Endless Colum" (C. Brancusi 1937) (Source: Creative Commons, https://creativecommons.org/licenses/, 2015)

reflects two complementary roles of human brain functions: analysis/synthesis and visualization/imagination. Decision-making and problem-solving follow a convergence–divergence process driven by the need for improvement and added value that is at the core of human thought and behavior; this also is reflected in group and societal organization actions. This process can provide a structure and specific improvement methods for the creative–innovation–production–societal implications' chain.

The convergence–divergence process is reflected in the coherent chain of ideas from the ancient to modern eras, in the evolution over time of knowledge and technology, and in the development of human organizations and industries.

This cycle also in reflected in art. For example, the succession of convergent and divergent stages in the human mind over the long term is suggested by Constantin Brâncuşi's sculpture "Endless Column" (Fig. 2).

In another example, the movie *Divergent* (2014) underlines the confluence of various types of human behavior that lead to open-ended scenarios. In the movie, people with multiple virtues are called "divergent"; they initially have difficulty fitting into any one of their society's standard factions based on virtues, but finally they have leading roles in creating the future.

An Index of Innovation

To conceptualize the influence of the convergence–divergence process on innovation, Roco et al. (2013) defined an index of innovation rate (I) that quantifies the potential increase of outcomes as a function of the process characteristics. The three-dimensional innovation spiral has a longitudinal projection along the convergence–divergence cycle, as shown in Fig. 1, and a transversal projection in the science and technology domain where the cycle takes place. The transversal projection is characterized by the time scale of information exchange (t) between the (S) science and technology components of a given domain. The time scale of the convergence–divergence cycle from the beginning of the creative phase A to spin-off outcomes D is (T). The two time scales are proportional (T ~ t), as they are the axial and transversal projections of the displacement along the innovation spiral. The index of innovation rate varies in direct proportion with the square of the size of S of the domain where the cycle occurs and from where information is collected (the area circumscribed by the transversal projection of the innovation spiral) ($I \sim S^2$) in direct proportion with the outcome ratio (O) between the output and input for known applications in the respective cycle and in inverse proportion with the cube of the speed of the convergence–divergence cycle ($I \sim 1/T^3$):

$$I \sim k\, S^2 O/T^3 \tag{1}$$

where k is a coefficient of proportionality.

This qualitative correlation shows that the innovation rate increases rapidly with the size of the convergence domain ($I \sim S^2$) and is significantly affected by the time scale of the convergence–divergence cycle ($I \sim 1/T^3$). This correlation has similarities with Metcalfe's law in information research (Shapiro and Varian 1999) that says that the number of possible cross-connections in a network grows as the square of the number of computers in the network increases, and the community value of a network grows as the square of the number of its users increase. Metcalfe's law is often cited as an explanation for the rapid growth of communications technologies and the Internet. The term (O/T^2) in the equation is in agreement with the empirical exponential growth model for science and technology (for illustration, see Moore's law and Kurzweil 1999), and the remaining term (1/T) is proportional to the knowledge and innovation diffusion rate.

Figure 1 and correlation (1) above consider the spiral of innovation in a single convergence–divergence cycle. This cycle is seen as a structural modular unit in the entire system of S&T development. A fractal structure between individual units and their assembly could be considered if the cause-and-effect mechanisms are qualitatively similar at different scales. An index of innovation for the larger hierarchical structure may be formulated where the terms S, O, and T characterize the larger hierarchical structure. Figure 3 suggests an assembly of interacting convergence–divergence processes where a multimodular spiral of innovation may be defined.

Enhancing the spiral of innovation and increasing the index of innovation of the overall convergence–divergence process at different hierarchical levels in the

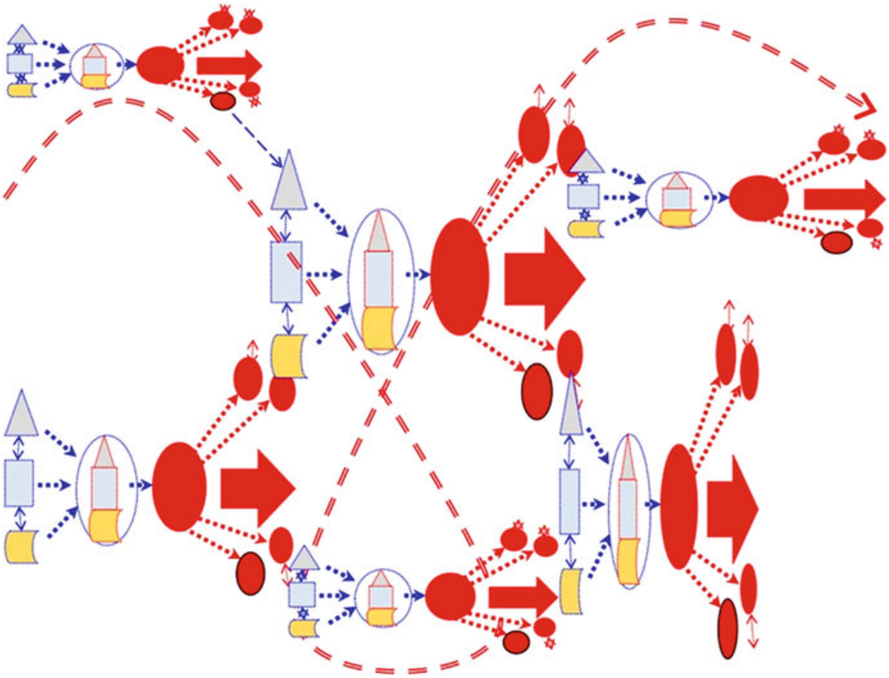

Fig. 3 Modular system architecture for science and technology development: coherent evolution among various S&T field cycles (modules with different domains and time scales) suggests possible cascade events and recombinations of technologies and outcomes

governance of science and technology provides an approach for improving the outcomes.

Convergence brings areas of knowledge together into a new system to spin-off applications and elements that can in turn be recombined and integrated. Research activities from across the spectrum – including pure basic research, use-inspired basic research, and "vision-inspired" basic and applied research – are needed throughout this repeating cycle (NRC 2014, p. 33).

National Program Case Studies

After passing important scientific and societal benefit thresholds, relatively few major discoveries and inventions have a lasting effect in terms of perpetuating the creative and innovation cycles and even fewer rise to the level of "megatrends" in science and engineering (such as the digital revolution, modern biology, and nanotechnology) where they build to a critical mass and induce widespread knowledge and societal changes. The size of the convergence domain at the confluence of many disciplinary components and the time of the cycle (T in Fig. 1) to move from discoveries to applications are larger for such megatrends. Michelson (2006) has

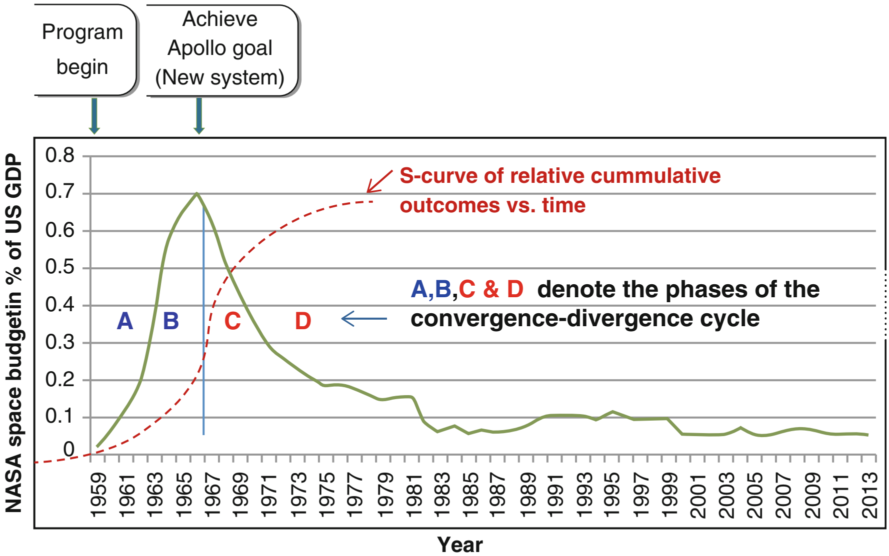

Fig. 4 Typical investments in a cycle illustrated with data for NASA's Apollo and related space program (OMB, White House 2014): The US NASA Apollo program landed a man on the moon in1967. This corresponds to the end of the end of the integration phase B (creation of new system, i.e., man landing on the moon) in the convergence–divergence cycle and also corresponds to the peak of the government R&D investment. Following achievement of the primary goal of the program, investment for the core program was reduced, as shown in the graph, while investments increased in spin-off applications that are not shown in the graph (as being part of the next cycles)

identified several indicators for the onset of a convergent technology process: increased government spending, new dedicated university programs, establishment of interfirm strategic alliances, intra-firm technological expansion, and a rapid increase in patent citations in the given area.

R&D investments reach a high plateau during the interval with a high rate of progress, typically when most scientific R&D funding is dedicated to new system design and corresponding inventions at the end of the integration phase (B) of the convergence stage. An illustration of the budget evaluation of government funding for the NASA Apollo and related space program is shown in Fig. 4; such discoveries, innovations, and corresponding systems spread over time into the mainstream of disciplines and products and are assimilated into general knowledge and applications. The R&D benefits typically increase following an "S" curve as a function of knowledge and technology progress. The point of inflection in the "S" curve typically corresponds immediately after the transition from the integration phase (B in Figs. 1 and 4) to the innovation phase C.

Some S&T megatrends in recent US history are recognized as national programs that follow these broad trends: the Apollo space program, 1963–1972 (OMB, White House 2014; Roco et al. 2013, pp. 456–457, as noted above and in Fig. 4); nuclear energy conversion R&D, since 1980 (IEA 2011); the Global Change Research

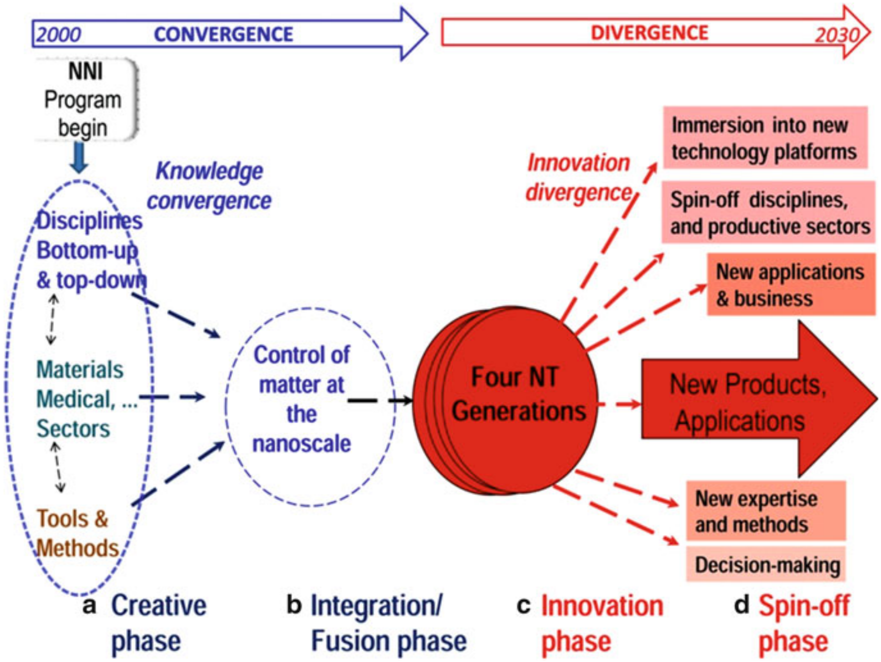

Fig. 5 The 2000–2030 convergence–divergence cycle for global nanotechnology development: (**a**) knowledge convergence for control of matter at the nanoscale, (**b**) integration and system design leading to four generations of nanotechnology products and productive processes, (**c**) innovation phase for new applications, and (**d**) spin-off divergence to novel technology platforms, expertise, and businesses

Program, 1989–present; and the Networking and Information Technology Research and Development (NITRD) program(s), 1991–present. Each of these has recognized and capitalized on the convergence of enabling technologies, as well as having generated significant numbers of divergent technologies.

Another example of a national program with global impact is the R&D program conducted under the auspices of the US National Nanotechnology Initiative (NNI). The development of significant new nanotechnologies has been estimated to take about 30 years to move from fragmented curiosity-driven science research beginning around 2000 (the start of the NNI) to full immersion of nanotechnology within the nation's economy anticipated by about 2030 (see the nanotechnology illustrations of the convergence–divergence cycle in Fig. 5). *In the convergence stage* of NNI-funded R&D, knowledge confluence (phase A) within various S&T areas (bottom-up and top-down disciplines, various sectors of relevance, different tools and methods of investigation, and nanostructure synthesis) and among various disciplinary areas have been leading to understanding and control of matter at the nanoscale. Increasing control at the nanoscale has enabled the creation and integration of four generations of nanotechnology products and production methods:

passive nanostructures, active nanostructures, systems of nanosystems, and molecular nanosystems – many of them incorporating new system designs and inventions (phase B). *In the divergence stage* of the nanotechnology development cycle, the spiral of innovation is leading to myriad new products, applications, and businesses that are estimated to be worth about $1 billion in the world in 2013 and to increase to $4 billion by about 2020 (phase C). These are being followed by spin-offs of new disciplines, establishment of new technology platforms, and immersions with other technologies (such as biological, information, and cognitive sciences and technologies) and socioeconomic projects, all of which are expected to be most fruitful from about 2020 to 2030 (phase D) before moving into the category of being generally accepted knowledge upon which new cycles of discovery can be built.

Possibilities to Enhance the Outcomes of Convergence–Divergence in S&T Governance

Challenges for governance of S&T development are evolving along with the acceleration of convergence–divergence cycles of scientific knowledge and technology development, the increasing numbers of researchers and the breadth of their networks, and the typical tension between collaboration and competition among the actors on a background of growing importance of S&T in society. The following are recommendations for proactively using the convergence–divergence process in governance of science and technology:

- Long-term planning and long-term budget allocations should *balance longitudinal support between the creative*, *integration*, *innovation*, *and outcome–spin-off phases* of the process (phases A to D in the cycle shown in Fig. 1). This implies a balance between education and research, between science and engineering programs, and between various investment policies during the cycle. Innovation is a beneficial link from scientific discoveries and technology inventions to commercialization and societal acceptance; focusing the investments only on innovation or any other stage alone is not sustainable for the entire cycle after few years. *Evolutionary approaches* in planning and management, such as computational and evolutionary biology (Carroll et al. 2014), are recommended. *Open collaboration*, including open source–open access networks, should be supported as a means to enhance the spiral of innovation in phase C of the cycle, as well as interactions among all phases.
- *Addressing the tensions between various phases of the cycle* also is critical; these tensions include those between bottom-up research and top-down vision, between knowledge and technology "push" for funding initiatives (originating in the convergence stage) and societal "pull" funding initiatives (from the divergence stage), between disciplinary programs and problem-driven (grand challenge) programs, and between encouraging opportunities for informal interactions among participants in R&D efforts and the more rigid formal interactions that are currently the norm.

- *Accelerating the speed of information exchange and of the implementation of the cycle* is essential, because it has been estimated that innovation outcomes increase in inverse proportion to the cube of time.
- Focus should be placed on developing methods for enhancing and scaling-up of knowledge and technology diffusion mechanisms *in the divergence stage of the cycle*.
- Emphasis should be given in S&T governance to *education of human* resources and preparation of infrastructure organizations to be effective in all successive phases of the convergence–divergence cycles.

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The Convergence of Curation

Michael Lesk

Contents

Abstract

Digital resources develop through a sequence of technical, economic, legal, and social steps. The computer problems have been solved first; the late Jim Gray once wished "may all your problems be technical." From a start with text, we can digitize and store images, sounds, and even 3-D objects. The economic problems are still serious but less so as the processes of digitization and delivery become less expensive. Legal issues are currently at the forefront, but even for objects old enough to pose few copyright problems, we can see social obstacles to the convergence of cultural institutions. Libraries, museums, and archives all have their own traditions of collecting, cataloging, preservation, user relationships, fund-raising, and now Web presentations. We can expect these traditions to outlast the physical design of buildings and the physical forms of early digital objects. Users may hope for a seamless presentation of cultural materials, but social and organizational issues will slow the convergence of the institutions.

M. Lesk (✉)
Library and Information Science, School of Communication and Information, Rutgers University, New Brunswick, NJ, USA
e-mail: lesk@rci.rutgers.edu

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In the digital space, what is the difference between a library and a museum? Today, we talk about "GLAM" institutions: galleries, libraries, archives, and museums. Their staff are called the "curatorial professions" or less politely "people who put things on shelves." The shelves are now websites. A student of Abraham Lincoln may be confused by finding that the Emancipation Proclamation is in the National Archives, the original copies of the Gettysburg Address are in the Library of Congress, Lincoln's hat belongs to the Smithsonian, and his sofa is in Illinois. Online images of all these objects, however, will be accessed in equivalent ways, and the kind of institution providing the image will be obscure.

Although the Web presences of different institutions may have obvious similarities, such as a catalog search, pictures of images, descriptions of the materials held, and discussions of the significance of the holdings, the traditions of these institutions are quite different. The curator of the future may still be constrained by the historical traditions of the employing institution. Museums often value a descriptive catalog, with a page or more on each object. Libraries rarely write individual descriptions of particular books, although the staff will know how to find reviews in newspapers and magazines. Archivists are often limited to describing folders of many letters, for lack of time and support to describe individual items.

New kinds of material are being curated. What kind of institution should hold Web pages? The Internet Archive calls itself an archive, obviously, and is officially also a public library. Web pages from Norway are stored by the National Library of Norway. There is also "The Big Internet Museum" or the Computer Museum. Or what about computer software? Who is responsible for saving and organizing open source programs, such as those in the *SourceForge* and *GitHub* repositories? Not only that no one today is responsible for software, but there is no generally agreed metadata standard for describing it.

A particularly important new kind of content is digital information from research projects. The National Library of Medicine includes the National Center for Biotechnology Information (NCBI 2013) which holds genome sequence banks. Many scientific archives are freestanding: the Protein Data Bank (Berman et al. 2000), the IRIS consortium (Incorporated Research Institutions in Seismology 2014), the Sloan Digital Sky Survey (Aihara et al. 2011), or the ICPSR (Interuniversity Consortium for Political and Social Research), which stores survey data of importance in the social sciences (Austin 1982). In 2011 the National Science Foundation started to require research projects to present plans for managing the data they collect and making such data available to other scientists (NSF 2011). Should this data go into museums (which traditionally collected the results of biological explorations), archives (which, at universities, traditionally held the papers of retired scientific faculty), or libraries? Many university libraries in the USA now provide a repository for storing such data and draft plans to placate NSF reviewers.

At the same time that new kinds of information flow into various institutions, some types of information are being withdrawn. Traditionally, libraries bought and saved scientific journals as paper copies. Many libraries now buy these online, and the typical contract with the publisher prohibits the library from systematically downloading and saving every issue that they are entitled to access (Baker and Tenopir 2006). Instead, the library is now dependent on the publisher to provide future access. Aggressive enforcement of the copyright laws, the laws about anthropological artifacts (such as NAGPRA, the Native American Graves Protection and Repatriation Act) (Nash and Colwell-Chanthaphonh 2010), and international treaties on archeological objects have raised doubts about what libraries can do with some objects. For example, the historic sound recordings in the Vincent Voice Library at Michigan State University were collected long before anyone thought about whether copyright transfers were needed to keep or copy them. And many museums have returned objects that raised ownership issues with respect to either Native American groups or foreign countries claiming patrimonial ownership.

So the world of curation is getting more and more complicated. A great many of the new issues – new modalities, new legal restrictions, and new access methods – affect all the traditional institutions. The response of these institutions, however, often reflects their own history.

The Worldview of Curatorial Institutions

The institutions may have similar functions, but their behavior and in particular their descriptive methods for their content reflect their different origins. They also reflect, to some extent, the economic models of the institutions. Museums are often funded by admission charges, with some exceptions such as the Smithsonian. For a museum, the website is often a way to interest visitors in actually attending. Libraries and archives rarely charge their users and are less interested in driving traffic to the building. Archives, in fact, often discourage novices, making clear that their collections are mostly of interest to researchers.

They also recruit staff with different backgrounds. A museum curator traditionally has an MFA degree, having specialized in some kind of art history. A librarian will have an MLS or MLIS, and for most libraries that is enough. However, an academic librarian will often have an advanced degree in a subject field as well. Archivists also often have an MLIS degree, from a school specializing in archival studies, and often a MA in History. The course of study for the MLIS usually includes public reference and cataloging, while the course of study for a museum curator will have exhibition design and something about materials and techniques.

Objects in museums and archives are usually unique. Art museums may have a few lithographs or prints, and there are many natural history museums with specimens of the same rocks, but the objects are normally thought of as individual. The majority of the collections in libraries, by contrast, are books printed in multiple copies. Other libraries will hold the same books. This has, for generations, been a stimulus to shared cataloging among libraries. Museums have had much less incentive to unify their catalogs, since that unification would result in few examples of exactly the same item description in two different museums.

Perhaps, the most significant difference is the typical funding model for the institution. Libraries, since Andrew Carnegie, rarely charge users directly. There are now only about a dozen private libraries in the USA that charge a membership fee. And even in those, the fee is a subscription, charged once a year. I cannot think of a single library that charges per visit. Museums, to the contrary, often receive significant revenue from admission charges. There are certain exceptions: the Smithsonian museums in the USA (mostly located in Washington, DC, but not entirely) do not charge. Nor does the British Museum. But the annual report of a small museum, the Norman Rockwell Museum, shows $1.4 million of admission revenue out of $4.5 million total. Archives, like libraries, rarely charge (and they are usually running on very restricted budgets).

This means that libraries and archives are normally part of some other organization, whether a town, state, or educational institution. They have a community that "owns" them, and they will have a mission to serve that community. If they can provide that service adequately via remote access, that is fine. The leader of an archive once said to me that if the Internet could clear the genealogists out of the reading room to leave more space for historians, that would be a good thing. Museums are often freestanding with independent governance and budget. Their mission is complex, including preservation of objects, studying art history, and bringing tourists to their town, but there is likely to be an ingredient of pleasing the people that walk in the door and pay for that access. The website is typically a way to encourage people to visit; for it to completely replace a visit would be a financial penalty.

Beyond the public institutions – the museums, the archives, and the libraries – there are now large amounts of cultural information in the databases of private institutions. Consider, for example, the Google Art Project or the billions of photographs in Flickr or Facebook. These institutions have motivations ranging from having eyeballs on advertising to self-promotion and to altruistic image preservation. There are also noncommercial organizations like ARTstor; originated by the Andrew W. Mellon Foundation, ARTstor is supported by fees paid by participating institutions, mostly educational institutions. Another example of a noncommercial institution with large cultural resources is the National Geographic Society, which has enormous photographic resources supported by a magazine, TV programs, and related activities.

All of these institutions save things and make them available to researchers and the public. They all care about object conservation, about digital surrogates for their objects, and about presentation of their content to people at a variety of skill levels, often including children. But they have completely different business plans, ranging from large endowments to charging visitors to charging advertisers.

Public Access

Who can enter a library, museum, or archive? Typically, as mentioned, a museum admits anyone but charges. A library usually belongs to some community, and members of that community are admitted, although many public libraries, although belonging to one town or state, admit anyone. An archive usually does not charge, but often restricts admission to scholars that have a need to use the materials. Some research libraries are similar.

Historically, the idea of libraries and museums for the general public dates to the nineteenth century. Earlier, it was assumed that most people would not be interested in educational or scholarly materials; before the eighteenth century, most people in the UK couldn't read. Early in the nineteenth century, museums might well be "curiosity" shows, such as PT Barnum's "American Museum" with a mixture of real and fake artifacts. The Crystal Palace of 1850 was a show, with a secondary purpose of education. But in the late nineteenth century, ideas of improvement, exemplified by Andrew Carnegie's support of free public libraries, grew in multiple countries. Museums also identified public education as a primary purpose. Many important institutions date from the second half of the nineteenth century: the Victoria and Albert was founded in 1852, the Metropolitan Museum of Art in 1870, the Art Institute of Chicago in 1879, and so on.

Should these museums and libraries be open on Sunday? If their goal was to help working people, that was typically the only day they might have off to visit a museum. But in the nineteenth century, it was assumed that Sundays should be spent in church and in reflection. We did not yet have televised football, although a crowd of 100,000 would attend rowing matches (Cornell 1895). The Metropolitan Museum, after a bitter fight, opened on Sundays in 1889. Archives, mostly intended for scholars, did not open on weekends, and even today they rarely do.

Online access has thrown a monkey wrench into the public access principles. Most libraries, museums, and archives have some kind of Web presence nowadays. All have catalogs of greater or lesser detail, and these are normally on the Web today. A museum is typically able to put online surrogates of its content (images of works). An archive also may do that but rarely has the budget to support the mass digitization. Libraries are normally not permitted to place most of their books online, as a result of copyright law. The various businesses that manage large amounts of information have yet different attitudes toward what can be done with it. Those that only want "eyeballs" for their advertising are quite happy to have lots of public access – think of Google, Flickr, or "icanhascheezburger" (funny cat pictures). At the other extreme are image sales agencies, such as Getty Images or Corbis, which rely on people paying to reuse their imagery. Some nonprofits with image collections sell very generous licenses to university libraries; examples are ARTstor or the Vanderbilt University Television News Archive. Some museums rely on image rentals for revenue and are fairly restrictive about high-quality imagery; others are very generous, including the Metropolitan Museum and the Rijksmuseum.

Sharing

What about loaning objects out? Libraries often consider loaning books one of their basic services. Again, they do not charge for this, although libraries which allow the general public in the door may limit loans to members of the community that supports them. Archives rarely lend anything, since their objects are unique. Museums lend, but they often do so for value. Some loans are paid for in cash, for example, the Wing Luke Museum quotes a fee of $10,000 to borrow an exhibition by works of Roger Shimomura for 10 weeks. Other loans are reciprocated, often within the same exhibition. In that form, two or more museums create a special exhibition out of a set of objects, and the exhibition travels from one museum to another.

Lending, in the digital world, usually involves sending a copy of something to the recipient. Libraries now can "lend" books for reading on a patron's e-reader, using companies like OverDrive that manage this service. Typically, the number of loaned copies at any time is limited, so that there will be a waiting list for a popular book. In addition, some publishers limit the total number of loans of a single item. For example, HarperCollins does not permit a book to be loaned electronically more than 26 times, after which the library needs to buy another copy. Their argument is that a physical book would deteriorate from handling and would have to be replaced at this point.

What about digital exhibits involving museums and archives? Many websites show images such as "all the Vermeer paintings," and they will typically not need permission for such presentations, Vermeer having died in 1675. Our traditions of either professional ethics or law do not quite cover the situation of somebody who has a collection of out-of-copyright items being asked for a full copy of everything, with no promise of getting any credit or benefit. It can take significant effort to collect material, and once upon a time, you could (in the USA) copyright such a collection based on a doctrine known as "sweat of the brow," which viewed hard work as similar to creativity. Then, in the famous case of *Feist v. Rural Telephone* (Feist 1991), the Supreme Court ruled out copyright protection for straightforward facts, and there is an implication that just collecting things which are in the public domain will not be protectable. The situation is confused because one can protect the arrangement of uncopyrightable objects, so long as some thought has gone into the arrangement (but just alphabetization is not enough). So archives may be leery of someone who says "I want a copy of everything you have," and they can refuse to fill such requests, but they cannot use a legal structure to protect their material. Nor do they have any recourse against somebody who uses their material and does not give them credit or acknowledgment. In some countries a principle of "moral rights" does enable the creator of a work to insist on at least some credit for it.

What about letting other people use your scientific data? Different scientific fields have different traditions about this. The journals in biochemistry have agreed that if somebody publishes a claim that they have measured the structure of a protein molecule, they have to deposit the structure in the public Protein Data Bank. Astrophysicists follow a guideline that you get a two-year private use of your measurements, but then you are expected to make them generally available. In some areas of chemistry and high energy physics, everything is kept privately. The fear of some scientists is that public availability of their data will enable other people to publish an article that they could have published if they had more time. In some areas patents are possible. For many years Myriad Genetics claimed exclusive control of the right to test a woman's genes for susceptibility based on patents of the relevant genes; recently, the courts have invalidated patents controlling genes in this way (Myriad 2013).

From the standpoint of a curator, this implies a need to store data with rules about access. It's not desirable to ask the original scientists to keep the data for some period of years and then turn it over; during that time information may have been lost or forgotten. Archives are familiar with requests to keep information confidential for some period of time; museums are not. As we see an increasing number of "data management plans" coming from NSF and NIH requirements, we will see more and more examples of restrictions that people try to put upon data. When the data also require technical effort to store or intellectual effort to catalog, the library may feel that this is a bad deal, and thus expect the costs to be covered by the original research grant.

It is not clear what conditions can be imposed on the recipient of a digital loan, whether of data or anything else. Must those using such a loan identify themselves? Must they promise to give a suitable citation for anything they do with the material? Must they promise that if they improve the material, they must offer it back to the original institution, as you might do if you find bugs in open source code? Can the recipients be charged with money? Again, the history varies among institutions: museums charge and expect acknowledgment, archives do not charge but do expect credit to be given, and libraries do not charge, and it would be extremely unusual for an author, when citing a published book, to say what library it was borrowed from. Interestingly, on the Web there is a habit of even more detailed acknowledgment; it is common to not just give the original source of something you are quoting but the name of an intermediate site that directed you to that quote, using the phrase "hat tip" (usually "h/t").

Cataloging Styles

How does one describe objects in a collection? For some decades, libraries followed a standard called AACR2, the Anglo-American Cataloguing Rules, 2nd edition (Gorman 2004). The traditional library style is so well known that a 2014 television series entitled "The Librarians," although showing characters with magical powers, still showed shelves full of books (which look as if they were purchased from some law library that had gone electronic) and traditional drawers of catalog cards, which few real libraries have used for over a decade. Although the cards are gone, the format of the information on them, stored in a format called MARC (Machine-Readable Cataloging), is still the same. A book description includes the title, the author, some subject headings, and the number of pages and the physical size. Except for children's books, the standard catalog record does not include the genre: it will not say if the book is aimed at scholars or the general public, for example. Nor does it include the details of the paper the book is printed on (woven vs. laid) or whether the book was produced on a letterpress, offset, or laser printing machine. And for public use, there is no interest in provenance; the library will have bought the book from some book wholesaler, but nobody cares which one.

One reason for the standardization of library catalog records is that books are produced in multiple copies, and so most of the books in a library exist in other libraries as well. For purposes such as interlibrary loan, or to help scholars trying to follow a citation, it is important to recognize when the same book is in two different collections. Thus, it's useful to have the catalog records in a common format. The idea of a national catalog, covering books in many libraries, goes back in the USA to the days of paper. Research libraries would often have a copy of the *National Union Catalog*, a 700+-volume work showing which libraries had copies of which books. For early books, international records had been accumulated. Pollard and Redgrave's *Short-Title Catalogue* covered books up to 1640 [PRG], and Wing's similarly titled work [Wing] continued the cataloging until 1700. Many of the books in these catalogs are of course rarer, and the purpose of the cataloging was more to discover copies rather than confirm duplication.

By contrast to libraries, the typical museum object is unique. Nobody else is going to have a copy, and so uniform cataloging is less important. The typical museum catalog record is longer and tends to be idiosyncratic. When works are not unique, as with lithographs, even the title of the work may vary between institutions. For example, both the British Museum and the Tate Gallery own a Picasso lithograph, *Faune dévoilant une femme* (*Faune dévoilant une dormeuse; Jupiter et Antiope, d'après Rembrandt*), but the British Museum (item PPA339317) translates the title as "Faun Uncovering a Woman," and the Tate (item P11360) translates it as "Faun Revealing a Sleeping Woman." And such aspects of the record such as the date acquired by the museum will usually vary between different institutions.

Museums almost certainly will record the provenance of the object, presenting information about when and where they acquired it. They will report the material it is made of and quite often the technique by which it was produced. A librarian who distinguished between letterpress and offset books would be considered obsessive-compulsive; a museum curator who failed to distinguish a lithograph from a seriograph would be considered sloppy. Librarians get credit for how many objects they can catalog in a day; a museum curator gets credit for writing a thorough and insightful description of an object, which might be published in a journal or book.

Archives, which have historically had fewer financial resources than either museums or libraries, usually do not catalog each item independently. This is called "item-level" cataloging, and most archives tended to catalog at the level of a "folder," which might contain dozens of letters or typescript pages. The descriptions were normally very abbreviated, giving a hint as to the contents of each folder sufficient to distinguish it from the next folder; a typical label might be something like "Letters, March 1925."

So what is happening now? The librarians are being pushed in two directions, with some hoping for longer and more careful description while others want shorter and cheaper metadata. Replacements for AACR2 are either Dublin Core (Weibel et al. 1998), which is shorter, or RDA, which is longer. RDA (Resource Description and Access) has a descriptive manual more than 1,000 pages long. Although specialists in metadata want the best possible descriptions, and produce elaborate formats covering special cases in elaborate detail, they are out of step with practical limitations. There has been substantial pressure in libraries to reduce cataloging costs and also to expand cataloging to more kinds of objects. Both of these demands encourage a simpler rather than a more extensive cataloging and thus encourage Dublin Core. Earlier, library catalogs started to become searchable online from a distance. Even before the Web, there was a service called "gopher" which enabled library catalog search remotely. Nowadays, the WorldCat service of OCLC enables a quick search of libraries everywhere to locate copies of books.

Archives, which historically did not share cataloging or even provide remote searching capability, began to share services about ten years ago. The Open Archives Initiative (OAI) encourages archival systems to store catalogs in a format called PMH (procedure for metadata harvesting) which enables a remote Web spider to download the cataloging information from multiple archives (Lagoze and Van de Sompel 2001). Then, the OAIster central search system, originally developed at the University of Michigan and now at OCLC, enables a worldwide search for archival holdings.

Museums are now being encouraged to make their records shareable as well. The most direct way to do this would be with Dublin Core. Given the greater wealth of information in museum catalogs, however, they are looking at a more detailed format, called "linked open data," in which information is not only shared across institutions, but is provided in a subject-predicate-object logical form, called RDF (resource description framework). There is a search system known as SPARQL (a protocol for an RDF query language) which enables remote searches of these logic statements.

The commercial services in general have no interest in sharing search capability; in general they are anxious to block search engines which attempt to amalgamate their services. Since their business model depends on people looking at their ads, they can't have some central service which would provide the searches without the viewers. In addition they are unwilling to spend money on manual cataloging, which would also be impracticable for the billions of photographs in Flickr or Instagram. So this results in a completely different kind of metadata, based on text words somewhere near the descriptions of the objects. For example, searching Google Images for either *dog* or *hund* will find a lot of pictures of dogs, but they are different pictures.

And what about the new research data content? In general, these resemble the archival searches: all you have is a general description. If you wish a survey reporting with how many teenagers go surfing, ICPSR has such data, but you have to search generally for surveys of leisure activities and examine in detail the column and row headings of the survey to know whether ocean surfing is one of the possibilities asked about.

Cataloging research data in detail is a current research frontier. Automated sensors may deliver tags describing each item. Most digital cameras, for example, record the time and date of each picture, and often more data such as the exposure, location, and focus distance. This is recorded in the EXIF (exchangeable image format) photographic data format and inserted into the JPG image header. There are great many data formats in common use, such as geographic data in FGDC (FGDC 1998) or seismology data in SEED (Standard for the Exchange of Earthquake Data) (Ahern and Dost 2006). The manual for each of those formats is more than 200 pages long. People would like to move to XML, but we do not yet have good standards for doing this; XML is a syntax and needs semantic detail to be applied to a particular collection. A more serious issue is that individual research projects often have defined their own data tables, and each one will need separate curatorial inspection. We can hope that unsystematized areas, such as biology and (surprisingly) chemistry, will define their own standard formats.

A major data archive could help by defining what it wanted to take in. Google Maps does routing by train and bus, which was enabled when Google published a spreadsheet format and said to bus operators "put your timetable in this format and upload it." If NSF in the USA or the research councils in the UK were to specify such formats and encourage the funded researchers to use them, that could help spread cooperative ways of doing things. It would also, helpfully, transfer a good deal of the work from the curatorial institution to the researchers themselves but introduce efficiencies that would generally accelerate the process.

The history, over a very long time, is that the number of items handled in libraries expands, and the cataloging detail is forced to decline. Many years ago, catalogers were expected to identify pseudonyms, such as Samuel Clemens publishing under the name Mark Twain or Charles Dodgson publishing his children's fiction but not his geometry books under the name Lewis Carroll. Today this is no longer demanded. In 2005 the Library of Congress considered abandoning subject headings in the catalog, although the community protested, and they are still being assigned. Several projects considered writing traditional catalogs for Web pages but gave up – with more than a hundred billion Web pages out there, it is inconceivable that any manual effort could succeed. Even the attempts to crowdsource tagging, in addition to the problems of quality control, cannot keep up with the number of items to be handled. Instead, we have full text search and its extensions.

So how will the curator of the future do cataloging? The most general formats are varieties of Dublin Core; we have, for example, VRA Core (VRACore 2014) for images (VRA is the Visual Resources Association) or Darwin Core (Wieczorek et al. 2012) for biological data. But creating these manually is doubtfully practical given the immense amounts of material involved. Even in 2002 I attended a conference session raising doubts about the future of metadata (JCDL 2002). The cataloger of the future is, perhaps regretfully, a piece of software.

Metadata Detail

All the institutions are converging on increasing sharing: all items should be searchable worldwide. So far these shared search systems are still organized by institution: WorldCat for the libraries, OAIster for the archives, and SPARQL for the museums. In each context there are advocates for more detail or less detail. One obvious direction to go is the "least common denominator," which would be a Dublin Core-based catalog system covering objects at a minimal level of detail. The most interesting possibility for more detail is not RDA, but the logical format RDF (resource description format). RDF contains triples, as mentioned above: subject-predicate-object. Typically, each of these is taken from some formal authority file. So, an RDF statement about a book might be from the British National Bibliography:

```
person/AustenJane1775-1817
blterms:hasCreated
http://bnb.data.bl.uk/id/resource/015594626
```

Here, the resource number describes the 2010 Cambridge University Press edition of *Pride and Prejudice*.

The British Museum states that the Rosetta Stone contains hieroglyphic script in the following way (YCA62958 identifies the Rosetta Stone):

```
<http://collection.britishmuseum.org/id/object/YCA62958/inscription/1>
<http://collection.britishmuseum.org/id/ontology/PX_inscription_script>
<http://collection.britishmuseum.org/id/thesauri/script/hieroglyphic>
```

And here is the National Archive (f/k/a/ Public Record Office) stating the date of publication for their document number 64:

```
<rdf:Description rdf:about="http://nationalarchives.gov.uk/pronom/Document/64">
<pronom:DocumentID>64</pronom:DocumentID>
<pronom:PublicationDate>17 Sep 2005</pronom:PublicationDate>
</rdf:Description>
```

Formal representations, whether XML or RDF, are going to be important in the world of research data. While text information is often understandable in isolation, numerical data is not. If a single item is the number 75, it could be a price, a weight, a temperature, or anything else, and even if you know it is a price, you don't know whether it is measured in dollars, pounds, or euros, not to mention the confusion of being told that the number is denominated in pounds but not knowing if that is a measure of weight or currency.

XML representations, normally, are thought of as single items: you identify one piece of data, but it often stands alone. RDF presentations come as triples, so that there is inherent context in each item. RDF triples are typically made of items from specific ontologies. For example, the British Museum data follows a standard known as CIDOC-CRM, an acronym which is a mixture of French and English but means the conceptual reference model for the committee of international (museum) documentation (Le Boeuf et al. 2014). The "subject" in the triples is a British Museum object identifier, the "predicate" is one of the specific lists from CIDOC-CRM, and the "object" comes from lists of geographic locations, dates, materials, or other knowledge bases. Is it realistic to talk about creating these knowledge bases for all curated objects? How much work would it be, for example, for all spreadsheets of measured properties in research projects to report the data in RDF? The problem is not so much the software to convert the spreadsheet; the difficulty is the lack of standards for most scientific areas. The problem for museums is the reverse – we have at least some of the standards, but encoding every object is daunting.

An increasing amount of data, however, is now formally encoded. For example, consider DBpedia or Freebase. DBpedia is familiar as the source of the formatted information in the boxes in Wikipedia; Freebase is a similar set of information, now run by Google. Data from institutional catalogs can be joined with these public sources to do some kinds of data mining. For example, one could list all artworks depicting a particular town and combining the catalog with geographic databases, all artworks depicting scenes in a particular county or within some distance of a place-name. This would require considerable extra cataloging effort. Library catalogs, for example, rarely record the location in which a novel takes place, even if it is a real rather than fictional location. Attractive as the idea of expanding open metadata in such ways, the resources required to do this are not readily available. Some of it can be done by volunteers; the website *Goodreads* (now part of Amazon) contains lists such as "books set in New Mexico."

Could we use RDF data for logical processing? For decades researchers have dreamed of computers proving theorems using formal data. Programs have tried to make formal deductions based on knowledge representation in areas as diverse as tax law and chemistry. Can catalogs be used in this way? One can imagine both inductions ("every book written by Jane Austen is a novel") and deductions ("the first English novel was published in 1719; *Pride and Prejudice* is an English novel; therefore, *Price and Prejudice* was published not earlier than 1719"). These examples trivialize a complex subject, but to date there has been very little success at more ambitious theorem proving.

If linked open data is to be used in this way, it will have to be held to a high standard of reliability. Suppose one wishes to ask a computer whether all Jane Austen's novels take place in England. There is potential confusion between Bath (Somerset) and Bath (Maine). This will make it difficult to rely on automated text mining to complete the databases. Although automated retrieval from texts is now familiar and widely used, automated cataloging of books is still rare, and efforts to do things such as make a conventional library-style catalog of Web pages using automated techniques have not been adopted.

Unfortunately, there is as yet no single ontology which applies to all these institutions. The British Museum follows the CIDOC-CRM standard and uses a different authority file from the British Library. The British National Bibliography identifies James Abbott McNeill Whistler as

bnb.data.bl.uk/id/person/WhistlerJamesMcNeill1834-1903

while the British Museum uses

collection.britishmuseum.org/id/person-institution/50934

and the Getty Union List of Artist Names names him as

ID 500012432.

Perhaps, the best identification would be

viaf.org/viaf/46804212

which is his Virtual International Authority File entry. All of these authority file items identify James Whistler, as opposed to Rex Whistler (an unrelated painter) or the goldeneye duck (*Bucephala clangula*, sometimes called a whistler). It is even harder to collapse the different predicate for words like “created” or “published,” which may include subtleties of meaning.

Extending linked open data to the paintings, drawings, and sculptures widely found in museums has no automated process at present. We cannot today identify a painter or a composer by automated recognition (Johnson et al. 2008), although we can recognize a copy of a particular work. Nor can we automatically locate a place depicted in a painting, although this is something we would like to have coded into the metadata: place depicted, time depicted, people depicted, and so on (I once knew someone whose job included tagging artworks with emotions).

We are thus facing a future world in which we’d like compatible logical data recorded for many cultural objects, and we will have a tradeoff between accurate hand-assigned data and inaccurate but cheaper data for books and most archival content (since we can OCR the typewritten material which dominates twentieth-century documents). Shared cataloging will mean that a larger fraction of books in libraries will have recorded data than of manuscripts in archives. For the artistic objects, fewer in number, we will have only the accurate information, but it may be scarcer. Archivists have the hardest job here, since today they typically have the least information about each of their holdings (only a “folder-level” description).

How important is shared formal cataloging? Users might well want to ask questions like “costume in Bath 1800–1820” and find answers that bridge many cultural institutions. If we have suitable RDF-encoded data, which can, for example, distinguish the year of publication of a book with the year(s) written about, we can answer a question like this. In this decade a generalization might be that library cataloging is getting simpler while museum cataloging is getting more complex. It may be unrealistic to hope that all books, documents, and objects will have detailed cataloging, but there are possible synergies possible if textual descriptions of artworks can be used to fill out the museum data structure. For example, any biography of Turner will identify the bridge in his painting “Rain, Steam, and Speed” as the bridge at Maidenhead, which would allow us to add that information to a catalog record for the painting (although in this case, the National Gallery catalog already recorded this fact). The success of Google and other search engines, estimating subject information purely from plain text, suggests that people do want to do such broad searches. Cultural institutions will be catering to this need by building more interoperability into their cataloging systems, with libraries getting there first, museums next, and archives last. Whether automated reasoning based on this data will be feasible remains to be seen. Hype about winning at Jeopardy is all well and good (Ferrucci 2012, Markoff 2011), but the need for anagrams in general life is pretty low. Whether there will be a demand for sophisticated question answering about cultural resources is not at all clear – the fraction of people entering museums with a particular question is small. Libraries and archives are quite different in this regard, and that difference is likely to persist.

Realignment

For all institutions, the Web presence is becoming more and more important. Students and faculty use the resources in a university library, but often they are not using them in the building. Nor are the resources located in the building, since an increasing fraction of library subscriptions are delivered electronically. The material remains at the publisher's computer, with students calling on it as needed. It has been commonplace to talk about access dominating over ownership. Figure 1 shows the idea of libraries passing information from those who take the role of publisher, or database, along to the readers. It has always been thus, but it now happens in milliseconds and without the library possessing the work until it is requested.

For many kinds of information, this distinction between the content and the delivery is even more common. Where are the JSTOR computers with the actual article images? Virtually, no user knows or cares (Princeton and Ann Arbor). So, as suggested by the Library of Congress decades ago, we can have wholesalers and retailers of information. Some institutions can specialize in their collections and others in presenting the information to the patrons. There are many websites which aggregate information from multiple sources; consider ARTstor, for example, which unifies images from multiple museum and university photographic holdings.

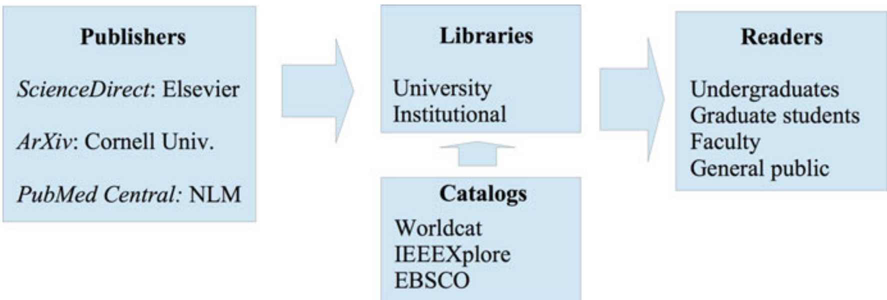

Fig. 1 Information passes from the issuers to the readers, via the traditional institutions

An example of the potential future is in astronomy. There are telescopes gathering data, including ground-based optical telescopes and radio telescopes, and also space-based observatories such as the Hubble Space Telescope or the Chandra X-ray Observatory. This data goes into databases, such as the Sloan Digital Sky Survey, 2MASS (the Two Micron All Sky Survey), and others. And the data from those collections is used in other systems that provide interfaces for users, ranging from professionally oriented operations, such as the Virtual Observatory and the Astrophysics Data Service, to the systems that provide access to the general public such as Google Sky and NASA's Whirlwind.

In this model, institutions would be described by their place in the continuum between the raw material and the patron. If the goal of your university is to teach students art history, it may be better to exploit ARTstor and the online collections of museums such as the Metropolitan and the Rijksmuseum than to attempt to collect paintings yourself. Another example, from the world of archives, is the family history centers operated by the Mormon Church; each of these locations does not necessarily hold large document filings, but rather the International Genealogical Index and the microfilms of records actually stored in Utah.

If institutions sort themselves out like this, it may be less important whether they call themselves archives, libraries, or museums than whether they focus on preservation and holdings or on delivery. What matters is what they add to either information description or access, because the alternative today is Figure 2, without any indexing, uniform terminology, or common metadata.

Data is important in this context, since it is harder to use without assistance. It is possible to imagine an uncurated collection of text or pictures; it is harder to understand how a data consortium could exist without professional staff at some level. The new alignment, in greater generality, would be as shown in Fig. 3.

What we do not yet know is whether the financial support of institutions will be based on the payments from end users to the delivery institutions to the holding

Fig. 2 The world without any curatorial institutions; no editing, no cataloging, no instruction

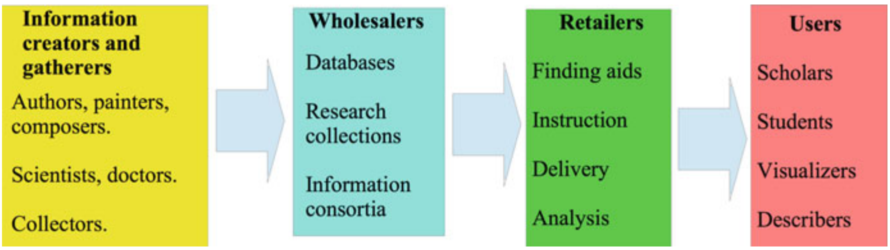

Fig. 3 If the curators sorted their functions by position between creator and user

institutions or on direct support to both kinds of institutions. The experiments so far are unclear. There are two large archives in Ann Arbor, Michigan: HathiTrust charges institutions to put data *in*, and ICPSR, the Interuniversity Consortium for Political and Social Research, charges institutions to take data *out*. Should either be called a "library" because they store material that people or computers read, or an "archive" because they are a long-term storage location for research information, or a "museum" because of their devotion to preservation? Does it matter?

Conclusion

Some convergence has already taken place. Canada has merged its national library and national archive into Library and Archives Canada. The province of Newfoundland and Labrador, in a variation, has merged its museum and archives into *The Rooms* in St. John's. There are a few institutions that are both libraries and museums, such as the Folger Shakespeare Library or the Huntington Library. Similarly, the Morgan Library recently became the Morgan Library and Museum, and the National Sound Archive (UK) joined the British Library a few decades ago. The New York Public Library has museum-level exhibitions, while the Metropolitan Museum of Art has a world-class library. The Yale Center for British Art has both museum and library collections, and the New-York Historical Society also renamed itself as both a library and museum. The Smithsonian Institution has everything (and thus its sobriquet as the "Nation's Attic"). Sometimes, mergers (not these) reflect financial pressures; many small museums have difficulty meeting modern standards for curation and preservation and may join forces with a university or other larger institution. Too often, however, separate catalogs for their museum and library materials persist even in institutions that cover both areas.

Some of the larger institutions are providing extended access to their materials. As noted earlier, the Metropolitan Museum and the Rijksmuseum provide publication-quality images without charge. The British Museum has its catalog on a SPARQL endpoint, enabling remote searching at a very detailed level. We have a good history of libraries acting as retailers for data where they purchase only access, not ownership. This includes image files (ARTstor), music libraries (Naxos), and numerical data services (ICPSR). Archives and museums, however, are still centered on ownership rather than access. The unified catalogs such as OAIster are not matched by a service that helps readers use the archival materials behind them.

The curator of the future, whether working in a library, museum, or archive, will be writing interoperable descriptions that can be used by robot Web sweepers to provide a very general search service. These descriptions will converge as most institutions begin to use common vocabularies and, my personal guess, a format derived from Dublin Core. Digital preservation will be needed in all these institutions, and everyone will use Web analytics to improve their services. With time, some of the cultural differences will also decrease. I suspect that all the institutions will move to a common tolerance of image lending and an encouragement of use by the general public.

Even if Dublin Core becomes the cataloging standard, organizational differences are likely to persist. To have libraries develop the fund-raising skills that freestanding museums need would take decades. Archivists are not routinely trained today to welcome schoolchildren. And museums will still focus on the object in a way that libraries holding current printed books need not.

These personal distinctions may persist for a very long time. Men's clothing fastens left over right, while women's clothing fastens right over left. Two common explanations for this are that suits of armor had to fasten left over right as a result of the way jousts are run and that upper-class women were customarily dressed by their maids who, if right-handed, found it more convenient to have the clothing fasten right over left. Whichever is true, the reason has been gone for more than a century, and yet the distinction persists.

So the future of the curatorial institutions involves a common offering of Web access to materials and a common search system, perhaps looking like some merger between WorldCat, OAIster, and SPARQL. Users will search and then read or stare. But the personal differences between the people at the institutions will last a lot longer.

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Decision Making in a Convergent Society

Igor Linkov, Viktoria Gisladottir, and Matthew D. Wood

Contents

Abstract

Decision analysis can help organizations which fund research (e.g., government agencies, technology incubators) to develop guidelines for promoting breakthrough interdisciplinary science in a transparent and replicable manner. An evaluation of the methods that encourage convergence requires data and preferences from varying temporal, spatial, and organizational scales and domains. It is necessary to identify and incorporate objectives of social, economic, and technical importance in the decision-making process. This necessary and holistic evaluation is of such complexity that individual decision-makers cannot effectively consider all these factors and their interactions at the same time (Linkov Cormier et al. Risk Anal 32(3):374–380, 2012; Roco et al. Convergence of

I. Linkov (✉) • M.D. Wood
Risk and Decision Science Team, US Army Engineer Research and Development Center, Concord, MA, USA
e-mail: igor.linkov@usace.army.mil

V. Gisladottir
Risk and Decision Science Team, US Army Engineer Research and Development Center, Concord, MA, USA

Department of Mechanical and Aerospace Engineering, University of California, San Diego, CA, USA

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knowledge, technology, and society: beyond convergence of nano-bio-info-cognitive technologies. Springer, New York, 2013). With regard to convergence, current guidelines are qualitative in the form of vision statements and road maps. Decision analysis can facilitate convergence by enhancing decision-making with quantitative, holistic, and structured tools that prioritize objectives in a transparent and replicable way and helps decision-makers to cope with overwhelming complexity. Multi-criteria decision analysis (MCDA) is of particular interest in enhancing this decision process. Once an objective is identified, then decision criteria, preferences for criteria, and alternatives are defined. Based on available scientific information, MCDA identifies feasible alternatives (e.g., training, changes to organizational structure, funding) and decision criteria (e.g., cost, importance, network diversification), assess the performance of each alternative relative to those criteria, and elicits or explores relative priorities among the continuum of incommensurable criteria (Linkov and Moberg Multi-criteria decision analysis: environmental applications and case studies. CRC Press, Boca Raton, 2012). Further analysis like value of information (VoI) boosts MCDA by identifying which uncertainties to reduce, e.g., by increasing-the accuracy of the information on which the decision is based, that results in a change in preference for alternatives or an increase in value for an alternative that is already preferred. When promoting convergence within the scientific community, MCDA provides research funding organizations with the ability to quantify the values and the trade-offs between criteria to provide practical and decision-relevant guidelines for individual scientific organizations to follow (Roco et al. Convergence of knowledge, technology, and society: beyond convergence of nano-bio-info-cognitive technologies. Springer, New York, 2013).

Introduction

Focusing innovation initiatives in science and technology requires transdisciplinary collaboration and alignment with complementary disciplines, i.e., convergence (Roco et al. 2013). Like the parable of the blind men and the elephant, scientists working in their own domain are unable to see the underlying nature of a problem (isolated view, Fig. 1a). Those who are getting input from or providing output to colleagues in other domains have a better but still limited understanding (coordinated view, Fig. 1b), while those who actively collaborate with colleagues in other disciplines and take collective action toward discovery have the best understanding of the problem's nature and complexities (convergent view, Fig. 1c).

The recent National Academies' panel on convergence proposed what research funding institutions should do to promote convergence, but provides little information on how to decide among those alternatives or when to implement a particular alternative (NRC 2014).

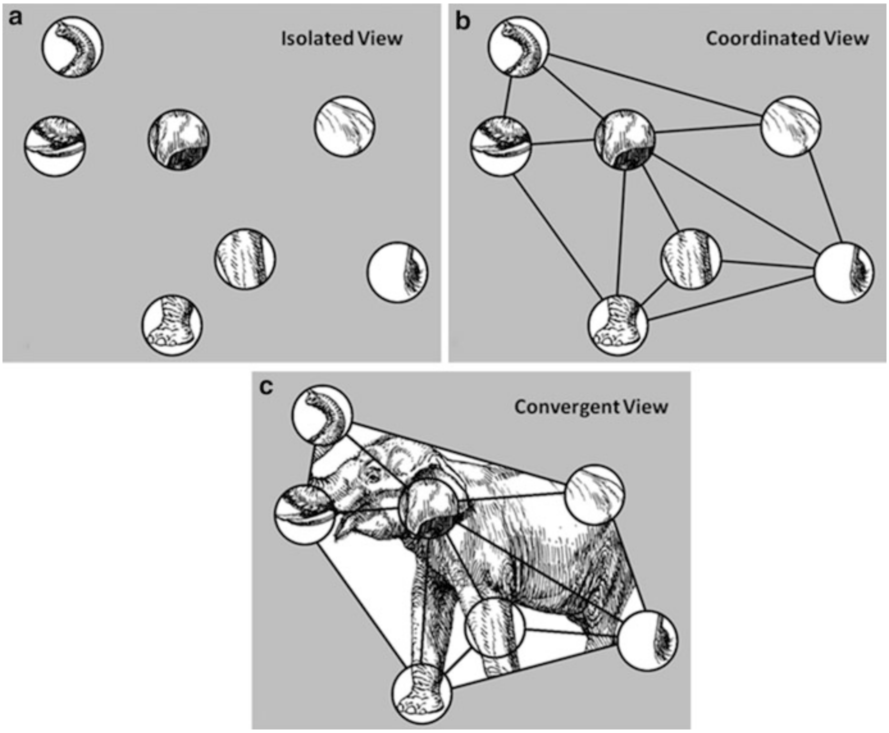

Fig. 1 Isolated, coordinated, and convergent views of science collaboration

Using a formal decision analytic process to enhance institutional actions like coordinated interagency efforts, collocation, and others (e.g., grant funding) can facilitate coordination of scientists from the right disciplines to take collective action in solving complex interdisciplinary scientific problems. Decision analysis provides a structure to define the common goal(s) the collaboration should achieve and can identify the best mechanisms to encourage scientists to be creative in connecting with others and move beyond the comfort zone of their limited disciplinary expertise. The decision analytic process requires evaluation of alternative ways of indirectly influencing scientists from the required disciplines to work together in a manner that provides the best chance of developing new knowledge about the problem and solving it. In the analogy outlined in Fig. 1a–c, this would be similar to taking actions that would engage the best combination of nodes in the "convergent view" (Fig. 1c) and reveals the largest and most appropriate area of the problem between network edges. Decision analysis techniques can enable research funding and academic institutions to more effectively promote convergence in a transparent replicable way.

An Introduction to and Brief History of Decision Analysis

Decision analysis is a portfolio of mathematical and logical methods designed to facilitate decision-making that is aligned with the internal thoughts and values with one or a collection of different stakeholder interests. Though a variety of methods exist for instantiating stakeholder values (Clemen and Reilly 2001), most methods provide a process for structuring the decision problem in such a way that the problem is broken down into discrete elements that can be evaluated independently. As a result, decision analysis is an inherently proscriptive approach, utilizing normative axioms of how rational decisions should be made and adapting them to accommodate common known deviations from rational behavior (Smith and von Winterfeldt 2004). The goal is to support the decision-maker(s) in making the best selection among alternatives not by focusing on the properties of the alternatives themselves but instead by emphasizing the objectives that the decision-maker(s) care about and the value which each alternative provides in service of these objectives.

Modern decision analysis as it is practiced today began with von Neumann and Morgenstern (1947) who outlined axioms for an expected utility model (EU) as part of their treatment on games. Expected utility here refers to the anticipated benefit of one choice compared to others. They show that a utility function can be devised from preferences inferred from a series of choices made by a decision-maker. The EU approach was extended by others, including eventually Keeney and Raiffa (1976) who developed a series of axioms and a methodology for expressing preference in terms of multiple objectives which the decision should achieve and the subjective value that specific choice alternatives provide toward an objective. This work provides the foundation for what is MCDA today. While different proposals on how to execute the MCDA approach have been proposed (Clemen and Reilly 2001; Linkov and Moberg 2012), all proposals for conducting the process include guidance for (1) eliciting one or more objectives that the decision problem will achieve, (2) developing a hierarchy of value that decomposes a decision problem into its core components and subcomponents and connects properties of the decision alternatives to decision objectives, (3) eliciting or expressing preference for some objectives over others in terms of weights, and (4) identifying and scoring decision alternatives. The decision-makers and stakeholders for a decision analysis are often identified through intuition and knowledge of the specific project context, although some guiding principles have been suggested (Keeney 1992; Mitchell et al. 1997).

Although generally an improvement compared to making decisions using "common sense," formal decision analysis processes are not without their criticism. For instance, the results of formal decision analysis exercises can sometimes deviate from what a decision-maker may identify as the most preferred alternative through intuition or common sense. While such situations may be considered a criticism against use of decision analysis techniques, Goodwin (2009) notes that this conflict presents an opportunity to improve the decision model and/or our understanding of the problem through comparison of the processes that give rise to model outputs or our intuitive judgments, respectively. The decision model may be missing an important objective that is considered as part of the common sense model, or conversely our common sense model overvalues one objective at the expense of others that should also be considered. In addition, when formal decision analysis is used to develop a decision aid for practitioners in the field (e.g., doctors), these practitioners may express concern that these decision aids do not fully accommodate the nuances of experience in the wild (Balla et al. 1989; Kleinmuntz 1990). Whether decision aids are instantiated as lookup tables, practical guidance, or even software programs, they are meant as just that “aids to the decision,” and the decision-maker should always compare the assumptions and results of any of these tools with his/her judgments to check for consistency before adopting the suggestions of a decision aid. These tools are meant to enable decision-making by suggesting preferred alternatives, but it is ultimately the practitioner who should decide what course of action to take.

Decision Analysis as a Tool for Convergence

Formal decision analysis is useful aid for guiding knowledge and technology convergence because it is transparent and quantitative. With all data, values, perspectives, and relevant information clearly specified in a governing framework and applied to the data of each unique decision, all parties now and in the future can be made aware of and deliberate the pros and cons of alternative pathways toward convergence. This also enables scenario and sensitivity analysis, where impacts on individual decisions can be assessed based on possible differences in perspective or data (Karvetsk et al. 2011). Also, by eliciting and incorporating information from all relevant organizational, political, and social levels, applications of decision analysis transcend many limitations of traditional bottom-up and top-down approaches.

Applied at the organizational level, quantitative decision frameworks can help businesses and organizations efficiently navigate technological decisions and maintain consistent direction toward their organizational goals. At the national or international level, instead of leaving researchers to their own devices, allowing scientists and engineers to independently stumble toward convergence, research funding organizations can aid the process by clearly specifying the objectives of technological progress and mapping potential alternatives that work directly toward those objectives. Recognizing that convergence is not an end in itself but rather a means toward more sustainable and equitable social outcomes, decision frameworks can be used to clearly communicate and quantify the goals of the desired future. For example, research funding organizations can systematically explore their decision preferences, reveal their decision criteria (perhaps drawing from the three common economic, environmental, and societal pillars of sustainability), and quantify their values and the trade-offs between criteria to provide practical and decision-relevant guidelines for individual scientific organizations to follow. These guiding frameworks can then be applied to evaluate the long-term, net expected social or other benefits of specific variations of converging technologies being developed drawing from knowledge and components in different scientific and engineering fields.

Regardless of the level of application, decision analysis has useful tools for evaluating complex decisions. These tools explicitly take into account data and preferences across many scales and domains and quantitatively relate this information to outcomes on multiple management criteria, helping decision-makers transparently and consistently design better alternatives, identify preferable decisions, and guide knowledge and technology convergence for holistic social benefit. Even though there are many formal decision-analytical techniques, MCDA is ideally suited for this purpose and provides a structured, transparent, and quantifiable approach that can guide institutions in promoting convergence (Keeney and Raiffa 1976; Linkov and Moberg 2012). MCDA is used to discover and quantify decision-maker and stakeholder considerations about a variety of (mostly) non-monetary factors in order to compare alternative courses of action in a transparent quantitative manner (Huang et al. 2011).

Adding Transparence and Reproducibility with Multi-Criteria Decision Analyses

Based on available scientific information, MCDA identifies feasible alternatives (typically enumerated by experts) and decision criteria (typically from decision-makers), assesses the performance (via experts) of each alternative relative to those criteria, and elicits or explores relative priorities (from stakeholders and decision-makers) among the incommensurable criteria (e.g., characteristics that cannot be reduced to single units; Linkov and Moberg 2012). Value of information (VoI) analysis extends MCDA by further identifying uncertainties whose resolution has a good chance of changing the decision or which most undermine confidence in the results. This leads decision-makers to guide knowledge and technology convergence for social benefit by quantitatively demonstrating how differences in the design of integrated products or technologies affect long-term, holistic social outcomes (Howard 1966; Linkov et al. 2011).

The MCDA process should be incorporated into designing and evaluating institutional convergence efforts actions either formally when selecting among actions or informally to facilitate the design and development of convergence actions in a way that directly addresses convergence objectives and relevant constraints. This process will help institutions like funding agencies, universities, and other research organizations to evolve beyond the historic research approach which focuses on identifying which discipline should be responsible for solving a specific problem to an approach where different unique disciplinary perspectives on a problem can be leveraged along with the synergies between these perspectives. The result of implementing these processes over time will be a research environment more accepting of interdisciplinary collaboration and therefore more productive with respect to the hard problems faced by the science and technology community today and tomorrow.

MCDA is opportune to help inform complex decision-making problems like convergence because:

(a) It enables integration of multiple stakeholders' interests. Stakeholders' interests are expressed as a set of decision-making criteria, with a set of weights for each stakeholder describing how much they prefer each decision criterion with respect to the others. This provides the ability to combine interests of multiple stakeholders, even in situations where those interests may conflict.
(b) It simplifies complex decision-making by providing easily understood outputs. Since MCDA provides a systematic approach to considering the values of different stakeholder groups, it provides a mechanism to compare values of disparate stakeholder groups with each other and facilitates identification of synergies and eccentricities. The way these values are combined can be clearly described to all participants, and the ratings elicited from participants can also be shared if all participants agree on a process to do this up-front and if they all believe that the same responses would be collected independent of whether ratings are made public.
(c) It has demonstrated effectiveness in a variety of decision-making scenarios. Modern use of MCDA for informing complex decision-making problems has been underway since the late 1970s, providing a mature platform for describing and coordinating stakeholder interests. Since that time, it has been deployed in a variety of contexts with beneficial results (Linkov et al. 2008).

MCDA is a tool that provides an overall score for each alternative, while simultaneously capturing alternative performance by objective. The process facilitates use of visual representations of preferences including a description of how preferences for alternatives may change with changes in stakeholder values or the relative importance ascribed to different combinations of stakeholder groups. MCDA does not make the decision for the decision-maker; rather, it promotes efficient, transparent communication and provides a decision-making environment that is conducive to developing team consensus. The typical MCDA process consists of nine steps. These steps are listed below in the context of promoting convergence (Fig. 2).

1. Formulate convergence objectives. These objectives capture what the research funding organization or other entity wishes to achieve through development of one or more tools or technologies that require the convergence of individual researchers or research groups with different types of expertise. These objectives inform both the decision model criteria and their associated value functions.
2. Identify decision criteria and sub-criteria that capture the objectives and any additional decision-making factors. Decision criteria are the factors that should be considered when making a decision and evaluating alternatives to ensure the

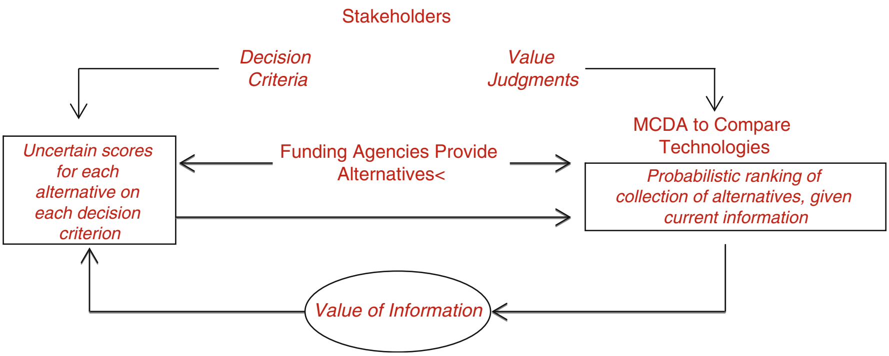

Fig. 2 Multi-criteria decision analysis schematic of the process

objectives are met. For convergence, these criteria are the specific capabilities which the research funding organization hypothesizes are required to achieve convergence objectives. Sub-criteria, in contrast, are factors that should be considered when making a decision, but only within the context of their parent main criteria. Each of the sub-criteria has an associated metric (or metrics) that provides a measure of impact on the criterion.

3. Formulate metrics for each sub-criterion in the decision tree. Metrics are measurable properties that characterize part of the system and are used to quantify and compare the predicted performance of the solutions on each criterion. Metrics may be (1) a specific physical quality such as the geographic distribution of research personal or offices, (2) an ordinal (low, medium, high) or interval (−2 to +2) scale used to elicit best professional judgments from appropriate experts, (3) a mathematical function of a set of several important factors like research products (e.g., weighted sum of journal articles and presentations) that can be used to measure expertise, or (4) any other measure that can be converted to a number and used as a proxy for performance on a criterion.
4. Develop value functions that relate performance scores on each metric to value on the criteria. Value functions are used in the MCDA model to convert the solutions' performance scores on each metric to a numerical value from 0 to 1 that captures the relative performance compared to alternatives on a fixed scale. The value function allows users to translate performance scores in different units to a common comparable scale and can accommodate complex relationships between metric scores and values. While value functions in most models are linear additive (i.e., value increases linearly with increases in performance score), they may also describe different relationships, thresholds, or ranges. For example, if there is a "sweet spot" for a metric where very high and very low scores are least preferred (e.g., number of days for a workshop), a triangular or trapezoidal function may be used that describes the point (triangular) or range (trapezoidal) where an alternative scored on that metric would provide the most value.

5. Develop a range of plausible alternative solutions that address the objectives.

   For convergence, these alternatives are the different collections of individual researchers or research groups which provide expertise in service of developing a tool or technology. Solution alternatives use technical information about the issues and criteria and sub-criteria for guidance during the solutions' development process.
6. Collect and assign weights to decision criteria that reflect their relative importance in the selection of an alternative solution. Weights capture the preference for, or importance of, each decision criterion relative to the others. Weights can be derived in a variety of ways, e.g., from structured interviews with relevant stakeholders, written justifications of past descriptions, etc. In these interviews, stakeholders are asked first to rate the importance of each main criterion with respect to the other main criteria and then to rate the importance of each sub-criterion with respect to the other sub-criteria under the same main criterion. The elicited weights are used in the utility calculation (Step 8) and sensitivity analysis (Step 9) to describe variance in preference for alternatives as a function of different decision mechanisms.
7. Evaluate the performance of individual alternatives with respect to each of the specified metrics and assign performance scores (Fig. 3). To determine the performance of each solution on each criterion, a technical evaluation is conducted to estimate the status of each metric expected under each alternative. Within the MCDA model, these performance scores were translated to normalize value scores according to the value functions developed in Step 3.
8. Run the MCDA model to calculate utility scores or weighted value scores for each alternative, and generate their ranking. Data gathered in the previous steps is then entered into the MCDA algorithm to calculate each alternative's utility and generate a relative ranking. For each alternative, the MCDA model combines each individual value score for all criteria into an overall utility score using a weighted sum of the value scores calculated for each alternative. The total utility, $U(\boldsymbol{a})$, for an alternative, $\boldsymbol{a}$ is calculated as,

Fig. 3 Proposed method for scoring individual researchers or research team capabilities with respect to desired convergence outcomes

			Researcher(s)		
			A	**B**	**C**
Capability	**I**	a	0.1	0.8	0.3
		b	0.05	0.75	0.25
	II		0.9	0.15	0.35
	III	a	0.1	0.2	0.3
		b	0.15	0.15	0.3
		c	0.1	0.7	0.4

$$U(\boldsymbol{a}) = w_1 \cdot V_1(a_1) + \ldots + w_n \cdot V_n(a_n), \text{(Keeney and Raiffa 1976)}$$

where a_i is the performance score of alternative a on criterion C_i for $i = 1$ to n, $V_i(a_i)$ is the value of alternative $\boldsymbol{a}$ reflecting its performance on criterion C_i, and w_i is the weight of criterion C_i where $\sum w_i = 1$. The utility score generally ranges from 0 to 1 and is the basis for the alternative rankings.

9. Conduct sensitivity analysis. Sensitivity analysis provides insights on the superiority of the most preferred solution alternative relative to other possible alternatives, shows how changes in criteria weighting or other factors affect alternative preference, and helps to estimate the robustness of alternative preference given the chosen weighting and criteria structure of the model. The technique is used to estimate the effect of individual model parameters, inputs, and assumptions on model results.

The MCDA process should be incorporated into the process of designing and evaluating actions to promote convergence either formally when selecting among potential researchers to assemble research teams or informally to find ways to facilitate development of research teams in a way that directly addresses objectives and relevant constraints. This process will help funding organizations and other entities to evolve beyond the historic research approach which focuses on identifying which discipline should be responsible for solving a specific problem to an approach where different unique disciplinary perspectives on a problem can be leveraged along with the synergies between these perspectives. The result of implementing these processes over time will be a leap in technological innovation beyond that achieved by current processes for requesting research and development on new technologies.

Conclusion

Convergence of science and technology is a vital component toward societal progress.

It provides the view necessary to grasp and address challenges as a whole. Despite the clear interest to promote convergence, guidance to research funding organizations and other groups on the actions they should take to tractably promote interdisciplinary collaboration and enhance convergence is lacking. The application of MCDA gives these bodies the ability to quantify the value and the trade-offs between criteria to provide practical and decision-relevant guidelines for individual scientific organization to follow. It can provide a significant improvement in the decision process by providing a clear and transparent methodology for making decisions and also offers a formal way for combining information from disparate sources. Using a decision analysis tool, such as MCDA, provides guidance for the scientific community in its inquiry toward the path of convergence.

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Dimensions of Research

William Sims Bainbridge

Contents

Abstract

In order to understand discovery and innovation, social scientists and historians have developed several systems for mapping kinds of thought and action, especially to learn where the convergence of multiple factors may achieve unusual progress. Even a simple descriptive scheme provides perspectives from which to see insights, such as how vision-inspired research can literally think outside the box. Thus it is worth considering how the individual scientist or engineer thinks, using a mind that is not merely the result of technical education, but that also reflects human personality dispositions. Yet progress requires individuals to cooperate, in teams and communication networks, through a dynamic division of labor assigning different roles to participants, according to changing conditions and opportunities. The convergence-divergence cycle plays out in ever more complex ways, as humanity becomes integrated into a single information society, so new kinds of research on the very dimensions of research will be required.

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Introduction

Sciences represent not merely different fields of knowledge but different approaches to knowing. An astronomer's telescope can be conceptualized as an inverted microscope, yet astronomers almost never have the opportunity to conduct experiments, while biologists often do while gazing through their optical instruments. Mathematical thinking is employed across the sciences, yet its methods are quite different in physics, paleontology, and economics. One way in which convergence can revolutionize a science is by importing the theories and methods of other sciences, in consequence triggering fundamental innovations that diffuse to multiple other fields via divergence. As an intellectual model of progress in science and engineering, the convergence-divergence cycle not only implies an integrated dynamic mental map of a variety of traditionally separate disciplines but also a dimensional space in which these movements take place. Maps are generally used not merely to contemplate geography but to plan travels, from tourism, to the shipping of products, to military invasions. In building a better future for humanity, we must identify multiple directions for progress to take place and routes from today's situation to future goals.

A very large number of analytic frameworks have attempted to map human behavior and social organization on a system of dimensions or categories, several of which claim to identify the primary sources of innovation. Given how much scholarly attention has been given to these systems, it is likely that many of them contain a good deal of truth, but no one of them is definitive. Indeed, it seems likely that each of these frameworks fits particular historical conditions best, so a leader who wishes to accomplish great innovations in science and engineering will need to be familiar with several frameworks and have the good judgment to know which ones need to be combined under the given circumstances. For civilization as a whole, therefore, several of the frameworks must be used simultaneously, each emphasized in its best area of application, but often integrating several at once in a coherent complex system.

Vision-Inspired Research

The admonition that scientists and engineers should "think outside the box" has become a cliché, yet given adequate preparation, it can be good advice. Convergence urges us to think outside any one disciplinary box, but there also exist more general conceptual boxes that we may also need to escape. A good starting point is the pair of review criteria used by the National Science Foundation, as described in the 2013 edition of its Grant Proposal Guide:

> The Intellectual Merit criterion encompasses the potential to advance knowledge.
> The Broader Impacts criterion encompasses the potential to benefit society and contribute to the achievement of specific, desired societal outcomes.

The simplest starting point is to conceptualize each dimension as a dichotomy, as Donald Stokes (1997) did in his book, *Pasteur's Quadrant*. Stokes identified two dichotomies that described the motivations behind scientific research, nearly identical to the two NSF review criteria: (1) quest for fundamental understanding and (2) considerations of practical utility. Each of these is a yes-no question used to classify a particular research project. A project for which the answers to both questions are "yes" is strong in both intellectual merit and broader impact and thus will tend to score higher than projects with only one "yes," not to mention projects where both answers are "no." However, some projects that emphasize only one of the criteria may qualify for public support, if they are especially innovative, because the real goal is to maximize both criteria across the entire portfolio of funded projects, balancing goals and projects harmoniously with each other. In other words, science and engineering require efforts of many kinds, each with its own mix of virtues. Table 1 diagrams the categories Stokes described.

Stokes named three of the four quadrants after famous innovators, nuclear physicist Niels Bohr, inventor Thomas Edison, and medical researcher Louis Pasteur. Bohr's work was abstract and theoretical, developing concepts of the nature of the atom, while Edison superficially was the quintessential tinkerer, for example, trying vast numbers of substances for the filaments of his electric lights. Yet Bohr's work contributed to the later development of nuclear technologies, and Edison discovered the "Edison effect" which became the basis of electronic vacuum tubes yet also added to our fundamental knowledge of the behavior of electrons. This, Bohr and Edison worked in very different styles, and yet each ultimately made major contributions of both intellectual merit and broader impact.

Stokes was especially interested in Pasteur's quadrant, use-inspired basic research. Pasteur was among the most influential researchers in early bacteriology, who demonstrated the "germ theory" of infectious disease and developed practical countermeasures, most famously *pasteurization* which is named after him. His analysis argued against the separation of pure from applied research, urging researchers to undertake convergent projects that would seek to achieve both goals simultaneously. He was not interested in the fourth quadrant, which apparently no prominent scientist occupied, and we have labeled it "ritualistic" because it describes researchers who go through the motions of doing science without having any motivating goals. This may be all too common and chiefly serves as an example of what to avoid.

Kenneth Brown (1998, p. 9), former director of the science statistics office at the National Science Foundation, has observed that Stokes was offering a conceptualization very different from the standard three-category system that even today is the basis for reporting agencies' budgets:

1. The objective of *basic research* is to gain knowledge or understanding of phenomena without specific applications in mind.
2. The objective of *applied research* is to gain knowledge or understanding necessary for meeting a specific need, rather than to expand the frontiers of knowledge.

Table 1 Four quadrants of research motivation

		Are considerations of the practical utility of the results crucial?		
		Yes	No	
Is the research a quest for fundamental understanding?	Yes	Use-inspired basic research (Pasteur)	Pure basic research (Bohr)	Vision-inspired research
	No	Pure applied research (Edison)	Ritualistic research	

3. *Development* is the systematic use of the knowledge or understanding gained from the research to solve the technical problems in bringing a new product or process into production.

The very fact that these three categories can easily be numbered reflects the fact that logically they often occur in this sequence, as a flow of information from basic to applied research and from there to development, whereas Stokes conceptualizes his categories as distinct expressions of particular human values that especially converge in Pasteur's quadrant. We could debate Stokes within his system, for example, stressing that pure research on the possible inflationary period in the early history of the universe has no practical use but is valuable in giving us a proper understanding of the nature of existence. More important is the question whether there might be some fifth category that exists outside his set of boxes. One possibility is *vision-inspired research*, which Table 1 represents as a box outside the system of boxes but also could be conceptualized as a third dimension transforming the Stokes system of four boxes into a system of eight. Are entirely new ideas being explored and invented? Can new uses emerge that are beyond known practical applications?

Thus, good visionary research and invention are transformative, going beyond the questions and applications that a field has already established. In the philosophy of science, it can be contrasted with a classic debate initiated by Karl Popper (1959). Scientists like to prove that their favorite theories are true, but Popper argued that strictly speaking this is impossible. A well-framed theory can be falsified by empirical research but not confirmed, he claimed, because even the best theory may be inferior to a better one and fail some future empirical test. Whatever their merits, Popper's ideas have been very influential, and they suggest two points relevant to visionary convergence. First, science cannot have as its sole goal the testing of theories that have already become popular within a science. Second, even the best of the popular theories are probably inferior to some other theory that has not yet been articulated.

A dichotomy like the one proposed by Stokes is only a starting point for a proper analysis, but social scientists have long used this approach as a technique for organizing early-stage thinking on a deep question, especially because it forces one to recognize that some of the logically possible cells in the table may not have been given sufficient attention in previous work. Among the most influential such

Table 2 Values and norms for human action

		Does the behavior follow conventional societal norms?		
		Yes	No	
Does the behavior accept the standard societal values?	Yes	Conformity	Innovation	Rebellion or scientific revolution
	No	Ritualism	Retreatism	

2×2 tables in the history of social science was one proposed by Robert K. Merton (1968) and shown here in Table 2. It is important to note that these tables use the same analytical methods, but the cells in two such tables will have very different meanings, because the two dichotomies are different. For example, we find ritualism in different cells of Tables 1 and 2.

Merton assumed a common social science conceptual framework that speaks of a culture's values and norms, relevant here because the scientific and engineering community is a form of culture and society. *Values* are the primary goals for human action held out as legitimate for all members of the society. *Norms* are rules about the legitimate means for reaching goals. Conformists follow the norms to achieve the values. Ritualists follow the norms but have given up on achieving the values, perhaps because they have experienced too much failure in their lives. Retreatists are in an even worse situation, dropping almost entirely out of society and following neither its norms nor its values. Perhaps the most interesting quadrant in Merton's scheme is the one labeled *innovation*, containing people who strive to achieve societal values but have given up on the norms. This is a perplexing quadrant, and Merton often placed criminals here. Yet creative artists, innovative engineers, and pioneering scientists might also fit, because they contribute positively to society but do so outside the constraints of conventional norms for thought.

One of the early criticisms of Merton's scheme was that he did not consider the possibility of rejecting both the values and norms of a society without falling into retreatism, most obviously by proposing entirely new values, plus the new norms that logically would be required to achieve them. In his later publications, Merton called this fifth category *rebellion*. However, in the context of science we might follow the lead of Thomas Kuhn (1962) and refer to scientific *revolution* instead. Thus, there are two ways in which a fourfold table like this can inspire thinking. First, once we have begun to sketch the four cells of such a table, we must think long and hard about the meaning of each cell, whether abstractly or through examples. Second, once such a table is complete, we need to think outside the box and consider the major possibilities it does not capture.

As Kuhn's theory of scientific revolutions consolidated in scientific thought, it seemed to apply to two kinds of situation that might arise in the history of a science. First, young sciences lack consensual paradigms, sets of theories, and methods that all scientists agree should be followed. So one kind of revolution establishes such a paradigm. Later in its history, a science may have accumulated a good deal of data that do not seem to fit the established paradigm, perhaps even contradicting it, but senior scientists are so committed to their paradigm that they cannot deal with this challenge to authority. A reform revolution must be led by young scientists, Kuhn believed, energetic people who are not yet fully indoctrinated into the old paradigm. Merton's theory is somewhat different from Kuhn's but quite compatible with it. People turn to innovation or rebellion, Merton argued, if they are ambitious but unable quickly to achieve the society's goals by the traditional means. In innovation, they violate norms to achieve the values, while in rebellion they substitute new values and develop appropriate means to achieve these different goals.

Convergence theory suggests that Kuhn should not have ignored two other kinds of revolutionary scientists, who might or might not be early in their careers or face any significant disadvantages. First, they may be immigrants to one science from another who embody convergence in their very brains, highly skilled in thinking in two or more paradigms. Second, a few high-powered individuals may have such distinctive personalities they are able to become visionaries, but with the intellectual clarity to avoid falling victim to delusions of grandeur. This point suggests we need to consider how theories of personality dimensions can characterize different styles of doing science and engineering.

Innovative Personalities

There may be some truth to the stereotype that great scientists are geniuses with abnormal intelligence and unusual or even distorted personalities. It may also be true to some extent that different fields of endeavor require different dispositions, such that on average different kinds of people are attracted to them: perhaps abstract thinkers to physics, fastidious plodders to microbiology, and emotional expressionists to psychology. Yet innovation in any competitive field may be facilitated by having characteristics that are not typical, and in any case the popular stereotypes may be entirely wrong. A good starting point for discussion of such issues is a standard but not entirely definitive theory of the dimensions of personality.

Over the second half of the twentieth century, a five-dimensional model of personality difference emerged, widely accepted within academic psychology but existing in multiple variants and open to various criticisms. Most easily remembered is the version that names the five dimensions with words whose initials spell OCEAN (McCrae and Costa 1996, p. 67):

1. Openness to experience: fantasy, aesthetics, and feelings
2. Conscientiousness: competence, order, and dutifulness
3. Extraversion: warmth, gregariousness, and assertiveness
4. Agreeableness: trust, straightforwardness, and altruism
5. Neuroticism: anxiety, angry hostility, and depression

This is the model of personality employed in a recent study of the personality of behavioral psychologist B. F. Skinner that considered which personality dimensions might more generally identify highly creative scientists (Overskeid et al. 2012). Alternative formulations tend to have about the same general concepts, but organized and named slightly differently. Some psychologists prefer "intellect" to "openness to experience." Neuroticism can be renamed "non-neuroticism" or "emotional stability" if the numerical coding of the items is reversed. This OCEAN model and the ones very similar to it are called the *Big Five*, which implies that there may exist other small dimensions of personality variation that are very real but less important.

One assumption behind the Big Five is that all human beings can be described in terms of them, while possibly some other characteristics are relevant only for some fraction of the human population (Bainbridge 2013). For example, a musical temperament may be irrelevant for most careers yet prepare the individual for innovation in musicology and acoustics. Another assumption is that each of the five dimensions is independent from the others – at right angles to each of the others or *orthogonal* as described in the terminology of the statistical method called *factor analysis* that extracts the dimensions from personality questionnaire data. Yet another assumption is that the dimensions can be measured through verbal communication with the person, rather than requiring observation of behavior or neuroscience studies. This means that the dimensions are ultimately derived from the terms used in ordinary language to describe interaction between people, rather than being wholly novel scientific discoveries, and they possibly ignore dimensions that are not significantly social in orientation.

The first dimension of the OCEAN model, Openness to experience, would seem to define a personality that is especially well prepared to make novel discoveries. An individual strong in this trait will explore, seeking novelty and solving puzzles. This is actually the most controversial of the Big Five, in part because many personality psychologists wanted all of the dimensions to measure characteristics other than pure cognitive ability, such as "intelligence" measured by IQ tests (Borghans et al. 2008). Another controversy surrounding this dimension is its apparent bias in favor of liberal political ideologies rather than conservative ones, although plausibly political positions could be mapped on psychological dimensions. The second dimension, Conscientiousness, would seem to be a requirement for all forms of science and engineering, creative research as well as path-breaking studies, because great care in collecting and analyzing data is required. Because they are orthogonal dimensions, rather than mutually exclusive categories, it is quite possible for some unusual individuals to be high on both the Openness and Conscientiousness dimensions. The study of Skinner concluded that this was true for him, but noted that run-of-the-mill scientists tend to be very conscientious but not very open to experience. It also described him as somewhat neurotic and extraverted.

Extraversion would seem a good quality for a leader, but a classic categorical framework within management science implies it could have two subdimensions. Douglas McGregor (1985) suggested that leaders have two very different strategies, based on different theories about workers. Theory X holds that people are naturally lazy and irresponsible, and thus leaders must assert control over them. Theory Y argues in contrast that people do take responsibility if the goals of the organization harmonize with their personal goals, so leaders should encourage autonomy and imagination, following an emotionally warm management style. Many management theorists tend to believe that Theory X is old-fashioned, perhaps appropriate earlier in the history of industrial societies when workers on an assembly line needed to be under dictatorial control, but obsolete today when the more enlightened Theory Y is most successful. A plausible alternate view is that each theory fits certain circumstances, so extraversion needs to express itself differently, either through assertion of direct control or warm encouragement, depending upon circumstances. However, Theory Y is clearly best when creativity should be manifested broadly throughout the social group.

Personality theories tend to assume that characteristics like Openness to experience are highly stable, perhaps etched into the individual's genetic makeup, or at the very least are such general strategies of behavior that the person naturally applies them in every situation. Yet there are two ways in which this could be a false assumption. First of all, many people in modern societies may be so skilled and so flexible as to be able to play one of these personalities as a temporary role, for example, being conscientious at work but impulsive during recreational activities. To use a game-playing metaphor, a person who possesses a full deck can freely decide which cards to play in any particular situation, thus capable of adjusting from one set of characteristics to another as desired or switching from introversion to extraversion depending upon the social environment. To decode this metaphor, we can say that educational convergence is designed to give each student a full deck of cards – to be a theorist in one situation or an experimentalist in another. To shift the metaphor from games to music, a convergent person can play both the white and black keys of the keyboard, modulating from one personality orientation to another as desired.

A set of perspectives often called *trait activation theory* points out that an individual's distinctive characteristics need not influence behavior significantly unless something about the surrounding circumstances gives them influence. For example, in Canada, people drive their cars on the right side of the road, while people in Britain drive on the left side of the road. But this difference does not result from Canadians being right-handed, and Britons being left-handed. Driving a car does not activate the trait of right or left handedness, because the traffic rules do not take account of this form of individual variation. Similarly, a personality trait such as Openness to experience might not render a leader especially transformative, if new experiences are not immediately available and work responsibilities require heavy investment in some other kind of activity.

Research examining how personality traits of leaders might be activated by different kinds of organizational environment is difficult to carry out, because large-scale experiments are almost impossible in this area and observational studies cannot control for all the other kinds of natural variation. A study by De Hoogh, Den Hartog, and Koopman (2005) can illustrate the ideas, however. In a questionnaire study of managers and their subordinates, the researchers hypothesized that some personality traits were more significant for leadership in dynamic work environments than for leadership in stable ones. In dynamic environments, where the team struggles with rapid change, leaders high in both Openness to experience and Neuroticism were rated more charismatic than others and rated less charismatic in stable work environments. While noteworthy, this one study could not provide definitive answers, and much research is needed on how environmental conditions can switch on or off the potential implications of various personality traits in scientists or engineers.

Charisma, often defined as an unusual ability to lead or persuade other people, has generally been studied not in technical fields but in the arts, religion, and politics. It is obvious that Openness to experience can facilitate discovery, but highly emotional Neuroticism would be expected to erode the cool logic required in technical fields. However, if it is necessary to motivate a team of people to accomplish something difficult under trying circumstances, neurosis-based charisma may be effective. William Friedland (1964) influentially argued that charisma was really the ability to express feelings that ordinary people had suppressed within themselves, such as fear or anger, and a degree of personal psychopathology may free some leaders to play this role, for better or worse.

In the history of science and technology, at least until very recently, leadership of groups may not have been central, and many of the most creative innovators worked essentially alone. Like Albert Einstein, they communicated with fellow scientists, but did not work in close cooperation with them. Under very loose conditions of social organization, personality traits may be important determinants of creativity, without necessarily having any relevance for leadership of work groups. This may be especially so during the early phase of development of a particular innovation, the inspiration for a radically new hypothesis or technology design notion. Individuals who are socially isolated and unrestrained by social expectations, while possessing unusual minds, will generate new ideas at an unusually great rate. Most of them will be bad ideas, but a few will just happen to be valuable, and retrospectively their inventors will be considered geniuses. However, for decades social scientists who study innovation have stressed not divergent individuals but people holding key social locations in convergent networks of communication.

Division of Labor Networks

When the ancient Egyptian pharaohs built their pyramids, they needed many workers, simply because the blocks of stone were heavy and individual humans are weak. Over the centuries, many kinds of work combined the labor of many people who were doing the same thing. But already with the invention of agriculture well before the pyramids, the *division of labor* had emerged in human society, and today most large-scale projects require different workers to perform many different tasks, whether in series, parallel, or a complex and constantly changing network of modules (Hage 1999; Ethiraj and Levinthal 2004). Science and technology convergence can be conceptualized as a modern conception of the dynamic specialization of labor, emphasizing how a vast diversity of contributions may be combined, whether in the mind of an individual or the work product of a multitude.

Trait activation theory applies not only to the personalities of individual human beings but also to the characteristics of groups, including their structures of social relationships. Yes, socially isolated individuals may disproportionally invent new ideas, at least of certain kinds, but these ideas will have no impact unless they can spread throughout a social network. In addition, as William F. Ogburn (1922) argued nearly a century ago, much innovation consists not of primary invention of an idea but a combination of two or more ideas invented by different people, thus a form of convergence requiring diffusion of information throughout the social world. Over the subsequent decades, especially after establishment of the Internet, a global knowledge economy has emerged, maximizing the convergence of vast numbers of ideas and facts that can combine to produce myriads of innovations (Powell and Snellman 2004).

Much of the early sociological research on social networks emphasized how a dense fabric of strong social relationships could empower teamwork, so it was a revolutionary step in 1973 when Mark Granovetter wrote about “The Strength of Weak Ties.” A key point in his analysis was that information communicates most rapidly and widely across extensive social networks, and long-distance communication is inhibited when the preponderance of one’s friends are also friends of each other. In Granovetter’s analysis, diffusion of information across a large network was slowed or speeded purely as a result of the geometry of the network, but a dense cluster of network ties can also change the nature of communications. *Groupthink* is a popular term for the tendency of highly cohesive human groups to resist new ideas (Janis 1982). Influential members of a cohesive group who have valuable social connections outside it have long been called *gatekeepers*, because they control much of the information flow into or out of the group. But they can also be called *brokers*, because they are in good positions to manage exchanges with other groups, including information.

The current view of Granovetter’s thesis is somewhat complex. Yes, extensive social networks that spread widely do facilitate transmission of information, such as innovations or fragmentary ideas and facts that can be combined to produce innovations. But diffuse networks are poorly designed to implement innovations, especially if much work and a degree of consensus are required. That is to say that dense networks are good at supporting norms for behavior that may be required to complete development and promote innovations, but can work against the “outside the group” thinking required to imagine the innovations in the first place (Burt 2004; Granovetter 2005).

A rather large body of social scientific literature has explored such principles in special areas of technical innovations. Automotive product development takes place with a division of labor between the major manufacturers and their suppliers, through complex patterns of communication (Takeishi 2002). Similar dynamics are found in biotechnology (Shan et al. 1994). The network of individuals and companies can be global in scope, as a study of the flat panel TV and computer display industry demonstrated (Spencer 2003). A study of automobile development specifically explored how brokers and other leaders can manage the balance between cohesion and openness to achieve success in all phases of the innovation process (Obstfeld 2005). Research very much like that involving social networks has been done using the keywords on scientific publications in several fields, mapping their changing conceptual structures just as researchers have mapped their social structures (Liu et al. 2014). We tend to think of innovation as the challenge of achieving change in a static system, yet the environment around an innovative organization is often not stable at all. Indeed, there can be different patterns of instability, for example, one model distinguishes three types (Meyer et al. 2005, p. 457):

1. *Jolts*: transient shocks that disrupt fields temporarily, perturb their organizational inhabitants, and then subside
2. *Step functions*: changes that sweep through fields, permanently altering features such as structures of competition, habitable niches, or market and industry boundaries
3. *Oscillation*: recurring cycles of field-level expansion and contraction, passing through periods of discontinuity near the zenith and nadir of each cycle

One way conceivably to transcend the tension between social convergence and divergence is to return to the concepts of Stokes and Merton, but consider them in a new way in terms of *facts* versus *norms*. Joel Mokyr proposes two classes of useful knowledge: (1) *propositional* concerning *what* is true in the natural world and (2) *prescriptive* concerning *how* we should go about accomplishing tasks. This is comparable but not identical to the common philosophical distinction between *descriptive* statements about what *is factually true* and *normative* statements about *what should be done*. While Mokyr is sensitive to ethical issues, his prescriptive category concerns technically effective instructions for accomplishing a goal, and the morality of the goal is a different question. He observes that science and engineering – proposition knowledge and prescriptive knowledge – were rather disconnected from each other centuries ago, even well into the Industrial Revolution, but now they are converging in an emerging information society in which propositional knowledge is applied through prescriptive instructions, the results of which are feed back into new propositions: “Education systems in the Western industrialized nations have shown more convergence than divergence over the twentieth century, and the useful knowledge that drove innovation was increasingly accessible as the scientific and engineering communities became more integrated” (Mokyr 2002, p. 274).

Yet Mokyr argues that the integration of societies can either encourage or discourage innovation, depending upon the economic and organizational requirements of the key innovations available at that point in the progress of science and engineering. He notes that societies that have innovated rapidly tend to lose that creative power, while societies that lack a traditional of innovation have difficulty getting started. That could be explained by the rigidity of well-organized social systems and thus less likely to occur when society is fragmented – for example, the fact that many nations competed on the continent of Europe, and if one lost the power to innovate, another would take its place. But disorganization can decay into uncreative chaos, and some technological revolutions require substantial investment and enduring commitment that only a well-organized society can attain. Thus we could imagine a diagram of four boxes, like those above, *descriptive* (yes versus no) crossing *prescriptive* (yes versus no). The "outside the box" visionary conception would add to fact and norms, the values from Merton's scheme, representing ethical values – not merely how best to achieve innovation on the basis of facts but whether to do so in the particular area.

Future Agenda

While the existing scientific literature on science and technology innovation provides good guidance for leaders, it is incomplete for three related reasons: (1) many of the theories and datasets remain fragmentary and of uncertain reliability and validity, (2) principles such as trait activation theory imply that many of the most fundamental principles are contingent rather than universal, and (3) enormous changes are under way in science, engineering, and the world at large, with uncertain implications of innovation and discovery. This suggests that extensive and diverse research studies are needed. The good news is that indeed innovations in research methods are taking place, which can encourage further innovations.

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Modeling and Simulation

J. Tinsley Oden

Contents

Abstract

This chapter addresses core issues of convergence and transdisciplinary research and academic study. It describes one approach toward creating an infrastructure for transdisciplinary research and true interdisciplinary study within a contemporary university in the United States. Solutions for overcoming traditional obstacles to this type of programmatic endeavor are outlined. The chapter focuses on computational science and engineering (CSE) as the central focus for building such programs and describes the structure and policies of ICES as a concrete example of how the major problems of creating an atmosphere for interdisciplinary work have been tackled.

J.T. Oden (✉)
Institute for Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX, USA
e-mail: oden@ices.utexas.edu

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The Computational Revolution of Science, Engineering, and Medicine

Computational science and engineering (CSE) is the discipline concerned with the use of computers and computational methods for scientific discovery and for engineering applications; it includes computational medicine and data-enabled science and technology and is often regarded as the multidisciplinary field concerned with the construction of mathematical and computational models to simulate natural events, or the behavior of engineered systems, or the outcome of medical procedures. Lying at the intersection of computer science, applied mathematics, and core areas of science, engineering, and medicine, it has gradually emerged as a new field that has changed the way science is done, revolutionized modern engineering and medicine, and expanded virtually all areas of technology.

Exactly why has this revolution begun and how it will impact society? The answer may depend on two fundamental truths: firstly, that the welfare, security, and overall well-being of the human species depend strongly on how well the natural and socioeconomic processes that control the universe and man's functioning within it are understood: to put it succinctly, it depends on science, the activity concerned with the systematic acquisition of knowledge. This is the premise that led to the creation of universities millennia ago, which in turn led to the remarkable technological advances we enjoy today and expect to see in the future. Secondly, the means to do scientific discovery and to apply science to the benefit of mankind has been enormously expanded by the advent of digital computing and advances in mathematics and science that enable computer modeling, simulations, and data processing.

Concerning the first truth, one may ask how knowledge is acquired, a question has been debated since the time of Socrates, Plato, Aristotle, and beyond. Equally important, how is it archived and disseminated to future generations so it can be put to use for the benefit for mankind? Science is the English word derived from the Latin *scientia* for "knowledge," which, according to the Cambridge dictionary, is the enterprise "that builds and organizes knowledge in the form of testable explanations and predictions about the universe." The acquisition of knowledge is, as embedded in this definition, the result of the scientific method, which, according to the Oxford dictionary, is a "method of procedure that has characterized natural science since the seventeenth century, consisting of systematic observations, measurement, experience, and experiment, and the formulation and testing and modification of hypothesis." These are the two classical pillars of science: (1) observation, empirical acquisition of information from experiments or perceived using human senses often aided by instruments, and (2) theory, hypothesis based on inductive logic, often expressed in the language of mathematics.

The second truth, the development of computing technology and science, has pushed classical notions of observation to levels unimaginable only a few years ago, with the expanding capabilities to acquire and interpret large volumes of data. In addition, computer modeling and simulation have made it possible to explore the consequences of numerous hypotheses on causes of events governing the behavior of complex systems, pushing forward the predictability of theory on which models are based. There is now irrefutable evidence that CSE represents a third pillar of science, a new avenue for gaining scientific knowledge (e.g., Oden 2013). As Heng pointed out (Heng 2014), "By necessity, a third way of testing and establishing scientific structure – in addition to theory and experiment – is via simulations, the use of (often large) computers to mimic nature. It is a synthetic universe in a computer." The third pillar has been manifested in a little more than a half-century of the 400,000 years of human history and, on a historic scale, in a blink of an eye. By its nature, it is inherently transdisciplinary, drawing adaptively from its basic components as required of the application or scientific discovery at hand.

The third pillar is much broader than just a routine implementation of computer simulation; it often embodies deep mathematical analysis of the theory on which computer models are based, the development of intricate and complex algorithms to effectively solve computational versions of the underlying models, data retrieval and curation, data mining, processing of large data sets, computer visualization, and the use of other specific advances in computing technology. These components of the broad processes underlying computational science cannot be addressed piecemeal by specialists drawn narrowly from the traditional component disciplines. They must be addressed by a new generation of scientists and engineers, including medical professionals, equipped with an understanding of the fundamental building blocks of the discipline: mathematics, numerical analysis, computer sciences, and the fundamentals of basic science and engineering.

The importance of CSE to contemporary research, education, and technology has been the subject of many studies commissioned over the last decade (e.g., Benioff and Lazowski 2005; National Research Council 2014; Glotzer and Cummings 2010; Glotzer et al. 2009; Oden et al. 2006, 2011; Reed et al. 2005), and all agree that a means to cultivate the discipline with today's educational institutions is of great importance. One of the most challenging aspects of CSE as a field to be fostered in a university setting is how to build an infrastructure, policies of operation, and an environment that will allow it to flourish and to further advance. The remainder of this chapter discusses an experiment underway to develop a new approach to interdisciplinary education and research in CSE in an attempt to overcome many traditional barriers in research and academic study prevalent in most university environments. The example used is that of the Institute of Computational Engineering and Sciences (ICES), in which an organizational structure has been laid down, which attempts to address every aspect of the transdisciplinary integration of mathematics, life sciences, physical sciences, engineering, computer science, and other disciplines embodied in the notion of convergence (see Fig. 1).

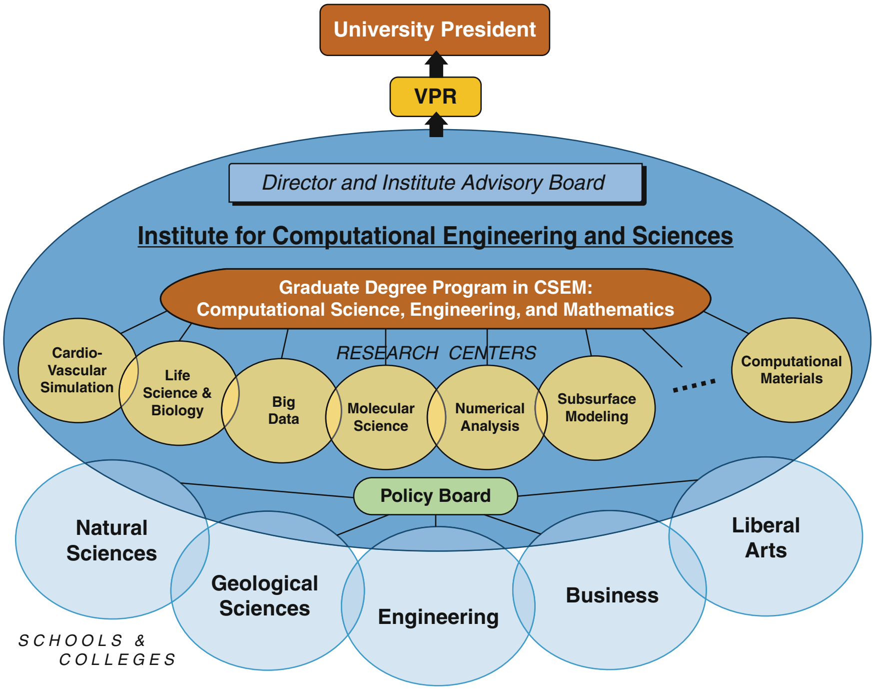

Fig. 1 ICES organization

ICES: An Attempt to Facilitate Transdisciplinary Research and Academic Study in CSE

ICES can be described as an experiment designed to facilitate the transdisciplinary integration of mathematics, computer science, physical sciences, life sciences, and engineering and align them in the true spirit of the concept of convergence. Ongoing strategies and practices designed to facilitate this convergence endeavor are discussed below.

Organizing Around a Common Theme, Problem, or Scientific Challenge

The central theme of ICES is CSE: computational science and engineering. Its mission is to provide the infrastructure and intellectual support for outstanding interdisciplinary research and academic programs in computational engineering and sciences. Over two decades ago, it was argued that CSE is, indeed, a new discipline and not a federation of disciplines that merely share interest in computer modeling and simulations. It is actually a multidisciplinary field that enables advances in the intersections of traditional academic units by adaptively drawing from its core: mathematics, computer science, and core sciences and engineering. To be effective, it must be able to readily access relevant component subjects, and it must have a level of autonomy to function and grow as an independent body of knowledge through new academic programs and research that emphasizes interdisciplinary collaboration.

Implementing Management Structures Tailored to the Challenges of Convergence in Each Institution

A unique organizational structure has been established for ICES that sets it apart organizationally from all the traditional academic units within the university: it lies outside the colleges and reports directly to the university President through the office of the Vice President for Research. The Institute itself owns no faculty lines; such tenure-track lines belong to the participating colleges, schools, and academic departments. At present, faculty from five colleges (Natural Sciences, Engineering, the School of Geological Sciences, the Business School, and the College of Liberal Arts) and 18 academic departments participate in ICES programs. The Director of ICES is provided the title of Associate Vice President of Research to further distinguish the unit from existing academic programs.

Within ICES, one finds 11 research units, called centers, and 8 groups. There are centers focused on big data, cardiovascular simulation, computational geosciences and optimization, computational life sciences and biology, computational materials, computational molecular sciences, computational visualization, computational distributed and grid computing, numerical analysis, subsurface modeling, uncertainty, and model verification and validation. One center has been created to facilitate CSE collaborations with KAUST of Saudi Arabia, and a new center for computational medicine is about to be formed. In the research groups, there are smaller concentrations of faculty, students, postdocs, and research scientists working on such subjects as applied mathematics, parallel algorithms, electromagnetics and acoustics, and computational hydraulics, the latter focusing on modeling the effects of hurricanes and storm surges. A thrust in geophysical fluid dynamics and oceanography is soon to be added. Other groups cover computational mechanics, biological systems, and bioinformatics. Research projects within ICES focus on topics in applied and computational mathematics, chemistry, physics, geosciences, materials science, engineering, medicine, biological sciences, neurosciences, and, occasionally, finance and economics.

In addition to the Institute Director, Deputy Director, and Assistant Director, management is guided by an Institute Advisory Board (IAB) made up of center directors, group leaders, and managers of the academic program. The IAB meets monthly to participate in strategic planning and management of the academic and research programs.

Another feature of the ICES strategic mission and structure, perhaps unique in the nation, is that it manages its own completely independent graduate degree program leading to the PhD and MS degrees in CSEM: computational science engineering and mathematics. This special program will be discussed further in the section on "Designing Education and Training Programs that Foster Convergence".

Outside the IAB, there is the ICES Policy Board, which consists of the deans of the academic schools and colleges involved, the Vice President of Research, and two members-at-large, who meet each semester. The Policy Board oversees the interactions between the traditional academic units and the academic program managed in ICES and also facilitates recruiting of new faculty for the Institute.

In addition to the Policy Board, a Board of Visitors (BOV) is appointed consisting of outside experts in CSE from academia, industry, and government laboratories. The BOV meets annually, generally for two days, and reviews all activities of the Institute, including the academic program. The Board provides a written report of its findings and recommendations to the Provost, the Vice President for Research, and the President of the University.

Fostering Opportunities to Interact Formally and Informally

The centerpiece of ICES is the Visitor's Program in which around 60 visitors per year are hosted by the ICES centers. Travel and local expenses for the visitors are covered for visits of a minimum of 2 weeks. This has resulted in numerous joint collaborative works, books, monographs, and colloquia over the 17 years of its existence.

ICES hosts a number of seminar series with a major generic series in computational science held twice a week and other weekly seminars in applied mathematics, computer visualization, computer sciences, and computational molecular biophysics. A popular biweekly event is the ICES Forum, which is designed to bring in a diverse list of speakers on topics ranging from modern work in decision theory, statistics, nano manufacturing, game theory, astrophysics, philosophy of science, mathematical finances, etc. – all presented at a level accessible to beginning graduate students from diverse backgrounds.

Changing Existing Faculty Structures and Reward Systems

ICES Faculty are generally divided into two categories: Affiliated Faculty, who are approved to teach courses in the program and are on the CSEM roster, and Core Faculty, who not only teach in the program but also conduct research, advise CSEM students and ICES postdocs, host visitors, and fund research scientists on institute projects. There are 116 Affiliated Faculty and 48 Core Faculty at ICES at this writing.

Several programs have been created to reward ICES Faculty for outstanding work in CSE. These include the annual Grand Challenge Awards, which provides funds to individual academic departments to cover the cost of release time from teaching so that awardees can devote full time to their research over one or two semesters. These are awards funded by an endowment managed by ICES. Around six awards are made annually. In addition, ICES recognizes excellence in research of Core Faculty in its Peter O'Donnell Jr. Distinguished Research Award, which provides substantial discretionary research funding for use by the awardee over a period of 4 years. In addition, Core Faculty mentor ICES Postdoctoral Fellows supported by a combination of funds from an endowment established for postdoctoral students and funds from research grants. Core Faculty also advise graduate students in the CSEM Program who are supported by 4-year CSEM Graduate Fellowships.

A remarkable outcome of the transdisciplinary nature of ICES is the recruitment of new faculty which is done primarily on the basis of their expertise in core CSE subjects and not on the particular academic department that may ultimately hold their faculty line. The result has been numerous joint appointments across several departments and colleges, a practice deemed virtually taboo a quarter century ago and a further indication of the recognition that the convergence of transdisciplinary knowledge is gaining acceptance across multiple disciplines.

Working With and Across Existing Departments

As noted earlier, faculty from 20 academic departments and five schools and colleges participate in ICES research and academic programs: seven Engineering departments, eight in Natural Sciences, and two in the School of Geosciences, two in the Business School, and the College of Liberal Arts. The Policy Board provides the formal apparatus for involvement of the academic deans, while the IAB provides broad faculty representation in management, recruitment, and strategic issues affecting the Institute.

Embedding Support for Convergence in the Promotion and Tenure Process

Via the ICES Policy Board, the Institute has developed an effective process for promotion and tenure reviews, in collaboration with participating colleges, the President, and the Provost. ICES conducts a detailed annual faculty evaluation of all core faculty and prepares a detailed report on the activities of each individual together with recommendations on merit raises, promotion decisions, and tenure. These faculty evaluation reports are provided to affected department chairs and deans as a supplement to other department and college evaluations. Interdisciplinary committees are organized to review and make recommendations on tenure cases affecting ICES Core Faculty.

Designing Facilities and Workspaces for Convergent Research

ICES has been extraordinarily fortunate to have received resources to construct a stand-alone research facility for the Institute and its academic and research programs. These are now housed in the Peter O'Donnell Jr. Building, which was specifically designed for interdisciplinary research in computational sciences. The 6-storied 186,000 sq. ft. structure contains offices for Core Faculty and designated offices for visitors, postdocs, and research staff. Students are provided with desks in well-furnished student areas located near student study rooms and computer labs. The building features a large auditorium, a café, an electronic classroom, and a modern visualization laboratory. There are no classes in this building, although it is the home of numerous seminar series and study groups. Space in the building and access to the facilities are reserved for faculty and students whose work is in programmatic alignment with the mission of the Institute.

ICES maintains seven computer clusters, with high-band network connections to the main supercomputers accessible at the Texas Advanced Computing Center (TACC), a large and modern visualization laboratory, over 17 conference rooms, a large auditorium, an electronic classroom, and a café accessible to all faculty and students. The computing facility at TACC features a 102,000 core, 9-petaflop machine, which came online in January 2013. Another Dell Linux cluster of 22,500 cores enables both high-performance computing and big data calculations. The visualization laboratory features a 328-million pixel screen and other top-of-the-line visualization equipment.

Designing Education and Training Programs That Foster Convergence

The great challenges in developing educational programs in CSE have been addressed in several reports (e.g., Petzold 2001). Within ICES, these challenges have been addressed by the creation of a unique graduate program called CSEM: Computational Science, Engineering, and Mathematics, leading to MS and PhD degrees. The academic program is divided into three major areas: areas A, B, and C, designed to provide considerable breadth needed in CSE education while also promoting a clearly interdisciplinary setting for graduate study and research. There is a heavy emphasis on computational and applied mathematics, which constitutes a core area in the program called Area A: Applicable Mathematics. In Area B, which is Numerical Analysis and Scientific Computing, students are expected to acquire graduate level proficiency in numerical analysis, scientific computing, software engineering, and some of the fundamentals of computer science. In Area C, Mathematical Modeling and Applications, students from diverse backgrounds of physics, mathematics, engineering, chemistry, biology, and other areas are given a broad two-semester introduction to modern concepts of science and engineering, beginning with continuum mechanics (the foundations of fluid and solid mechanics), quantum mechanics, statistical mechanics, and molecular biology. At the conclusion of their first year, a battery of written exams is given to determine in which of the three areas (A, B, C) students may require additional coursework. Although students may enter research groups in their first year, the first year of the program is primarily designed to provide some level of uniformity in understanding the basic foundations of CSE. Students begin to migrate toward specific application areas during the third and fourth semesters in the program. On average, those students beginning the program with a bachelor's degree in engineering, mathematics, physics, or some other physical science generally take around 5 years to complete requirements for a PhD in CSEM.

The academic program is managed by a Graduate Studies Committee consisting of 12 members, who represent equally the component Areas A, B, and C. The program is not large. It currently involves between 70 and 80 PhD students, most of whom are supported by fellowships and graduate research assistantships. Graduates of the program, not surprisingly, are in high demand. Currently, around one third find employment in industry, around 60 % go to academic positions, and the remainder finds jobs in government or private research laboratories.

Establishing Partnership Arrangements Across Institutions

As noted earlier, ICES has several student and visitor programs. The most significant is the Visitor's Program, which accommodates around 60 visiting scholars per year. To date, over 800 scholars from other institutions have visited ICES, spending a minimum of 2 weeks per stay and some much longer depending on project goals and available resources. Around one third of the visitors come from the United States and the remainder from other countries; particularly, many South American and European visitors have participated in ICES programs in recent years.

ICES also manages the ICES postdoctoral fellowship program, which is highly competitive, and processes between 50 and 60 applications per year while granting around six 2-year postdoctoral fellowships that are assigned mentors from one of the existing, affiliated centers. Another 40 postdoctoral students are supported by research grants.

In addition, ICES has established an Undergraduate Summer Internship Program, which accepts approximately 14–20 undergraduates per year to work over a summer in one of the ICES centers under the mentorship of an ICES Core Faculty member.

Exploring Sources of Funding Within and Beyond Government Agencies

ICES receives grants from around 12 federal funding agencies supporting around 150 research projects, with special attention given to the interdisciplinary nature of the project. All projects potentially involve multiple academic disciplines and departments. As a measure of the interdisciplinary nature of research projects, the IQ: *the Interdisciplinary Quotient* is computed which expresses the number of departments for all projects divided by the number of projects. The annual ICES IQ is consistently around 2.40. Eighty percent of current projects involve two academic departments, and close to 20 % involve three or more academic departments.

Beyond federal funding agencies, a large number of projects are supported by industry or by foreign institutions. Most notably is the program with KAUST: King Abdullah University of Science and Technology of Saudi Arabia, with whom ICES is an AEA (Academic Excellence Alliance) Partner. The Program has generated numerous joint research projects and research visitors via workshops and colloquia involving collaboration between KAUST and ICES centers. In addition, ICES holds memoranda of understanding (MoUs) with many universities that establish exchange programs for graduate students and postdocs. Currently, these include Italy, Portugal, Brazil, and Spain.

The ICES experiment in facilitating transdisciplinary research and academic study has been made possible by extraordinary support by numerous university and administrative leaders who understand the fundamental importance of transdisciplinary work and the way it is gradually transforming the scope and mission of educational and research institutions across the globe. The great value of this organization is already being recognized with similar programs appearing worldwide.

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Science and Technology Forecasting

David Rejeski, Eleonore Pauwels, and Joyce Koo

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Abstract
Forecasting through futurism has historically been characterized by a lack of both focus and accuracy. Reflexive governance may be capable of addressing the limitations that often cause forecasting failures. Now may be the critical time for implementation of a policy that effectively and adequately addresses cutting-edge scientific issues in a complex world.

Forecasting failures often occur because of cognitive bias, institutional limitations, and the increasing tendency of scientific problems to move toward complexity. As such, it may be a more productive use of resources to shift focus to an adaptive and reflexive method of addressing problems that have not yet manifested in the present. This method is embodied in reflexive governance. Through long-term collaborative research groups, trading zones, and large-scale cross-sector networks, reflexive governance is capable of tackling all three limitations that often cause forecasting failures: (1) expanding perspectives to reduce the impact of cognitive bias, (2) leveraging the power of numbers to grow beyond institutional limitations,

D. Rejeski (✉) • E. Pauwels • J. Koo
Science and Technology Innovation Program, Woodrow Wilson International Center for Scholars, Washington, DC, USA
e-mail: david.rejeski@wilsoncenter.org

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and (3) enhancing adaptive management by embedding policy-makers and thereby increasing the speed with which they can respond to complex issues. While reflexive governance is not a new concept, now may be the critical time to implement it, to bring our policy-makers to the frontier of science research, and to increase public confidence in policy-makers' ability to quickly and adequately tackle issues arising out of scientific research in a postmodern world.

A Look Back at Futurism

For the past 15 years, a 3D-printed object has been lying on a bookshelf at the Woodrow Wilson International Center for Scholars. When a scientist at MIT first presented the plastic widget as a gift, the message was clear: Additive manufacturing would change the world and the world needed to pay attention. Disruptive change was on the horizon, or so the thinking goes. Next to the 3D-printed piece sits a wireless sensor node, a reminder of another new idea, now over a decade old, of how mesh networks would change just about everything and help usher in the Internet of Things. Unfortunately, it took 10 years to work out the communication protocols that would allow these networks of sensors to effectively exchange signals. These objects sit as mute reminders that the exuberance of science doesn't make things happen in the real world, and forecasting technological progress, even the timing of market entry, is a difficult endeavor.

Let's go back to a much simpler world in the early 1950s, where the most connectivity we had was the telephone or the postman and the initial annual budget of the National Science Foundation (NSF) stood at $3.5 million. At that time, there was significant strategic interest in anticipating the technological capabilities of our Cold War adversaries, which kick-started a cottage industry in science and technology forecasting. What was once the strict province of science fiction writers like H.G. Wells or Jules Verne became fertile territory for high-minded policy advisers like early presidential science advisor Vannevar Bush, whose 1949 *Atlantic* magazine piece, "As We May Think," provided a prescient view of the future of computing.

But to achieve lasting policy relevance, forecasting had to change – it had to become a "science." Predictive methods of the past, such as divination by throwing stones, the inspection of animal livers, or the visiting of oracles, were unlikely to meet the demands of a new technocratic elite. After WWII, early studies on the use of expert predictions to inform policy-making showed that predictions made by groups of people were more likely to be correct than those made by individuals working alone (Kaplan et al. 1950). This led to the development and use of a number of group-based forecasting methods. In the late 1950s and early 1960s, the RAND Corporation (a think tank established by the US Air Force) undertook a series of exercises to forecast technological capabilities, many of them based on a method referred to as the Delphi technique. One particularly ambitious forecasting project, reaching out 50 years and covering scientific breakthroughs, population, automation, space, the probability of war, and future weapons, became the most famous and visible of these exercises (Gordon and Helmer 1964).

In 1975, RAND undertook a critical examination of more than a decade of its Delphi exercises; this survey included an "emphasis on the scientific appraisal of the principles, method, and practice of the Delphi" (Sackman 1975). Among the major findings, the Delphi exercises had a tendency to be highly vulnerable to the concept of "expert," seriously confused aggregations of raw opinion with systematic prediction, typically generated snap answers to ambiguous questions (representing inkblots of the future), and gave an exaggerated illusion of precision, misleading uninformed users of results. In response to these shortcomings, modifications of the technique were developed such as Sequential Polling and Review of Interacting Teams of Experts or SPRITE (Bedford 1972). People also began moving beyond Delphi, and methodological development expanded to include qualitative, semiquantitative, and quantitative tools such as cross-impact analysis, the Futures wheel, agent modeling, environmental scanning, morphological analysis, relevance trees, trend impact analysis, time series forecasting, visioning, scenario planning, and games. But a question continued to plague the entire forecasting enterprise: Did any of these methods actually work?

In 1977, the NSF, under its now long-forgotten Research Applied to National Needs, or RANN, program, conducted a meta-analysis of forecasting methodologies and the emerging field of "futures research" (Green and Lepowski 2006). The report emphasized, "[W]hile forecasting is still one of the primitive arts and research can make a difference in many instances, the field is without a research agenda" (Boucher 1977). Even today, forecasting remains an amorphous field with no dedicated research agenda and few formal training programs. (One of the remaining programs is at the University of Houston, which offers a Master of Science in Foresight.)

Where technological forecasting seemed to work, or at least work better, was when quantitative and more deterministic modeling could be used to predict capabilities, such as forecasting communications satellite output capacity or the characteristics of long-endurance aircraft. But when technological currents mixed with social, cultural, and political ones, predictive accuracy often fell precipitously. Though early studies attempted to separate science and technology forecasting from the human and social environment, the interactions between these two spheres was, and remains, critical (RAND Corporation 1967).

In the final analysis, the problem was not a lack of tools but a lack of demand and the tendency of the forecasting field to be captured by charismatic prophets who substituted opinion for robust analysis. As Philip Tetlock's analysis of more than 80,000 expert predictions showed, the so-called experts seldom beat a coin flip, but unfortunately these people occupy a significant amount of media real estate (Tetlock 2006). A new study by two Canadian researchers shows much higher predictive accuracy by highly trained analysts operating in the intelligence community, who seem to show more caution and accountability than the pundits that Tetlock studied (Mandel and Barnes 2014).

Technology gurus love to take credit for predicting the “next big thing,” but much of this enthusiasm is often attributable to the so-called hindsight effect, where much more credit is given to predictions after the fact than they deserve (Fischhoff 1975). Even if predictions about technological capacity are correct, secondary and tertiary impacts on society are often grossly wrong. Think for a moment about the ripple effects of air conditioning, a technology developed in the early twentieth century to increase productivity in the textile and paper industries, but which has resulted in serious environmental issues (Cooper 2002).

In addition, new technologies rarely replace the old ones, and we remain surrounded by a blend of the old and the new, as seen in building construction, heating/cooling systems, warfare, and aviation and other modes of transportation. Most futurists make their living betting on the new; if they viewed technology based on its actual use, rather than its pizazz and promise, it would fundamentally change the prediction game. As historian David Edgerton has pointed out: “[F]uturology of the past has affected our history. From it we get our focus on invention and innovation . . . from this literature . . . we get a whole series of clichéd claims about technology and history” (Edgerton 2007).

Facing DTPs (Damn Tough Problems): Specifics on Forecasting Failures

The forecasting endeavor faces a number of constraints, which have limited success in the past and will continue to provide challenges in the future:

– Cognitive biases
– Institutional limitations
– Complexity

Forecasters are human, subjected to cognitive biases, and operating in institutions that are often handicapped in terms of their ability to address the future. The cognitive biases are well known and include such things as the hindsight effect (already mentioned), anchoring on vivid events, omission biases, and the common tendency to discount the future. As people like psychologist Daniel Kahneman have pointed out, “[W]e believe we understand the past, which implies that the future should be knowable, but in fact we understand the past less than we believe we do” (Kahneman 2011).

As soon as we move beyond the individual to confront large collective action problems such as climate change, ecosystem management, or global health challenges, organizational solutions are often required. Organizations fall into a number of traps when trying to address emerging issues at the nexus of science and technology, which include:

– *Scanning failures* where there is a lack of situational awareness in both space and time and issues never appear on anybody’s radar screen until too late

– *Integration failures* where silos fail to connect the dots, boundary-spanning functions are missing, or effective transdisciplinary strategies do not even exist in the organization
– *Incentive failures* in which decision-makers simply lack the motivation to act or confront severe disincentives when addressing future issues
– *Learning failures* where the past never informs the present or future (Bazerman and Watkins 2008)

A more general failure mode is the "novelty trap," which involves businesses and governments making overly optimistic claims for new technologies and downplaying possible risks, based on reassurances from past technologies (Rayner 2004). This often triggers a counterattack by nongovernmental organizations, which argue risks are being ignored to ensure market acceptance and competitive advantage.

The severity of these constraints often leads to forecasting activities being relegated to their own department or "outsourced" to organizations or individuals that can later be conveniently ignored. Recent attempts to stimulate more long-term, anticipatory thinking in the US government have fallen largely on deaf ears. A very ambitious study about the need for anticipatory governance was supported by dozens of former high-level US government decision-makers, but has gained little traction (Fuerth and Farber 2012). Studies to identify critical success factors for forecasting often point to the need for high-level support for the analytical products and/or a precipitating crisis, which has forced decision-makers to look longer term (at least in the short term) (Glenn and Gordon 2000).

The new twist to the forecasting game is the sheer complexity of the socio-technical systems that surround us. In the past, forecasters could often ignore complexity, and it did not have much of an impact on their results. People were less connected, markets were less integrated, disciplines were more separated, and the flow of knowledge was severely limited (compared with the present day).

Early technology forecasting grew out of the field of operations research after WWII, where there was a belief that one could use mathematical models to unravel and optimize the behavior of complex systems. Operations research was adequate in predicting the outcomes of complicated systems, even with thousands of parts, as long as the interrelations were governed by deterministic laws. But there is a fundamental difference between *complicated* and *complex* systems.

As Tom Friedman noted, "[T]here is something different about the flattening of the world that is going to be qualitatively different from other such profound changes: the speed and breadth with which it is taking hold.... This flattening process is happening at warp speed and directly or indirectly touching a lot more people on the planet at once. The faster and broader this transition to a new era, the more likely is the potential of disruption."

Some researchers, including Scott Page, Director, Center for the Study of Complex Systems, University of Michigan, have characterized complex systems as inherently “difficult to explain, engineer, and predict” (DEEP). Complex systems often defy any attempts to forecast outcomes because of the sheer number of interactions, the existence of nonlinearities, and the influence of the initial state of the system on its evolution. As Kupers and Colander have recently noted, “Sensitivity to initial conditions has a number of implications for thinking about policy in [complex] systems. For one, such an effect makes forecasting difficult, if not impossible, as you can’t link cause and effect. For another it means that it will be very hard to backward engineer the system. . .” (Kupers and Colander 2014). If we want to think about and respond to complexity, the future is a major roadblock.

Part of the growing complexity challenge involves technological convergence, the increasing interaction of multiple fields, such as nano, bio, info, and cogno, which rapidly expands the range of possible impacts that need to be considered in any forecasting exercise. Ten years ago, nanotechnology was celebrated largely for its impacts on chemistry and materials science, but the ability to precision engineer matter at a biologically relevant scale has resulted in significant advances in biology and neuroscience, such as creating the ability to interrogate networks of neurons or cheaply sequence large genomes.

Rather than add to the plethora of forecasting tools, it may be more productive to reframe our exploration of the future as an approach to organizational learning and adaptive management, an idea that was advocated many years ago by Royal Dutch Shell, one of the pioneers in the use of scenarios (DeGeus 1988). In this case, the focus shifts from prediction to preparation, reflection, and flexibility of response.

A Shift to Adaptive and Reflexive Learning

The future, just as the present, will be full of “matters of concerns,” for which adaptive and reflexive learning on the fly will be critical. The experiment is an easy one (Latour 2005). Just brainstorm any set of contemporary issues: genome editing and its biosafety and biosecurity implications; distribution of skills, knowledge, and thus power through decentralized networks and techniques like 3D printing; and neuromorphic computing and its ethical and cultural ramifications. Around each of these areas of concern, we will see growing entanglements of passions and controversies embedded in a complex web of stakeholders. In the end, we will be more connected to each other by our doubts, our questions, our ignorance, and the issues we care for, than by any set of predictions, values, opinions, and principles.

Beyond designing new forecasting tools, we will need to design ways to “manage complexity,” where actors from different fields and practices can question how we frame complex socio-technological systems and their transition pathways – opening these issues up for debate (Smith and Stirling 2008; Stirling 2008). For this endeavor to succeed, the actors need to be empowered by their organizations as suggested by Andrew Jamison: “[C]hange-oriented research is about empowerment, by which the research applies knowledge gained from experience to processes of social learning, carried out together with those being ‘studied’” (Jamison 2010, p. 13).

Reflexivity presupposes that we leave enough room for different frameworks of thinking to come together, exchange ideas, and ultimately develop visions that are based on a true diversity of perspectives. That kind of diversity – institutional, legal, epistemic, disciplinary, and discursive – is part of what it takes to be more reflexive. Diversity is not synonymous with reflexivity or even conducive to it, but it is a necessary prerequisite for a healthy reflexive discourse on our technological futures and must be preserved and appreciated.

What does "reflexivity" mean and how does it differ from "reflection"? Reflection is thinking broadly about all the possible facets of a phenomenon as if they were possible in an environment. Good forecasting is inherently a process of reflection, though it may not necessarily be reflexive. Reflexivity involves situating yourself as an observer in the system, dissociating from this system your own interests, and thinking about your position amidst the things being considered. How can we correctly implement reflexivity? It is about creating arenas and spaces where matters of concern can be unveiled, where interactions between fields do not suppress dissenting voices. Such arenas are the intellectual and collective spaces where it becomes possible to question the status quo and shape our technological futures.

Reflexive Governance: The Path to Successful Science Policy in a Postmodern World

Reflexive governance approaches would place the consideration of technological futures and their impacts *inside* the organizations that are funding and conducting the science, rather than outsourcing these considerations to external experts and advisors. Such an approach must also address the three constraints on forecasting that so often results in forecasting failure – cognitive biases, institutional limitations, and complexity – by incorporating nonconventional governance mechanisms. Addressing these constraints on forecasting can be approached through three mechanisms:

– *Expanding perspectives* – and simultaneously reducing exposure to potential blind spots – through concerted efforts to intermingle specialists across disciplinary lines, thereby addressing cognitive biases based on limitations of individual perspective and specialization
– *Leveraging the power of numbers* (e.g., through crowdsourcing techniques such as prediction markets) to tackle limitations posed by institutional boundaries
– *Enhancing adaptive management* by placing policy-makers at the front lines of scientific and technological research, to address complexity, which may require quick and decisive action on critical matters as they arise

Critics of adoption of a new form of governance may claim that such a change is unnecessary or impractical because it is too difficult to manage. However, implementation of reflexive governance approaches not only circumvents the need to redesign or reimagine our limited capabilities in forecasting, a potentially fruitless enterprise, it is also fundamentally a natural extension of the way in which the world is moving. As disciplines intermingle and share ideas and as experts tap into their colleagues' expertise, from across the hall to across the globe, the world is gradually becoming more connected. New fields are emerging on the technological frontier, spurring on the rise of new fields of study on campuses around the world. This connectedness and intermingling may sometimes result in synergies in the development and awareness of responsible governance policies among individuals and groups. A recent success, for example, is the development by commercial providers of synthetic DNA in collaboration with the Department of Homeland Security of a voluntary policy to screen orders of synthetic doubled-stranded DNA. This policy emerged from a multiyear, cross-sector engagement process, which included the public.

Rather than allowing this process to experience fitful starts and stops in different companies, industries, jurisdictions, and fields, concerted support for reflexive governance both at the microlevel, impacting individuals and groups, and at the macrolevel, impacting institutions and sectors, was necessary. Under its auspices, it is possible for governance to remain aligned with science and technological advances and to assure that governance is sufficiently flexible and adaptable to face the challenge of responding to the unknown.

Reflexive governance, admittedly, is not a new concept. However, what may be novel is the growth of new scientific fields and ideas at an unprecedented pace. Today, we have a larger population of highly trained, expert scientists researching and working together than ever before. The effect of this supply side pressure is seen everywhere, from a surge in patent applications and journal submissions to an increase in the financing of scientific research and development by private companies and governments. Not only do sheer numbers play a role in the more rapid advancement of recent science, but an increased focus on interdisciplinary work groups and big-data projects that rely on massive amounts of gathered, storable, sortable data also supports quicker development of science and technology.

Regardless of the reasons behind the rapid pace of scientific and technological progress, it is apparent that we have arrived at a new status quo where policymakers need to stop playing catch-up with the ever-widening gap between their current policy-making focus and the scientific frontier. We are at a crossroads where the act of maintaining the status quo versus the act of implementing an already well-conceived and discussed form of governance may, for better or worse, affect the state of our scientific and technological progress and results for years to come.

If we are to implement reflexive governance, one place to start is at the microlevel, focusing on individuals and small groups. At this level, a number of approaches can be explored, both alone and in various combinations, including long-term collaborative research groups, trading zones, and cross-sector networks.

The concept of collaborative research arises as a potential solution to the problem of a particular kind of culture gap. More than 50 years ago, in the Senate

House in Cambridge, the celebrated novelist C. P. Snow delivered his now famous intervention, *The Two Cultures and the Scientific Revolution*. As Snow noted, the “two cultures” – the humanities and the sciences – have a tendency to diverge (Snow 1993). The resulting gap is often a disservice to both communities, most noticeable when social scientists, lawyers, and politicians are tasked with crafting measures to address scientific advances or when scientists are required to present their findings to social scientists, lawyers, and politicians. Such measures from the culture of the humanities may demonstrate a fundamental lack of understanding of the science and result in a clear mismatch that could negatively affect future investment in critical research.

On the other hand, presentations from the culture of the sciences could fail to convey the nuances of research in a manner that makes it meaningful to others or could fail to address ethical or political concerns that are inherent in applications of the research. In either case, this failure of communication from the culture of the sciences could also result in unfortunate setbacks for those advocating advancement of the research. One obvious solution to this problem of the two cultures is to bring the two communities together regularly, so that each is more grounded in the understanding of the expertise and fields of the other.

To push regular commingling, the two cultures could develop permanent working groups. Long-term collaborative research groups that embed those who are from the “culture of humanities” into the “culture of sciences” is what social scientists Daan Schuurbiers and Erik Fisher call “lab-scale intervention” (Schuurbiers and Fisher 2009). These “interventions” can increase the legitimacy of scientific work, as it assures the public that ethical, social, and legal concerns are being raised upstream in the research process, ideally at the level of engineering and design. At the same time, scientists will receive exposure to and training in thinking about and responding to such concerns, so that they improve their ability to be an effective ambassador of their work to those outside of their culture and to the public.

Collaborations that share individual expertise and challenge underlying assumptions, perspectives, or any propensity toward groupthink (the “not-invented-here” syndrome) can help safeguard both experts and the public against runaway expectations and exaggerated promises. Policy-makers, in particular, should be concerned with averting the negative impact of failed promises on the public, which serves to further alienate those who already have reservations about government support for science they do not fully understand or support.

Embedded collaborative research groups can dramatically reduce the lag time between scientific discovery and subsequent governance by providing more rapid feedback to decision-makers, who may themselves be embedded in or closely collaborating with the group. Even if these decision-makers are only immersed in a fraction of the work at the frontier of research, it is more likely they will be ready to respond to emerging issues and guide policy-making. This change in the decision-maker’s ability to handle new scientific or technological research occurs by virtue of their exposure to the science and to networks of scientists and by virtue of the increasingly interdisciplinary nature of scientific work.

However, simply commingling two groups together does not automatically result in fluent exchanges. For collaborative research groups to be successful, whether assembled across "the two cultures" or assembled from scientists across different fields, group members must be able to communicate with each other, going beyond their native, disciplinary language. Scientists have undergone rigorous training and accumulated extensive experience in the jargon and specialist terminology of their field. To compound the communication process, sometimes the same term in one scientific field may have entirely different associations or nuances in another field.

In 1997, historian of science, Peter Galison, asked how scientists and engineers could work together to build particle detectors, radar, and other systems despite coming from apparently incommensurable expertise communities. His answer was that they form "trading zones," beginning by having participants agree on shared meanings for certain terms, then evolving a kind of pidgin for talking among themselves and, if the trading zone continues long enough, a creole that can be taught to a new generation of scientists working in a new, merged field. Galison concluded that, in the case of scientists attempting to bridge incommensurable scientific paradigms, members must sometimes go through several stages in the development of an adequate working language (Galison 1997).

Trading zones that facilitate trading of information and ideas at interdisciplinary boundaries would assist in this development, especially if they build on what sociologists of science, Harry Collins and Robert Evans, refer to as an "interactional form of expertise" (Collins and Evans 2002). Key interactional experts would come not only from disparate scientific and technological fields but would also other cultures, such as the humanities. A 6-month-long study on the interactions within a working group consisting of scientific experts, policy-makers, and representatives of civil society organizations found that even short-term exposure to regular dialogue with members within this interdisciplinary trading zone brought about exchanges that reflected more willingness to delve into complexity, avoid simplistic answers, and probe into a more diverse set of issues about the research and its implications (Pauwels 2013).

This trading zone in the study focused on the life-cycle assessment (LCA) of a genetically engineered arsenic test kit for detecting levels of arsenic contamination in drinking water systems in Bangladesh (Pauwels 2013). A critical mass of the experts involved shared cross-field expertise, which allowed them to cross paradigms from life sciences to social sciences to policy and, ipso facto, to shape and conceptualize the discussions along these boundaries. The group also gathered around a common underlying goal, which was flexible enough to be progressively reframed. The underlying goal was of "sustainability," i.e., to use LCA to discuss the problem of arsenic contamination in Bangladesh and make decisions that can lead to a creation of a cheap, easy-to-use, accurate field test. The intention of engaging experts at an early development stage was to mitigate upstream concerns and also to guard against any "lock-ins" that may lead to any unintended environmental, ethical, or societal concerns as the test kit moved to market.

This trading zone was a successful exercise in anticipatory and inclusive governance. First of all, the exercise occurred early in the development process – before and during the design stage – much earlier than usual procedures of assessment. While occurring upstream, the trading zone helped illustrate the main factors, constraints, and drivers that were part of the technological innovation process for a specific application. Moreover, the trading zone contributed to addressing and translating technological uncertainties about potential risks to health and ecosystems in a way that can be discussed early and treated potentially by policy-makers in an inclusive setting.

In addition, the trading zone improved participants' predictive accuracy by aggregating diverse perspectives from a variety of sources. These perspectives were used to build scenarios to deal with the future both in terms of the evolution of the biosensor and its interaction with society, the environment, and other technologies. The fact that these interdisciplinary assessments of techno-scientific scenarios occurred before the situation was locked in was crucial. This indicates that scenarios might be an important complement to the use of metaphors and group-specific languages within trading zones.

Large-scale networks across different sectors, including researchers, policy-makers, practitioners, and the public, can not only improve engagement among sectors, but they can also guide reflexive governance approaches in their path toward upscaling and broadening impact on communities at large. Networks extend the reach and impact of reflexive governance beyond the collaborative scientific or technological research group (the target of embedment policies) and beyond groups of groups (the target of trading zone policies).

Recently, high-level decision-makers have pointed to the importance of relying on large-scale networks to promote US science, technology, and innovation (STI). According to two renowned experts in the Global Science and Technology field, William Colglazier and Elizabeth Lyons, "The new global landscape of science is more distributed and networked – the United States needs to look around at such linkages. Many scientific advances are now propelled not just by individuals working within individual labs, but increasingly by overlapping, fluid, and largely self-organizing networks of scientists, engineers, technologists, and entrepreneurs. These networks frequently extend across and beyond research intensive institutions" (Colglazier and Lyons 2014).

Building on this diagnosis, William Colglazier and Elizabeth Lyons propose to develop a new platform to elucidate the dense matrix of potential partnerships between the United States and foreign science institutions. "Information on national and international science priorities, forward-looking activities, and knowledge mapping needs to be organized, synthetized, and made more widely available across the decentralized American STI enterprise," Colglazier and Lyons write. "This includes information to identify trends in cross-disciplinary connections, in innovators and agents of change, or in geographic STI distributions and linkages.... Such information would establish a solid base from which to nourish and grow global knowledge networks" (Colglazier and Lyons 2014).

Currently, there are a number of cases where companies, individuals, or groups of individuals have taken the initiative to share data openly, encourage collaboration, and engage in crowdsourcing through networks.

The Research Data Alliance: a network that supports international data sharing among researchers and innovators

The Open Science Framework: a software system and network that supports collaboration, crowdsourcing, and sharing of research materials

InnoCentive: a company that provides an award system for problems it openly crowdsources

Harlem Biospace: a shared lab and biotechnology incubator for start-ups that offers entrepreneurs and innovators access to lab space, equipment, classes, and legal assistance

By tapping into the skills and strengths of the greater global community at large, networks provide flexibility, improved access, and expanded innovation potential at lower costs. But despite the efforts of visionary researchers and decision-makers, cross-disciplinary and cross-sector networks do not often overcome the divisions between the two cultures of humanities and natural sciences; the STI landscape is still seen largely as the realm of natural scientists and engineers.

At the macrolevel – namely, at the level of institutions and organizations – each of the microlevel aspects could be brought to scale, with adaptations to address factors specific to a larger-scale model. At the institutional level, for instance, researchers from social sciences and humanities should be embedded in labs that are conducting representative, cutting-edge research, where research and development funding is concentrated and where ethical, social, and political concerns are more likely to arise. At the organizational level, organizations should establish trading zones for any research that involves interdisciplinary collaboration, allowing scientists who have expertise in multiple disciplines to assume the role of interactional experts and actively guide collaborations between scientists across different fields. At the macrolevel, institutions and organizations should also support the creation and maintenance of networks outside of the organization, with other organizations, policy-makers, and the public.

Each of these aspects of reflexive governance is critical to creating a reflexive governance approach that can respond to real-time situations and scenarios in a postmodern scientific world. As the history of forecasting demonstrates, we are currently ineffectual at anticipating future events and predicting trajectories involving causality – and the likelihood that we will suddenly and significantly advance our ability to forecast increasingly complex scenarios with more unknown variables is dim.

Moreover, the three constraints on forecasting previously discussed – cognitive biases, institutional limitations, and complexity – are likely to only grow larger in influence, hindering the good governance of scientific and technological research. As the body of scientific and technical knowledge becomes increasingly specialized for individual experts at the top of their fields, cognitive bias and a shortsightedness when it comes to thinking outside of their training could also increase.

As institutions reach the limitations of size versus efficiency tradeoffs, they, too, will need to look outside of their local pool of employees for low-cost, ready, and available human and knowledge resources. Our governance models have addressed much of the "low hanging fruit," leaving behind problems of greater complexity where decision-makers face consequences of greater proportions. Often called "emerging systemic risks," these "wicked problems" have become "super wicked problems," and in some cases, it is the public policies themselves that have created conditions that paradoxically resist their implementation. John Sterman at the MIT Sloan School calls this tendency for policies to be defeated by the systemic response to the intervention itself, *policy resistance* (Sterman 2008).

We face an ever-widening chasm of understanding and communication between scientists and social scientists, policy-makers, and the public. Particularly troubling is the time lag between scientific research at the technological frontier and how long it takes for policy-makers to achieve sufficient understanding of the research to grasp the implications and craft suitable policy responses.

The public frequently becomes disenchanted with messaging from experts and policy-makers on scientific and technological research. Experts often fail to communicate research in simple terms and develop effective policies for ensuring both the relative safety of the public while advancing and the research to improve public well-being.

With social scientists embedded in scientific and technological research groups, available to both represent the public interest and to accurately interpret findings to the public, reflexive governance can help narrow the gap of understanding and awareness between the public and the scientists and begin to address the existing distrust.

Bringing social scientists and policy-makers closer to the technology frontier where scientists are working on cutting-edge research will foster dialogue and pave the way for real-time feedback. With this communication, these reflexive governance approaches may be capable of improving our ability to shape the future.

And the stakes are high. Risks and benefits of scientific research and new technologies are of paramount concern, affecting more and more people. Both the public and researchers need to know that policy-makers are on top of the research – not years or decades behind it.

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Self-Organization and Emergence of Dynamic Systems

James K. Gimzewski, Adam Z. Stieg, and Victoria Vesna

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J.K. Gimzewski (✉)
Department of Chemistry and Biochemistry, University of California-Los Angeles, Los Angeles, CA, USA

California NanoSystems Institute (CNSI), University of California-Los Angeles, Los Angeles, CA, USA

WPI Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science, Tsukuba, Japan
e-mail: gimzewski@cnsi.ucla.edu; gim@chem.ucla.edu

A.Z. Stieg
California NanoSystems Institute (CNSI), University of California-Los Angeles, Los Angeles, CA, USA

WPI Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science, Tsukuba, Japan
e-mail: stieg@cnsi.ucla.edu

V. Vesna
Art|Sci Center, Department of Design Media Arts, University of California-Los Angeles, Los Angeles, CA, USA

Program in Empowerment Informatics, School of Integrative and Global Majors, University of Tsukuba, Tsukuba, Japan

W.S. Bainbridge, M.C. Roco (eds.), *Handbook of Science and Technology Convergence*,
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Abstract

Self-organized criticality (SOC) has been widely adopted as a useful paradigmatic generalization to capture an array of observations found to be intrinsic in many natural and human-made systems. It often manifests itself in the form of dynamic metastable patterns that are not attributable to any constituent element of the system. As our world becomes increasingly network centric, assessment of the emergent unpredictable fluctuations increasingly play an important role in understanding the system dynamics of society and economics. To date, complexity and SOC lack a systematic convergence of theoretical approaches and experimental methodologies. The attitude of many hard sciences in relation to complex systems can often be described as "the elephant in the room," a metaphorical idiom for an obvious truth that is largely ignored by scientists, even if recognized as critical in assessing risk and inherent uncertainty. Here we provide a brief background on the roles of SOC and emergence that seem to spontaneously appear with a plethora of spatial-temporal fluctuations on all scales. We propose that a deeper understanding of these phenomena requires a convergent effort of the sciences, arts, and humanities both in research and education. Further, it is proposed that a unified approach is necessary to achieve a more quantifiable, analytical, and predictive methodology to determining risk and resilience in complex systems with the goal of better understanding the world around us.

Introduction

Today, more than ever in human history, we have a heightened awareness of a complex world that can be divided into two classes – the first one being a structurally complex system, in which the components have little freedom of action and where cause and effect are linearly related. This class avails itself to "systems analysis" where one can predict system functioning from its individual component parts. The second class is much larger and is interactively complex with the elements having a much greater freedom of action where cause and effect have a cascading-like interaction, unsuitable for systems analysis. Many of the dynamical behaviors observed in the complex networks of biology, society, economics, and the natural world have been interpreted by using the concept known as self-organized criticality (SOC) (Bak 1999). The latter class is subject of this chapter and is not intended to provide a concise or comprehensive mathematical description of SOC. Rather we discuss how it serves as a useful *heuristic metaphor* for a wide range of complex behaviors similar to the way Darwin associated ideas of classical economics and biology in his theory of evolution.

Aside from a few idealized systems in physics such as magnetism, detailed mathematical verification of SOC and emergence in complex systems is often challenging, although certain observations point to their existence. SOC is found to be intrinsic in many complex dissipative systems where it takes the form of dynamic metastable patterns. For example, SOC has been proposed as an alternative mechanism to natural selection in biological systems as well as a model for the functioning of the brain (Johnson and Lam 2010). On our planet, the biocomplexity of ecosystems has also been described in terms of SOC (Proctor and Larson 2005). Similarly, as new technologies become network centric, their internal connectivity increasingly plays a crucial role in societal and economic dynamics.

Building from his seminal work on emergence in the early 1970s, Nobel Laureate physicist Phillip Anderson recently made an illuminating statement on SOC's importance in the contemporary world:

> Self-organized criticality seems to me to be not the right and unique solution to these and other similar problems, but to have paradigmatic value, as the kind of generalization which will characterize the next stage of physics. (Anderson 2011)

This chapter considers phenomena ubiquitous in nature and human experience whose existence underlies much of our socioeconomical behavior and technoevolution. Here we provide a brief background on the roles of SOC and emergence in complex, dynamical systems. We propose that further insight into these phenomena require convergence of the sciences, arts, and humanities both in research and education. It is suggested that such an approach is necessary to achieve a more quantifiable, analytical, and predictive approach to better understand the world around us. The science of complexity represents what many view as the next great challenge for the twenty-first century following humankind's achievements in Newtonian Physics, Quantum Mechanics, and General Relativity. It is an effort to understand the interplay of what we interpret as order and disorder.

The Limits of Reductionism

The difficulty to "scientifically" understand complexity in a meaningful and general manner may be traced to our long-standing reliance on reductionism. During the late seventeenth century Newtonian mechanics and the time-reversible laws of motion enabled the Industrial Revolution and provided a successful model for technological developments during the nineteenth and twentieth centuries. This period of history was characterized by an unquestioned reliance on the use of mathematical equations from which machines with precise and deterministic properties could be designed. The revolution was aided by the "scientific method," where reductionism served as a key problem solving methodology to enable reliable production of increasingly complex systems such as computers, automobiles, airplanes, and rockets to name a few. At that time, *complexity* was an attractive term implying higher-level technologies, accessible to system analyses enabling better machines, more automation, and of course better control. Concurrently, James Clark Maxwell provided elegant equations that enabled a clear understanding of electromagnetism relevant to light and magnetism.

By the dawn of the twentieth century, this deterministic conception of the world was abruptly thrown into disarray due to a series of experiments in atomic physics that yielded transformative breakthroughs and the development of the field of Quantum Mechanics. The fundamental underpinnings of the laws of motion, engineering, and even the philosophical tenets of "The Age of Enlightenment" were challenged by the new physical laws. These included inherent uncertainties, the new role of the "unattached observer" as an inherent and inescapable perturbator, wave-particle duality, and a variety of other quantum features alien to our intuitive understanding of the natural world. Today, we all rely upon electronic devices such as computers, smart phones, communication networks, and other technologies that evolved from that early discovery of quantum phenomena but whose operational principles escape the average person's understanding.

The moment of the observation and manipulation of atoms at cryogenic temperatures and later of individual molecules at room temperature in the mid 1980s marks a critical point exposing the limits of reductionism (Gimzewski and Joachim 1999). Thirty years later, in 2015, IBM produced an electronic circuit using semiconductor fabrication techniques on the scale of 7 nm (approximately 20 atoms across). Feyman's famous talk "Plenty of Room at the Bottom" (1959) has inspired many, but the ultimate limit on the atomic level has been reached and not much room is left. SOC is a phenomenon that occurs on all scales, and a new method capable of observation and analysis of complex interconnected phenomena is needed.

The Case for a New Complexity

The complexity and unpredictability of our world including many natural disasters and disruptions such as forest fires, earthquakes, weather patterns like typhoons and tornadoes are apparent to most of us. Likewise, human-centric behavior including traffic jams, "memes gone viral," and other emergent dynamics (trending) in social networks, financial instabilities in banking, stock markets, global network security, and even wars are all subject to inherent unpredictable fluctuations that follow similar patterns as discussed later. This type of behavior extends to many aspects of biology and neuroscience. Complexity is regarded as one of the most important challenges of the early twentieth century as stated by Stephen Hawking in 2000:

> I think the next century will be the century of complexity.

Unlike the deterministic basis of physical sciences and engineering, complexity lacks a generally applicable descriptive language both philosophically and scientifically. As far back as 1665, Dutch scientist Christian Huygens, inventor of the pendulum clock, observed an "odd kind of sympathy" between the pendulums of two clocks placed distantly in the same room. Many centuries later we understand this as an emergent property of even a simple system. One can describe complex phenomena as revealing the delicate relationship between order and randomness in a world where fundamental physical laws are obeyed but where systems are subject to inherent unpredictability because of the dynamics of many-bodied interactions. Whereas linear systems behave in a predictable way, they are approximations even in relatively simple systems. Nonlinearity better describes most situations outside the controlled environment of laboratory experiments, and no exact solution to nonlinear systems exists mathematically. They are typically "open" systems implying a flow of material or energy through them as opposed to the "closed" environment of a chemical reaction occurring in a flask. "Dissipative structures" are physical or chemical systems that appear to develop "order out of chaos" and to be "self-organizing." In analogy with biology, matter and energy flows through the structure where primarily energy and negative entropy are "dissipated."

Ilya Prigogine was awarded a Nobel Prize in Chemistry (1977) for his description of complex systems maintained far from thermodynamic equilibrium that are time irreversible. Twenty years later, he makes an important statement that *"The more we know about our universe, the more difficult it becomes to believe in determinism"* (Prigogine 1997). He reflects a view in stark contrast to Newtonian and quantum physics that has important implications ranging from biology to cosmology. Prigogine's recognition of indeterminism in the study of unstable systems and the thermodynamic consequences of that remains one of the big questions in mathematics, physics, and chemistry as well as life sciences in general. Further, one can imagine that in the real world causation is not a unidirectional process. Feedback loops between the causes and events can result in unpredictable behaviors that are not attributable to a single source.

Self-organized criticality and emergence can usefully serve as a descriptive language for the dynamics of disorder that is commonly called "complexity." Essentially, SOC and emergence may occur in a sufficiently complex network of dynamically interacting elements. W. Ross Ashby introduced the term "self-organization" during the early days of cybernetics (Ashby 1947), and it was later discussed by Norbert Wiener in the 2nd edition of *Cybernetics: or Control and Communication in the Animal and the Machine* (Weiner 1961). Since those early days, many lineages of complexity sciences have evolved outside of cybernetics, embracing practically every discipline in biology, network science, cognitive science, the humanities, and ecology (Fig. 1). Despite the multidisciplinary importance of complexity, no generally agreed upon conceptual framework exists to date that spans science in a unified manner. Indeed, a lack of a generally accepted form of mathematics, or an adequate linguistic dialogue, suggests that a new approach is needed to complexity.

The science of complexity is by no means new, and wide-ranging efforts have been undertaken over decades to overcome the limits of reductionism in understanding the natural world. Despite an accepted recognition of the importance of complexity, progress has been sporadic and somewhat disjointed to date. Recent advances in network science and the dawn of the so-called big data era, which permeates nearly all aspects of modern life, provides a collectively unique opportunity to rethink our approach to the study and utilization of complex systems (Barabasi 2012).

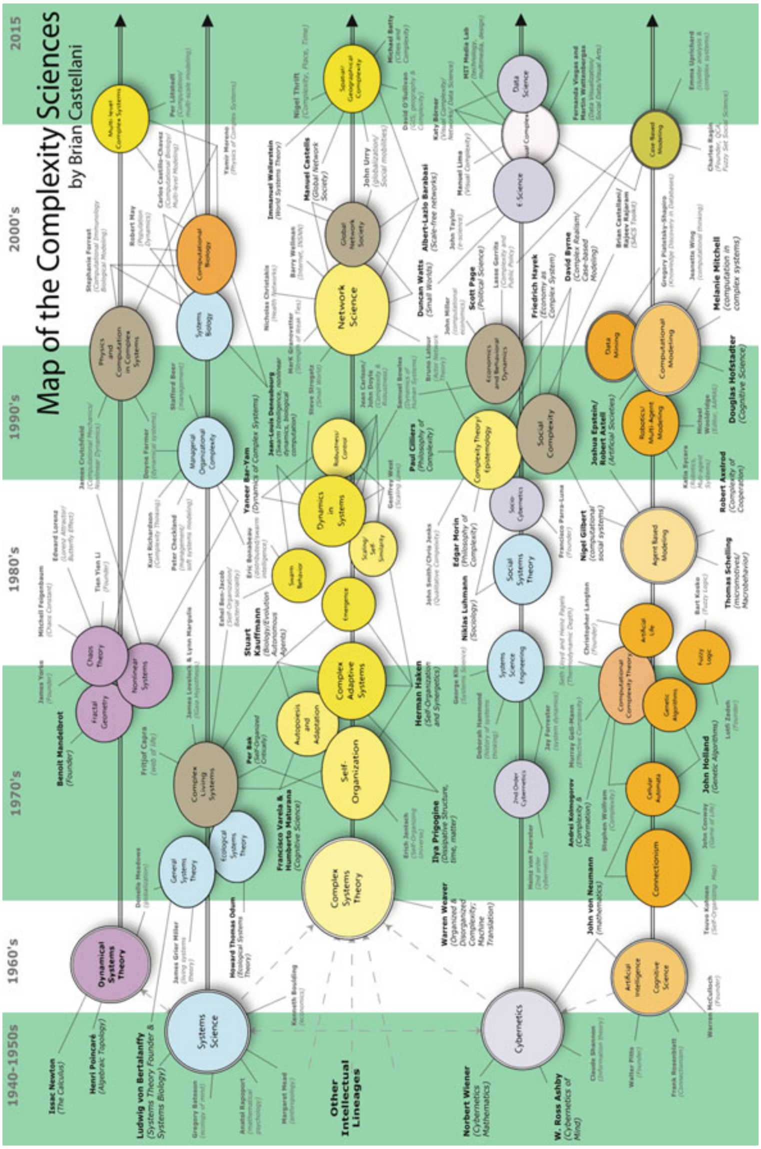

Fig. 1 A map of complexity sciences in the twentieth century paradoxically illustrating a need for convergence across disciplines (Used wither permission from Castellani, B. *Map of Complexity Science*. Cleveland, OH. Courtesy of Arts and Science Factory, LLC. In “9th Iteration (2013): Science Maps Showing Trends and Dynamics,” *Places & Spaces: Mapping Science*)

Self-Organization

The self-organization of spontaneously ordered dynamical structures could create new emergent macrolevel properties. Structure and function from microlevel interactions is a property of constrained systems involving bottom-up causality. To illustrate a simple model of self-organization, consider a magnetic material where, at sufficiently high temperatures (Fig. 2), the component atoms have randomly oriented spins, indicating their magnetization directions. The system is initially disordered due to thermal energy which allows spins to flip up and down. However, as the material is cooled some of the magnetic spins become oriented in certain regions of the sample and their local alignment causes other atoms to align spins. At a certain point the alignment will cascade through the system, giving rise to large ordered domains of magnetism. This spontaneous appearance of order arises from bottom-up causality. The small regions of higher magnetic alignment that start the ordering are called "attractors." In the words of De Wolf and Holovert *"Self-organization is a dynamical and adaptive process where systems acquire and maintain structure themselves, without external control"* (De Wolf and Holvoet 2005). While used for illustrative purposes, this example has been approximated using what is known as the "Ising model" which only accounts for nearest neighbor interactions and is applicable in two dimensions. This set of simple conditions is generally not found in natural systems where the interactions contributing to observed dynamics arise from both short- and long-range dynamically adaptive hierarchical structures in three spatial dimensions.

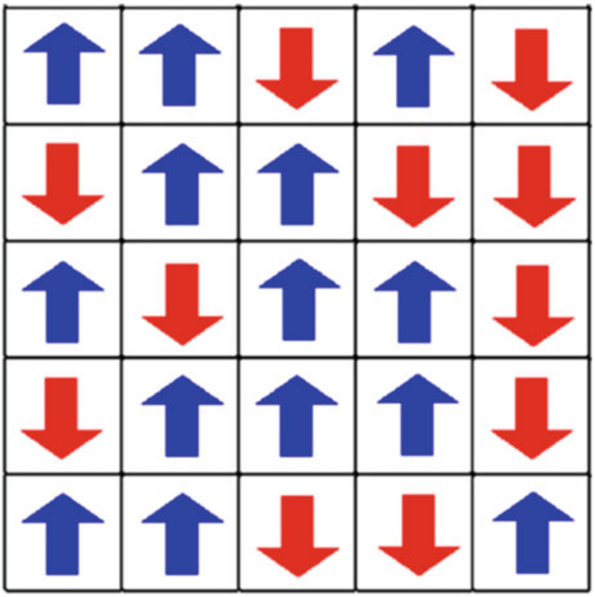

Fig. 2 A schematic plot of the Ising model for an idealized ferromagnet consisting of spins that can be in one of two states (*up* or *down*) arranged on a square lattice. In its simplest rendition, each spin interacts only with its nearest neighbors. Such simple local interaction rules can result in rich collective behavior depending on the temperature of the system (Used with permission from Salvatore Torquato, Phys Biol, 8, 015017 (2011))

It is perhaps surprising that while many aspects of the world around us are the result of self-organization, such concepts are practically ignored in modern education and remain outside the mainstream discussion in the scientific community. Indeed the awareness of self-organization is something that is peculiar to the twenty-first century and the strange dynamics unfolding in this age of high interconnectivity mediated by information technology communication (ITC) systems.

Emergence

In complex systems emergence can arise from the collective interactions among the constituent elements of a system at the microlevel that produce properties and patterns at the macrolevel. In general emergence requires no leader or organizer. While there are various conceptions and definitions of emergence, four basic elements underpin emergence in a complex system (Hazen 2005):

1. *A sufficiently large "density" of components, with increasing complexity as the concentration increases, up to a point*
2. *Sufficient interconnectivity of the components, with increasing complexity having greater and more varied types of interconnectivity, up to a point*
3. *A sufficient energy flow through the system to enable the system's components to perform the work of interacting in the self-organized way characteristic of the energized system*
4. *Flow of energy through the system in a cyclic manner, presumably facilitating the spatiotemporal patterning characteristic of organized systems*

Familiar examples of emergence are the dynamical patterns of bird flocks, the behavior of schooling fish, or the swarming of insects. Emergence is not limited to biological or living structures and can be illustrated in relatively simple situations such as a gas and its related pressure. A single molecule does not have a definable pressure, however many confined molecules in the form a gas do through their interactions. The emergent property of pressure physically constrains the motion of individual molecules by collisions with surrounding molecules. Complex emergence can also be observed in chemical reactions such as the dynamic pattern formation of carbon monoxide and oxygen coadsorbed on a smooth platinum surface shown in Fig. 3.

Computer simulations have proven useful toward understanding emergent phenomena. For example, the emergent patterns observed in bird flocking can be approximately understood and modeled in a computer by using three rules: (1) keep close together (attraction), (2) but not too close to collide (repulsion) and (3) try to move in the general direction of others in the flock. On an even simpler level, cellular automata and Conway's "game of life" are simple computer programs displaying black and white squares (cells) on a checkerboard. Both have very close analogies to the rules of the board game "Go" originating in China over 2,500

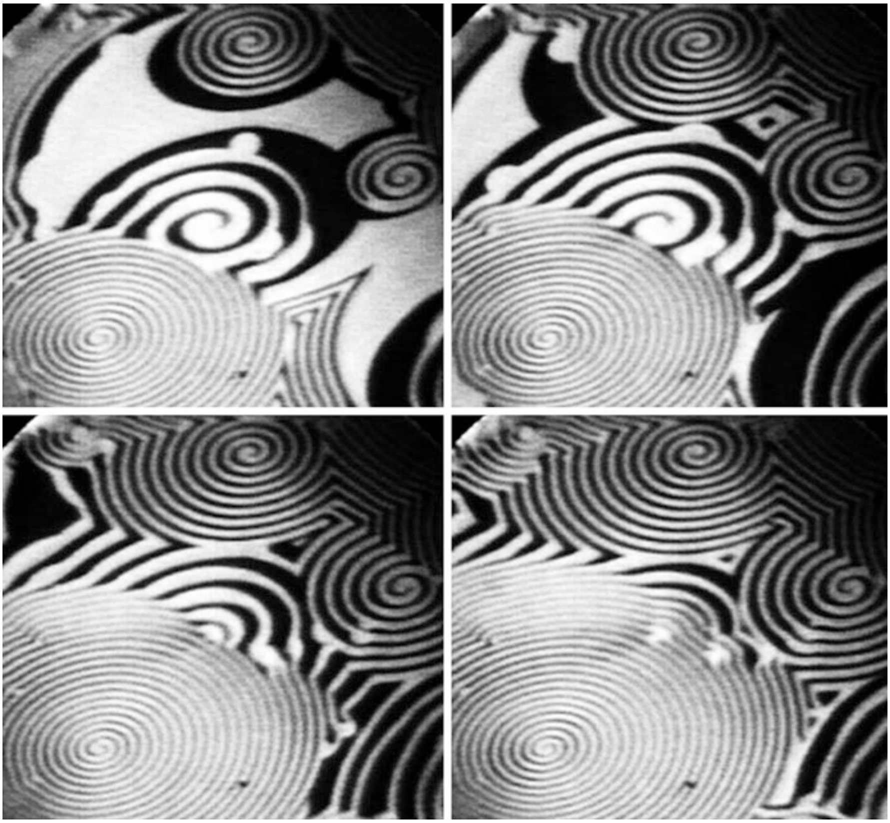

Fig. 3 Time-lapse microscopic images of carbon monoxide (*white*) and oxygen (*black*) domains on a flat platinum crystal revealing emergent pattern formation (Reproduced with permission from Nettesheim et al. (1993). Copyright [1993], AIP Publishing LLC)

years ago. Using simple sets of rules such as *Any live cell with two or three live neighbors lives on to the next generation* and starting with a seed pattern, iterations of such simple rules generate all sorts of interesting dynamics of pattern formation. Emergence in dynamical systems is ubiquitous in the natural world when system complexity reaches a sufficient level, ranging from the stars in the sky to networks of modern technologies. As such, the development new methods and approaches toward its understanding remains essential.

Self-Organized Criticality

Self-organization is a natural path for systems to reach thermodynamical equilibrium in a closed system. In an open system, with energy flow there are multiple low-energy systems that coexist at the same time. When it reaches the edge of

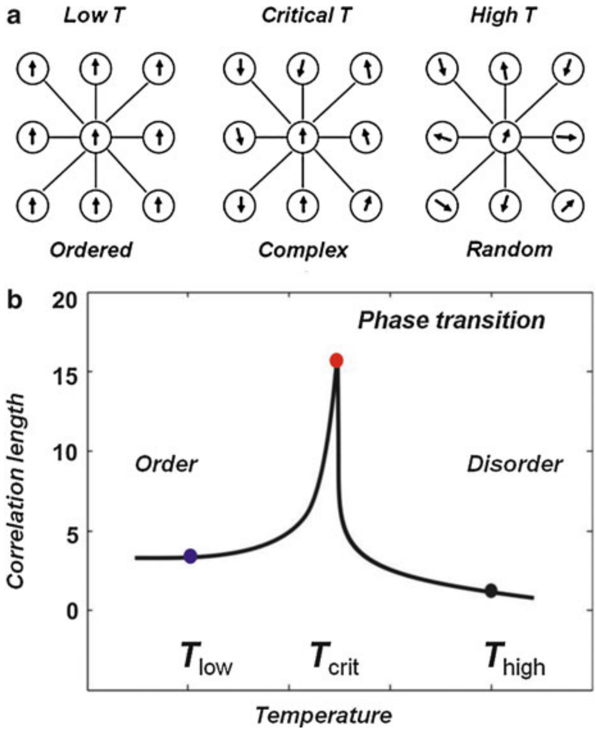

Fig. 4 **A simplified diagram of magnetic spins in the Ising model** (**a**) showing the production of a very ordered state at low temperature, a disordered state at high temperature, and a complex state at some critical temperature where nearest neighbor interactions and thermal fluctuations are balanced. (**b**) The system **correlation length** rapidly approaches a maximum value at the critical temperature (Adapted and used with permission from Beggs and Timme, Frontiers of Physiology 3(1),163, 2012)

criticality, it is crucial to the emergent properties of complex systems. They are adaptive processes that affect overall order without being obviously determined by external control. When considering large, dynamical systems, one tends to encounter self-organized, emergent properties whose behavior can be described in the context of criticality, or self-organized criticality (SOC) (Bak and Paczuski 1995; Jensen 1998). To illustrate criticality in simple terms using well-known concepts of critical points and phase transitions, let's revisit the previous example of magnetism in a little more detail as shown in Fig. 4. Starting from a scenario with nine aligned magnetic spins, the system can be considered ordered, or subcritical, at low temperatures (Low T). With increasing temperature, thermal effects cause a randomization of spins (High T). However, at some intermediate temperature (Critical T) the system exhibits a complex distribution of spins, with dynamics somewhere between order and disorder. By traversing this critical point (temperature) the system is in fact undergoing what is known as a (2nd order) phase transition. At this critical point, the system is considered to be complex due to the presence of both order and disorder. There are various consequences of reaching the critical state. In particular, at a critical point all particles form a communication network with extended lengths, and this is simply described as the "correlation length." Here, a dramatic increase in correlation means that communication between spins across the magnetic sample is maximized as indicated by the peak seen in Fig. 4b.

One can generically view criticality in terms of a tipping point analogous to the phrase "the straw that broke the camel's back" which is an indefinable moment. It can be approximately understood in terms of an avalanche where snow builds up and even a small sound can cause thousands of tons of snow to become connected and to cascade down a mountain. A band of behavior can replace the black and white concept of a system being either ordered or chaotic where it is described by self-organized criticality where it's on the edge as shown in Fig. 5.

While we are only starting to glean the workings of the human brain, there have been a number of interesting observations using various techniques that point toward SOC playing an important role in its spatiotemporal dynamics. Magnetic resonance imaging (MRI) and electroencephalography (EEG) of brains, as well as multielectrode array (MEA) studies of neuronal cultures, are prominent techniques used to examine the dynamics of neuronal activity via blood flow oxygenation or electrical activity via measurement of electrode arrays. A large body of experimental evidence accumulated from the use of such techniques indicates that the brain exhibits functional dynamics that can be most readily described in terms of SOC. Such evidence has been provided by measurements carried out over many spatiotemporal scales, ranging from the interactions between individual neurons to studies utilizing functional-MRI imaging of the brain of live subjects. While there still remains a vestige of objections to theories of SOC in neuroscience, the work of researchers showing that brain dynamics exhibit key properties of criticality are standing up well to the test of time. In the words of Dante Chialvo (2014),

> Now the field is mature enough to stand up to any fair criticism.

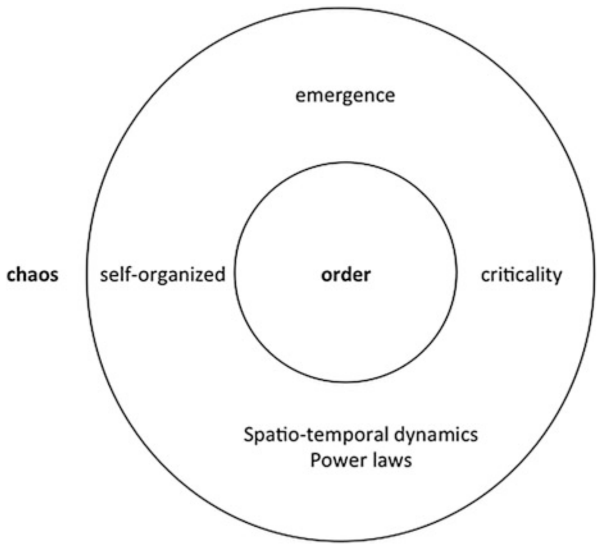

Fig. 5 Schematic illustration of self organized criticality. The separation between order and chaos forms a band where emergence of spatio-temporal dynamics, pattern formation, avalanche dynamics, long-range connections and a host of amazing behavior can appear

Computation and Society: A Case Study

By the latter part of the 20th century, governments and corporations, particularly in the US, optimistically thought the world could be stabilized and consequently become more peaceful through the use of new technologies using computers and networks and programs to make feedback control systems. For instance, feedback control of the temperature in a room uses a thermostat, which involves measuring temperature with a thermocouple and using the information to switch on or off the heating system to maintain the desired comfort level. With the advent of computers and its newfound capabilities it seemed reasonable that many aspects of society such as economics and politics, although much more complicated than the thermostat, could be stabilized and controlled in a deterministic manner by computer algorithms. This idea of stability and peace through the mediation of computers was captured by the poem "All Watched Over By Machines Of Loving Grace" written by Richard Gary Brautigan in 1967 when he was Poet-in-Residence at the California Institute of Technology:

> I like to think (and the sooner the better!) of a cybernetic meadow where mammals and computers live together in mutually programming harmony like pure water touching clear sky.
>
> I like to think (right now, please!) of a cybernetic forest filled with pines and electronics where deer stroll peacefully past computers as if they were flowers with spinning blossoms.
>
> I like to think (it has to be!) of a cybernetic ecology where we are free of our labors and joined back to nature, returned to our mammal brothers and sisters, and all watched over by machines of loving grace.

The title of the poem was subsequently used for a three-part documentary series by filmmaker Adam Curtis (2011), who proposed that those early computers not only failed to achieve this goal but also in the process created an oversimplified and distorted view of the world. The various outcomes of the computational integration also represented the opposite of the Silicon Valley born "Californian Ideology" of the day. The basic tenet inspired by the new age of computers was that computer networks would, without hierarchical control, stabilize all aspects of society. In particular, in the field of global economics, people, computers, and new financial instruments collectively produced a highly complex global network that even the most brilliant physicists and economists could not predictively model and certainly could not control. Unpredictable outcomes emerged from the system including major instabilities in global financial markets as compared to the existing models of the time. Multiple layers of feedback loops interacted with each other creating part of the problem.

An important aspect of today's technology is that computers don't use bottom-up causality. At the device level, a set of hierarchies or prescribed programs instructs transistors when and how to perform operations. The resultant processing proceeds in a well-defined manner as dictated by system architectures, maintained by error correction routines to compensate for electronic noise or defects occurring at the lower-level computational steps. In other words, computer causality is a top-down process where the program and data drive causation. The program and data as such are also nonphysical entities, and the computer can be considered as an extreme example of determinism rarely found in natural systems. This architecture, originally developed by Jon von Neumann, remains at the core of all modern computation (von Neumann 1988). Even artificial neural network programs are driven by this deterministic top-down system.

In contrast, biological systems incorporate a process of both bottom-up and top-down causation through adaptive selection where goals are selected by feedback control. Randomness plays a role in such bottom-up processes arising from naturally occurring noise, quantum-thermal jittering, and other chemomechanical effects. The result is to introduce probabilistic outcomes internal to the system. This in turn provides a variety of outcomes that are then selected by evolutionary goals in the form of survival and genetics. Here, genetics drives the top-down causation part of the loop.

A New AI: Morphic Computing

One of many predictions of increasing computational capacity in comparison to that of the human brain is the technological "singularity," a term coined by Ray Kurtzweil. In this scenario, computational equivalence with that of the human brain is proposed to give rise to a sudden and massive increase in intelligence that will be dominantly nonbiological. This concept is essentially based on a long-range extrapolation of previously observed trends in computational power that extend well beyond Moore's law, which predicts that the number of transistors per square inch on integrated circuits, or the "brain" of the computer, doubles every year. Prior to the invention of integrated circuits, mechanical calculation was leapfrogged by vacuum tubes, displaced by discrete transistors, which in turn were engineered into large-scale integrated circuits. A graphical summary of chronological developments in computation shown in Fig. 6, points toward a future "equivalence" in computational power to that of the human brain, but we do not really understand the brain sufficiently. However, the shrinkage of electronics and the continuation of massive scale integration has limits set by heat dissipation, quantum tunneling, and a variety of other factors such as ultimately the size of an atom. These impending limitations have promulgated future predictions beyond 10 years from now that includes fundamentally new approaches to computation. They range from what are called quantum computers to memristive like systems, which merge memory and processing in single elements incorporating memory capacity directly into processor elements as well as hybrid Complimentary Metal-Oxide Semiconductors (CMOS)-morphic systems. Even biological as well as systems such as slime mold and chemically inspired approaches such as molecular electronics are being explored. Many of these approaches fall under the general classification of *unconventional computation*. Nevertheless, the problem of creating a brain-like computer has to overcome the first mistake in designing such a system:

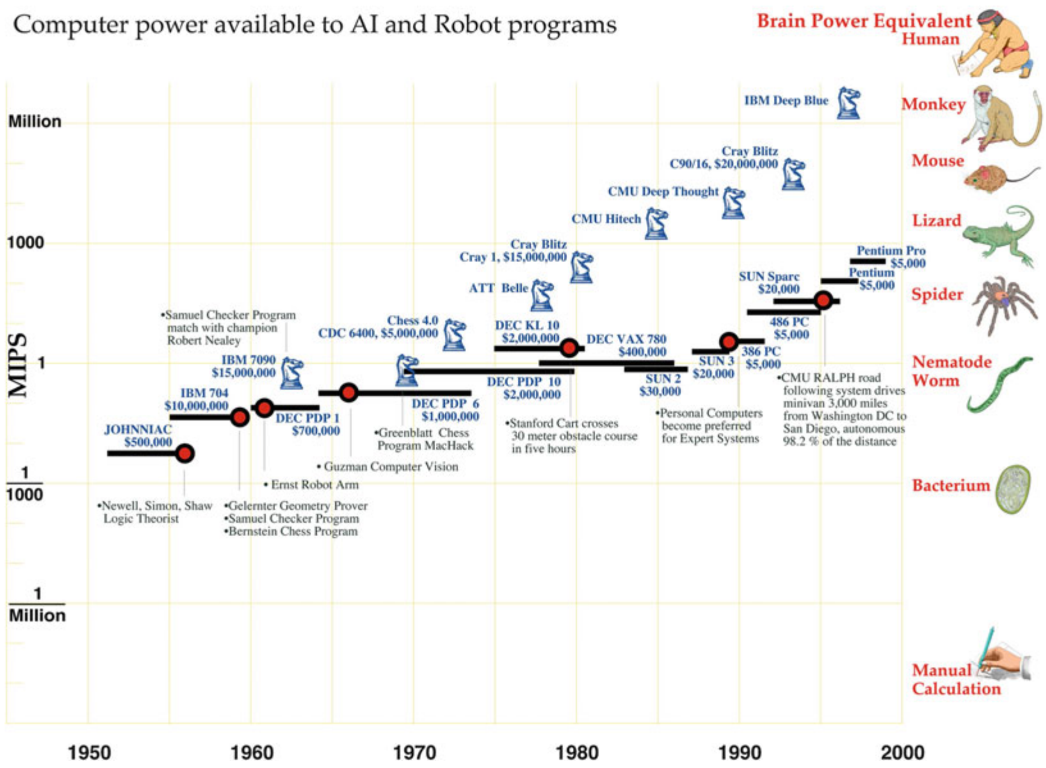

Fig. 6 A recent history of AI and robotics research reveals that while the cost of computers declined dramatically over 30 years (1960–1990) the processing power available to individual AI programs remained at a level equivalent to that of an insect. Machine cost then stabilized, followed by a period of yearly doubling in MIPS, where the exception of special-purpose chess machines reveals the outcome of leveraging purpose-built hardware (From: Moravec, Robots, Re-evolving Mind (2000))

Reductionism (Binder 2009). This is where awareness of SOC as a terminology for an open real-world environment is essential.

Currently there are a number of computer-based systems commercially available that claim some sort of AI such as cleaning robots or voice recognition such as SIRI™. However, this is termed "narrow" or "weak AI" in neural network programming, even with the addition of multiple sensors, by realistically achievable design limitations, optimized for a narrow range of tasks such as spatial navigation in floor cleaning tasks in an environment of change such as the particular arrangement of chairs and tables in a room. This is not really "strong AI," and according to Marvin Minsky, a major contributor to the foundational concepts of AI,

> The trouble with AI is that each person says they're going to make a system based on statistical inference or genetic algorithms, or whatever, and each system is good for some problems but not for most others. The reason for the title The Emotion Machine is that we have these things called emotions, and people think of them as mysterious additions to rational thinking. My view is that an emotional state is a different way of thinking.

In other words, what is known as strong AI requires a new language and mathematics as well as multiple ways to look at and analyze a problem. The "Emotion machine" represents an attractive break from the direction AI had taken, and poses an ultimate challenge for science as well as for the linguistics of AI.

For the efficient realization of AI, new forms of computational hardware provide an exciting potentiality that seeks to extend beyond recent advances in algorithmic approaches such as Deep Learning (LeCun et al. 2015) and Cognitive Computing (Modha et al. 2011). While such approaches have shown dramatic improvements in computational power and efficiency, when compared to more traditional neural network and connectionist approaches, their capacity for computation remains rooted in the underlying algorithm rather than in the properties of the system itself. The concept of neuromorphic systems, first proposed by Carver Mead in the late 1980s, comprising purpose-built electronic hardware designed to emulate neural systems, was met with very limited success due to aforementioned scaling limits of Moore's Law as well as the deterministic nature of computation as seen by the experts of that time.

The growing importance of network dynamics, both natural or technological in origin, combined with an increasing awareness of the approaching limits imposed by fundamental physical laws and economical scalability of current computers has recently promulgated a new wave of interest in unconventional, natural approaches to computation (Kari and Rozenberg 2008). Carver Mead's term "Neuromorphic" has being renamed "morphic" due to the latter's operationally different underlying principles that often involve bypassing the von Neumann bottleneck. In terms of proposed future architectures, devices utilizing simple crossbars with embedded synthetic synaptic elements are a popular approach that, despite their deterministic lineage, moves device architectonics further into the brain-like arena. Higher-level devices might include circuitry inspired by the structure of the biological neuropil of the mammalian neocortex, also known as the gray matter associated with consciousness.

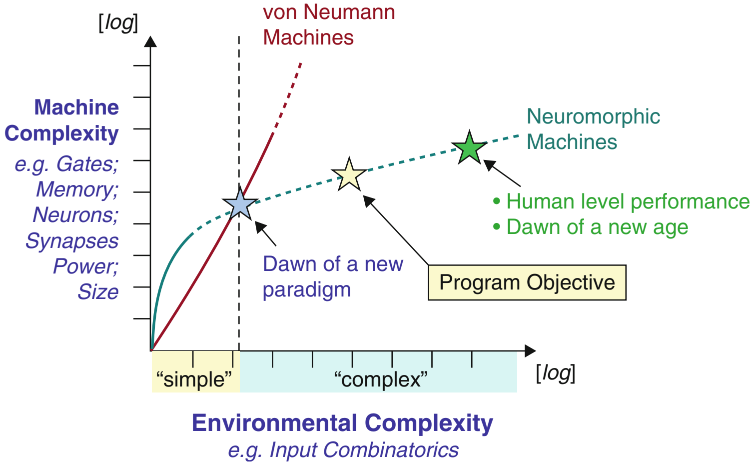

Fig. 7 Illustration of how conventional computers scale as input combinatorics increases. In contrast the scaling of a Neuromorphic or morphic approach inspired by the brain could result in a better scaling in line with the way the human brain can deal with complexity (Courtesy of DARPA)

The creation of higher-density networks relates to the role of scaling in self-organized systems to map and study complex behavior and to harness its intrinsic capabilities. Whereas scaling CMOS devices with increasing complexity is excellent for systems analysis approachable problems, it scales very poorly as data quality decreases and the environmental complexity of inputs increases. Natural and brain-like computation aims to autonomously process information in complex environments. It does this through automatic memorization via distributed synaptic strengths of network nodes using self-organization to find stable features/associations. In conventional computers as environmental/combinatorial complexity increases its ability to compute tapers off massively in contrast to brain-like systems. Recent examples of bold efforts to take these types of processes to a new level include DARPA's Synapse and Physical Intelligence programs whose generalized goals are shown in Fig. 7, which essentially illustrates the challenges of conventional computation and the possible outcomes of brain-like approaches.

One interesting approach to bridging concepts of self-organized criticality with engineered computational systems is to actually produce experimental systems that exhibit SOC (Langton 1990). The original sand pile model of Bak, Tang, and Wiesenfeld involved a simple model with rules that dictated when and how avalanches would be created in ways somewhat similar to cellular automata. Later, in the laboratory the "sand pile" was created not with actual sand grains but by using long-grained rice where grains of rice were sequentially added one by one! Additional complications of momentum made a real sand pile less useful for experimentation. To follow the dynamics, a high-speed camera was required to watch the avalanche dynamics even though the actual experiment was slowly driven grain by grain. This is actually a criterion for SOC – a slow driven system exhibiting fast dynamical reactions.

Recently, critical dynamics have been realized in an analogue device consisting of memristive elements self-organized in a complex network (Stieg et al. 2012). The device is called an Atomic Switch Network (ASN) and has been shown to produce emergent system-wide dynamics with spatiotemporal characteristics strikingly similar to those observed in many natural systems. The device functions using the nanoscale motion of ions as well as electrons in the form of junctions called atomic switches. The advantage of the nanoscale junctions lies in speed – the motion of the ions across small distances is extremely fast (nanoseconds) under the influence of an applied voltage. Synthetic device architectures such as the ASN, made from functional nonlinear elements including atomic switches and other memristive systems, provide the ability to gain a greater understanding of SOC and emergence by exploring the dynamics of complex networks while at the same time forging a new path toward the creation of morphic computing systems which function at the intersection of complexity, neuroscience, and engineering.

Outlook

SOC is used as a term in many areas of humanity today ranging from describing environments where informed decisions are often not obtainable through systems analysis such as “command and out of control” all the way up to mathematical descriptions of plasma instabilities. The challenges of a highly interconnected and complex environment in technology, biology, nature, and society requires a new science and technology to evolve. Convergence of many disciplines is necessary to handle the universally ubiquitous uncertainties resulting from connectionism and interdependence. We are ourselves in a SOC moment where we can anticipate the emergence of an environmental paradigm shift that includes new relationships of humans, animals, and machines.

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Systemic Interdependencies

Gregorio D'Agostino and Antonio Scala

Contents

Abstract

The increasing complexification of our society is creating and/or tightening interdependences among all its component systems; it is thus crucial to understand the consequences of such an evolution. We will discuss how such interdependences can lead to systemic risk, i.e., to the emergence of unforeseen behavior that could have not been predicted from the understanding of the single systems. In this chapter we will pose some examples of systemic interdependences and introduce some tools and models that allow to understand their possible consequences in sociotechnical systems; we will then revise some reference literature with particular attention to complex network approaches.

G. D'Agostino
ENEA, Centro Ricerche Casaccia, Rome, Italy

A. Scala (✉)
CNR-ISC, UoS "Sapienza", Rome, Italy
e-mail: antonio.scala@cnr.it; antonio.scala.phys@gmail.com

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Introduction

The structural organization of our modern society is experiencing a terrific enhancement of its complexity. Any single device devoted to ordinary life becomes increasingly more technological and smart. Both the materials and the technology involved are continuously improved, while a cyber layer represents a usual component of smart tools. In general, we are immersed in a world composed of System of Systems (SOS), where the functioning of a system (like the Internet) critically depends on other systems (like the electric power network). While single systems are well engineered and to some extend objects of which we understood the functioning and the risk, the interaction among such systems lays ground for new emerging phenomena. In fact, the ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct everything: this constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. At each level of complexity, entirely new properties appear, and we are nowadays convinced that the whole becomes not merely more but very different from the sum of its parts (Anderson 1972).

To be more concrete, let's consider the case of infrastructures. The huge concentration of people in the cities and the increase in the world population demands for giant provisions of basic goods, such as both edible and sanitary water, food, electric energy, gas, fuels, etc. To securely convey and distribute such a variety of services represents one of the main issues in modern society. Quality of the provided services and efficiency in their distribution requires accurate planning and optimization; but beside basic services, modern society relies on more sophisticated services including banking, finance, information, transport, and other complex systems that are normally referred to as infrastructures. In the following, we will refer to the term "infrastructure" as a set of humans, physical devices, and their organizational rules designed to provide a service or good. Among infrastructures those assuring basic services or vital goods are often referred to as "critical"; such infrastructures are highly interdependent, and the well functioning of each of them depends on the others (Rinaldi et al. 2001).

All the former characteristics result from the synergistic functioning of the allocated humans and devices. Human intervention can be "a priori" while defining and assessing "contingent plans" or "ex post" by real-time change of the operational setting of the infrastructure. There are several reasons for which static rules are not sustainable to manage infrastructures; among them the following are worth mentioning: the advent of "Smart Society"; the improvements in the materials and devices; the rise of new types of attacks (new threats); the discovery of new vulnerabilities of the system; the reduction/increase in the allocated funds or humans; the increase in the demand; and even possible climate changes.

During last decades, the owners and handlers of infrastructures have reached a very high level of performance in all those abovementioned respects. They are able to face most of the predictable and even unpredictable adversities, behaving according to predefined rules contained in the "contingency plans" and practiced during continuous exercises. However, most of the countermeasures foreseen to deal with contingencies do rely on the availability of other commodities or services. For instance, small fires can be doomed by autonomous systems, yet larger ones require the intervention of firemen rescue teams. Similarly communication infrastructures can stand short-time electric power outages by resorting to their UPS (uninterruptible power supplies) and their fuel reservoirs, yet long enough ones require either refueling or recovery of the electric systems (ES). Telecommunications can be reactivated after a main event (such as an earthquake or a flood) providing the transports (mainly highways and roads) are available to allow mobile bridges appropriate allocation and deployment "in situ."

Generally speaking an infrastructure is said to depend on another when the second is required for normal functioning of the first or to enforce contingency plans upon undesired events. When two infrastructures do depend on each other they are said to be mutually or reciprocally dependent. Reciprocal interdependence has the highest potential for conflict because it requires the most amount of communication having the output and input of activities flow both ways between units. Sequential dependence is an asymmetrical chain of one-way interactions. When different infrastructures do exhibit a series of dependences in closed chains they are said to be interdependent. Interdependence represents a resort for efficient provision of services, as it allows savings and allocation "on demand," yet it may hide systemic risks. Systemic interdependence implies systemic risk, that is, one not strictly related to a part of the system but just arising globally.

The concept of "systemic risk" arose to the chronicles after 2008 crises in finance. No company was exhibiting any apparent problem; nevertheless a liquidity lack triggered the largest financial crisis after 1930. Generally speaking, "systemic risk" may be defined as a global risk not related to a vulnerability of a specific part of the system but to its global behavior. The system may collapse as a whole entity while none of its components appears vulnerable. The reason is basically related to interdependence: banks as well as stocks depend on each other, and a fall in the prices of one results in that for another; this possibly leads to a domino effect. In general, the complexity of a system lays the ground for the possibility of systemic risk, i.e., for systemwide failures that cannot be predicted from the analysis of the single components but emerge from the interdependence of constituting systems. Thus systemic interdependence is a central issue in our world.

In the following, we will explicit some models for systemic interdependences that highlight the emerging properties of a SOS.

Models for Interdependence

There are several difficulties while fostering the control of the effect of interdependences among systems: among them, probably the most difficult to model are the human (individual) and the social component. In the following we will analyze some models that can guide our intuition of the consequences of interdependences according to the topology of the interactions among the systems and on the nature of the dynamics occurring in/among the systems.

There are several organizational models to integrate different units into a coordinated system of systems. Pooled interdependence is the lowest form of interdependence resulting in the least amount of conflict. Departments (or single infrastructure in our case) do not directly depend or interact with one another; however, they do draw resources from a shared source. This model is rarely representative of real systems where pairwise provision-demand agreements dominate. More complex organizations normally imply pair (and in some rare case multiple) interactions. In principle there could be a thinking entity responsible to plan these interactions (and in the future there will possibly be); however, generally speaking the different owners of the infrastructure will establish agreements to receive and/or provide services or commodities. In other words the systems are self-assembled according to individual goals. It is worth noting that even if the pooled interdependence is a very simple one it may explain several phenomena, such as a volatility crisis in a network of loans. Normally several banks and financial institutions have both credits and debits. They provide credits when the beneficiary owns goods (real estates, etc.) or other valuable assets. When looking at the system locally (i.e., from any single unit perspective), no problem is seen. However, it may happen that one (even a small one) of the entities needs some liquidity and hence claims its credits; this may induce a cascading effect on the whole system (Huang et al. 2013). The effect is also predicted assuming that all entities take their money from a common source that experiences a deficiency. This represents a kind of mean field approximation to the real situation where credits are claimed on a specific network. The same applies to the electric system. When extra power is injected it may produce a chain of faults; however, even homogeneous distribution of the extra power that corresponds to both the mean field approach and to simplified pooling dependence may induce cascading effects (Pahwa et al. 2014). These are typical systemic risk problems: the system appears in perfect shape locally, and yet it experiences collapse.

Generally speaking when modeling a system of systems one has to perform basically the following steps:

1. Turn all the information of the systems (that are often given in natural language) into a handleable representation: this may range from a simple Universal Model Language agent representation to more complex systems where relations are represented by several analytical and/or stochastic equations.
2. Select the appropriate level of abstraction (including granularity) of possible representations, depending on the goal of your analysis.
3. Analyze the system to outline the interdependences of the different component systems.
4. Provide a means to outline the emergent behaviors of the system that do not depend on specific dependencies but on the whole set of them.

Models can be classified according to general types. Among several of them we will discuss the most diffused models with a focus on those employed to study systems of infrastructures.

Design Structure Matrix

The topology of mutual dependences among systems contains already a lot information on the system as a whole. Such a topology can be naturally represented as a graph or network (Fig. 1). A graph is a triple $G = (V, E, f, w)$ where V is the set of nodes or vertices (in our case representing the systems), $E \subseteq V \times V$ is the set of oriented arcs or edges, f is a function that assigns to each node $v \in V$ its weight, and w is a function that assigns to each edge $e \in E$ its weight. An oriented edge from node v to u indicates that system v depends on system u. A very neat application of this representation is represented by the "Design Structure Matrix" (Eppinger 2001), a very useful tool for managing and coordinating projects. A DSM lists all the information exchange, interactions, and dependence patterns among the constituent elements of a project (subsystems/activities). DSMs can be broadly distinguished in two main categories: static and time-based (Browning 2001). Static DSMs represent systems of systems where all of the elements exist simultaneously and are equivalent to an adjacency matrix or a graph. The main analysis tool for static DSMs is usually clustering algorithms (Estivill-Castro 2002) that help separate the systems of the SOS in groups that are mostly related. On the other hand, time-based DSMs are akin to directed graphs, and the ordering of the rows and columns indicates a flow through time: earlier activities in a process appear in the upper-left of the DSM and later activities in the lower-right. Since activities in the past cannot depend on activity in the future, time-based DSMs are acyclic and can be thus analyzed using sequencing algorithms reordering the matrix elements to minimize the amount of feedback (off diagonal elements) making them as close as possible to the diagonal (Eppinger and Browning 2012). No single clustering and/or reordering algorithm is known to cope with general case of a SOS, that is, directed, signed graphs that can contain cyclic dependences that can be also of negative signs (negative feedback).

Extended Input-Output Models

During the 1950s Nobel laureate Leontief introduced a simple linear model for interaction of the different sectors in economy (Leontief 1987).

Moving from similar reasoning, a simple approach based on inoperability has been developed to describe interdependent systems. This may represent one of the simplest models accounting for the interdependences. In the Inoperability I/O Model (IIM) each infrastructure is modeled by a node i in a network with a given "inoperability" $Q_i \in [0, 1]$ measuring to what extent the node i is performing the function it is devised for; alternatively, it may also be interpreted as the probability for a node to be fully inoperable. The system of systems is described by means of a linear equation (Crowther and Haimes 2005):

$$Q_i = \sum_{j=1,N} M_{ij} Q_J + \gamma_{iA} \cdot D_A. \tag{1}$$

This is a static approach that allows to calculate all inoperabilities while an external disturbance d_i is applied and the matrix of interdependences M (usually the same as standard I/O tables) is known. The disturbance may result from both an undesired natural or anthropic event (such as a flood, an earthquake, or a synchronized intense demand) or an intentional attack. It is worth stressing that the system is only apparently linear due to the constraint $0 \leq Q_i \leq 1$ that affects the possible equilibria each time an infrastructure becomes totally inoperable.

One can extend the former approach to provide the system with a temporal dynamics:

$$Q_i(t + \Delta t) = \sum_{j=1,N} M_{ij} Q_J(t) + \gamma_{iA}(t) \cdot D_A(t) \tag{2}$$

which, in turn, becomes a stochastic differential equation when Δt goes to zero:

$$dQ_i = \sum_{j=1,N} h_{ij} Q_J(t) dt + \gamma_i(t) \cdot dD_A(t) \tag{3}$$

where the power of disturbance $dD_A(t)$ appears and matrix h is introduced:

$$h_{ij} = \lim_{\Delta t \to 0} \left(M_{ij} - I \right) / \Delta t \tag{4}$$

Equations 1, 2, and 3 give an idea on how the same basic idea can be implemented to different purposes. When the external disturbance and the reactivities of the components are constant and the inoperabilities lie within the [0, 1] range, one can provide an explicit solution of the previous equations that exhibits all the features of a system upon an attack or an undesired contingency:

$$Q(t) = \left(I - e^{-Ht} \right) H^{-1} \gamma(0) \cdot d(0) + e^{-Ht} Q(0) \tag{5}$$

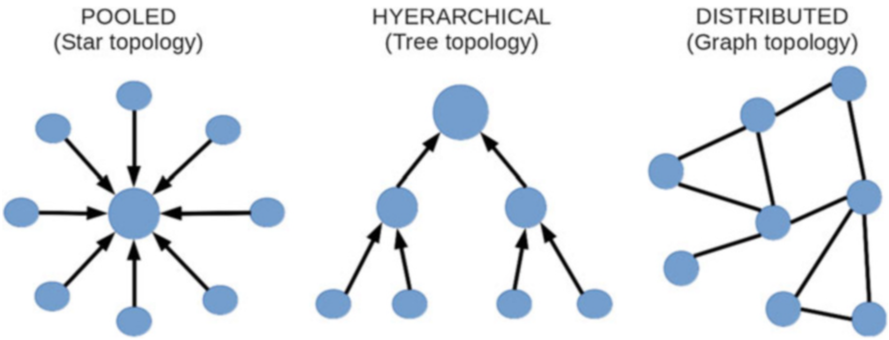

Fig. 1 Topologies for systemic interdependences. Notice that the natural way to represent such topologies is in the form of graphs or networks, where nodes represent the systems, arcs represent mutual relations, and oriented arcs (*arrows*) represent dependences

The system with initial inoperabilities $Q_i(0)$ tends to an equilibrium $Q_{eq} - H^{-1}\gamma(0) \cdot d(0)$ which depends (linearly in this case) on the impact of the external disturbance d (disturbance per unit time) on the inoperabilities of the different components.

Figure 2 shows how starting from a disturbance localized on one infrastructure it may spread to the others.

It is important to stress that the systemic behavior reflects precisely in the fact that the response of the system does not depend on local quantities (such as the γ_{iR}) but on its global characteristics. The inverse of the matrix H does in fact depend on all its components. Also the transients are dominated by global properties as the typical relaxation time is related to the slowest eigenvalue of the matrix H. Finally, when the maximum eigenvalue $\lambda_{\max}$ of the matrix H is positive one of the components always reaches the total inoperability: again, such a failure is related to a global property of the system, since the eigenvector associated to the maximum eigenvalue $\lambda_{\max}$ is typically unlocalized. Thus, all the typical emergent phenomena observed in real systems are mimicked by the very simple Extended I/O model above. Far from being unrealistic, similar reasoning has been successfully applied in finance to a system of institutions (banks) related by debt/credit relationships responding to some economic crisis (Battiston et al. 2012). To understand the

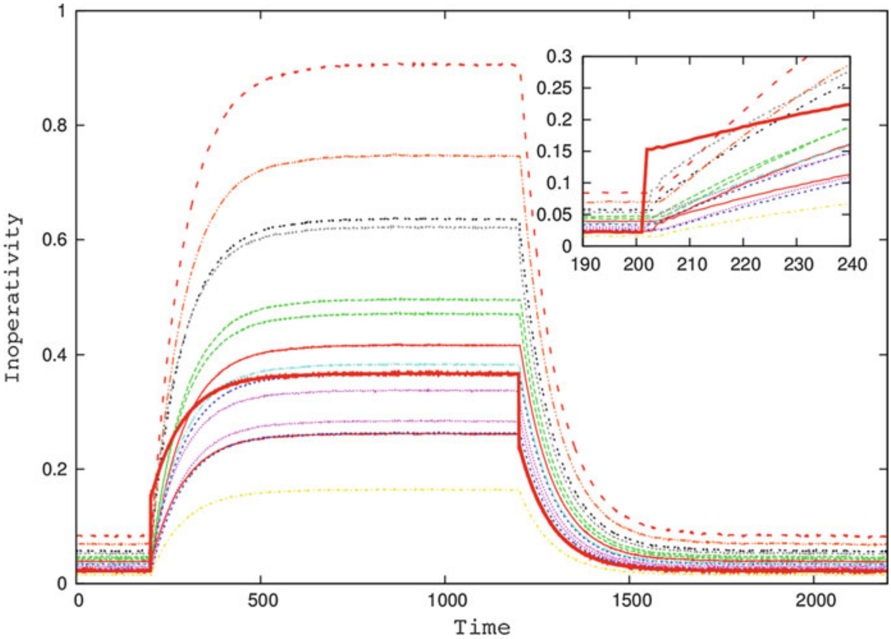

Fig. 2 The typical evolution of inoperabilities upon an undesired event impacting on the onset on one component only (*red bold line*). Inset: initial evolution of the system after the shock. As can be seen, due to systemic interdependences the fault propagates, and shortly after the failure the component suffering the maximum inoperability is not the one subject to the initial fault. The figure shows that the system has a finite recovery time after the failure is patched; again, the observed finite time is due to the presence of systemic interdependences

parallel, just regard d_i as the loss on an economic asset that impacts by an i^{th} institution and the matrix H as the financial dependence among institutions.

Fault Propagation Models

Another interesting group of models is represented by the ones inspired by epidemics. In this case each component is given a boolean value representing its operability. Null operability is transmitted to those components that are directly connected. The typical example is given by local "fault propagation"; again each component can be in an operable or nonoperable state; there exists a probability rate of restoring normal behavior and a probability rate that a fault induces another one on a component that depends on it. We can name this model *VIV* (Vulnerable, Inoperable, Vulnerable). From the mathematical point of view it would just correspond to the classical *SIS* (Susceptible, Infected, Susceptible) model of epidemiology. If one further assumes that after the first fault the lesson is learned and a component cannot undergo the same type of fault, there exists a third state to be accounted corresponding to invulnerable nodes. Hereby, this simple model will be referred to as *VIP* (Vulnerable, Inoperable, Patched): it corresponds to the classical *SIR* (Susceptible, Infected, Recovered) model in epidemics. Since several different independent faults may take place, one should deal with competitive multiple epidemics spreads.

The *VIV* model is a stochastic one (Fig. 3). If one introduces the probability $u_i(t)$ for component i to be infected at time t, the *VIV* model reads

$$\begin{cases} \dfrac{dv_i}{dt} & = & -\beta\sum_j A_{ij}w_{ji} + \alpha u_i \\ \dfrac{du_i}{dt} & = & \beta\sum_j A_{ij}w_{ji} - \alpha u_i \end{cases} \tag{6}$$

where $v_i = 1 - u_i$ is the probability of not being infected, A_{ij} is the adjacency matrix ($A_{ij} = 1$ if i depends on j, otherwise $A_{ij} = 0$), and w_{ij} represents the conditional probability of component j to be infected given that component i is not. The healing rate α is often referred to a Mean Time to Repair (MTTR), which is a very common index of resilience capability of the infrastructure, while the infection rate β is often referred as MTTF (Mean Time to Fault), which is also a common metric for infrastructural vulnerability. According to the value of $\tau = \beta/\alpha$, the initial fault may spread all over the network or extinguish. The critical value at which this phenomenon takes place is the epidemic threshold of the system and depends on the topology of the network only. It has been demonstrated that the inverse of the maximum eigenvalue of the adjacency matrix is lower bound for the epidemics threshold (Wang et al. 2003; Li et al. 2013). The threshold can also be estimated by neglecting correlations and substituting conditional probabilities w_{ij} with u_i that corresponds to the so-called quenched mean field (Pastor-Satorras and Vespignani 2001).

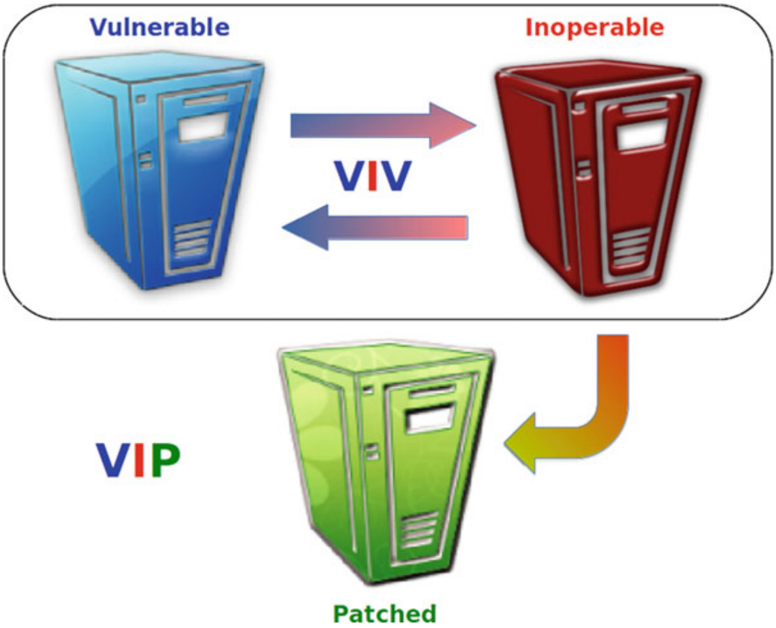

Fig. 3 *VIP* model: each platform in a network can be in one of three states: Vulnerable (Susceptible), Inoperable (Infected), and Patched (Recovered)

When patching is also allowed, the probability R_i of being in the patched status is introduced, thus leading to slightly different equations:

$$\begin{cases} \dfrac{dv_i}{dt} = -\beta \sum_j A_{ij} w_{ji} \\ \dfrac{du_i}{dt} = \beta \sum_j A_{ij} w_{ji} - \alpha u_i \\ \dfrac{dR_i}{dt} = \alpha u_i \end{cases}$$

The estimates for the critical thresholds hold also for this case. Hence, similarly to what we outlined for the extended I/O models, the global properties of the system (such as the maximum eigenvalue of the adjacency matrix of the Laplacian or some simple combinations of the degree distribution's moments) are the only features to decide whether the epidemics will spread or not.

The former approach can be extended also to the case where the single system is modeled not as a single note but as a network itself; as an example, a SOS composed of five systems of size N_i, $i = 1 \ldots 5$ can be modeled using an enlarged adjacency matrix $\tilde{A}$:

$$\tilde{A} = \begin{bmatrix} A^1 & B^{12} & \cdots & \cdots & \cdots \\ B^{21} & A^2 & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & B^{45} \\ \cdots & \cdots & \cdots & B^{54} & A^5 \end{bmatrix}$$

where A^i is a $N_i \times N_i$ matrix describing the dependences among the components of the i^{th} system while B^{ij} is a $N_i \times N_j$ matrix describing the dependences among the components of the i^{th} and the j^{th} system.

Diffusive and Harmonic Models

Diffusion is the most fundamental dynamic mechanism allowing the propagation on a system (D'Agostino et al. 2012). It describes the propagation of any scalar quantity on the system through random exploration; by defining the adjacency matrix A such that

$$A_{ij} = \begin{cases} 1 & \text{if } i, j \text{ are neighbours} \\ 0 & \text{otherwise} \end{cases}$$

we can describe the change in the probability p_i on being on the i^{th} system at time t as $\partial_t p_i = -\gamma p_i + \gamma \sum_j A_{ij} p_j$ where γ is the probability of moving away from a system. Thus, the evolution of the probability distribution can be written as

$$\partial_t \mathbf{p} = -\gamma \mathcal{L} \mathbf{p} \tag{7}$$

where $\mathbf{p}$ is the probability vector $((\mathbf{p})_i = p_i)$, $\mathcal{L} = D - A$ is the Laplacian matrix, and D is the diagonal matrix with elements $D_{ii} = \sum_j A_{ij}$. Again, the system dynamics is dominated by collective effects: in fact, for a wide set of topologies, there is a typical longtime timescale $\tau = (\gamma \lambda_1)^{-1}$ where λ_1 is the first nonzero eigenvalue; at such timescales, the system dynamics is described by the decay of the associated unlocalized eigenvector and involves all systems.

Notice that we have an analogous situation in the case of another wide class of dynamics, i.e., oscillations around equilibrium positions (harmonic dynamics). Suppose in fact that the state of our system is described by a parameter x_i describing the small deviation of the i^{th} system from equilibrium; for $\|\mathbf{x}\|$ small enough the restoring force on i due to j will be $\sim -k(x_i - x_j)$, i.e., the system is described by the equations

$$\partial_t^2 \mathbf{x} = -k \mathcal{L} \mathbf{x} \tag{8}$$

that have the same spectrum of Eq. 7. Hence, the longtime behavior is dominated by a collective mode corresponding to the unlocalized eigenvector associated to the smallest nonzero eigenvalue λ_1. Analogous considerations can be done in the more generic case of damped oscillations

$$\partial_t^2 \mathbf{x} + \eta \partial_t \mathbf{x} = -k\mathcal{L}\mathbf{x}.$$

Notice that, like in the previous section, considering the explicit structure of the systems corresponds just to considering an enlarged system with more components. However, it is possible to show that a peculiar behavior happens when one starts from decoupled systems and switches on slowly the interdependences among the systems. In fact, let's consider the case of two systems I and II with the same number of components, and let's consider that each component i in a system interacts with the homologous component in the other system with an interaction strength σ. Thus, the composite system is described by the Laplacian

$$\widetilde{\mathcal{L}} = \begin{bmatrix} \mathcal{L}^I + \sigma\mathbb{I} & -\sigma\mathbb{I} \\ -\sigma\mathbb{I} & \mathcal{L}^{II} + \sigma\mathbb{I} \end{bmatrix}$$

where $\mathbb{I}$ is the identity matrix. It can be proven (both for this case and for more general ones) that for small values of σ the system behaves as two separate systems, while for big values of σ the system behaves as a whole (Martin-Hernandez et al. 2014). In fact, there exists a value σ_c such that for $\sigma < \sigma_c$ the eigenvector associated to $\widetilde{\lambda_1}$ can be composed from the eigenvectors associated to λ_1^I and λ_1^{II}, while for $\sigma > \sigma_c$ it is delocalized on the whole system $I + II$.

In general, the spectrum of the matrices associated to the system interdependences has often strong bounds with the dynamics of the model describing the SOS; as an example, the largest eigenvalue Λ_1 of the adjacency matrix is linked to the percolation threshold, while the ratio λ_2/λ_N of the first nonzero eigenvalue and the maximum one of the Laplacian matrix influences synchronization. Synchronization is the capability of the systems to function in unison and is often modeled with the nonlinear Kuramoto model (Kuramoto 1975). In general, it is a nonlinear dynamics where special tools like the master stability function (Pecora and Carroll 1998) must be applied. Ref. (Arenas et al. 2008) contains a wide review of synchronization on networks.

Conclusions

Since the beginning of system theory (for a still actual and enlightening introduction, look at von Bertalanffy's book (von Bertalanffy 1968)), systemic thinking has evolved into understanding that "more is different" (Anderson 1972) and systemic interdependences play a crucial role in determining new characteristics that cannot be understood from the analysis of the single systems.

Systemic interdependences have been shown to be relevant even in the human body where network physiology reveals relations between network topology and physiological function (Bashan et al. 2012). In this case one does not observe specific symptoms but a complex global syndrome. Again details on functioning of specific organs (and relative treatments) are not enough to deal with the general pathology.

The interest on systemic interdependences is witnessed by the blossoming of the related field of networks of networks: over the course of 2014, one book (D'Agostino and Scala 2014) and several reviews (Boccaletti et al. 2014; Kivelä et al. 2014) have been published, and a major EU project (MULTIPLEX - Foundational Research on MULTIlevel comPLEX networks and systems http://www.multiplexproject.eu/) involving 23 research groups and producing more and resulting in almost 200 publications has ended in 2015.

Beside the efforts in understanding the systemic behavior, the research in the field is following several different directions. Dealing with real infrastructures requires models to assess operational parameters, and the systemic behavior cannot provide such information. To such an aim, agent-based models can be introduced to simulate the behavior of the different infrastructures (or their components), and interdependence analysis provides information on how they interact. Since the systems are brought around some desired stable condition, the simulations are carried in the discrete event paradigm which consists in finding novel equilibria after undesired events. In some rare case one may employ accurate domain-specific codes to simulate the different infrastructure in detail while using the interdependences as reciprocal boundary conditions. This type of approach is named "federated modelling and simulation." The fundamentals of all the previous approaches can be found in Kröger and Zio (2011), D'Agostino and Scala (2014). However, at the present stage models catching the emergent behaviors are not able to provide applicable recipes to manage real infrastructures and systems of systems; while detailed models can mimic the accurate evolution of the systems, the accuracy itself often hides the global picture.

Our society in experiencing a remarkable change due to the advent of the smart paradigm, that is, the introduction of computer-aided networks to control any activity of our life from domotics and Internet of Things to smart grids, buildings, cities, and nations. The theory of complexity may enhance the awareness in the scientific community and hopefully in the whole society of the systemic risk that is not limited to finance or other known systems but is a general mechanism related to the increasing amount of interactions among people, systems, and devices needed to implement a smart society.

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Visionary Scenario Development of Emerging Fields

Anita Street, Nora Savage, and Angela Page

Contents

Abstract

Many prolific and arguably creative scientists (many of whom are Nobel laureates) are avid practitioners of some art form and can link this engagement with the arts back to creativity in their scientific work. So, what innovation can we expect to see in the next 500 years? It is in the space where art and science come together that revolutions are born. Arguably, the convergence of nano-, bio-, info-, and cognitive technologies (NBIC) is at the forefront of that revolution. If the goals of NBIC are to be realized, research must be interdisciplinary, visionary, and collaborative. Art can be a catalyst for creative problem solving and critical thinking just as science can inspire great art. Ultimately, scientists must use all the tools at their disposal to push the boundaries of their imaginations. Science fiction offers a means to explore possibilities and test ideas. This chapter will explore the effect science fiction literature in singularly and in combination

A. Street (✉)
United States Government, Washington, DC, USA
e-mail: acstreet5@gmail.com

N. Savage
Office of Research and Development, Environmental Protection Agency, Washington, DC, USA
e-mail: savage.nora@epa.gov

A. Page
U.S. Environmental Protection Agency, Washington, DC, USA
e-mail: page.angelad@epa.gov

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with scenarios has had on science and technology research and innovation and how it can be used to (1) drive scientific and technological discoveries; (2) foment an interdisciplinary landscape to address the global, complex challenges ahead; and (3) facilitate the dialogue between scientists and the general public to reduce barriers to acceptance of science concepts and technologies, including NBIC.

Introduction

Art and science share a long intertwined history fraught with complication, inspiration, and revelation. Science (and by extension technology) and the arts are popularly thought to represent very separate disciplines with distinct cultures and traditions. Since the Enlightenment seventeenth century, there has been increasing specialization in the arts and sciences. However we have only to look back at the lives and works of Leonardo da Vinci and Michelangelo to see how the confluence of their artistic talents and deep interest in and knowledge of mathematics, engineering, and the human anatomy came together in spectacular fashion. They were also perspicacious observers of the natural world. Da Vinci could be looked upon as the creator of the first examples of biomimicry. His bird- and bat-inspired sketches of flying machines hang in art galleries and are admired for both their artistic beauty and engineering mastery. For the next 500 years, this integrated way of thinking led to astonishing leaps forward in nearly every field of human endeavor. Many prolific and arguably creative scientists (many of whom are Nobel laureates) are avid practitioners of some art form and can link this engagement with the arts back to creativity in their scientific work. So, what innovation can we expect to see in the next 500 years? It is in the space where art and science come together that revolutions are born. Arguably, the convergence of nano-, bio-, info-, and cognitive technologies (NBIC) is at the forefront of that revolution. If the goals of NBIC are to be realized, research must be interdisciplinary, visionary, and collaborative. Art can be a catalyst for creative problem solving and critical thinking just as science can inspire great art. Ultimately, scientists must use all the tools at their disposal to push the boundaries of their imaginations. Science fiction offers a means to explore possibilities and test ideas.

Unidirectional linear thinking is not enough to address the twenty-first-century existential problems we face. A more holistic approach, incorporating both right- and left-brained thinking, will be necessary to understand how we can prevent, lessen, and eliminate current and future world problems. New and innovative ways of examining problems in a flexible and open-minded way will be necessary for future scientists and researchers. To be prepared, the academic system and the workplace will have to adapt and build an infrastructure to support and promote individuals with expertise across a variety of disciplines. Einstein was quoted as saying “great scientists are also artists.” To this point, the Rhode Island School of Design (RISD) has broadened the STEM (science, technology, engineering, and mathematics) education and research framework to include “art” as an essential and necessary component. The goal of STEAM is to incorporate art and design into the STEM framework to promote innovation across science and technology. They believe that true innovation can be achieved by combining the minds of scientists and technologists with that of artists and designers.

To that point, C.P. Snow's famous lecture of more than 50 years ago, "Two Cultures," ignited a debate about the existence of this separation between scientists and humanists. Underlying this observation was ostensibly a failure of modern educational systems that promote specialization and reinforce this divide – the creation of a false dichotomy. The idea emerged of a third culture proposed by Snow – a cadre of nonscientists who could effectively bridge the gap between scientists and humanists. It is in this space where science fiction literature can influence science and vice versa. Science fiction has long inspired scientists to probe novel areas of research and look for solutions to the world's greatest challenges – poverty, poor health, and sustainability. With respect to converging technologies, science fiction can serve as a window into consensual futures and the inner workings of the innovation process in a manner that allows for a democratic way to contextualize innovation and potentially provide early warning of potential complications in the real world. Science fiction literature and future casting tools, such as scenario development, can be effectively used to unlock and broaden the imaginative capacity of students (K-12) throughout their academic experience. Such exposures can be instrumental in shaping their interests toward future pursuits in science and technology. The face of the "next generation of scientists" may largely depend on how well we educate and expose students to new ways of looking at problems and solutions. The integration of NBIC and the arts will be integral for future innovation and creativity and help push human knowledge beyond what is currently feasible, thereby providing a motivating force to accelerate scientific and technological discoveries.

In parallel to using science fiction literature to awaken curiosity and imagination in students and scientists, we can also capitalize on science fiction's storytelling appeal to train students to be better communicators. Randy Olson, author of *Don't Be Such a Scientist*, recognizes the importance of storytelling and how it can be a powerful tool scientists can use to communicate difficult and seemingly uninteresting research and results to the public (Olson 2009), a scientist who became a filmmaker, says that storytelling is equal parts art and science. Effectively communicating with the public is a necessary step to ensure their engagement, as well as ward off anxiety and fear around emerging technologies. The convergence of NBIC and the arts will be integral to future innovation and creativity and help push human knowledge beyond what is currently feasible; thereby, providing a motivating force to accelerate scientific and technological discoveries.

As the artificial barriers and boundaries continue to dissolve between scientists and artists, science fiction literature can serve as a platform to help foster cross-fertilization among the disciplines and help them to embrace new ways of thinking about current and future societal issues. This chapter will explore the effect science fiction literature in singularly and in combination with scenarios has had on science and technology research and innovation and how it can be used to (1) drive scientific and technological discoveries; (2) foment an interdisciplinary landscape to address the global, complex challenges ahead; and (3) facilitate the dialogue between scientists and the general public to reduce barriers to acceptance of science concepts and technologies, including NBIC.

Science and Vision

Science fiction literature links science and art together as they explore, investigate, and seek to understand and communicate the natural order of the world. Science fiction is largely defined as “stories about how people and societies are affected by imaginary scientific developments in the future.” For the purposes of discussion, science fiction includes written and visual formats describing utopian or dystopian futures. This includes the subgenres such as space, time travel, alternate history, superhuman, etc. The portrayal of emerging technologies has long been the subject of popular fiction and film.

Thomas Michaud in his 2008 paper on converging technologies and science fiction argues that innovation and science fiction are linked in several ways. He describes how it has been used as a means to diffuse “positivist spirit” of science and technology to the masses citing the popularity of Jules Verne, for example. Secondly, he describes how science fiction “invents innovation.” Here he refers to Hugo Gernsback’s coining of the word “scientifiction.” These are the ideas (inventions) that inspire scientists to pursue the unknown. Science fiction is in some ways used to “mediatize” innovations. Specifically, special effects in filmmaking are a way of “advertising” technologies that may or may not exist yet (Michaud 2008, Westfahl and Slusser 2009).

The prophetic nature of science fiction both inspires people to dream about the future and scientists to innovate. For instance, Gene Roddenberry’s 1960s television series, *Star Trek*, is a common archetypal reference utilized when discussing the influences of popular science fiction on science and society. Star Trek was groundbreaking in its treatment of technological possibilities as well as a mirror reflecting sensitive social issues of that time. This classical science fiction series confronted issues such as racism, gender equality, classism, and social mores that still exist today while inspiring generations of watchers to pursue the materialization of technologies beyond our reach. Subsequent Star Trek spin-offs *Star Trek: The Next Generation*, *Star Trek: Deep Space Nine*, *Star Trek: Voyager*, and *Star Trek: Enterprise* as well as the *Star Trek* film series continued to confront social issues and leave a lasting imprint on our collective cultural landscape. Additionally, numerous articles have been written about how *Star Trek* technology (the tricorder) has inspired real-world innovations such as the development of personal digital assistants (PDAs) and research on teleportation. Also, in 2012 the XPRIZE Foundation-announced Qualcomm Tricorder XPRIZE, a competition to build a functional medical tricorder device, was launched at the Consumer Electronics Show. The winner will be selected in 2016 from 10 finalists chosen in 2014.

Other such examples of this mutual relationship and science fiction's ability to inspire and advance science can be seen in the oft-cited example of the invention of the communication satellite which is credited to Arthur C. Clarke, who said that this invention was inspired by stories published in "Astounding Science Fiction." Additionally, in September 2014, University of Rochester scientists created a "cloaking device" inspired by the invisibility cloak worn by Harry Potter in the famed novels. Additionally, there are countless examples over the decades of inspiring tales of space exploration, robotics, and alternative worlds. This is perhaps what distinguishes science fiction from other literary forms. It has the capacity to provide a creative space where innovation can thrive – a space to examine other realities and imagine new worlds. Imagination helps us to not only envision things outside the realm of our experience but also be shaped by our real-world experiences.

Stereotypically speaking, the imagination is frequently associated with the pursuits and goals of artists and writers, while the goals of the scientist are associated with facts and the discovery of truth. As with most stereotypes this view is oversimplified and inherently misguided and incomplete. Imagination is the fodder for creativity and can also contribute to the growth of knowledge. Dr. Timothy Williamson a professor of logic at Oxford University writes that the "obvious role of imagination is the context of discovery. Truth be told, unimaginative scientists don't produce radically new ideas." (Williamson 2010) Herein lies a powerful argument for fostering collaborative relations between writers and scientists.

Many prominent scientists speak and write unreservedly about the influence science fiction has had on their personal and professional lives. From Carl Sagan, Michio Kaku, Stephen Hawking, and Neil deGrasse Tyson to Edwin Hubble all have made no secret of the profound effect science fiction had on their decisions to pursue careers in their chosen fields. Carl Sagan, an astrophysicist, cowrote and narrated the 1980s science fiction television series, Cosmos: A Personal Voyage. Fast forward to 2014, Neil deGrasse Tyson, also an astrophysicist and inspired by Sagan, resurrected and updated the 1980s series and called it Cosmos: A Spacetime Odyssey. Both scientists used the power of science fiction to provide viewers with an outer space experience while explaining complicated and technical concepts in astronomy and physics. In fact, many people who work in science and technology often credit the stories of science fiction writers such as Ray Bradbury, Robert Heinlein, Isaac Asimov, and Arthur C. Clarke as the creative force behind career choices or lines of research to pursue. Beyond the obvious entertainment value, there are opportunities for scientists to use science fiction as a medium to express and communicate concepts in science and technology and help push human knowledge beyond what is currently feasible. Equally, opportunities exist for science fiction writers to explore what is possible in more plausible and realistic ways. This interconnectedness and notion of mutual influence are borne out through the work by Bassett et al. who developed a model that describes the mutual influence between science and science fiction (Bassett et al. 2013).

Not surprisingly, the body of literature linking science fiction and innovation continues to grow. Results of a 2001 National Science Foundation (NSF) survey indicate that an interest in science fiction can influence how people think or relate to science. This interest can be a motivating factor in making career choices as previously stated and appears to correlate with positive attitudes about science and technology endeavors (i.e., the space program).

Similarly, in 2010 SIGMA – a group of science fiction writers that came together to advise government officials – conducted a survey to determine the extent to which science fiction influenced the respondents personally and professionally. The results of this survey and other studies indicate that science fiction can be an excellent communication tool for the general public to familiarize laypersons with scientific ideas and concepts through its ability to affect the way people think about or relate to science.

Federal agencies such as the Department of Homeland Security (DHS) and the National Aeronautics and Space Administration (NASA) have developed collaborative relationships with science fiction writers in hopes of leveraging the creative process and reframing issues. DHS has enlisted the expertise of SIGMA (mentioned previously) to develop scenarios to help the government combat terrorism. In a 2011 press release, NASA announced a partnership between its scientists and engineers and Tor-Forge (a noted science fiction publisher) writers to create a series of more fact-based novels to raise awareness and enhance the public's general interest in STEM. As a result, NASA hopes to boost recruitment and retention of students focused on STEM studies to strengthen the capabilities of the agency and the nation's future workforce. The first of the NASA Tor-Forge collaboration is entitled *Pillar to the Sky* and was published in December 2013. *Pillar to the Sky* tells the story of four individuals' quest to build a tower to space which would harvest solar power and supply humanity with cheap energy forever. In a similar fashion, the Intel Corporation initiated *The Tomorrow Project* in an effort to explore possible futures through a combination of science and fact-based science fiction coupled with video conversations from scientists and science fiction authors, world renowned experts, advocates, and everyday people.

In the late 1990s to the mid-2000s, the Environmental Protection Agency (EPA) and the Woodrow Wilson International Center for Scholars' then Foresight and Governance Project and the Institute for Alternative Futures engaged in a full-scale scenario planning effort to promote strategic thinking within EPA. These efforts were interdisciplinary and frequently involved collaborations with scientists, sci-fi writers, game developers, members of the creative arts, and other stakeholders. Though short-lived, this effort resulted in groundbreaking work in the areas of nanotechnology and computational toxicology and was often informed by public engagement activities (Olson and Street 2002).

In light of these revelations, writers and scientists are collaborating in more deliberate ways and discussing how to address the world's biggest challenges to build a better future. For example, at Arizona State University, the Center for Science and the Imagination is collaborating with Intel and the Society for Science and the Public to combine the humanities, arts, and the sciences to promote broad public engagement. The center brings together scientists and engineers, writers, and artists, as well as others, to cultivate imaginative thinking across disciplines. Such collaborations to write science fiction stories will enable scientists and researchers to better engage the public and communicate complex and difficult to understand topics. In addition there is the Creative Science Foundation (CSf), a voluntary charitable organization that has as its goals to design, support, explore, and promote the application of methods that encourage creative thought processes as part of science and engineering innovation. This is done through various activities such as promoting and sponsoring workshops, seminars, conferences, journals, publications, and projects. CSf has sponsored an annual international event since 2010 to stimulate science fiction based on science fact, exploration of the real-world implications, and uses of future technologies.

There is broad recognition about the importance of public engagement when it comes to the adoption of technology. In 2014, the Pew Research Center conducted a survey in the Smithsonian magazine which asked Americans about near-term advances like robotics and bioengineering to more "futuristic" possibilities like teleportation or space colonization. Respondents were also asked to share their feelings and attitudes toward emergent technological developments that might become commonplace in the near future. From the results below, Americans have relatively high level of expectations about certain scientific breakthroughs in the next 50 years but have concerns over near-term developments that they perceive as controversial and negative (Pew Research Center 2014) (Figs. 1 and 2). Having this data is useful; however, it would be even more valuable to understand how these opinions were formed and if they were influenced by science fact or fiction.

In addition, science fiction is an effective means for moving people to contemplate the future they desire. Science fiction and science fiction-based scenarios can and do offer a compelling means to work through tough questions and to enable consideration of a wide range of alternative futures with critical discernment. This includes the societal implications of technology that could have life-altering consequences or even change the course of human development. Genetically modified organisms (GMOs) are often cited as an example of the result of a controversial technology that a considerable segment of the public opposed. The perceived risks and lack of confidence in institutions remain a barrier to acceptance. Early engagement with the public known as "upstream engagement" is a practice that has had proven success when it comes to identifying public attitudes and a concern about controversial technologies like Genetically modified organisms. The most vociferous reaction was seen in the European Union; however, once these upstream approaches were employed and products were properly labeled, some of the public's fears and reservations were dispelled. Although labeling addressed the issue of full disclosure, GMOs are still a source of controversy in places where these foods are more available. Scientists can leverage science fiction and scenarios as tools to help to dispel fears about the unknown. It has the potential to open a dialogue and engage the public alongside scientists, engineers, and the creative

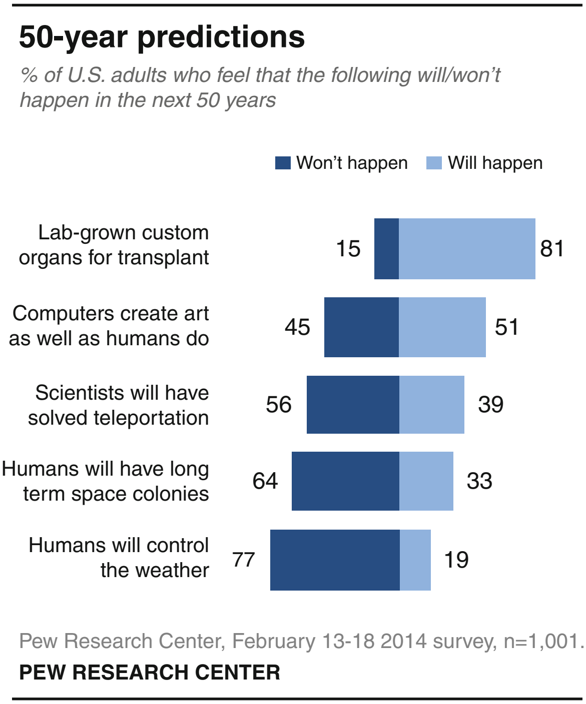

Fig. 1 50-year predictions ("U.S. Views of Technology and the Future," Pew Research Center. Washington, DC (April 2014) http://www.pewinternet.org/2014/04/17/us-views-of-technology-and-the-future/pi_2014-04-16_techfuture_near_term_changes/)

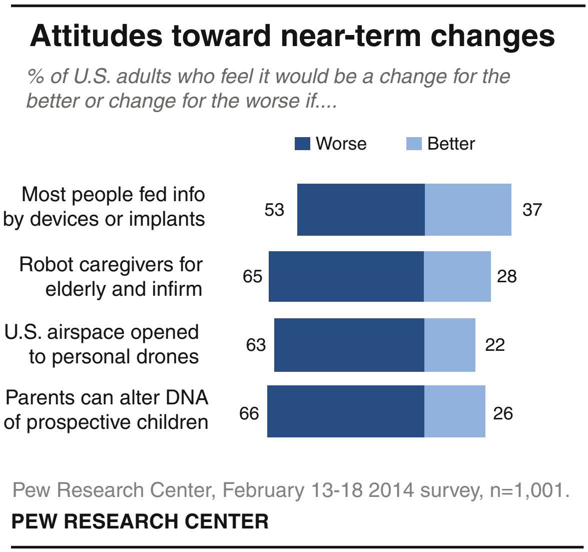

Fig. 2 Attitudes toward near-team changes ("U.S. Views of Technology and the Future," Pew Research Center. Washington, DC (April 2014) http://www.pewinternet.org/2014/04/17/us-views-of-technology-and-the-future/pi_2014-04-16_techfuture_near_term_changes/)

community in ways not typically explored. This is not to say that models do not exist to invite such collaborations in science and technology decision-making, but historically consideration of the moral, ethical, and/or social implications of emerging technologies is not always given their due. Communicating scientific concepts in accessible and relatable ways can go a long way to engender public trust, acceptance, and understanding which will be necessary if NBIC research is to forge ahead. This is of particular importance given how technology is changing so rapidly. The notion of public acceptance is not a trivial matter. Studies in the United States and parts of the developed world show that generally science is viewed as public good. In spite of this opinion, science literacy among laypersons is low and highly contextual. Perceptions by the public can be heavily influenced by folk mythology and conspiracy theories. Pragmatism on the part of the public can often be at odds with the goals of research and scientific inquiry which the public may perceive as lofty or perhaps irrelevant to societal good.

In terms of technological change, scientist and inventor Ray Kurzweil predicts that in the coming years the acceleration of disruptive technological change and innovation will occur at an unprecedented scale and speed. He further hypothesizes that technological change is exponential, contrary to the "intuitive linear" view. At today's rate, the expectation is that the world can expect to experience the equivalent of 20,000 years of progress in this century alone (Kurzweil 2001). Should this prediction bear out, researchers need to better understand the implications converging disciplines in order to harness the benefits and mitigate the risks of NBIC. To accomplish this in a meaningful way, an argument can be made for the heightened pursuit of approaches that spark the scientific imagination, foster creativity, and provoke visionary thought. There are many approaches that exist in addition to scenario development, such as futures analysis, science fiction prototyping, and simulation, all of which can be and have been influenced and informed by science fiction.

Futurism – scenario-based foresight, for example – shares similarities with science fiction literature. Both apply the narrative form to explore future worlds by extrapolating from the present. Where they may diverge is in motivation. Futurism is more often than not concerned with directing attention to present-day challenges by highlighting evolutionary pathways (Cascio 2014).

Science fiction prototyping (SFP) also uses the rich tradition of storytelling as a means to examine the implications emerging technologies might have on future societies. SFP was originally designed as a tool for engineers to enable broader contextual thinking when it comes to design, but its application has been expanded and popularized by the likes of Intel Corporation's resident futurist Brian David Johnson to tackle deeper issues related to technology deployment. Intel's The Tomorrow Project sponsors writing competitions focused on science-based fiction as a means to explore alternative futures. As a result several anthologies have been published with the hopes of developing a common language to discuss the future as we want it to be and to avoid possible harmful outcomes.

Simulation and gaming are also effective tools to test assumptions when applied to complex systems. Given the heavily contextual nature of technology development, so-called serious games provide a safe and stimulating environment to investigate how people will react to new technologies or can help examine intended or uncover previously undiscovered unintended consequences associated with deployment. Projects such as the Serious Games Initiative created by Ben Sawyer and David Rejeski in 2002 describe serious games as “applications of interactive technology that extend far beyond the traditional videogame market, including: training, policy exploration, analytics, visualization, simulation, education and health and therapy.” The hypothetical nature of game scenarios and science fiction makes for a compelling union of storytelling to test alternate realities and avoid potential policy perversions that may arise when dealing with complex social, economic, technological, and environmental systems.

Science, technology, and society are coevolving. The need to address increasingly complex societal issues is impacting the way in which research is done. NBIC research is no different. Emerging trends in science have given rise to considerations of interdisciplinary approaches that acknowledge different perspectives and values. This also includes creating opportunities for greater engagement between scientists and stakeholders while increasing scrutiny of how and what research will be conducted particularly if this research is to address social challenges. This adds another level of complexity to the process which can be explored using the tools described above. These tools are in no way meant to represent the universe of approaches to address NBIC research, but in the context of science fiction and innovation, they are well suited for stirring the imagination. Scenarios and science fiction prototyping in and of themselves are brands of fiction in a manner of speaking and potentially add great value by infusing an element of strategic thinking into the research and development process.

The point has been made previously that creativity is at heart of both the scientific and artistic processes. In trying to understand the world, both can arrive at the same place but by using different means. Alexa Wright, a London-based artist, and Dr. Alf Linney a medical physicist write about the nature of the artist/scientist collaborative relationship. It is the view of Wright and Linney that science is, for the most part, focused on altering our physical relationship with the natural world; art is oriented toward a philosophical and emotional understanding (Wright and Linney 2006). They further go on to state that at the highest level both disciplines demand acts of imagination in order to produce new discoveries. Whether in art or science, revolutionary ideas come when boundaries are tested. Science fiction and science-based scenarios can create a space for collaboration as well as give writers and scientists a new creative lease on life.

Conclusion

Just as we use both of our eyes to see stereoscopically, so must we engage both hemispheres of our brains – the analytical, logical left side and the creative, imaginative right side. Fully engaging the brain results in options, alternatives, and solutions to the myriad challenges the world/global society, and its inhabitants, will face in the future. As we strive for a sustainable and resilient world, academic, governmental, and corporate structures must integrate the currently siloed disciplines – sciences and humanities – to be ready for the accelerated rate of innovation set to happen in science and technology. To do otherwise would stifle and stagnate our ability to advance as a global society. The ability to create and successfully deploy emerging technologies is dependent upon the integration of both the arts and the sciences. One way to accomplish this is by using science fiction along with future casting approaches to help inform the ethical and legal development and responsible deployment of novel technologies such as the convergence of nano-, bio-, info-, and cognitive technologies.

Using future-based scenarios and more science fiction literature that incorporates plausible plot lines can spark imagination and serve as a stimulus to ignite creativity and out-of-the-box thinking, resulting in more effective and innovative solution generation and ideas about how to avoid problems and manage uncertainties. The trend of increased requirements within governmental and private research supporting organizations for interdisciplinary research teams is evidence of the realization that great ideas stem from diverse thinkers working in concert. The different perspectives brought to bear on difficult scientific problems can generate solutions which are more holistic and compelling. Solutions, obtained through integrated, multidisciplinary efforts, are often more sustainable than those developed through independent, stovepiped thinking and activities.

The academic community can draw upon science fiction's entertainment value to attract and inspire students in K-12 to be more interested in a future in science. As our educational system recognizes the value of an integrated training in K-12, incorporating humanities along with the sciences will enable a well-rounded student population to enter colleges and universities. This strategy of merging the sciences and humanities will not only engage more students opting to enter science but will lead them to a path to attain a broader perspective about the world, problem solving, creative thinking, and novel scientific discoveries.

In addition, training a new generation of scientists as global citizens that are capable of deftly moving between humanities and the sciences will potentially lead to untold scientific and technological developments of which currently we can only dream. Sustainable solutions to improve the human condition in relation to global issues such as the eradication of abject poverty, the provision of clean water and sanitary living conditions, the production of clean energy, and the elimination of pollution.

The employment of science fiction as a tool to engage in dialogues with the public about societal issues surrounding emerging technologies can be very effective as it can pave the way for discussions about deployment of technologies both equitably and safely. In addition, science fiction can serve as a conduit to gauge public opinion and perspectives. Understanding of public perspectives about various technological developments can eliminate misconceptions, reduce unwarranted fears, and strengthen public trust in the scientific community (Savage et al. 2013).

Although there are currently efforts under way as previously described to restore the union of the humanities and the sciences, a continued strategic, focused, and deliberate effort is needed. Scientists should be encouraged, to embrace science fiction (both as reader and writer) and scenarios as a form of mental exercise to encourage and share thought-provoking ideas. There is no single mode of interaction that defines a successful collaboration, but both groups are better for the experience. More commonality exists between the two than not. Scientists and writers are both dreamers and doers.

Consequently, the employment of scenarios by academia, industry, and governments through science fiction is a powerful toolbox for meeting current and future challenges faced by societies. This toolbox must be stocked by creative minds and out-of-the-box thinkers who are products of cross-disciplinary training. The two currently disparate areas of humanities and physical sciences must specifically become more closely connected as they once were hundreds of years ago. Such a merger could likely result in an explosion of new science fiction which in turn will lead to more creative and innovative scenarios. Improved scenario development will inspire scientists to seek more robust, sustainable, and useful solutions to improve the quality of life for the global society. Let's try writing a new inspired chapter about the future, for the future.

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Part II

Foundational Technologies Platform

NBIC

Mihail C. Roco

Contents

Abstract

Progress in science and technology (S&T) is increasingly integrated across disciplines, application sectors, and societal goals. At the core of this process in the first part of the twenty-first century is the convergence and emergence of four foundational and transformational S&T fields, briefly called nano-, bio-, information, and cognitive (NBIC) technologies. Each of these four foundational S&T fields (a) has a basic building block, that is, an atom, gene, information bit, or neuronal synapse; (b) interacts with other fields within the NBIC system at all length and time scales and levels of complexity; (c) has a similar computational architecture building from its respective elements up to macroscopic systems; and (d) leads to conceptually new opportunities for knowledge, technology, and socioeconomic advancement. Unifying concepts of NBIC that were first introduced in 2001 by Roco and Bainbridge (2002) aim at achieving a better

M.C. Roco (✉)
National Science Foundation and National Nanotechnology Initiative, Arlington, VA, USA
e-mail: mroco@nsf.gov

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understanding of nature, branching out from new R&D results to create novel S&T platforms, creating new products and services, and improving human potential in activities such as working, learning, and aging. The NBIC convergence concept brings cognitive sciences together with the physical, chemical, and biological sciences into a system of foundational transformative intellectual and technical tools. This chapter briefly presents a history of NBIC convergence, along with its current status and future potential.

Introduction

The term "converging technologies" refers to the dynamic and synergistic combination of both new and relatively traditional technologies. As of the beginning of the twenty-first century, this convergence is being driven by the emergence of a subset of them, the foundational nano-, bio-, information, and cognitive (NBIC) technologies. The convergence of nanotechnology, modern biology, the digital revolution, and cognitive sciences promises to bring about tremendous improvements in knowledge and transformative tools, to generate new economic activities, and to enable opportunities to meet and enhance human potential and societal achievements (Fig. 1).

The NBIC convergence process builds on previous stages of convergence, first, of *coincidental convergence* characterized by the ad hoc, partial integration of scientific and technological disciplines. On that basis, the deliberate support of convergence at the atomic, molecular, and macromolecular level led to *progress in nanotechnology* as illustrated by the National Nanotechnology Initiative (NNI,

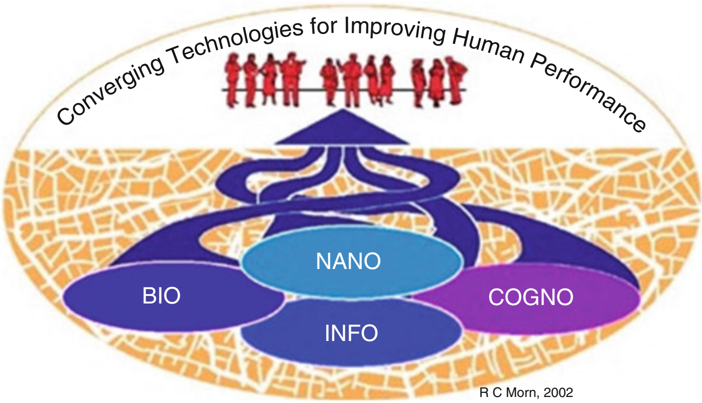

Fig. 1 Convergence of foundational and emerging technologies would have the effect of changing the societal fabric. "This picture symbolizes the confluence of technologies that offers the promise of improving human lives in many ways, and the realignment of traditional disciplinary boundaries that will be needed to realize this potential. New and more direct pathways towards human goals are envisioned in working habits, in economic activity, and in the humanities" (Roco and Bainbridge 2003, figure by R.E. Horn)

which started in 2000) and similar programs in over 80 countries. This chapter addresses a third level that of *convergence between emerging NBIC S&T fields* (Roco and Bainbridge 2002). This, in turn, is being followed by the *holistic convergence of knowledge*, *technology*, *and society* (CKTS) that manifests among other areas in the coherence of S & T evolution (Roco 2002). These four stages of convergence introduced over the past several decades have been described in studies sponsored by the US government and various professional organizations that have documented these trends, as in the following examples:

1. ***The preliminary interdisciplinary stage of convergence*** (Study: AAAS 1989). Because many research themes transcend disciplinary boundaries, the interdisciplinary approach to explain the early stage of S&T convergence, particularly evident in the second half of the twentieth century, has proven fruitful in explanation, in theory, in observation, and in design. Coincidental confluence of disciplines has led to better investigatory methods in research and education, new topical S&T domains, and emerging new interdisciplinary areas of societal relevance.
2. ***The nanotechnology stage of convergence*** (Study: Roco, Williams, and Alivisatos 1999). In the late 1990s moving into the 2000s, the field of nanotechnology provided integration of disciplines and technology sectors of the material world building on new knowledge of the nanoscale inspired by the goal of controlling matter at that scale. Concerted efforts to research and develop nanotechnology have called attention to the convergence of many formerly distinct scientific and engineering disciplines (biology, chemistry, condensed matter physics, materials science, electrical engineering, medicine, and others) when new nanoscale knowledge is applied to the material world.
3. ***Convergence of nano-***, ***bio-***, ***information***, ***and cognitive*** ("***NBIC***") ***technologies*** (Study: Roco and Bainbridge 2003). In the early 2000s, NBIC convergence – beginning from key basic elements (atoms, DNA, bits, and synapses) integrated across scales using a systems approach – led to new foundational tools, various emerging S&T fields with radical transformations, and multifunctional systems. A series of forward-looking reports on this process included Roco and Montemagno (2004) and Bainbridge and Roco (2006a, b).
4. ***Convergence of knowledge***, ***technology***, ***and society*** ("***CKTS,***" also referred to as "beyond-NBIC"; Study: Roco et al. 2013). Systematically beginning about 2010, this fourth stage of convergence consists of integration of essential human activities in knowledge, technology, human behavior, and society, distinguished by a purposeful focus on supporting societal values and needs. "Convergence is the escalating and transformative interactions among seemingly distinct scientific disciplines, technologies, communities, and domains of human activity to achieve mutual compatibility, synergism, and integration, and through this process to create added value and branch out to meet shared goals" (Roco et al. 2013, 1). NBIC is one of the five main platforms of CKTS convergence besides the system behavior, human-scale, Earth-scale, and societal-scale platforms.

Variations of the above definitions for converging technologies were produced in the EU, Asia, and Latin America as well as various organizations in the United States. According to Nordmann in the European Union (2004), “Converging technologies are enabling technologies and knowledge systems that enable each other in the pursuit of a common goal.” Pak and Rhee in Korea (Korean Ministry of Science and Technology 2007) wrote, “Convergence technology can be defined as a technology of creating new results by combining various existing technologies.” In Brazil, convergence (CGEE 2011) was described as “Technological convergence points to the current interaction between emerging areas of research and technological development previously separated. It is a new way to look at the problem and address the solution.”

Sharp and Langer (2011) focus the definition at convergence of biomedical research with science and engineering. The National Research Council of the US National Academies published a report in 2014 illustrating convergence of life sciences, physical sciences, and engineering, which it described as “. . .the coming together of insights and approaches from originally distinct fields” and “. . . an approach to problem solving that cuts across disciplinary boundaries (NRC 2014, vii, 1).

NBIC Convergence and the Systems Approach

NBIC refers to the synergistic combination of the four foundational emerging S&T fields, nano-, bio-, information, and cognitive, building from their basic elements (atoms, bits, genes, and neuronal synapses) into hierarchical systems up to the macroscale and using similar systems architecture concepts. The impetus for NBIC R&D is to achieve common core goals in advancing knowledge and technology (such as better comprehension of nature and advancing innovation) and in improving human performance (such as learning, productivity, and aging) (Fig. 2).

The *systems approach* is another foundational field that has implications beyond NBIC integration. New communication and collaboration tools, such as the Internet and the scientific web of researchers, support the growth of this cross-disciplinary field.

NBIC convergence is based on the unity of nature at the nanoscale. It is arising now because unification of scientific disciplines, new collaborative approaches, and improvement of human potential has accelerated over the last six decades or so. As an example, cognitive technologies based on computer science, psychology, neuroscience, philosophy, anthropology, economics, and sociology are only now becoming recognized as vital to expanding our understanding of the human brain and using that understanding to broadly benefit individuals and communities in an increasingly complex and interconnected world.

A main characteristic of NBIC research is “*serving people*” and bringing people closer to technology by setting broad human development goals for research and uniting them with molecular medicine and neuroscience, sustainable development,

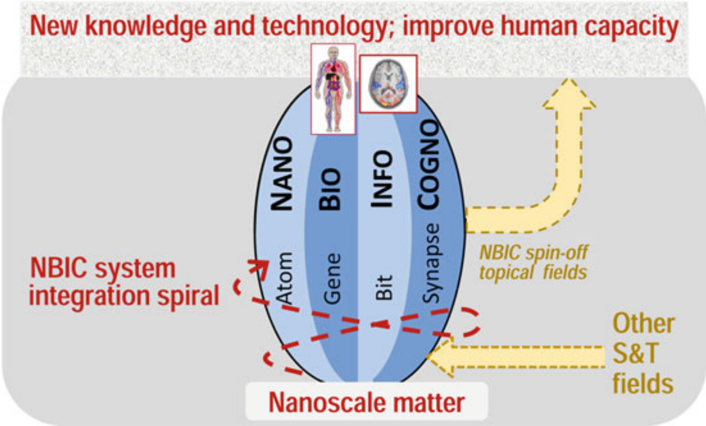

Fig. 2 NBIC system: Schematic for integration spiral from nanoscale up and across the four foundational S&T domains: nanotechnology (NANO), biotechnology (BIO), information technology (INFO), and cognitive technologies (COGNO)

human-machine interfacing, and complementary robotics – to name a few NBIC characteristics – to enhance human wellness and well-being.

Figure 3 represents the NBIC foundational technology system and suggests approaches for creating new topical S&T fields by spin-offs, confluence of two or more other fields, or recombination of two or more fields.

Convergence principles may be focused around one, two, three, or four components of NBIC, leading to the so-called nano-centered, IT-centered, bio-centered, and cognition and neuro-centered NBIC convergence efforts, as illustrated below.

Sample Nano-centered Convergence Advancements

- Nanotechnology will progress from scientific discovery to technological and medical innovation for nanosystems applied in all sectors of the economy by 2020.
- Using the same physical, chemical, and biological properties of nanoscale elements has proven valuable in application areas ranging from advanced materials such as metamaterials and nanophotonic structures, nanoelectronics such as 10 nm CMOS, and spintronic memory devices to nanobiotechnology and neurotechnology.
- Ability to probe single atom, single electron, single photon, single phonon, single charge, single spin, single-molecule vibration, and other parameters at the nanoscale has opened new capabilities for measuring, simulating, and changing "continuum" properties at the macroscale in all S&T areas.
- New synthesis, fabrication, and manufacturing techniques have been developed in diverse contexts based on specific nanoscale processes such as chemistry or

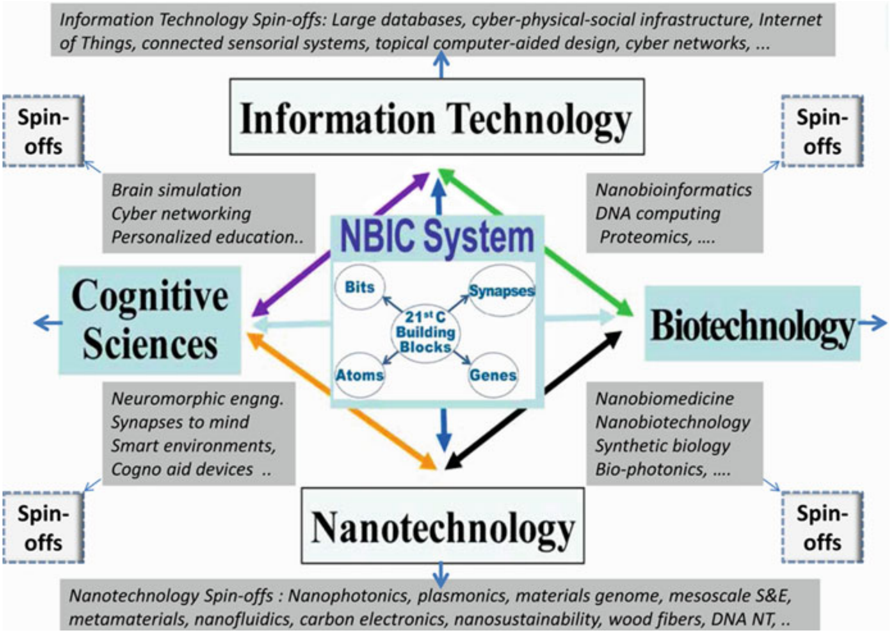

Fig. 3 Schematic for foundational NBIC technologies that branch into topical S&T fields that are formed by (**a**) spin-offs from one foundational field, (**b**) a confluence between two other fields, or (**c**) a recombination of two spin-offs and/or intersection fields (Modified from Roco et al. 2013, xvii, Fig. 2a)

biomolecular recognition and self-assembly, quantum dots, plasmonics, and additive nanoscale processes, many with support of IT-enabled simulations.

- Creation of knowledge and technology platforms are now based on previously unrecognized nanoscale carbon materials, nano- and bio- and hybrid systems, atomically engineered nanostructured metals and polymeric materials, subcellular research, and nanorobotics; these and many other applications are based on new nanotechnology principles and tools.
- Convergence of nanotechnology with modern biology and medicine has made significant in roads (Roco 2003).

Sample IT-Centered Convergence Advancements

- The quest for smallness and speed in IT devices will be enhanced by nanoscale architectures, 3D integration, new functionalities, and integration with applications.
- Convergence is visible in the hardware used in many high-tech fields, all of which rely on the same types of composite, electronic, photonic, magnetic, and/or biomaterials and devices in their nano- and microscale components, e.g., in computers, cell phones, and medical devices.

- Cloud computing connects computational algorithms and codes for shared software for NBIC and other S&T fields; these are linked to electronic storage; connect computational algorithms between scales, phenomena, and fields; connect to cyber, physical, and social systems; and also connect to sensor networks.
- Cognitive computing includes extracting synthetic information from data, biology-inspired cognizant systems to emulate brain functions, top-down software and bottom-up hardware research, as well as more futuristic DNA and cell computing concepts.
- Big data provides unifying information and conceptual links. The databases are increasingly interconnected and integrated, crossing NBIC and other S&T fields. Such networking applies to software, physical computer connections, systems of nanosensors, personalized medicine, business services, and other applications. Information sharing will advance towards a "universal domain of exchange."
- The "knowledge society" ecosystem depends on modeling and computer simulations (sometimes available to be run remotely) that include calculations for designing new nanocomposite and biological materials, integrated experimental with simulation approaches, and nanosystems and hybrid systems by design. Convergence between big data analytics and high-performance modeling and simulation is poised to converge to large-scale data-driven modeling and simulation.

Sample Bio-Centered Convergence Advancements

- There is synergistic progress being made in molecular medicine, a pharmaceutical genome (e.g., Bader 2011) and precision individualized medicine using nanodevices and cyber connections.
- Improvement of human potential is being made possible in learning, working, aging, and other areas of human activity by integrated progress throughout all branches of NBIC.
- System biology and cell biology are bringing together researchers from all domains of biology, nanotechnology, informatics, medicine, and other areas.
- Synthetic biology is a fast-growing field at the confluence bio- and nano-science and engineering with applications in medicine, energy, and agriculture, to name a few.
- Biomedical informatics is increasingly based on knowledge from NBIC domains (Martin-Sanchez and Maojo 2009)

Sample Cognition-Centered Convergence Advancements

- Explanations are becoming possible for some aspects of human behavior beginning from physicochemical–biological processes at the nanoscale, neuroscience, and system approach.

- Recognition and development of nonverbal communications are improving human interactions, such as spatial cognition, alternative sense modalities, and brain-to-brain and brain–machine interfaces, including assistive robotics.
- New opportunities are being formulated for systematically enhancing creativity and innovation and for anticipatory, holistic, and adaptive governance measures ("learning before doing").
- Cognitive technologies are increasingly penetrating various sectors of the economy such as artificial intelligence assisting human activities, cognitive computing, human–machine interaction through cognitive interfaces, computer vision and language-processing capabilities being integral to new vehicular and communications capabilities, and robotic assistance augmenting search and rescue operations and caregiving for disabled and elderly persons.

Progress in NBIC Convergence After 2000

Concerted efforts that acknowledge and assist the NBIC processes as a fundamental principle of progress can achieve major goals that support broad societal benefits. On this basis, a series of visionary scenarios for 20–30 years ahead were formulated in 2001 in the report *Converging Technologies for Improving Human Performance* (Roco and Bainbridge 2003). Twelve challenging ideas from that report are listed below that are already a reality or are in development as of 2015:

- A hierarchically interconnected world (vision of the world as a distributed, interconnected "brain" based on individual rights to privacy, access to information, and shared progress) – *a reality in 2015*
- Nonintrusive brain-to-brain communication – *an accepted capability*.
- Computer personal advisor, as in a laptop or smartphone – *a reality*.
- Brain–machine and brain-assistive robotics systems – *in development*.
- From physics/chemistry processes in brain to mind, behavior, and education – *focused research exists in several countries*.
- Centers of learning that apply brain research to education methods – *in operation*.
- 3D printing of replacement parts and regenerative medicine – *accepted*; *applications have been submitted for several tissue types*.
- Nano-, info, and biomedical developments – *a reality*.
- Proteases activated by the brain – *proof of concept and applications have been achieved*.
- Education for NBIC-related knowledge and skills being provided earlier in the education continuum – *modules have been developed for K–14 settings*.
- Intelligent environments – *in development*.
- National and international communities for ethical, legal, and societal issues (ELSI) – communities *already had been organized by 2010*.

Several new areas of NBIC-based knowledge and technology that have emerged since 2001 include the following:

- *Quantum information science*, which relies on convergence of information technology (IT), nanoscale and subatomic physics, a systems approach for dynamic/probabilistic processes, and entanglement
- *Eco- and bio-complexity research*, which relies on convergence of biology, nanotechnology, a systems approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms, an interface between ecology and economics, and epidemiological dynamics
- *Brain research*, which relies on connecting physical–chemical–biological phenomena and processes to human mind and behavior
- *Neuromorphic engineering*, which relies on convergence of nanotechnology, biology, IT, and neuroscience
- *Cyber physical systems*, which relies on convergence of IT, nanotechnology, biology, and others
- *Synthetic biology*, which relies on convergence of biology, nanotechnology, IT, and neuroscience
- *Environmental nanosensing*, which relies on convergence of nanotechnology, biology, IT networking, and environmental sciences
- *Emerging technologies for sustainable development*, which rely on nanotechnology for efficient energy conversion and storage, for water filtration, for precise nanomanufacturing, and for reducing the consumption of raw materials, among others
- *Adaptive systems engineering*, which relies on convergence of neuroscience, cognitive technologies, adaptive systems for unpredicted events, and others
- *Enhanced virtual reality*, which relies on convergence of nanotechnology, IT, cognitive and biotechnologies, personalized learning, and reverse engineering of the brain

Beginning in 2003, the US Defense Advanced Research Projects Agency (DARPA) initiated several programs that rely on NBIC convergence to "harvest biology" to enhance warfighter performance:

- *Brain Machine Interface* to communicate with the world directly through brain integration and control of peripheral devices and systems
- *Metabolic Engineering* to develop methods for controlled metabolism in cells, tissues, organs, and organisms needed by the US military
- *Exoskeleton for Human Performance Augmentation* to develop technologies to remove the burden of mass and increase the soldier's strength, speed, and endurance
- *Continuous Assisted Performance* to prevent the degradation of cognitive performance caused by sleep deprivation

Various benefits from convergence that are evident today include new capabilities with more efficient solutions to S&T challenges, scientific results and outcomes not possible without the NBIC approach, and novel transdisciplinary tools serving NBIC applications, enabling of open-source networks, and restructuring of national research and education programs. Examples are presented below:

1. *More efficient solutions to S&T challenges*: The gene sequencing cost decreased by three orders of magnitude from 2008 to 2011 after wholesale adoption of approaches from nanoelectronics such as microarrays, massive parallelization, and even mainstream CMOS (complementary metal-oxide semiconductor) technologies (Rothberg et al. 2011; Wetterstrand 2013).
2. *Scientific and technology results not possible before*: In the biomedical field, creation of scaffolds for artificial organs became possible only after 2010 as a result of combining additive manufacturing with nanotechnology and tissue engineering.
3. *Novel transdisciplinary tools*: Research, design, and manufacturing NBIC tools that have emerged for electronic systems, applications in medicine, health, human–machine interfaces, optic control of neuronal activity, and many others.
4. *Enabling of open-source networks*, such as:
   (a) HUBzero, the cyber-infrastructure framework for the nanoHUB (http://nanohub.org/), has embraced the open-source distribution model for its user community (Klimeck et al. 2008; McLennan and Kennell 2010). The HUBzero–nanoHUB model goes beyond the distribution of open-source codes to provide the NBIC community with open simulation services.
   (b) The Observational Medical Outcomes Partnership (OMOP; http://archive-omop.fnih.org/), a public–private partnership "established to inform the appropriate use of observational healthcare databases for studying the effects of medical products," will use the open-source model to develop and distribute its informatics tools (FNIH 2012).
   (c) Returning the open-source model full circle to its roots in manufacturing, the desktop manufacturing community is embracing open source to accelerate innovation.
   (d) Open-source tools such as "analysis of functional neuroimages" are becoming increasingly important for creating informatics in the domain of noninvasive human brain imaging. Because functional brain studies are extremely expensive, the sharing and reuse of data between research groups has become a priority.
5. *Restructuring of research and education programs* to take advantage of developments in NBIC convergence includes:
   (a) New research programs on the human brain: the European Union's 2013 funding of its Future and Emerging Technologies flagship project; the Human Brain Project, for measurement and modeling of brain research (http://www.humanbrainproject.eu/); and the US Administration's BRAIN Initiative (Brain Research through Advancing Innovative Neurotechnologies) (https://www.whitehouse.gov/BRAIN).

(b) Many of the newer projects supported by the National Science Foundation (NSF):
   - NSF has established several NBIC-based engineering research centers in the last 10 years, e.g., for Synthetic Biology, Advanced Self-Powered Systems of Integrated Sensors and Technologies, Sensorimotor Neural Engineering, Biomimetic Microelectronic Systems, Revolutionizing Metallic Biomaterials, and Quality of Life, focused on emergent biological machines.
   - NSF's awards for its Science of Learning Centers were funded beginning in 2004. These centers make connections from brain research to learning processes using NBIC-based knowledge and tools:
     – Center for Excellence for Learning in Education, Science, and Technology (CELEST) at Boston University (http://cns.bu.edu/CELEST/)
     – Center for Learning in Informal and Formal Environments (LIFE) involving University of Washington, Stanford University, and SRI International (http://life-slc.org/)
     – Pittsburgh Science of Learning Center for Robust Learning (PSLC) involving Carnegie Mellon University and University of Pittsburgh (http://www.learnlab.org/)
     – Spatial Intelligence and Learning Center (SILC) involving Temple University, Northwestern University, the University of Chicago, University of Pennsylvania, and Chicago Public Schools
     – The Temporal Dynamics of Learning Center (TLC) at University of California San Diego (UCSD), with participation from scientists at Rutgers University, Vanderbilt University, and University of California Berkeley
     – The Visual Language and Visual Learning Center led by Gallaudet University

Current Indicators of Interest in NBIC-Related R&D

Indicators of interest in NBIC convergence include numerous new national and international investments in NBIC-based research programs and industrial applications. The first report on NBIC convergence (Roco and Bainbridge 2003) was followed by various research programs and facilities starting up in the United States and around the world, each one using specific convergence methods (Roco et al. 2013). Examples include the NSF convergence projects that are part of the US NNI; the EC annual converging technologies program; the Kurchatov Center for Converging Technologies in Russia; various bio-nano-cogno programs at IMEC in Belgium; the Centre for Converging Technologies in Jaipur, India; China's (CAS) research institutes that combine information science, advanced manufacturing, and biomedicine in Shenzhen, Chongqing, and several other cities; Japan's AIST/IBEC centers (information and communications technology, biotechnology, energy/environment technology, and converging technology (http://www.open-innovation.jp/ibec/); Korea's Institute of Convergence Science centers (ICONS)

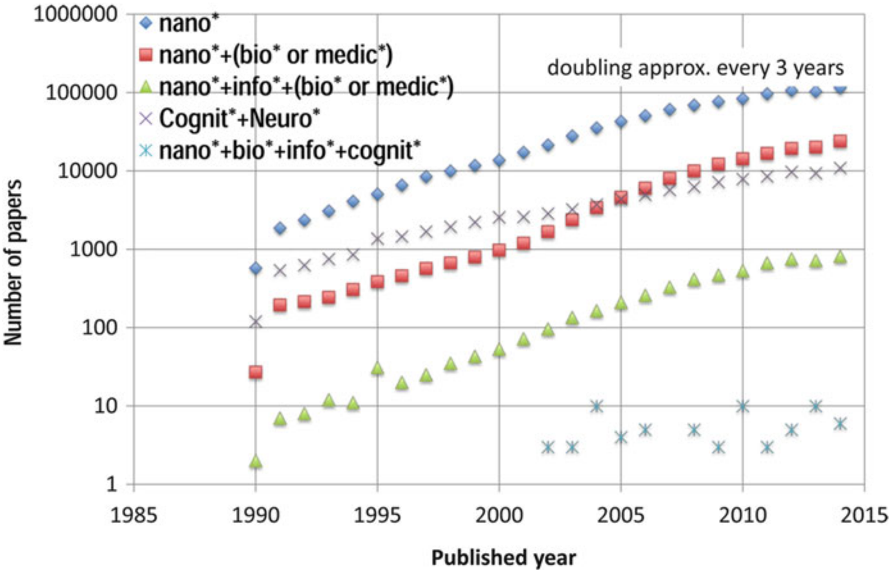

Fig. 4 Number of papers searched by keywords on foundational NBIC domains (1990–2014): search of titles, abstracts, and keywords in the Word of Science database

(http://icons.yonsei.ac.kr/centers.php?mid=n03_01) at Yonsei University; and other programs spread over five continents. Korea established the National Development Plan for Converging Technologies for 2009–2013 based on NBIC convergence with \$8.5 billion over 5 years, representing about 12 % of national R&D investment. According to the Korean Convergence Research Policy Center, in Korea's second 5-year plan (2014–2018), there is a new R&D effort called Converging Technology Development Strategy for the "creative economy" and an economic implementation plan called the National Development Plan for Industrial Convergence.

The topics of peer-reviewed scientific papers constitute another indication of the acknowledgement worldwide of the importance of NBIC convergence. For example, the number of scientific papers with nano- and bio- and nano-, bio-, and info keywords has doubled each 3 years since 2000, a rate of increase of 20–25 % per year. On the other hand, in the same time period, relatively few papers have referred to all four domains of NBIC (Fig. 4).

Yet another indicator of interest in research in the NBIC convergence field is the proportion of relevant awards in the general research portfolio. At the National Science Foundation, for example, this proportion is about 5 % of the total number of all NSF awards over the last 5 years (Fig. 5), and the most supported NSF research topic has been related to nano- and bio-convergence. The number of NSF awards related to convergence themes, searched by keywords in the title and abstract, has varied in that interval between 700 and 900 per year.

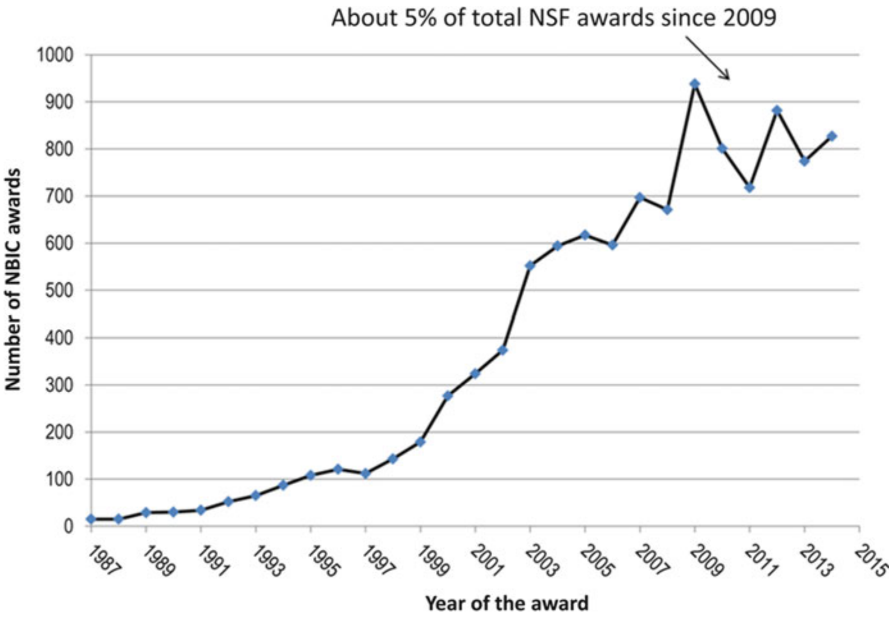

Fig. 5 Number of new NBIC awards at NSF (1987–2014)

Some Societal Implications of NBIC Convergence

Convergence of the foundational NBIC science and technology fields is expected to have a number of significant societal implications going forward, leading to:

- *New fundamental knowledge and new topical S&T fields*. Examples are newly possible explanations of the transition of matter from inert to living systems, molecular medicines based on subcellular treatments, understanding of quantum effects in both biological systems and the galaxy structure in the universe, and numerous emerging topical S&T fields such as plasmonics, synthetic biology, nanobioinformatics, and neuromorphic engineering.
- *Significant improvements in products and services and creation of new technology platforms*. Several examples are cyber-NBIC manufacturing platforms, personalized medicine, Internet-driven services (such as "Uber"), Internet of Things (IoT) cyber-physical and social systems, Cloud cyber services for computing and communication (such as Google, Microsoft, Facebook, and Twitter), and DOE Energy Innovation Hubs (interdisciplinary research centers modeled after Bell Labs and Xerox PARC that seek to bring basic and applied research together to develop innovative new technologies).
- *Connecting citizens and boosting their involvement in science and education*. Illustrations are "Citizens Science Association" activities since 2012 that reflect

public participation in scientific research (citizen science, volunteer monitoring, Pro-Am partnerships, community-based research, and more) and the Living Laboratory® (since 2005) at the Museum of Science in Boston for improving education of children, aiming to educate the public about child development by immersing museum visitors in the process of scientific discovery.

- *Improvements in human potential and sense of well-being in daily activities* through achievement of NBIC-based enhancements in learning theory and tools, work efficiency, healthcare, and maintenance of physical and mental capacity for aging individuals, as well as entertainment and safety.
- *The combination of richer web content and faster search engines with the Internet and big data to revolutionize every aspect of human lives*, for example, in terms of broader and more rapid communication tools and access to knowledge and information. The scientific process is undergoing a similar transformation based on rapidly expanding IT-based abilities to access, analyze, and merge large, complex datasets. Experts say that the new "scientific web" will yield higher-quality science, more insights per experiment, increased democratization of science, and a higher impact from major investments in scientific instruments.
- *More likely adoption of a systems approach in environment*, *health*, *and safety* (*EHS*) *and ethical*, *legal*, *and societal implications* (*ELSI*) *policy* with respect to emerging technologies to address their secondary implications proactively.
- *Creation of visionary ideas at the confluence of foundational NBIC technologies*. Examples can be seen in universal databases, cognition and communication developments, human–robotics systems, platforms for unmanned vehicles, the space program, the research program on fundamental particles (Higgs et al.), and the birth of entirely new disciplines such as synthetic biology and quantum communication. One specific illustration is the technological breadth and complexity of smart phones and other "wearable" communication–audiovisual–computing platforms.

In sum, NBIC convergence is poised to effect radical transformations in paradigms for human endeavors across many fields of activity (Roco and Bainbridge 2003; Roco et al. 2013). Some of these transformations are specifically scientific, such as NBIC support for emerging and converging technologies in wide-ranging programs that rely on both bottom-up–discovery-driven and top-down–vision-driven scientific and technological R&D. However, many of these transformations, as noted above, are oriented to human activities at both the individual and societal levels. NBIC convergence can support expansion of human physical and cognitive potential; achievement of higher societal and economic productivity and efficiency through newly focused citizen participation and groundbreaking local, national, and international governance initiatives; expansion of human knowledge and cognitive capabilities and empowerment of individuals and groups through new education paradigms and added-value decision analysis; and provision of new economic possibilities through clustering and broadly distributed manufacturing infrastructures.

Despite the inspiring potential benefits made possible by the new NBIC convergence paradigms reviewed above, there are some specific risks for emerging technologies that are based on NBIC convergence. These naturally include the increased technological complexity and uncertainty of NBIC-based technologies in comparison with traditional technologies. They also include the complex interdependency of today's industrial and social systems and the increased significance of unpredictable societal impacts of new technology releases. It is thus imperative to reduce the time delay between development of new scientific knowledge and evaluation of its societal implications. Significant barriers to overcome are the insufficient interconnections between NBIC converging technologies and other convergence platforms for human-scale, Earth-scale, and societal-scale activities.

Closing Remarks

It must be emphasized that NBIC convergence is likely to realize its potential only if supported by suitable, proactive governance initiatives (Roco 2007). Good governance of converging sciences and technologies needs to thoughtfully and judiciously balance the following *basic attributes* of effective management:

- *Transformative*: Governance of NBIC convergence must bring added value to knowledge, technology, and human dimensions of S&T as compared to existing governance of individual disciplines and technologies.
- *Responsible*: Governance of NBIC convergence must focus on improving social benefits of R&D without increasing health, safety, and other risks to people and the planet.
- *Inclusive*: Governance of NBIC convergence must pioneer broadly inclusive participation in S&T decision-making, involving all key stakeholders.
- *Visionary*: Governance of NBIC convergence must identify and support widely shared visions and/or goals that can inspire sustained investment.

The NBIC converging technologies governance functions apply to a *governance ecosystem at various levels* as a function of the level of technology transformation. Issues related to changes in the components of technological systems (such as introduction of carbon nanostructures, individual genetic testing, and mapping of brain functions) typically can be addressed by *adapting existing R&D programs*, *regulations*, *and organizations* to include the new knowledge about the emerging technologies. Issues related to instituting new technology systems (such as technology platforms for hybrid nanobiosystems, synthetic biology, and brain treatment) can be best addressed by *establishing new R&D programs*, *setting new regulations*, *and establishing suitable organizations* specifically to handle the new converging technology domains. Issues related to societal changes potentially affecting all citizens (such as investments for NBIC convergence and appropriate labeling of consumer products) can be best addressed by *national R&D programs*, *policies*, *and laws* as well as by building capacity for addressing these issues within national institutions. Finally, issues affecting *multiple countries and international relations* (such as EHS policies, intellectual property rights, and support for innovation of emerging technologies in international organizations like the Working Group on Biotechnology, Nanotechnology, and Converging Technologies of the multilateral Organisation for Economic Co-operation and Development) require making international agreements, engaging in collaborative projects, and coordinating regulation.

Today's interest in instituting global governance tools is an aspect of the S&T governance ecosystem for NBIC convergence that is itself a product of convergence and is basically unprecedented in historical terms. Five of the most relevant possibilities for global governance for improving NBIC convergence are:

- Creating science and technology *converging technologies platforms* and developing corresponding *tools for convergence* in areas of highest societal interest such as forecasting and scenario development. A specific goal is developing appropriate methods, organizations, and informatics for rigorous evaluation of NBIC convergence, its benefits, and its risks. Anticipatory measures are needed for preparing people, tools, organizations, and infrastructure.
- Establishing *open-source and adaptive models and mechanisms* to enhance converging technologies discovery, education, innovation, informatics, and commercialization in the global S&T ecosystem. This includes promoting a culture of convergence in organizations based on common goals and related activities and supporting networks and academic–private–government–civil–public linkages. Governance of convergence should support both individual and group creativity and innovation.
- Developing *internationally recognized EHS and ELSI requirements*, including risk management methods – voluntary, science-based, data-based, and incentive-based approaches – and risk assessment of revolutionary discoveries. This includes taking into consideration public perceptions and expectations that are changing over time, for example, in terms of balancing requirements for privacy against some advantageous but potentially invasive attributes of smart phones, cyber medicine, and long-distance learning.
- Supporting global *communication and international partnerships*, empowering stakeholder participation, and partnering in all phases of governance, facilitated by international organizations and consultative groups of experts. International coordination and competitiveness are significant dynamic factors in formulating the investment policies.
- Making commitments to *combined short- and long-term R&D planning and investment policies*, based on priorities, global scenario development, and anticipatory measures. Convergence needs to be guided by higher purpose criteria such as economic productivity, improvement of human potential, and "life security" that includes sustainable development. Improving and rewarding convergence efforts are needed in S&T management and planning.

NBIC convergence is a timely knowledge and technology engine of change that, with foresight and attention, has the potential to provide far-reaching solutions in improving economic productivity, to generate presently unimagined disruptive industries with new jobs and products, to increase human physical and cognitive potential, and to secure an equitable and sustainable quality of life for all citizens.

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Cognitive Technology

James L. Olds

Contents

Introduction

In recent years, as brain science headlines have become common, the public awareness of neuroscience has skyrocketed. President George H. W. Bush's "Decade of the Brain" in the 1980s led to the grassroots movement, "Decade of the Mind," in the first decade of the twenty-first century and most recently the White House BRAIN initiative (Sacktor 1996; Albus et al. 2007; Alivisatos et al. 2012). This public awareness was not always so. Indeed, scientists who studied the brain, while being well represented among the Nobel Prizes of the twentieth century, did not even call themselves *neuroscientists* until the 1970s with the founding of the Society for Neuroscience. Even until the turn of the millennium, the popular view of the brain scientist was as primarily a psychologist (in a white lab coat) studying rats exploring a T-maze (Tolman and Honzik 1930). Relevant to the subject matter of this chapter, in the technological fields, the public also viewed transistor-based solid-state devices as inherently separated from the human brains

J.L. Olds (✉)
Department of Molecular Neuroscience, Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA, USA
e-mail: jolds@gmu.edu

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that created them. All of the above have rapidly changed over the last decade, and we will argue in this chapter that the driver of change was a set of convergent neurotechnologies (NTs) that, taken together, are revolutionizing the discipline and, more importantly, are offering the potential for practical application in many areas of human activity.

Arguably, NTs were first introduced in the mid-twentieth century as tools to conduct intracellular electrophysiological recordings from individual neurons (Barbara 2006). These early NTs fundamentally changed the context of the questions that scientists could ask about nervous systems. In a sense, for investigators, the study of the brain was transformed from investigating a “black box” (with behavior as the main dependent variable) (Skinner 1953) to studying a “machine” with constituent parts. The “brain machine” was subject to reductionist approaches such as those used in the more mature fields such as physics or chemistry. Over time, this change in scientific approach, from mostly behavioral studies to neurophysiological ones (and subsequently to imaging and genetic approaches), allowed for investigators to ask scientific questions that had immediate practical applications, whether in the public health or industrial sectors. While in the past, researchers had largely confined their research questions to those limited ones that can be asked about animal models, in the new paradigm, human brain diseases, memories, human cognition, and emotion all became fair game, both for the bench-top scientist and for the clinician.

Perhaps the single most important NT within this context of practical brain science was the advent of noninvasive human functional brain imaging, initially using single-photon emission computed tomography (SPECT), then positron emission tomography (PET) in the 1980s (Nutt 2002), and subsequently functional magnetic brain imaging (fMRI) in the 1990s (Ai et al. 2012). These NTs made it possible for euroscientists to visualize and measure the functional activity in brains of conscious human subjects (who were sometimes patients). Hence, questions which could not be asked in model organisms (e.g., mouse or the fruit fly) were now also amendable to hypothesis-based experimentation.

The mass media quickly realized that news stories about the functioning brains of human subjects were far more compelling to the public than the reports about rodent behavior. This media interest was accelerated by the common use of pseudo-colored images for representing functional neuronal activity upon a neuroanatomical background. These sorts of images made already fascinating data instantly compelling.

In parallel, the twentieth century psychopharmaceutical revolution led to mass deinstitutionalization (Angermeyer et al. 1998). It was combined with wholesale changes in psychiatric diagnoses (DSM) and resulted in a general public awareness of the chemical nature of neurotransmission and the possibility of altering it via drugs. These included the first generation of antipsychotic drugs such as the chlorpromazine, the benzodiazepines, and the tricyclic antidepressants. As these drugs and their subsequent derivatives became ubiquitous, their use constituted a kind of neurochemical NT. Indeed some of the same drugs (or their chemical derivatives) that were once employed in the context of psychiatric illnesses are now used either recreationally or, in some cases, to augment human cognition.

In the late twentieth century, the tools of molecular biology entered the neuroscience laboratory (Mullins 1972) to stay. These included sequentially sequencing, cloning, and genetic engineering. Today most neuroscience research teams at the wet-lab bench use genomic tools in the same way that the early brain scientists might have used a stopwatch or a microscope.

The massive use of genomics in neuroscience has once again changed the types of questions that investigators can ask. One of the most exciting of the genetic tools involves the use of genetically engineered photosensitive ion channels: optogenetics. The recent development of optogenetic NT allows investigators to reversibly lesion a single neuron or a population of neurons. In a very real sense, optogenetics allows for formal reverse engineering of real neural circuits and has played a key role in the development of neuroengineering as a new field.

We will argue in this chapter that the development of this engineering approach was another key convergent factor in raising the public awareness of NT. For scientists, the public, and decision-makers, the former "black box" now incorporates a "wiring diagram". The 1.3 kg of "gray and white matter" is now 10^{11} neurons, each with approximately 10^4 synapses for a total of 10^{15} neurocomputational "atoms."

Another convergent factor driving the recent primacy of NT is Moore's Law (Schaller 1997). As computers have become exponentially more powerful, they have played increasingly dominant roles in the way neuroscientific data is collected, analyzed, and curated. Simultaneously, the constituent parts of computers, such as "hard drive" or "memory," have been widely used both by neuroscientists themselves (as metaphors) but more recently by members of the media as they strive to make a very complicated subject matter more accessible to the larger public.

Moreover, the existence proof of a human brain as a 20-Watt ultrahigh performance computer has, in turn, begun to drive computer R&D. Using molecular approaches such as the above mentioned optogenetics, neuroscientists are reverse engineering the architecture of real biological brains in order to realize both their performance and their power efficiency. This is an additional convergent driver which will not only potentially create strong AI but also will lead to hybrid machine-human augmentations way beyond the prosthetics now being developed for traumatic brain injury (Kotchetkov et al. 2010).

The emergent effect of these convergent strands of neurotechnological innovation is to create new opportunities for society, especially in the area of human cognition. These opportunities will manifest at the intersections of global health, economics, and the human evolutionary trajectory. With these opportunities however come challenges, particularly in the domain of ethical, legal, and social issues. A major challenge will be to engage thought leaders early so that policy hazards (Lowrance 1976) can be avoided. Further, with all technological advances comes the potential for oversell. The field of artificial intelligence fell victim to its own expectations in the 1970s and took years to recover. Presumably as neurotechnologists advance their field, they will be able to avoid that same danger having learned the lessons from AI.

This chapter will now address in detail the following: (1) the question of how the development of instrumentation to conduct neuroscience led to the development of NTs and the field of neuroengineering, (2) how reverse engineering of biological brains has the potential to qualitatively change our understanding about brains and behavior, (3) how NT advances will be driven by convergence, and (4) how that convergence might shape a societal discussion of the ethical, legal, and social issues tied up in NTs.

How Neuroscience Became Engineered

As mentioned above, the Society for Neuroscience is only about 40 years old. In contrast, the use of modern scientific techniques to study nervous tissue dates from the late nineteenth century. In 1906, Santiago Ramon y Cajal and Camillo Golgi shared the Nobel Prize for key methods and discoveries which to this day play an important role in modern neuroscience (De Carlos and Borrell 2007). Golgi was awarded his share of the Prize for inventing a novel tissue staining method which got around the issue of tight neuronal packing by stochastically revealing 0.01 % of the neurons. Cajal shared the Prize by exploiting Golgi's method to reveal brain wiring diagrams and neuronal classifications using optical microscopy. Moreover, Cajal's hypothesis on the synaptic nature of neurotransmission, subsequently confirmed, was instrumental in the development of modern neuroscience. Cajal's careful observations and beautiful drawings are still used today in a pedagogical context.

The Great Depression and the two World Wars led to something of a hiatus in the development of neuroscience. The direct study of neurons was eclipsed temporarily by the rise of behavioristic approaches such as those of B.F. Skinner (Capshew 1993). Nevertheless, the advances in electronics during the war (such as radar) were crucial to the subsequent transformations of neuroscience in the postwar years. The theoretical notion that "neurons that fire together, wire together" put forward by Donald Hebb in 1949 (Hebb 1949) was also a central force in the transformation of the field since it was evident that to test the hypothesis, it would be necessary to record the neural dynamics of cell assemblies.

With realization that testing Hebb's theories would require the development of sophisticated electrophysiological techniques, the notion of using simple mollusk animal models became prevalent not only because their neurons were often very large (Kandel et al. 1967) and therefore amenable to measurements but also because of the notion that discoveries from those systems would be evolutionarily conserved in mammals (Bailey et al. 1996).

Another key driver of the field's modern evolution was the development of new animal models that could exploit the mid-twentieth century advances in molecular biology (Bolker 2014). These included the fruit fly, zebra fish, and mouse. Such approaches were complementary to the use of human subjects for noninvasive functional brain imaging experiments. With the sequencing of the human genome, these two approaches became merged and fMRI data is routinely combined with genetic data in the same human subjects (Liu et al. 2009).

To fully trace the origins of how engineering became embedded in neuroscience, however, it's necessary to go back to the point of the mid-twentieth century, following the Second World War, when the dependent variable in brain science experiments shifted from the behavior of the animal to the activity of the neurons themselves. Ralph Waldo Gerard's invention of the glass micropipette electrode in 1946 (Graham and Gerard 1946) marks the key inflection point in the field (although he had been also a pioneer in using extracellular electrodes to record neural activity earlier). The intracellular microelectrode (subsequently called a "sharp") allowed researchers to "peer" electrically within a single neuron and to record the resting membrane potential and the rapid all-or-nothing change in potential known as the action potential or spike. Quite rapidly, the sharp electrode, combined with the oscilloscope, led to K.C. Cole's invention of the voltage clamp technique for measuring ionic currents across the neuronal membranes (Cole 1968). The use of voltage clamp subsequently led to Hodgkin and Huxley's discoveries about the ionic basis of the action potential and their mathematic formalism for describing it (Hodgkin and Huxley 1952).

A parallel electrophysiological technique, multiple-unit recording, developed by Renshaw et al. in the 1940s (Renshaw 1946) and subsequently paired with real-time computer control and data acquisition to study freely behaving rats learning a food reward task by Olds Sr. et al. in the 1960s (Kornblith and Olds 1973), paved the way for the further integration of engineering into the field of neuroscience. In multiple-unit recording, a small metallic extracellular electrode recorded the action potentials (units) from multiple neurons proximal to the electrode.

From the development of multiple-unit recording onward until the first decade of the twenty-first century, electrophysiological measurements dominated neuroscience as a field. The many advances made possible by the technique were a result of a coevolution between the sophistication of the sensors (electrodes) and the computers used for acquiring and analyzing the complex time series data. Moore's Law (Moore 1995) certainly played an important role in this coevolution: the PDP-8 (an early minicomputer manufactured by Digital Equipment Corporation) used to acquire and analyze single unit data in the 1960s is dwarfed by the power of a current smartphone.

In the domain of sensors, electrodes became more sophisticated and eventually employed nanomaterials to enhance their performance (Yang et al. 2013). The discovery of the naturally occurring green fluorescent protein (GFP) and its subsequent molecular modifications to serve as a multifunctional biosensor resulted in a shared Nobel Prize for Osamu Shimomura, Martin Chalfie, and Roger Tsien (Zimmer 2009). The technique replaced many of the earlier molecular probe technologies first with laser-scanning confocal microscopy and later with more advanced super-resolution techniques (Sullivan and Kay 1999). The advances made possible new advances in neuronal imaging that, in some cases, were able to replace electrophysiology as a method for investigating neuronal function (Tian et al. 2009). The subsequent invention of the optogenetic approach as a tool to turn on and off neuronal ensembles was made possible by the discovery of channel rhodopsins that could be similarly engineered to serve as a laser-activated neuronal switch (Deisseroth 2011). Optogenetic methods make it possible to treat neuron cell assembles in a fully reductionist manner: each component can be reversibly removed from the circuit to determine function. This approach was recently used to engineer a reversible amnesia to a specific fear memory in mice. In the future, optogenetics may be used to reverse blindness by stimulating human ganglion cells in human subjects, bypassing rod and cone photoreceptors (Liu et al. 2012).

As important as the electrophysiological techniques were tomographic methods that made possible noninvasive functional brain imaging in humans. In PET, collimated gamma radiation detectors were linked to detect positron-electron annihilation events. These were then tomographically reconstructed to produce functional brain maps. And perhaps most importantly, nuclear magnetic resonance spectroscopy was both reimagined and then reengineered to become magnetic resonance imaging making possible fMRI using fast Fourier transform to achieve reconstruction.

In the field of neuropharmacology, the promise is mostly still in the future with the possibility of personalized medicine and sophisticated molecular approaches that manipulate genomes such as CRISPR (Cong et al. 2013). Neuropharmacological progress has been historically stymied by an unwillingness to move beyond small organic molecules and a dearth of understanding of the etiology for many of the most prevalent neurological and psychiatric diseases.

Today engineering is thoroughly embedded in neuroscience. New academic programs in neuroengineering at elite institutions represent the modern fulfillment of a trend that began 60 years ago.

Reverse-Engineering Biological Brains

Brains are extremely complicated. If we consider each of the human brain's 10^{15} synapses as computational "atoms," then it is not surprising that the human brain has been called "the most complicated machine yet discovered in the Universe" (De Garis 1993). Elucidating the brain's wiring diagram (dubbed recently the connectome) (Sporns et al. 2005) will clearly be a challenging task. Further, because the connectome undergoes massive changes over development and also changes daily throughout adult life (Gage 2002), the task is even more daunting.

There are simplifying principles however. For example, there are a limited number of neuron types (perhaps a thousand) (Koch and Marcus 2014). Further, connections are constrained by many factors including the absolute requirement that presynaptic axon and postsynaptic dendrite be in close physical proximity. Additionally the number of chemical neurotransmitters is also probably low (10^2), and neurotransmitter systems are in many cases functionally linked (Reiner 1993).

Addressing the above challenge has required the development of new scientific approaches. Specifically, the large-scale science that is currently deployed in fields such as particle physics and astronomy has been adapted in the neuroscience context. As an example, the use of assembly line industrial approaches to brain mapping in Jeff Lichtman's laboratory at Harvard is making possible significant progress toward the challenge of mapping the mouse neocortex (Lu et al. 2009). Both the White House BRAIN Initiative and the European Human Brain Project represent significant public investments in this area. In the private sector, the separate but very unique approaches of the Allen Brain Institute and the Janelia Farm Campus of the Howard Hughes Medical Institute also represent substantial commitments.

The goal of these new "big science" approaches is really twofold. The first is to improve the public health through better therapies for brain diseases. The second is to extract architectural principles from the biology that can then be deployed in new technologies such as strong AI, deep learning (Bengio 2009), robotics, and advanced brain-machine interfaces. Those architectural principles include the modular organization of neocortical columns (Horton and Adams 2005), tri-synaptic circuit of the hippocampus (Teyler and Discenna 1984), massive parallel processing (Hinton and Anderson 2014), and feedforward as well as feedback inhibition (Lamme et al. 1998), among many others. They are the result of many years of work and, taken together, represent an altogether different approach to cognitive computing. This notion of neural-inspired computing is being pursued on many fronts, both in the context of practical application (Merolla et al. 2014) and in the context of serving as a tool for neuroscience exploration (Markram 2006). At a deep level, the former approach is driven by the attractiveness of computers which approach the power efficiency of brains. The latter approach is driven by the notion that only by fully simulating brains, in silico, can we fully understand them.

In thinking about what these reverse-engineered artifacts might be used for practically, it is useful to consider human higher cognitive abilities. In particular, humans have a considerable ability to autonomously navigate their environments using sophisticated cognitive maps (O'Keefe and Nadel 1979), to recognize objects, to represent knowledge symbolically through language, and perhaps most importantly to interpret intention using theory of mind (Leslie 1987). Thus, it seems possible that applications might range across a very large waterfront: from self-driving cars to robotic assistance for the elderly. The key common denominator of all of these strands is the notion that cognitive computing applications require machines that take advantage of biological brain architectures. This is an altogether different approach from the current high-performance computing regime of Moore's Law-based technological development.

How NT Advances Will Be Driven by Convergence

The notion of convergence as a technology driver has been described previously (Bainbridge and Roco 2006). In the case of NT, convergence has played an important role as evidenced by the advances in electrophysiological signal processing, imaging, and molecular biology that were described above. The development of all the major noninvasive human brain imaging modalities was a direct result of this type of convergence.

At the same time, a different type of convergence may be emerging: one based on the coevolution of biological brains and NT artifacts. In this case, the evolution of biological brains refers not to the classical Darwinian type but rather to the concept of neural Darwinism advanced originally by Gerald Edelman in his book *Neural Darwinism* (Edelman 1987). Briefly put, it may well be that individual brains modify the processes by which neural group selection occurs as a result of perturbation by a NT-based brain-machine interface. Likewise, as brain-machine interfaces become more advanced, they are likely to become ever more adaptive and hence will evolve their own modes of interfacing in response to changes in brain biology. Further, such coevolution may be taking place even now, while the brain-machine interface is most commonly found somewhat removed (at the smartphone touch screen). The outcome of such coevolution is not easily predictable. In the above case, however, the convergence will be between brains and man-made NT, rather than the technologies themselves.

Given the difficulty in predicting how the convergence of NT will play out, what are the possibilities? First, it seems likely that these technologies will become ubiquitous. Much in the same way that broadband access and smartphone technology was once the province of the technological elite and now has penetrated globally, so also it seems reasonable to believe that NT will have a similar trajectory. Second, it is likely that these technologies will have a significant effect on both the public health (writ large) and as importantly health-care expenses. This is particularly true for neurodegenerative diseases such as Alzheimer's which both cost a lot and affect large numbers of the aging population. Third, in so far as these technologies may be used to enhance as well as heal, it is likely that a large market may develop (in the same way that Google-based search built online advertising). Finally, in that human decision-making is currently limited by human cognitive capabilities, it is possible that with neurotechnologically enhanced cognitive capabilities, decision-making may be improved to the benefit of humankind, or not. The complexities of coevolution make these futures uncertain.

How Convergence Might Shape a Societal Discussion of the Ethical, Legal, and Social Issues Tied Up in NTs

From a philosophical standpoint, because of the intimate and recursive nature of humans studying their own brains, neuroscience has always raised a slew of ethical, legal, and social issues (ELSI). In general, these relate to the emerging scientific consensus that consciousness and self-awareness are the products of neurobiological processes and that these things represent the most salient and personal aspects of our human existence. As the methods of neuroscience evolved, the ELSI questions became more urgent: a human experimental subject in a brain scanner is an altogether different context than a rat with an electrode in its head. For one thing beyond the obvious, the human's innermost thoughts are exposed (although as yet un-decoded) to the experimenter. We impute a greater value to those human inner thoughts than to those of the rodent. Recently, various private companies purport to detect deception using fMRI. Further, there are quite serious machine-learning approaches that seem to map between functional activity signatures and concepts such as nouns (Mitchell et al. 2008).

Because self-awareness and consciousness seem to be so tightly coupled to our identity, there are clear ELSIs raised because of the perceived ability of NT to both "read out" and "perturb" that innermost self. Further, these are the baseline ELSIs before one considers the convergence of NT and human brain function described earlier.

With the NT convergence, all of these ELSI will become more acute. As a "primitive" example, consider the modern version of the famous "trolley problem" (Otsuka 2008): Google's self-driving car. Clearly the car requires strong AI to keep its passenger(s) safe. At what point might that AI act to jeopardize the safety of the passenger in order to protect the safety of other human beings who might themselves be at risk from the self-driving car? The answer is by no means simple and is representative of a whole collection of analogous tripping hazards that will present as adaptive technology becomes fully integrated with living human brains. It is not terribly difficult to imagine a future set of NTs that will need to consider utilitarian considerations as they are simultaneously serving individual human beings.

At the same time, the NT convergence will present a quite different set of ELSI from the standpoint of augmented cognition. There will no doubt be a cost for individuals to acquire NTs that improve their cognitive abilities. How will that market be regulated? As an example, should it be possible for parents to purchase a few extra IQ points for their child? On one level, the answer seems to be yes for the same reasons that parents can purchase education (as opposed to receiving free public education). On the other hand, NTs are fundamentally different from education in terms of the brain-machine interface being far more directly connected to the "hardware" than a teacher or even an online course. If such NTs made possible cognition improvements that were beyond incremental, there would be a serious risk of societal backlash from those individuals whose children were left behind.

Finally, to lift a phrase from former Secretary of Defense Rumsfeld, there are the unknown unknowns. It is clear that the convergence of biological brains with NTs represents at the very least a new conformation of coupled complex adaptive systems. The unintended consequences of such coupling may represent the greatest challenge to our ethics and the societies in which those ethics are embedded.

Conclusions

With the onset of NTs during the course of the twentieth century, our knowledge about the workings of the human brain (and hence of mind and behavior) was transformed. In turn, this new knowledge about brains enabled the development of novel NTs designed to interact and work with brains, rather than to just take measurements. The convergence of these new NTs with our increasing knowledge about brains is leading to a coevolution between the two: the new NTs lead to better neuroscience, and the neuroscience leads to more advanced NTs. That process of coevolution, already clearly moving at the speed of the technology pipeline, may also come to operate within individual brains at a more rapid speed subserved by Hebbian assemblies that coevolve with brain-machine interfaces in ways that will be certainly complex and possibly unpredictable.

As a whole, this NT convergence offers the opportunity for societal renaissances marked by reduced conflict, better decision-making, and generally improved human potential, particularly within the context of brain disease and aging. However, with the convergence comes the risk of policy hazards that arise from the sheer complexity of existing human brains and the emerging complexity of NT-based machines.

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Complex Biological Systems

Andrew J. Spakowitz

Contents

Abstract

Biological entities range in scale and complexity from the simplest viruses to multicellular organisms with specialized cells, tissues, and organs. Within a cell of any organism, there are an enormous number of biomolecular complexes that perform physical and chemical tasks with remarkable speed and fidelity. The goals in many nanoscale engineering applications mirror the major challenges that Nature has overcome in the engineering of biomolecular systems. As such, there exist some basic paradigms of biological design that can either be mimicked or exploited for nanoengineering applications. In this chapter, several paradigms for biological control at the nanoscale are identified, and several

A.J. Spakowitz (✉)
Department of Chemical Engineering, Stanford University, Stanford, CA, USA

Biophysics Program, Stanford University, Stanford, CA, USA

Department of Applied Physics, Stanford University, Stanford, CA, USA

Department of Materials Science and Engineering, Stanford University, Stanford, CA, USA

Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory, Menlo Park, CA, USA
e-mail: ajspakow@stanford.edu

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key examples are leveraged to identify how these ideas can be used in a range of engineered systems.

Introduction

The natural world is teeming with examples of nanoscale engineering. Our ability to assemble, manipulate, and exploit nanoscale structures for functional purposes cannot compete with the capabilities that even the simplest life forms have established. Granted, these engineered systems required eons to design and perfect, and our patience for results is far less accommodating than is necessary for evolutionary design to serve as a paradigm for most nanoengineering applications. However, it is useful to use Nature as guidance, both as inspiration and as a source of existing tools for engineering applications.

The purpose of this chapter is to provide several key examples of biological systems that can serve as inspiration or be co-opted for nanoscale engineering. The goal is to provide examples of biological processes that are particularly amenable for this purpose. This chapter is not intended to be an exhaustive description of the potential avenues where biology can interface with nanotechnology. In fact, such an exercise would prove impossible given the remarkable potential for tapping into biological systems for their exquisite molecular control.

This chapter is particularly timely. The current state of biological sciences emboldens us to think broadly and to act quickly to utilize biological systems for various applications. Recombinant protein expression enables us to synthesize proteins with exact control over the specific amino acid sequence (Baneyx 1999). Notably, the 20 amino acids provided by Nature have been expanded to include nonnatural amino acids that introduce additional chemical functionalities that are advantageous for various applications (Langer and Tirrell 2004; Liu et al. 2007). The identification of protein function in various biological processes has been dramatically accelerated by the combination of chromatin immunoprecipitation and high-throughput DNA sequencing (i.e., ChIP-seq technology) (Park 2009). Our ability to quickly edit genes in organisms throughout the tree of life is now possible leveraging clustered regularly interspaced short palindromic repeats (or CRISPRs), resulting in facile manipulation of protein expression and introduction of non-endogenous proteins (Qi et al. 2013). These biotechnological advancements (and many others) allow us to design, synthesize, and analyze biopolymers at an unprecedented level of speed and accuracy.

Our ability to physically characterize biological processes and systems at a molecular level has also experienced a revolution in recent years. Single-molecule manipulation (AFM, optical and magnetic tweezers) has enabled the manipulation of individual biopolymers, facilitating the direct measurement of the physical forces involved in various biological processes (Bustamante et al. 2003; Greenleaf et al. 2007). Super-resolution microscopy has enabled the determination of the spatial organization of biological structures and materials within living cells at an unprecedented level of precision (Pavani et al. 2009; Shtengel et al. 2009). The development of large-scale molecular dynamics (MD) simulations of proteins and nucleic acids has emerged as a powerful predictive tool for biological systems, culminating in the 2013 Nobel Prize in Chemistry (awarded to Karplus, Levitt, and Warshel). The development of these approaches (and many others) represents a paradigm shift in our physical understanding of biological systems.

The convergence of fundamental and applied approaches to understanding biomolecular systems leads us to a point where we can make considerable steps in leveraging a range of such systems for nanoscale engineering. This chapter contains several examples that illustrate the remarkable opportunities for this approach. The focus is on several key paradigms in Nature that can be exploited or mimicked in a variety of settings. In some cases, such systems have had a limited historical impact in engineering applications, despite the amazing potential that they have to establish an unprecedented level of molecular control of complex structures and assemblies. This illustrates the untapped potential that this course of action may have in future applications.

Autonomous Self-Assembly and Self-Maintenance

Complex multicellular organisms have relatively modest beginnings. At the point of conception, humans exist as a single fertilized egg that has embedded itself in the mother's uterus. All of the instructions for development are contained within the genomic DNA of the fertilized egg. The mother provides raw materials and fuel for embryonic development. However, the assembly of molecules, cells, and tissues is conducted by the growing embryo without any outside instructions or manipulations.

A complete multicellular organism has cells that specialize to different tissues and tasks. Within each cell is a menagerie of proteins specialized to different biological processes, many of which comprise the life's work of very gifted researchers and could be discussed extensively in this chapter. However, the goal of dissecting an entire multicellular organism to illustrate its engineering potential is not possible and would be entirely overwhelming if it was possible. Instead, this section turns to a more humble creature as a whole-organism source of biological inspiration.

A bacteriophage (Latin for bacteria eater) is a virus that infects a bacterium. This simple life-form is composed of a protein shell (called a capsid) that contains a nucleic acid genome that carries the instructions for building the capsid proteins and other proteins needed for its assembly and infection. The bacteriophage ϕ29 has a double-stranded genome and infects *Escherichia coli* (or *E. coli*). Our understanding of the molecular-level processes involved in bacteriophage formation and infection is dramatically influenced by single-molecule experiments (Smith et al. 2001), which directly probe the forces involved in the packaging and ejection of the DNA genome within the capsid shell. The left image of Fig. 1 shows a schematic of the ϕ29 genomic DNA (red and blue) being packaged by the ϕ29 packaging motor (orange) into an assembled capsid (purple).

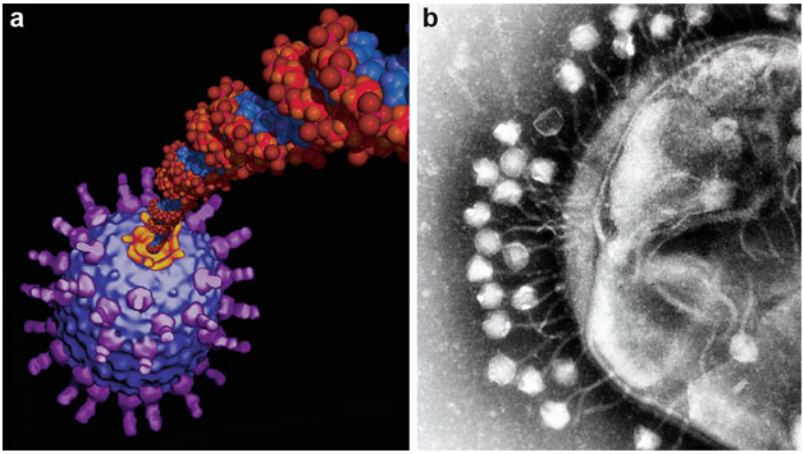

Fig. 1 Images of a virus packaging its DNA (*left*) and delivering its DNA to a bacterium (*right*), demonstrating the exquisite molecular control that even the simplest organism has acquired. *Left image* shows a bacteriophage ϕ29 (*purple*) packaging its genomic DNA (*red* and *blue double helix*) by the action of the ϕ29 packaging motor (*orange*) (Smith et al. 2001). The *right image* provides an electron micrograph of a bacteriophage (coliphage T1) infection of a bacterium (see http://spider.science.strath.ac.uk/sipbs/staff/Chris_van+der+Walle.htm)

Even this simple life-form exhibits remarkable self-assembly capabilities that far surpass our fabrication capabilities. Synthesis of the capsid proteins, either within the host *E. coli* cell or by in vitro synthesis, leads to the spontaneous assembly of empty capsids that are ready for DNA packaging. The packaging motor is able to generate forces of up to 57 pN, which makes it one of the most powerful protein motors measured. This force is necessary to overcome the considerable resistance to confining the viral DNA within the ~50 nm capsid. In fact, the eventual ejection of the viral genome during bacterium infection (see right image of Fig. 1) is partially driven by the internal pressure of the compacted genome. The life cycle of a bacteriophage is such that the assembly of an active virus occurs within a living cell, so the cellular machinery is available to the virus only during the initial stage of its life cycle. Many subsequent functions occur outside the cell, and the active virus must be primed and ready for infection with no external sources of materials or energy.

Although a bacteriophage typically packages its DNA genome, a bacteriophage can be coaxed to package other charged and uncharged substrates (Karunakaran 2007). This permissive motor is shown to reliably package synthetic DNA substrates that differ in charge, chemical structure, and sequence. In this regard, ϕ29 may be a useful engineering platform for packaging different chemical moieties within a nanoscale compartment. Furthermore, chemical treatments can be used to induce the internalized DNA to spontaneously release from active viruses, suggesting a method to release the sequestered contents of the filled capsids. The wealth of biochemical manipulations that have been established for the study of bacteriophage promotes the remarkable potential for redesigning viruses for a range of engineering purposes.

Design and Assembly of Complex Macromolecular Architectures

DNA is a remarkable molecule. The molecular structure of DNA results in the preferred formation of a double helix such that complementary base pairs (i.e., adenine-thymine and cytosine-guanine) form hydrogen bonds in the interior of the phosphate backbone double helix. Our genome is composed of a 3.2 billion base sequence of DNA, and its complementary strand zips up to form a double helical strand that is approximately 1 m in contour length. Thus, this long stretch of complementary bases results in the formation of a continuous double helix. However, disruptions in the sequence can lead to the formation of more complex three-dimensional structures that can be designed to assemble into specific architectures.

This ability to form complex secondary structures can be exploited to assemble extremely complex nanoscale structures. Figure 2 shows a series of images of self-assembled nanostructures composed entirely of DNA (Rothemund 2006) along with the computational designs of these structures. As can be seen, the structures can be designed computationally, with specific DNA sequences determined in silico such that the unique structure is assembled upon mixing the DNA strands in solution. The structures can be geometric and repeating, as in the lower images. However, complex non-repeating nanostructures can also be designed and assembled. For example, the image of the world map includes details at multiple length scales, including features of continental shapes and interior structures (e.g., Lake Titicaca in Peru is visible in the AFM image).

Base pairing has several advantages as a self-assembly mechanism. Unlike block copolymers that rely on soft nonspecific interactions, DNA nanostructures can be formed with non-repeating structures with specifically designed registry of individual molecules. This hinges on the sequence identity driving the assembly, leading to specific DNA strands assembling into specific locations in the assembly. DNA can be reliably synthesized, either through recombinant methods or by solid-phase synthesis. Thus, thousands of DNA molecules with distinct sequence identities can be synthesized for assembly. The design of such structures has been aided by computational approaches (Rothemund 2006) that mitigate issues of structural defects by choosing sequences that reliably form specific structures with minimal undesired products. Thus, this paradigm for controlled assembly of complex nanoscale architectures has the potential to reliably assemble complex structures with specifically tailored features.

Responsive and Reconfigurable Structures and Materials

A hallmark feature of biological self-assembly is the ability to form nanoscale assemblages with remarkable structural specificity through the orchestrated coordination of multiple subunits. These characteristics are desirable for many technological applications, including nanoscale materials for photovoltaic and energy-storage devices and biosensors for the recognition of rare cancer cells within a sample. Furthermore, soft interactions and molecular elasticity can be exploited to

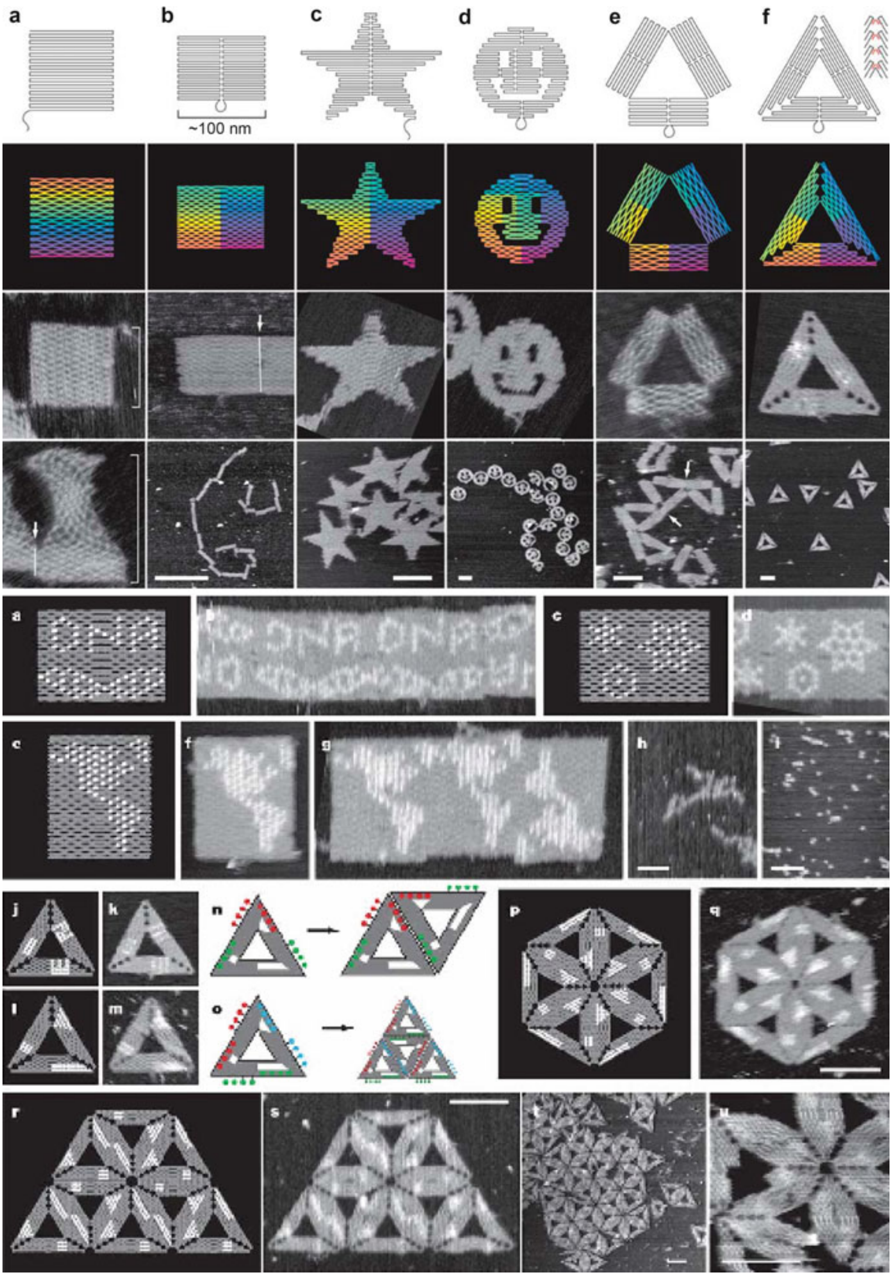

Fig. 2 Self-assembled nanostructures composed of DNA showing precise nanometer-scale control of structural features (Rothemund 2006). Scale bars for top AFM images: (**b**) 1 μm; (**c**–**f**) 100 nm. Scale bars for top image: (**h**, **i**) 1 μm; (**q**, **s**–**u**) 100 nm

enable structural transitions, resulting in nanostructured materials that are reconfigurable by external chemical or physical cues.

For example, clathrin is a protein that plays a major role in the creation of transport vesicles in cells. Clathrin is an essential component of the common intracellular trafficking mechanism known as clathrin-mediated endocytosis (CME). A monomer unit of clathrin is a massive protein complex (trimer of dimers) that adopts a pinwheel (or triskelion) structure, shown in the upper left image of Fig. 3. Patchy charged on the triskelion legs lead to favorable interactions between triskelia, driving collections of clathrin triskelia to assemble into cagelike lattices, an example of which is found in the upper right image of Fig. 3. During CME, these cagelike clathrin lattices stabilize highly curved membrane buds that grow into vesicles as they engulf associated cargo (see bottom image of Fig. 3 for a schematic of this process). In vitro assembly of clathrin within a solution results in closed, nanoscale cages with various shapes and sizes.

This remarkable process hinges on the clathrin and membrane being able to respond to the surrounding conditions by undergoing a range of physical transformations. Upon binding to the cell membrane, the cargo elicits a response on the cell surface, leading to recognition of the cargo and clathrin recruitment on the interior of the cell. At this stage, the clathrin must reorganize to form a cagelike assembly as the membrane wraps around the cargo. The cell must accommodate cargoes of varying size (~40 nm to several hundred nanometers) and shape; thus, the growing invagination must be sufficiently flexible to enable transport of a broad spectrum of vesicles. In this regard, the clathrin lattice must be sufficiently fluid in order to reorganize its connectivity to match the local shape of the cargo.

Although clathrin locally prefers six-membered rings (as in a honeycomb), the lattice is able to form five-membered and seven-membered defects by deforming the clathrin legs. For a closed polyhedral structure, Euler's polyhedron formula $V - E + F = 2$ dictates the relationship between the number of vertices V, edges E, and faces F (Euler, 1752–1753). For example, a cube has $V = 8$, $E = 12$, and $F = 6$, and Euler's polyhedron formula gives $8 - 12 + 6 = 2$. Similarly, a soccer ball is geometrically defined as a truncated icosahedron, which has 60 vertices ($V = 60$), 90 edges ($E = 90$), 12 pentagonal faces, and 20 hexagonal faces (total faces $F = 32$). Thus, the truncated icosahedron also satisfies Euler's polyhedron formula $60 - 90 + 32 = 2$. Clathrin's ability to form ringlike structures with different number of edges is essential in its ability to form closed structures that wrap around cargo of varying sizes and shapes.

Once the cagelike lattice is established, the clathrin lattice plays a role in stabilizing the invagination. Thus, the lattice must undergo a transformation to a solid-like structure after the connectivity is set to match the cargo shape and size. It is not clear whether this transformation is through some chemical signal or if the transformation is purely physical. However, modulating membrane fluctuations and local curvatures can induce fluid-solid transformations in a model clathrin system (Cordella et al. 2015). In this regard, one can envision using subtle changes to the local environment to induce transformations. These designed transformations

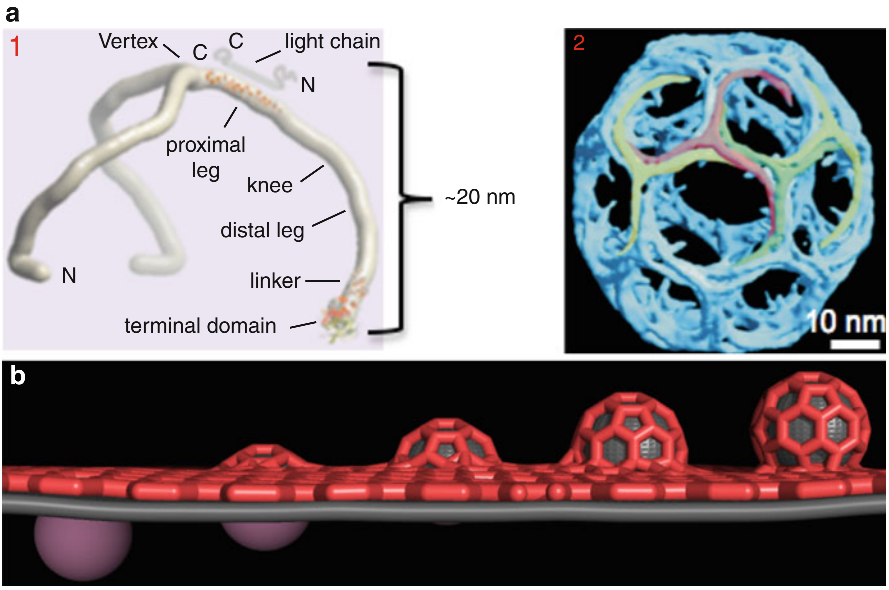

Fig. 3 Images of the protein clathrin, which spontaneously assembles and disassembles into nanoscale cages during endocytosis. The *upper left image* shows the structure of a clathrin triskelion, which is the monomer unit of clathrin that assembles into the cagelike lattices. The *upper right image* shows an example of a cagelike lattice that spontaneously assembles in vitro. The *bottom image* shows the progression of the events involved in endocytosis – the process that a cell uses to bring cargo from its exterior to its interior

would be desirable in a range of applications, including self-healing and controlled-release materials.

DNA nanostructures, as shown in Fig. 2, offer a pathway for the design of molecular architectures that undergo large-scale transformations. This idea of making molecular "transformers" is exploited to make DNA-based structures that undergo controlled nanoscale motions (Marras et al. 2015). The basic principle exploits the precise control over nanoscale assembly that is afforded by designed DNA sequences along with existing understanding of engineering design of mechanical structures. This culmination of macroscale engineering principles with molecular-level design provides a new approach to the formation of responsive and reconfigurable structures at the nanoscale.

Controlling Polymer Entanglement and Topology

The behavior of polymeric materials is strongly influenced by a range of physical effects that arise from the large molecular weight of the comprising polymer chains (Doi and Edwards 1999). Perhaps most significant for the dynamic behavior of polymeric materials is the influence of entanglements on the motion and relaxation of polymer chains within their spaghetti-like environment. The conformation of a chain in a highly concentrated polymer solution is almost unaffected by the interactions with their neighboring chains (Flory 1953). However, the motion of a polymer through the surrounding chains involves a fluctuating, sliding-type mechanism dubbed reptation (de Gennes 1971). This dynamic mechanism is extremely sensitive to the molecular weight of the polymer chains. For example, the simplest prediction for the scaling of the diffusivity D versus the molecular weight M results in the relationship $D \sim M^{-2}$ (Doi and Edwards 1999), which is close to the experimentally observed behavior. This extreme sensitivity of the chain motion to entanglements manifests a range of physical behaviors that are common characteristics of polymeric materials, including elastic response, viscoelasticity, and plasticity.

These issues of entanglement are also relevant to the dynamics of DNA within a prokaryotic cell and within the nucleus of a eukaryotic cell. Imagine, for example, the process of disentangling two meter-long strings that are wrapped up within a small enclosure. In the case of our genomic DNA, this enclosure is several microns across, yet the DNA "string" is still a full meter in length. Furthermore, the replication of the DNA results in the parent and daughter strands exhibiting similar final states after replication completes, which implies that they would be highly entangled. Thus, separating these strands into separate cells during cell division is complicated by the daunting task of disentangling these massively long polymers within an extremely small, crowded space.

The cell has devised a remarkable solution to this problem. There exists a family of proteins called topoisomerases that perform a range of manipulations on DNA (Wang and Giaever 1988). One such protein (called topoisomerase IV (topo IV)) is able to identify local crossings of DNA that constitute an entanglement, cut one of the crossing DNA strands, pass it across the crossing, and reconnect the DNA on the other side. This process effectively eliminates the entanglement and allows the DNA to undergo unhindered motion that is necessary for a number of life cycle processes, including segregation. Single-molecule measurements of the tension response of chromosomal DNA extracted from a frog egg (i.e., *Xenopus* egg cell) show a mechanical response that is much more compliant and fluid if topoisomerase IV is present than if it is absent (Marko 2008). In this regard, one can imagine utilizing topoisomerase IV to modulate the entanglements within a DNA material, which would alter its viscoelastic properties dramatically.

In many instances, DNA exists in a circular form such that the ends are married together into a continuous ring with no breaks. Closed rings exhibit several properties that cannot be altered regardless of how you reshape the ring. For example, imagine that you tie a knot in a string and then connect the ends. No matter how you deform the knotted string, the knot will not go away unless you cut the string. Thus, there is a property of the knotted ring that remains the same regardless of how you deform it. Another useful example is a telephone cord. If you twist a telephone cord and set the receiver down, the telephone cord will form interwound coils. Upon flattening the coiled cord without picking up the receiver, the shape of the cord now adopts a flattened conformation with no coils. The coils reform if you release the

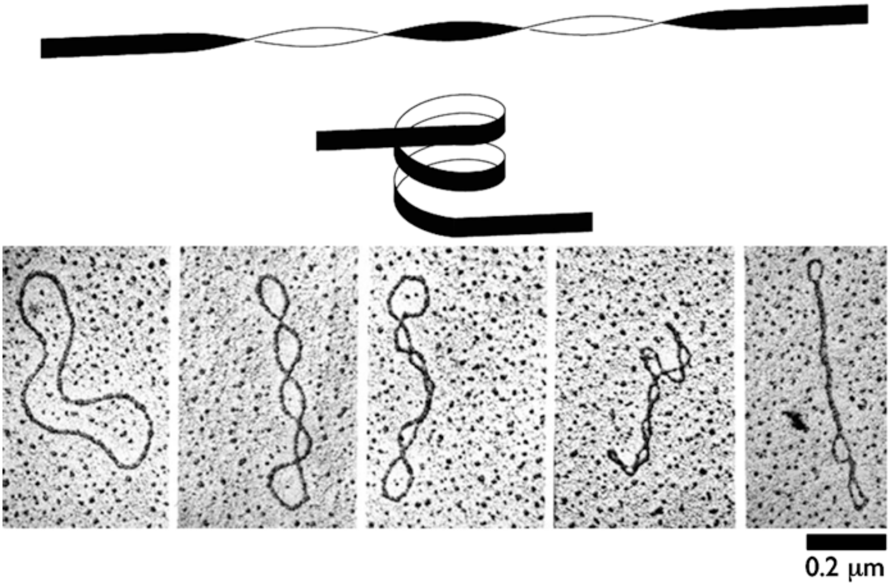

Fig. 4 Images showing the topological constraints that arise in a twisted DNA strand, resulting in a supercoiled structure. *Top image* shows a schematic of the interconversion of twist *Tw* and writhe *Wr*, resulting in the topological invariant linking number $Lk = Tw + Wr$. The *bottom image* presents electron micrographs of plasmid DNA with increasing linking number *Lk*. The writhed coils of DNA are called supercoils and are akin to the coiling of a twisted telephone cord

telephone cord, and they cannot be eliminated unless you pick up the receiver (breaking the loop) and untwist the cord by letting the receiver rotate until all the twists are eliminated.

The two examples in the previous paragraph represent properties of a closed ring that are analyzed in a branch of mathematics called topology. Topological invariants arise in many systems. Various examples can be used as curious and peculiar thought puzzles. For example, a teacup can be deformed into a donut, since both cases are described by a topological invariant of surfaces that contain a single hole.

Similarly, there is a topological invariant called the linking number *Lk* (White 1969) that applies to a closed ring (e.g., a DNA plasmid). The linking number *Lk* is defined as the sum of two topological quantities called twist *Tw* and writhe *Wr*; thus, $Lk = Tw + Wr$. The twist *Tw* is the number of turns of twist that is introduced into the ring, and the writhe *Wr* is a quantity that gives the average number of times the ring crosses itself in three-dimensional space. Figure 4 shows a schematic of the interconversion of twist and writhe. The top image has two turns of twist ($Tw = 2$) and no writhe ($Wr = 0$), and the bottom image is untwisted ($Tw = 0$) and has a writhe $Wr = 2$. Thus, the linking number remains $Lk = 2$ regardless of how the twisted ribbon is deformed. The bottom image of Fig. 4 shows five electron micrographs of plasmid DNA with increasing amounts of linking number, resulting in an increasing writhe in the form of tighter coiled structures (or supercoils).

The topoisomerase family of proteins includes members that twist and untwist the DNA strand (Wang and Giaever 1988). The various topoisomerases function by a range of mechanisms to introduce negative or positive turns of twist into the DNA. For example, the topoisomerase called gyrase binds to DNA, forms a small loop, cuts the DNA, and passes the DNA through itself (Reece et al. 1991). This process introduces two turns of negative twist per cycle. The balance of the various topoisomerases acting on the DNA dictates the degree of supercoiling throughout the cell cycle.

As indicated in Fig. 4, the degree of supercoiling dramatically influences the conformation of the DNA strand. Increasing the linking number by twisting the strand leads to tighter supercoiled structures and a more compact conformation. Since topoisomerases can control the degree of supercoiling over a broad range, these proteins have a remarkable capacity to control the global conformational properties of large DNA strands through the local process of introducing twist into the strand. These types of manipulations are very difficult to introduce into conventional polymer systems. However, topoisomerases provide an avenue for using polymer topology to dramatically manipulate the conformational properties of polymeric materials, resulting in materials that could undergo local and global shape transformations.

Interfacing Biomolecules and Inorganic Materials

Proteins have a range of accessible chemical moieties, including the 20 natural amino acids and numerous nonnatural amino acids (Langer and Tirrell 2004; Liu et al. 2007). However, a pure protein material is predominantly composed of elements in the organic region of the periodic table. Thus, the formation of inorganic materials based on biomolecular assemblies requires interfacing organic biopolymers with inorganic elements.

The natural world has numerous examples where inorganic elements interface with biomolecules Weiner et al. (2003). For example, the Great Barrier Reef (see Fig. 5) is a massive structure composed largely of calcium carbonate that is produced and maintained entirely by living organisms. This structure, which is viewable from space, is the largest example of such a structure. As such, it is reasonable to assume that interfacing biomolecules with inorganic compounds can result in the mass production of materials.

Several protein sequences have been identified to nucleate the formation of inorganic materials using solution-based chemistry (Seeman and Belcher 2002). Such materials open the door to the formation of a range of ionic, metal, and metal oxide materials using biomolecular structures as a template. For example, clathrin (discussed in the previous section) has been used as a template for the formation of nanoparticles of several metal oxides (Schoen et al. 2011). The approach is to

Fig. 5 The Great Barrier Reef is the world's largest structure that is produced and maintained entirely by living organisms. This structure demonstrates the ability for biomolecules to template and grow inorganic materials

develop peptide sequences that have one section that binds specifically to clathrin proteins and a second section that nucleates the inorganic material. This allows the facile incorporation of inorganic compounds at specific positions on the biomolecular nanostructure.

This concept is not limited to clathrin (or proteins in general). In a previous section, the concept of DNA-based assembly is introduced as a potential pathway for the assembly of complex nanostructures. The incorporation of specific DNA-protein sequences that bind to specific points on the nanostructure and nucleate inorganic materials may serve as a powerful framework for using such nanostructures for the formation of complex inorganic structures.

Conclusions

This chapter provides a general picture of how biological systems can be exploited for nanoscale engineering applications. The basic paradigms that are outlined within this chapter are illustrated using several key biological examples that are either currently exploited for specific applications or are ripe for translation to future technologies. Two main strategies are discussed for leveraging biomolecular systems – mimicking and co-opting. Both of these strategies have the potential to dramatically influence how we design, synthesize, and exploit molecules for the assembly of nanoscale structures. Following this path may lead to engineered systems that begin to incorporate the remarkable capabilities that biological systems have evolved for a range of chemical and physical processes.

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Convergence of Nanotechnology and Biotechnology

Hyo-Jick Choi and Carlo D. Montemagno

Contents

Abstract

This chapter is devoted to discussing the engineering and exploitation of life processes in artificial systems, the importance of value creation, and examples applying nanobiotechnology to solve current technical problems in environment and health. Understanding the process of life is a crucial step in the

H.-J. Choi (✉) • C.D. Montemagno (✉)
Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB, Canada

Ingenuity Lab, Edmonton, AB, Canada
e-mail: hyojick@ualberta.ca; montemag@ualberta.ca

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design and application of nanobiological systems. This naturally links an understanding of how life formed and evolved to how life processes can be engineered and purposefully harnessed. The union of nanotechnology and biotechnology has culminated in a new discipline, nanobiotechnology, through the synergistic leveraging of fundamental control of chemical, physical, and biological processes. Nanobiotechnology has, in turn, enabled both biologists to explore biochemical networks to develop a better understanding of life processes and engineers to propose an alternative approach to conventional fabrication technology. Because nanobiotechnology employs knowledge from both engineering and life science, methodology in both disciplines must be adapted to take full advantage of the opportunity to develop and demonstrate new ideas. The greatest challenge to achieving the full potential of nanobiotechnology is the successful transition from a bench-scale demonstration to the development and deployment of an economic technology. Presented are concepts and methodologies currently being exercised to advance laboratory achievements into solutions to environmental, health, and societal challenges.

Introduction

Nanotechnology has been one of the most frequently used terms in both academic and nonacademic disciplines in recent years. Manipulation in the small dimension has endowed nanotechnology with a multidisciplinary nature because understanding, synthesis, analysis, and modification on the nanoscale require skills and knowledge from many different fields. The term nanobiotechnology is used to describe the interface of nanotechnology with biology, which can be interpreted as the convergence between engineering and life science.

The framework and contents of a nanobiotechnological solution can be different depending on how one looks at the nature of the problem and how one approaches it. Despite the great number of efforts looking to employ "nano" solutions to biological challenges, scant attention has been paid to applying systemic engineering methods in nanobiotechnology. As a result, it has become more difficult to oversee the emerging technology and its trend due to the lack of a methodical perspective and the wide range of research topics nanobiotechnology embraces. There is a need to have organized approaches that can clearly guide the nature of research activities in this field.

The body of this chapter is comprised of three major sections. First, the general mechanisms associated with life are introduced in the context of engineering applications. Second, two different views are further discussed by introduction of biotechnology-nanotechnology interface and strategies of nanobiotechnology by adopting engineering models used in computer science. Lastly, exemplary research efforts are presented to support the applicability of nanobiotechnology in resolving big problems.

The Essential Components of Life Processes

Emergence of Life

The question of how primitive prebiotic systems evolved to the complex cellular life forms in existence today has been an important research topic to scientists. While its review is out of the scope of this chapter, studying hypotheses for the generation of life provides us with important lessons in engineering life processes or in applying the ideas/materials of nature to the fabrication of engineered devices/ materials. Several hypotheses that have been proposed to explain the origin of life in abiogenesis include (i) the primordial soup, (ii) the RNA world, (iii) the metabolism first, (iv) the lipid world, etc. (Oparin 2003; Luisi 2006). The primordial soup theory hypothesizes that the atmosphere of early Earth produced simple organic compounds spontaneously and their accumulation in water resulted in the synthesis of more complex structures such as amino acids, nucleotides, and proteins. The RNA world describes the RNA molecule as a critical, multifunctional component, which can self-replicate, catalyze biochemical reactions, and store information, at the early stage in the evolution of life. This approach is closely related to the emergence of a proteinless biological world. However, the metabolism-first approach hypothesizes that primitive metabolism formed by prebiotic chemical pathways preceded RNA. By looking at the difficulty of forming complex RNA structure in the prebiotic environment, the lipid world model argues that compartmentalization played a critical role in the emergence of cellular life and lipid-like molecules came before nucleic acid and peptide synthesis. Lipids self-assembled to form a boundary between internal and external environments, thus enabling diverse biochemical reactions. Thus, lipid world theory suggests that self-replicating, catalytic, and energy transforming vesicles are presumed to have contributed to the generation of a small environment enabling life processes.

Learning from Early Stage Life Generation in View of Engineering

Key concepts used in each hypothesis can be summarized as synthesis of both simple and complex molecular structures (nucleotide, peptide, lipid, and protein), storage/transfer of genetic information, catalytic activities, self-assembly/self-organization, self-replication, compartmentalization, and metabolism. Strictly speaking, several decades of studies have provided theoretical models, but there is relatively little evidence to support any of the hypotheses. None of the theories present a complete picture of the generation of life in a generally acceptable manner. As a model example among all the hypotheses, the demonstration of catalytic activity of RNA molecules (i.e., ribozymes) in biochemical reactions was regarded as a big leap toward a proteinless world (Kruger et al. 1982; Doudna and Lorsch 2005). As a result, experimental validation of the theory has predominantly been attempted by investigating RNA. This has contributed much to our understanding of early stage life in an RNA-dominated era and to the advancement of the RNA world theory.

In the view of biologists and chemists studying the origin of life, the most critical question they seek to answer is "which came first." However, when viewed from an engineer's perspective, importance is placed on applicability of the system, i.e., materials and principles, and application performance/efficiency. That is, major structural/functional components and principles in the evolutionary history of life provide good research tools to engineers, including (1) small and macro biomolecules, such as DNA, RNA, metabolite, ribosome, ribozyme, peptide, carbohydrate, protein, and lipid; (2) biological processes such as transcription (DNA to mRNA), translation (mRNA to protein synthesis), membrane/nonmembrane protein activity, self-assembly, and semipermeable function of the lipid membrane; and (3) collective metabolism that coordinates many individual components in the system. Since the primary goal for engineering research is to maximize the performance of a system and/or to create a system with new and unique functionality, engineers diverted attention to more complex natural organisms and their evolutionary life process, i.e., what components are essential to originate and maintain life and how the principles and materials of life processes can be controlled or applied to develop new systems.

Evolution of Life and Its Meaning to Engineering

An important question is how biological evolution can have impact on engineering. It is generally accepted that continuous evolution played an important role in the formation of a highly coordinated and functioning cellular system with well-defined structures, leading to the generation of emergent functionality. In line with the quote by Emerson "nature encourages no looseness, pardons no errors" (Emerson and Cabot 1883), organisms have evolved through natural selection to adapt to the new and changing environments, resulting in the appearance of new and complex features. This means that cells/organisms become better suited to an environment over time. It is important to note that this perspective is based on the selectionist hypothesis that molecular evolution is the result of positive selection. Although negative selection holds true, organisms were predicted to maintain constantly high genetic fidelity by adapting themselves to environments (10^{-10}–10^{-9} per base pair per generation) and by controlling mutation rates by diverse mechanisms (Miller 1996).

In contrast to the selectionists, neutralists believe that majority of mutations are neutral and governed by random genetic drift (Kimura 1968). Taken together, in spite of natural selection, mutation rate of living organism cannot go down below a minimum level possibly set by intrinsic physiological limitations (cost of fidelity) or by genetic drift (Drake 1991; Sniegowski et al. 2000; Lynch 2010). From this perspective, it can be inferred that current organisms with life cannot have zero mutation rate and their evolutionary mutation may depend on the current location in the big picture of evolutionary history of their life. In other words, a biological system with zero mutation rate cannot be the model for engineers.

It is therefore natural for engineers to seek more significant values from concurrent cellular forms than from primitive cellular system. By doing so, there arises a question regarding what organisms to choose for one's research model. While it is not closely related to our topic, it is worth noticing that ethology/neuroethology is focused on understanding how diverse organisms produce similar behaviors and in the case of neuroethology comprehending common mechanisms for those behaviors. However, it is accepted that current technology cannot fully track past evolutionary history nor predict future evolution of each organism; nevertheless, it is possible to examine and evaluate its life process. Therefore, the authors believe that this is the place where engineering efforts begin. Finding a biological system, understanding its life processes, and utilizing the structure and function in engineering device are the cornerstone steps to enable the convergence of biology and physical sciences.

Engineering of Life Processes

Interfacing Biotechnology with Nanotechnology

Living Systems as a Guideline in Engineering

An important question is why engineers try to learn from living systems. As described in section "Learning from Early Stage Life Generation in View of Engineering," due to the evolutionary process of natural selection, biological organisms have developed a current cellular system with a highly complex, but also efficiently functioning structure. Most of all, organisms have evolved to have high-fidelity replication of their genome which enables genomic stability. It is important to note that, to date, even the most advanced technology has not successfully fabricated such a precisely functioning and efficient machine in the few-nanometer size range.

The ready-made biomolecular machines in cells, through further functionalization or modification, can meet the needs of various technological applications. The neuronal network of a human brain can perform information processing ~10^4 faster than latest smart phone and has 500 times more memory capacity than the world's largest capacity hard drive while using a very small amount of energy (Fischetti 2011). This is a good example showing how a seemingly simple neuron can generate emergent functionality upon forming a complex network. Water transporting activity of aquaporin (AQP) proteins is another example showing how efficiently our biological system is designed and organized. AQPs function like a valve to transport water molecules across the cellular membrane in response to osmotic gradient. It is notable that the water transporting performance of AQPs is two to three orders higher than commercial reverse osmosis (RO) membranes. Similarly, F1 motor of ATP synthase exhibits near 100 % energy conversion efficiency surpassing any present mechanical systems available (Wang and Oster 1998).

It is also interesting to compare fidelity level between the engineering and natural systems. Although direct comparison is not justified given the life span difference, it is noteworthy to observe that the error rates during transcription by RNA polymerase and translation by ribosome in *E. coli* have been estimated to be $\sim 10^{-5}$ per nucleotide and $\sim 10^{-4}$ per amino acid, respectively. On the contrary, the yield for the semiconductor device, which can be fabricated in short time using the most advanced nanofabrication technique, is just about 80 % even with an optimistic estimate. Therefore, although current biological system is constantly in a state of evolution, the fact that up-to-date technology cannot compete with evolved natural systems in terms of efficiency and fidelity can lead to the conclusion that living organisms with near-optimal functionality can be used as a guideline in engineering systems.

Biology for Nanotechnology

The structure and function of biological systems can provide a new path to challenge conventional technological problems in engineering. It is useful to ask how engineers can apply natural systems to solve technical problems. At one level, microscopic and macroscopic cellular components can be regarded as biomolecular machines functioning as selective barriers, sensors, motors, pumps, filters, actuators, pipes, conveyor belts, etc. (Drexler 1992). On the other hand, emergent functionality and inter-/intracellular communication including metabolism and neural information processing provide a path that motivates engineers to develop higher-level functional system with lifelike efficiency. This means that engineers can utilize biological system not only as a component set to construct engineered devices with new or improved functionality but as a knowledge model to create a new system-wide approach or framework.

The distinguishing features of the cell include metabolism, compartmentalization, self-assembly, and self-replication (Fig. 1). As a whole, cells can be viewed as biological system with emergent functionality resulting from the processing of information through the manipulation and synthesis of materials in response to diverse environmental conditions. In living organisms, the level of information and dominant life processes will vary depending on the scale of the subject system, namely, whether the activity lies at the subcellular or cellular or multicellular level. For example, single-molecule activity in a cell can be evaluated as a part of the integrated metabolism of the entire cell. However, the appearance of emergent functionality which is the result of interactions among many small/large molecular interactions makes it difficult to distinguish and characterize the biological role of specific components in such a complex system. This is in part due to the lack of proper analysis tools that identify the role small-scale components have in system-level function.

It is natural to ask what levels of biological systems can be interfaced with engineering. There have been two approaches in biological science to understand life processes: top down and bottom up. The first approach is to understand the

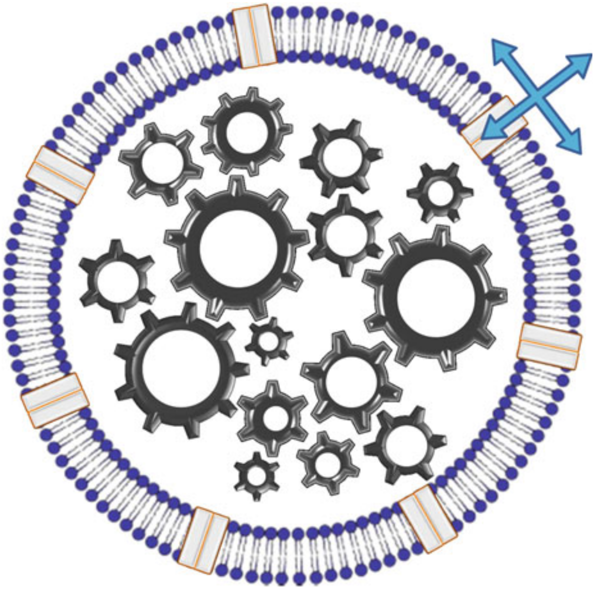

Fig. 1 Schematic representation of a cell. Cellular compartments enable modulation of biological process in a coordinated way. The cell is constantly professing information via intercellular and intracellular biochemical networks. *Arrows* indicate the direction of information flow. The same principle can be applied to an organelle

entire picture of biological behavior of the system and then decompose it to acquire detailed information. The second approach combines scattered information from elementary- or molecular-level components to build a system-level understanding.

In the context of nanotechnology, the top-down and bottom-up approach indicates the fabrication of small products (devices or materials) from bulk materials and formation of large assembly from elements or molecules, respectively. It is important to note that nanotechnology used the top-down and bottom-up terms to reflect the direction of the change in the physical size of materials. However, in biology, the relative degree of abstraction of information determines the top-down (toward low-level abstraction with more details) and bottom-up (toward high-level abstraction with less details) approach. Systems biology provides a good example (Kitano 2001). Top-down systems biology is driven by a large experimental data set to find biological mechanism via high-throughput genomics and bioinformatics. In contrast, bottom-up systems biology combines component-level mechanisms into a model for the entire system behavior. In the bottom-up approach, small modules assemble to form a system. Traditionally, the top-down approach has been adopted in biotechnology to investigate life processes of living organisms.

Top-Down and Bottom-Up Approaches in Nanobiotechnology

The question of what approach nanobiotechnology employs is the same as the one of whether nanobiotechnology can be split into nanotechnology (engineering) and biotechnology (biology). In many cases, it might be meaningless to ask which approach dominates the system if one does not want to lose the philosophy of nanobiotechnology, which is an integrative fusion technology. While a system can be decomposed based on physical factors such as size, it is difficult to differentiate the relative importance of each discipline in the creation of the system because the term "nanobiotechnology" is used to mean various things in a wide range of areas.

Synthetic biology and biotic/abiotic hybrid systems provide good examples of the bottom-up approach. The synthesis of amphiphiles, formation of vesicles or synthetic membrane from their self-assembly, construction of an artificial organelle using protein-incorporated vesicles, intervesicular communication through the exchange of substances (i.e., information transfer), in vitro replication of cellular metabolism, and protocells featuring division, gene replication, and gene expression represent a bottom-up approach (Ellington and Szostak 1990; Szostak et al. 2001).

Examples of a top-down approach can be found in research utilizing genetically modified organisms to enhance application-specific characteristics of an existing organism. In microalgae research, there has been considerable focus on synthetic genomics, genetic modifications, and metabolic engineering for the improvement of lipid synthesis (yield and composition) by increasing growth and photosynthetic efficiency (Chisti 2007). In tissue engineering, both the top-down and bottom-up approaches have been used to make engineered tissues by combining cells and scaffolds. Therefore, instead of struggling to unravel the biology and engineering strands, it may be more reasonable to understand nanobiotechnology as a merger of multiple disciplines, enhanced with new features, or a mediator between those two disciplines.

Nanotechnology for Biology

Compared to the contribution of biology as a source of materials and principles, nanotechnology mainly provided ways to investigate biological phenomena. This is attributed to the origin of nanotechnology. Since the first introduction of nanotechnology as a concept in 1959, its development has been driven by semiconductor device fabrication technology (Feynman 1960). Due to the direct impact of the technology to the market, huge efforts have been successfully made to increase the memory capacity/speed of semiconductors and to scale down the feature size.

There is no doubt that semiconductor device fabrication technology has driven the growth of microelectromechanical systems (MEMS). Consequently, process technologies such as semiconductor and MEMS have evolved to find applications in biology and medicine. Nanotechnology research has been focused on the development of (1) measuring tools in biological science, (2) implantable nanomachine/therapeutics, (3) sensors, (4) analytical biochips, and (5) drug delivery mechanisms.

In parallel, nanoparticle research evolved in the fields of chemistry, physics, and materials to develop new functional materials for use in the life sciences. The main topics of research focused on the development of (1) new particle architectures (shape/morphology control), (2) production techniques (simple process/method, high yield), (3) active drug delivery systems (optimal drug loading, protection against environment, controlled release), and materials with (4) biocompatibility (bioinert/stealth) and (5) target-specific recognition, reporting, and action (fluorescence, optical/electrical/magnetic properties, cytotoxicity, other surface modification for multiple functionalization).

A list of examples showing how fabrication technology and nanoparticles benefited biological science in understanding cellular physiology can be found in earlier reviews (Roco 2003a; Panyam and Labhasetwar 2003; Erickson and Li 2004; Sun et al. 2008). Historically, both fabrication and nanoparticle technologies have focused on making tools to detect, diagnose, visualize, deliver, and treat disease. Addressing this challenge requires the application of multidisciplinary knowledge in the areas of (i) surface modification/functionalization and organic particle synthesis from chemistry; (ii) fabrication technology, process development, and inorganic particle synthesis from engineering; and (iii) biocompatibility, cellular/biomolecular materials/life process from biotechnology, and in vivo animal/clinical study from medicine. This multidisciplinary approach has resulted in major advances in the development of medical therapeutics and diagnosis.

A key historic characteristic of process technologies, engineered systems, and in vitro systems lies in "value-creation activities" by developing a new design, process, material, and/or device for providing solutions to technical problems. In engineering, value is created through optimization of existing technologies and invention of a new technology. This can take many forms including increases in efficiency and performance through the optimization of processes and manufacturing methods, the addition of new functionality, or by providing a contribution to the society in the form of public goods such as environmental safety, health, education, and national security.

Silicon-based semiconductor device manufacturing showcases an important role, not only as a driving force for scale-down of materials and devices but as a representative successful example of nanotechnology. Scaling-down technology could reduce the manufacturing costs and improve device performance. That is, a close relationship between technology development and profit maximization in semiconductor industry presumably led to considerable research efforts devoted toward smaller scales.

The driving force for technical advancement of nanobiotechnology can be primarily credited to economic and social value-creation activities. In most cases, interconnections can be found among technical, economic, and social values (Roco 2003b). This relationship can be illustrated in view of the vaccine industry. Limited market size (> \$25 billion worldwide in 2010), expensive vaccine development process (~\$1 billion in 2010), long development period (10–30 years to approval), and high production costs (\$50 million to \$300 million for manufacturing plant) have been recognized as the major hurdles to vaccine development (Douglas et al. 2008). This is one of the main reasons for failure of transition from Phase II to Phase III clinical trials for new vaccines (Davis et al. 2010). Despite society's desire, market's inability to provide new vaccines exemplifies the importance of the economic value even in the advance of the biotechnology. It also demonstrates that the meaning of "value" can be further extended to include public/society value, when it is related to the social welfare such as public health and security in both the bio-to-nano and nano-to-bio approaches. Although the costs outweigh the financial benefit, societal value can play an important role as an input factor in promoting technical development. As another example of the interconnected relationship

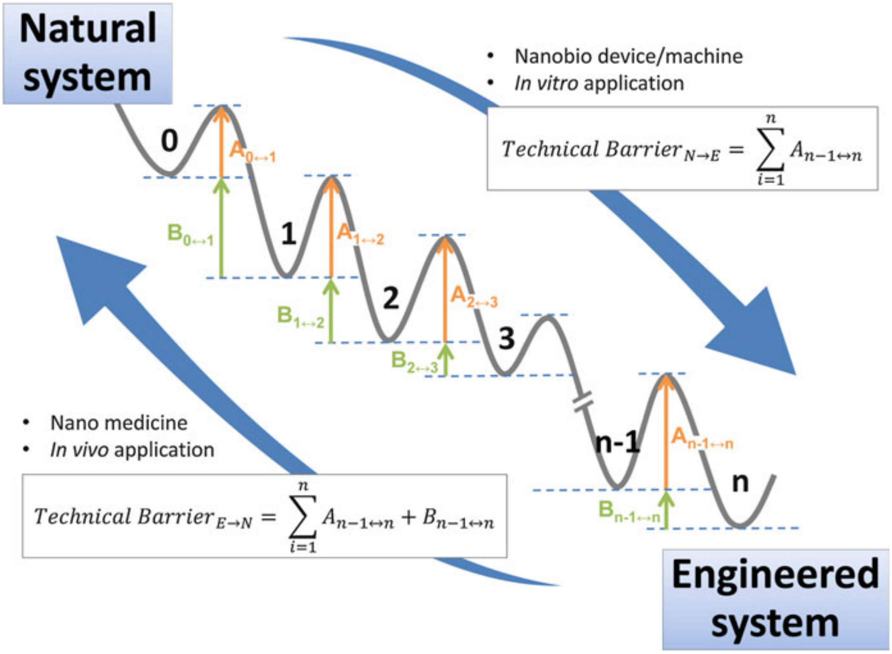

Fig. 2 Schematic diagram showing a possible sequence of barriers for the biology-to-engineering and engineering-to-biology routes. Therapeutic application of engineered system is expected to face higher barriers due to more strict requirements

among the three segments, the lessons learned from semiconductor technology may imply that the major part of the "value creation" in engineering can be achieved by commercialization of the technology in the market because of its direct implication on the society. Therefore, except in special cases, to be successful, the developed system must overcome the technical barriers of scalability, within-batch and batch-to-batch quality control, low production cost, environmental safety, stability under environmental conditions, etc. (see Fig. 2). Additionally, any engineered systems aiming at in vivo application (nano-to-bio) such as nanomedicine need to comply with the more strict safety and efficacy requirements, thus increasing the technical barrier in Fig. 2.

Strategies of Nanobiotechnology

Engineers assemble a broad array of skills and knowledge and apply them toward solving important technical problems of our age by creating inventions and ideas, constructing new materials and systems, and improving the performance of existing systems. Precedents suggest that the advancement of technology, whenever possible, should have economic and social values. But, before one discusses how nanoscale technologies can solve large societal problems, the first, most critical

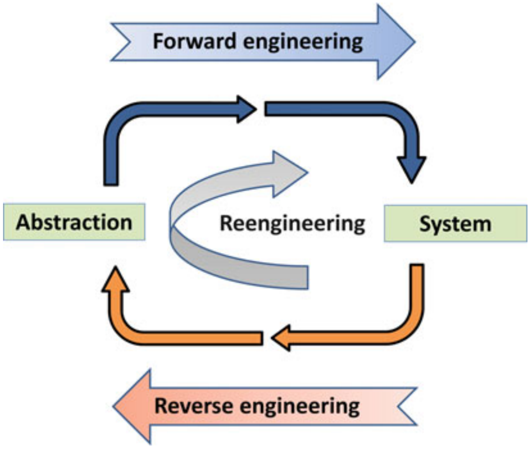

Fig. 3 Schematic representation of different engineering approaches

step is to identify strategies for analyzing and improving a system and how to collect and realize ideas. This question is closely related to the overall engineering process, which can be effectively applied to nanobiotechnology. Therefore, the authors would like to discuss how nanobiotechnology can be interpreted in terms of the three engineering approaches: forward engineering, reverse engineering, and reengineering approach, following the introduction of the basic definitions (Chikofsky and Cross 1990). Our goal is to find a descriptive language and establish a conceptual framework for the systematic assessment of nanobiotechnology.

Forward Engineering Approach

Forward engineering shows how abstraction can be shaped into a real system, representing normal system development process (Fig. 3). The forward engineering approach is composed of three major steps: (i) recognizing problems/goals (requirements), (ii) defining solutions (design), and (iii) building/constructing and testing/evaluation (implementation). Moving from high-level abstraction to the subject system increases the amount of complexity. For example, forward engineering transforms a model into a physical realization using working tools, like going from blue prints to building a car. It is also noted that forward engineering concepts can be applied not only to the whole process but to transformations between two different levels of abstractions and within the same abstraction level.

Reverse Engineering Approach

In contrast to forward engineering, reverse engineering analyzes the subject system to understand how structural and functional components behave (Fig. 3). In other words, reverse engineering aims at decoding the system to disclose key ideas or methods of the product in the following order: product, opposite design process, and abstraction. Then, this information can be used as an efficient method to systematically monitor and maintain the software, as well as to duplicate or improve the hardware. In the same way as forward engineering, the reverse engineering approach can start from an existing system, thus spanning the whole stage or at any intermediate stages. Since reverse engineering decodes the principle of system functionality, it has been widely adopted in industry to inspect and/or reproduce existing products in the market. Importantly, reverse engineering itself does not change the system. Rather, it mainly focuses on the investigation of the whole or a part of the system.

Reengineering Approach

Reengineering is defined as the transformation process when an existing system is restructured into a new one for improved characteristics (Fig. 3). In this case, as can be predicted, reverse engineering should be followed by forward engineering. When the existing system does not accommodate the technical or economic requirements, information/knowledge learned from reverse engineering process can be used to replace the entire or part of the old system with new architecture and features. As a result, reengineering can be described by the sum of reverse engineering, forward engineering, and change of the system (i.e., changes of functionality or implementation technique). However, it is important to note that each approach has its own strength and importance. Then, when does one need reengineering? The answer to this question depends on the benefits of reengineering, which can be quantified by the decision matrix proposed by Jacobson and Lindström (Jacobson and Lindström 1991). According to a changeability-business value relationship, reengineering is only desirable when a system exhibits low changeability and high business value.

Engineering Approaches in Nanobiotechnology

Nanobiotechnology consists of two axes, i.e., the natural and engineered systems, as exemplified by biology and engineering, respectively (Fig. 4). As previously described, nanobiotechnology functions to link biology to engineering, and biological materials or principles of life processes have been adopted to develop high-performance engineering materials or devices. A practical perspective for looking at biological system is to describe its contribution to engineering in two different ways: structure and function. Structure represents the materials or components contained in the organisms. Function represents principles or metabolisms used to maintain the life process of the organism. Viewed from an information technology perspective, structure and function serve as hardware and software to represent living organism (i.e., a subject system), respectively. In other words, structure and function play a role as an information source in creating engineering systems. For example, DNA which stores genetic information can be seen as software, and ribosomes, which use the information delivered by DNA to synthesize proteins, can be tantamount to hardware.

Nanobiotechnology can function to bridge the gap between information source (e.g., biology) and realization of the concept/generation of a new system (e.g., engineering). In general, development of new engineered systems proceeds along the following steps: (1) development of goal set to meet demands, (2) system design by identifying optimal components (materials, functionality, performance, etc.),

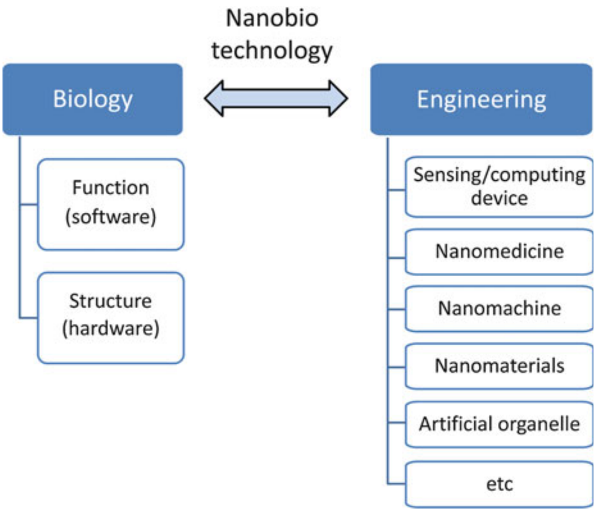

Fig. 4 Application-/function-based division of nanobiotechnology into biology and engineering. Nanobiotechnology can be the output of a fusion of two disciplines (biology and engineering) and/or functioning as a conduit connecting them

(3) preparation of components and building up a system by adopting useful techniques (genetic engineering, protein engineering, nanofabrication, biochemical engineering, etc.), and (4) evaluation of the system. This begins with concept/objectives and ends with construction of a nanobio system, which can be defined as forward engineering approach.

Note that an existing natural or engineered system can be decomposed for better analysis of its system using nanobiotechnology (reverse engineering), which can then be used to create more advanced system (reengineering). A biological system is composed of multicomponent interactions comprised of genes, proteins, and metabolites. The development of high-throughput microarray technology paved a way to investigate signaling pathways among those constituents. This has resulted in reverse engineering being the preferred approach to study intracellular biochemical networks such as metabolism, protein signaling, and gene regulation by monitoring specific cellular response through the analysis of mRNA, DNA, proteins, and metabolites under various perturbation conditions. Therefore, not only can biomolecular or biochemical characterization tools including flow cytometry, Förster resonance energy transfer, and fluorescence cross-correlation spectroscopy play an important role in probing biological networks, but genetic engineering methods such as construction of artificial constituent or network system to identify and modify existing network are used to better understand biological networks.

The tremendous potential of nanobiotechnology lies in the fact that it provides tools for both detection and treatment. Functionalized nanoparticles, as one example, can be employed to sense specific intracellular signaling cascades. Nanomachine/nanomedicine can detect, diagnose, and fix errors in biological networks. Therefore, development of nanobiotechnology can be envisaged to contribute to extending insights into biological system to modification/treatment of life. To this end, reverse engineering and reengineering may provide a good strategy when working together with a synergistic relationship.

Strategies for Implementation

Clearly, a key element to the realization of idea incorporates the proper selection and development of material manipulation techniques for all engineering approaches chosen. This means that synthetic/natural materials, devices, processes, functionality, and architecture comprising the system should be specifically modified and designed to implement ideas. To this end, technologies used in life sciences and chemistry can be employed to engineer biomolecules or to interface biological system with engineered system (and vice versa). However, due to the application-specific nature of implementation methods, it is difficult to sort out and describe all the relevant technologies in detail in this chapter. Therefore, research strategies relevant to the manipulation of major natural/synthetic molecules are selectively discussed below.

Bioconjugation

One of the key techniques in nanobiotechnology is how to establish intermolecular linkage (see Fig. 5). Bioconjugation methods have been widely used in life sciences to build a molecule-molecule complex by coupled chemical or biological reactions between reactive groups and functional target groups present on diverse molecules (i.e., nucleic acids, oligonucleotides, amino acids, peptides, proteins, antibodies,

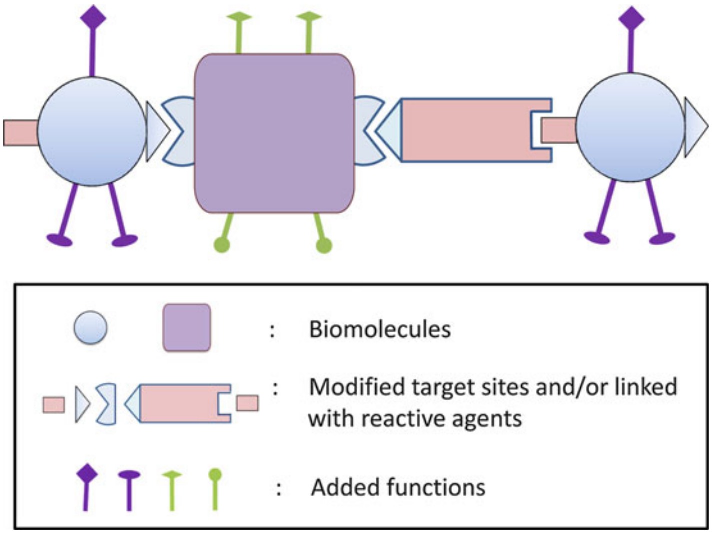

Fig. 5 Schematic representation of the bioconjugation strategy for biomolecule-to-biomolecule linkage

carbohydrates, lipids, synthetic polymers, etc.) (Hermanson 2013). Bioconjugation process can be described by two steps: (1) selection of functional groups to attach and (2) modification of attachment site. More specifically, the first stage adds new functions to the target molecules such as cross-linking and tagging for the purpose of change in physical properties, immobilization, selective isolation, identification, and detection. The second stage includes identification and modification of target sites on the molecules/substrate, followed by conjugation with reactive functional groups. Bioconjugation reactions can involve multiple steps with different types of biomolecules and reactive agents. However, alternation in the biomolecular structure may induce conformational change or shield/modify important functional groups of biomolecules. Therefore, it is important to design a conjugation strategy such that original functionality of involved molecules should not deteriorate after modification and/or conjugation processes. From practical application point of view, bioconjugation methodologies can be used as essential tools to build biomolecule-based engineered system through precisely controlled molecular assembly (e.g., immobilization of biomolecules on chemically/biologically modified substrate).

Selection of Aptamers/Recognition Elements

Aptamers are affinity molecules such as oligonucleotides and peptides with target binding specificity through the artificial evolution process (described briefly below) (Klussmann 2006; Mayer 2009). In case of nucleic acids aptamers, binding depends on three-dimensional structure of the single-strand nucleic acid. Thus, alteration of its sequence can provide the control and greater flexibility in target-specific conformation for binding to diverse targets (ranging from ions to cells). Aptamers are isolated by the repeated cycles of in vitro selection and amplification, which is called SELEX process (systematic evolution of ligands by exponential enrichment). Briefly, a pool of nucleic acids undergoes a binding test with target molecules, followed by the selection of bound oligonucleotide and amplification using polymerase chain reaction (PCR for DNA) and reverse transcription polymerase chain reaction (RT-PCR for RNA). Thus, as one can expect, multiple rounds of the process increase the target-site specificity during the selection process of optimal sequence with highest affinity. On the other hand, peptide aptamers are selected by affinity tests between target proteins and a library of bioinert scaffold proteins with a variable peptide loop. For example, genes encoding peptide libraries can be inserted into the coat protein genes to be expressed on P3 of M13 bacteriophages. This phage library is incubated with target proteins, followed by the selection of bound phages. After elution, *E. coli* cells are infected by the selected phage for amplification and production of phage for next cycle. Multiple selection and amplification processes result in the optimal peptide aptamer. The high selectivity and affinity of aptamers offer potential clinical applications to diagnostics, therapeutics, and biosensors. From the perspective of engineered systems, the principles of aptamer and its screening process have been applied to functionalize materials (e.g., nanoparticles, quantum dots, nanotubes, and cantilever) for selective detection and immobilization of target materials (see Fig. 6).

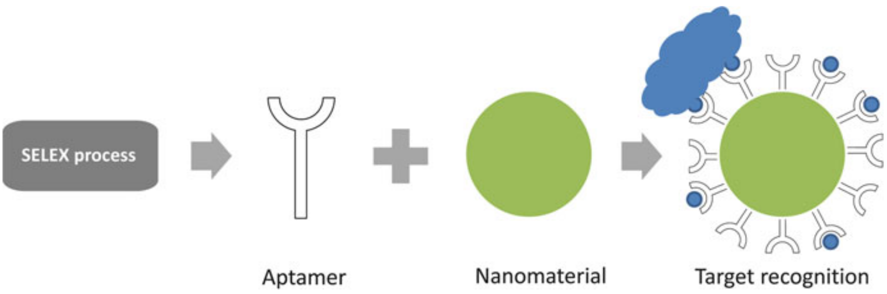

Fig. 6 Schematic representation of aptamer-functionalized nanomaterial generation

Polymer Design/Functionalization

One of the biggest challenges in nanobiotechnology is to increase candidate materials available to engineering (Jones 2008). Proteins and nucleic acids are made by sequential arrangement of building units such as amino acids and nucleotides, respectively. The characteristics of individual unit, sequence, content, and interunit interaction determine structure and function of biomolecules. Lipid blocks self-assemble to form membranes of cells. Biomolecules and block copolymers share a common feature to construct architecture by assembly of their own building blocks. This indicates potential applicability of block copolymers in mimicking cellular components. For example, amphiphilic block copolymer can spontaneously self-assemble to form nanostructures such as micelles and vesicles. The benefits of polymers over natural lipids are their long-term stability, flexible surface functionalization, and easy scale-up. So, without lowering activity of embedded proteins, synthetic polymers provide engineers with more freedom/flexibility in design and enhance economic benefits. Regarding assembly of each block, customized polymers can also be designed for specific applications through the selection and assembly of ready-made polymer blocks with diverse functional groups (Fig. 7).

In order to achieve this goal, polymers need to be modified to have reactive functional groups, which can be coupled with other blocks or molecules. Organic chemistry techniques used in bioconjugation process can be also employed to modify polymer blocks containing conventional functional groups (e.g., amine, carboxylate, thiol, hydroxyl, and carbonyl) and attach desired functional groups (e.g., UV cross-linker and cycloadditional reaction groups) (Hermanson 2013). Abundant tools supplied from organic chemistry enable the manipulation of both natural and synthetic materials, the fabrication of natural/synthetic or biomolecule/engineered device hybrid systems, the construction of architecture to mimic the structure and function of natural biological system, the establishment of polymer-based building block library, and the scale-up production of cost-effective high-performance materials as an alternative to native biomolecules.

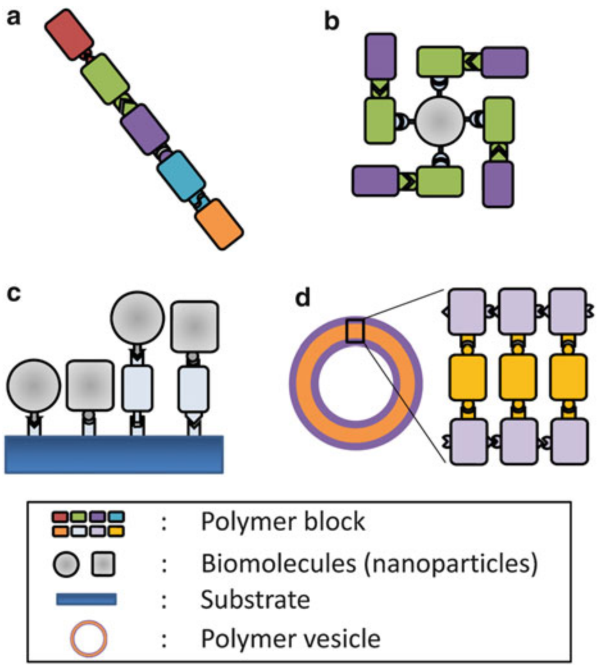

Fig. 7 Application of polymer building blocks to the construction of (**a**) sequential array of polymer blocks, (**b**) functionalization of biomolecules or nanoparticles, (**c**) immobilization of biomolecules/nanoparticles on substrate, and (**d**) polymer vesicles

Small-Scale Nanobiotechnology Challenges Big Problems

Most experts do not deny the potential importance and impact of nanobiotechnology, but when asked about the future, they are inconsistent in their opinions. This is presumed to be related to the uncertainty about commercialization of nanobiotechnology in the near future (Mazzola 2003). It is important to note that novel ideas do not always lead to products, especially if they do not fulfill scale-up requirements. The technology must be competitive in ideas (e.g., creativeness, high performance), market (e.g., cost-effectiveness, existing and latent demand for the technology), and manufacturing (e.g., batch quality control, low investment, low production cost) and be compatible with environment and health. Certainly, such severe requirements raise concerns among scientific community that commercialization of nanobiotechnology may only be a myth in the distant future. At the same time, undeniably innovative ideas and constant progress with a systematic approach can greatly accelerate the commercialization process.

For this reason, three research ideas are proposed in this chapter to showcase how nanobiotechnology can be employed to challenge big problems in environment and health. In a broad sense, two strategic approaches have been adopted: ideas from nature provide a solution to air/water pollution problems and ideas from engineering provide a solution to health problems. This section also highlights how implementation tools described in section "Strategies for Implementation" can

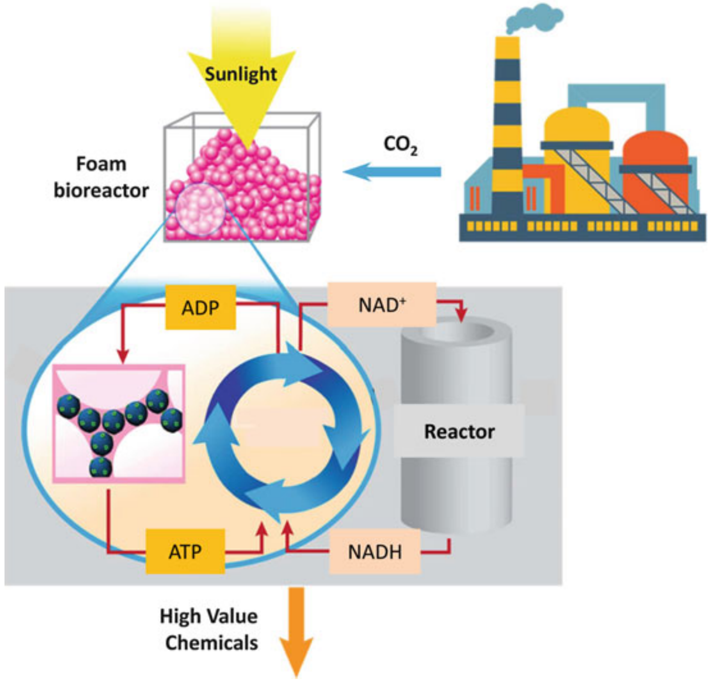

Fig. 8 Schematic representation showing the foam-based artificial photosynthesis to capture carbon dioxide and its application to produce carbohydrates from flue gas

contribute to the transformation of ideas to reality. Although a limited number of empirical examples are provided below, they are expected to show that generation of creative approach will advance the progress of nanobiotechnology by creating more opportunities.

Air Pollution

Carbon capture and storage (CCS) technologies have gained popularity in the last decade as a means to reduce carbon dioxide (CO_2) emissions from fossil fuel plants. Despite being highly effective in lowering carbon emissions, they have not become a commercialization reality yet because of high cost for CO_2 separation (capture and desorption) (Haszeldine 2009). Fortunately, plant cells mitigate CO_2 in the form of photosynthesis to produce carbohydrates such as sugars and starch. Individual plant cell acts as a biochemical reactor taking CO_2 as input and delivering carbohydrates and oxygen as output. With this background in mind, an idea of artificial photosynthesis system can be proposed for CO_2 sequestration (Fig. 8). The key driver of this technology is twofold. First, a significant value of the artificial photosynthetic system is its capability to capture CO_2 without any energy intake other than sunlight due to enzymatic cascade reactions. Second, carbon fixation leads to the production of carbohydrates as a by-product, which can be converted into new valuable chemical compounds (i.e., biofuel, sugar compounds).

To realize ideas, a bottom-up approach can be employed to accommodate the following technical challenges:

1. Light-driven ATP producing artificial organelle can be produced from BR-ATP synthase-polymersomes, which can power Calvin cycle enzymes (Choi and Montemagno 2005; Wendell et al. 2010). Efficient material consumption and recyclability are representative characteristics of cost-reducing factor.
2. Creation of an environment for artificial organelle as a mimic of cellular cytoplasm can be addressed by thin aqueous channel of foam, which can be applied to generate near-cytoplasmic physiological environment for biomolecules and organelles. The coexistence of the nano- and macrostructure within the same platform makes foam ideal for application in scaling-up of the nanobiological system.
3. Reconstruction and control of Calvin cycle metabolism by redesigning or engineering of enzymes and/or photosynthetic pathways. The goal is to maximize stability and activity of enzyme and thus to increase efficiency of carbon fixation and carbohydrate production by modifying existing biomolecules in a creative way.
4. The bioreactor and separation methods can be designed for selective collection and purification of metabolites. This will contribute to the reduction of manufacturing/material costs.
5. Carbohydrates (i.e., glyceraldehyde-3-phosphate) can be further converted to more valuable products. These will significantly increase the value of end products.

This project shows how engineering can be interfaced with biology from the design of the application-oriented concept to the realization of the idea by the modification of the life process. Important success factors in this project are how to optimize performance of individual functional/structural unit, how to engineer collective metabolic pathways, and how to design whole process system. These will determine the cost competitiveness of the product. In spite of substantial technical hurdles ahead, considering current progress in artificial organelle, foam technology enabling scale-up of nanobiological system, and bioreactor design, realization of plant cell's photosynthesis is certainly not far away from now.

Water Purification

Almost 10 years ago, protein-embedded membrane concept was proposed as an alternative to conventional water purification membranes. This idea began by identifying the function and mechanism of AQP proteins found in bacteria, plants, animals, and human (Borgnia et al. 1999). Remarkable properties of AQPs such as high water permeability, high selectivity, and low activation energy for water transport satisfy critical requirements for application in water purification membrane fabrication. These advantages led engineers to apply AQPs to the development of water purification membrane. But earlier results were not consistent and deviated from expected performance level. For this reason, a new approach can be suggested here to gain highest level of both salt rejection and water permeability. The core of the proposed concept lies in an ideal division of duties between biomolecules and the engineering process to overcome existing technical problems. This can be accomplished by maximizing functionality of individual components in a separate but well-coordinated way utilizing bioconjugation and polymer functionalization techniques.

Depending on the strategy of membrane design, vesicles or planar membranes with embedded AQPs have been used in fabricating water purification membranes. Considering the pros and cons of each method, a new approach can be designed for multi-objective optimization, thus to maximize the performance of the protein and membrane without compromising scalability. In brief, the idea can be described as the immobilization of AQPs onto the functionalized substrate using engineered β-sheet peptides. The proposed strategy is composed of four feasible stages:

1. Genetic modification as well as optimal purification technology can be employed for high-yield protein production toward cost-effectiveness of the technology.
2. Detergents stabilizing membrane proteins can be replaced with functionalized β-sheet peptides (Fig. 9a) (Tao et al. 2013). Importantly, middle or end of the peptide can be modified to have cross-linking functional group for the creation of chemical bonding to the substrate and surrounding materials (Fig. 9b(i)).
3. Surface of support membrane (or substrate) can be functionalized to covalently immobilize AQPZ proteins to substrate (Fig. 9b, c). Specifically, alkyne-functionalized support can be used to immobilize AQPZ proteins stabilized by azide end-functionalized β-sheet peptides through azide-alkyne cycloaddition (Fig. 9b).
4. Peptide-to-peptide or peptide-to-filler materials can be cross-linked to prevent ionic leakage (Fig. 9d). Cross-linking neighboring peptides or filling space with ionic leakage-free and cross-linkable materials can prevent leakage, resulting in high salt rejection. Also, cross-linking does not affect the structural and functional activity of AQPZ proteins because proteins are not involved in the reaction, but functionalized engineered peptides are.

The key concept of this approach was inspired by the engineered β-sheet peptides as a replacement of detergents; however, more value was found in functional modified peptides. That is, it is possible to manipulate AQPZ proteins without adversely affecting their water transporting activity. In addition, since AQPZ immobilization principle depends on specific chemical reaction between protein-stabilizing peptides and support membrane, it is possible to form a single

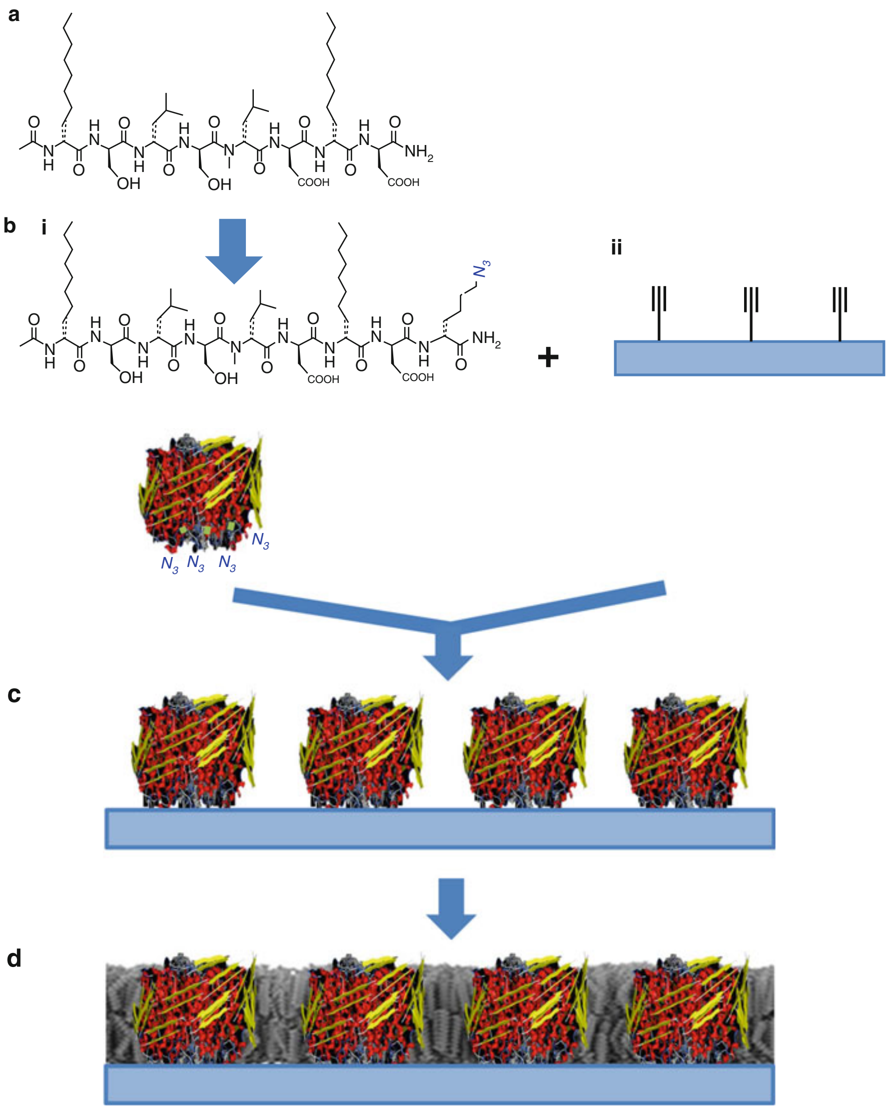

Fig. 9 Fabrication of AQPZ-immobilized water purification membrane. (**a**) Engineered β-sheet peptides; (**b**) (*i*) azide functionalization of the peptide and stabilization of AQPZ, (*ii*) alkyne-functionalized support; (**c**) immobilization of AQPZ onto the support; and (**d**) filling empty space between peptides with ionic leakage-free cross-linkable materials

AQPZ layer on the support on a large scale. Lastly, this research project shows how engineers can obtain ideas from living organism and how optimally functioning biomolecules can be employed to solve the technical problem of water purification membranes.

Oral Vaccine Delivery System

Realizing the potential of oral vaccines, various types of nanoparticles or microparticles (i.e., micelle, vesicle, solid particle, hollow particle) have been tested for this purpose but none fulfilled demanding requirements. As it turned out, all traditional delivery structures exhibited diverse problems such as low loading efficiency, poor protection against low pH of the stomach, or poor dose release behavior. To tackle these technical challenges, a new vaccine delivery vehicle is proposed to target the ileum with variable loading capacities by exploiting the specific architecture of the delivery system, protecting the vaccine in the acidic gastric environment, and efficiently releasing vaccine near target area by utilizing the pH responsiveness property of the material.

The following approach shows how the concept of nanoporous vaccine delivery system was shaped for specific requirements (Fig. 10):

1. The proposed vaccine delivery system targets the ileum. As a requirement, the material used for the design of oral vaccine delivery vehicle should maintain intact structure at low pH of the stomach (pH 1–3) and dissociate at neutral pH of the ileum (pH >7). Considering pKa values, anionic copolymer such as poly (methacrylic acid-co-methyl methacrylate) (PMAA-PMMA) can be suitable candidate for this pH-dependent gating behavior.
2. The vaccine delivery vehicle must allow easy and high vaccine loading efficiency. In response to these needs, planar porous membrane is proposed as a new vaccine delivery vehicle (Fig. 10a). Planar membrane architecture is advantageous in terms of easy loading process (Fig. 10b(i)). After drug loading, membrane pore mouth will be closed with the anionic polymer to form a pH-responsive capsule (Fig. 10b(ii)). Since the structural integrity is controlled by the environmental pH, this delivery vehicle is expected to stabilize vaccines at low pH by closing pores and facilitate a rapid release of vaccines at neutral pH by reopening pores (Fig. 10b(iii)). Finally, the size of the membrane can be controlled from a single nanometer-sized pore unit to a macroscopic scale, meeting the requirements of scalability and manufacturability.
3. Vaccine needs to be formulated to prevent destabilization during drying and storage. The addition of a stabilizer can inhibit drying-induced conformation change of antigenic proteins. In addition, viscosity of the formulation can be controlled to kinetically suppress phase transformations such as crystallization and phase separation.

Previous case studies in sections “Air Pollution” and “Water Purification” illustrated how nanobiotechnology, in form of ideas inspired from nature, can be engineered to solve the perennial problems of air/water pollution. Differently from those, but still a part of nanobiotechnology, another approach starts from engineering materials to influence the life process. Although nanoporous planar membrane is proposed mainly for oral vaccine delivery, its application can be easily extended to diverse kind of pharmaceuticals. The most critical factors for successful

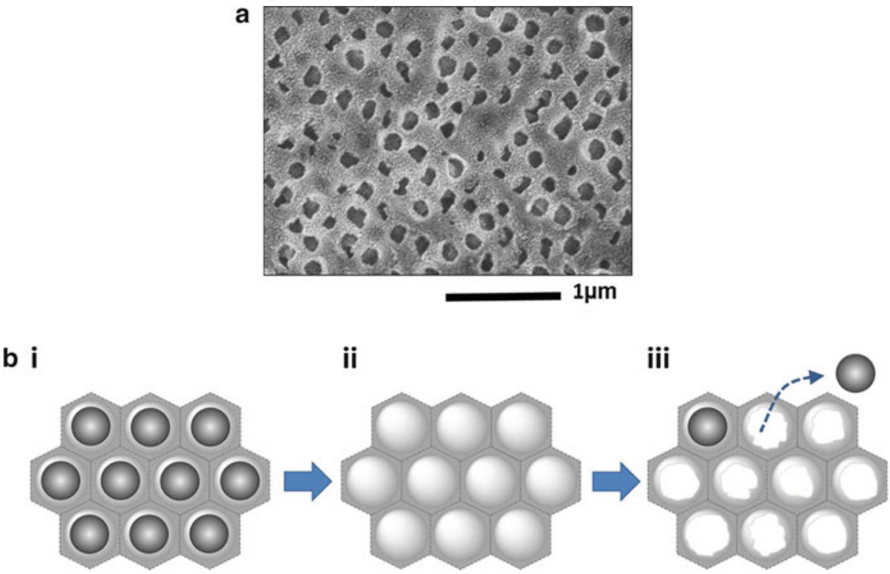

Fig. 10 Schematic representation of vaccine patch preparation. (**a**) Image of porous membrane concept. (**b**) (*i*) Vaccine loading into porous membrane, (*ii*) pore closure to protect vaccine, and (*iii*) pore opening to release vaccine at targeted site

demonstration of the concept would be control over the assembly of polymers to form porous membrane structure and target-specific pKa values of the polymer by modifying the chemical composition, adjustment of pharmaceutical-specific pore size of the membrane, complete closure of the pore mouth, and development of pharmaceutical-specific formulations. Eventually, this technology may contribute to the development of custom-made vaccine/pharmaceutical cocktails, which could provide protection from diverse diseases.

Conclusions

Since the introduction of nanobiotechnology, most efforts have been focused on the demonstration of how and what one can make and measure and what new properties were observed or created in the small scale. It is not difficult to witness skepticism around us about the future of nanobiotechnology. This signals that the technology and science happening in the small scale have not firmly taken root among us, even though huge progress has been made in academic research. Rich and diverse resources coming from the combination of both living organism and engineering provided the basis for rapid establishment of nanobiotechnology. However, scattered efforts may also result in weakness of nanobiotechnology. It is noted that research activities within a nanoscale space are crucial, but equally important is to extend the value of the technology to a macroscale world, resulting in social benefits.

As scaling down to nano accompanies the stepwise development of manufacturing technologies from macro to micro to nano, elaborate efforts are required to bring the benefits of nanobiotechnology to the macroworld. The key is how to shift from small-scale subsystems to a large-scale system without sacrificing the performance or characteristics. From the authors' own experience, it is suggested that development of a new mediator platform as well as creative generation of methodology may offer a way to mediate transition from nanobiotechnology to large-scale application. The platform should be able to contain nanobiological system, provide favorable environments for the active functional components, and conform to the scale-up requirements. Lastly, the authors hope that this chapter may help to remind researchers of the importance of narrowing the gap between bench-scale and full-scale research in the beginning stage of research design.

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Information Technology Supported Convergence

George O. Strawn and William Sims Bainbridge

Contents

Abstract

Modern information technology is transforming the collection, management, and sharing of scientific data in ways that greatly encourage convergence. Data-intensive science has evolved beyond the point at which all the information required for a research study can be centrally located, so interoperability across systems is required, with the additional benefit that data from different sources can be combined. Interoperability of heterogeneous data is a difficult challenge, requiring carefully specified metadata and well-conceptualized data management approaches like Digital Object Architecture. Scientific literature has become so complex and voluminous that it also must be managed in new ways, for example, using knowledge graphs to map connections as in Semantic

G.O. Strawn (✉)
Federal Networking and Information Technology Research and Development National Coordination Office, Arlington, VA, USA
e-mail: strawn@nitrd.gov

W.S. Bainbridge
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Medline. In the commercial realm, systems like Google Knowledge Graph and the related Knowledge Vault have begun to appear. For more than a decade, it has been recognized that future science will depend heavily upon distributed resources, including data archives, distant experimental facilities, and domain-specific research tools to enable new scientific discoveries and education across disciplines and geography. Similar approaches will become valuable for the development of abstract theory, for example, the cooperative construction of rigorous modular theories, in fields as diverse as physics and sociology, as scientists around the world contribute concepts and connect them by means of computer-based online tools.

Introduction

The convergence of knowledge is the subject of this handbook. However, in science the convergence of knowledge is hampered by the *huge size* and *complexity* of science and of the scientific record. Regarding size of the scientific record, many scientists cannot even keep up with the new knowledge being created by their own field, let alone that of allied fields. For example, the US National Library of Medicine (NLM) maintains a database of the titles and abstracts of biomedical research articles called Medline (Kharazmi et al. 2014). This database currently contains 22 million articles. Regarding the complexity of science, there is disciplinary isolation created by independent technical vocabularies and non-interoperable data. This chapter will describe recent developments in information technology (IT) that are extending the scientific paradigm in ways that promise to increase interoperability and to support convergence by enabling connections among otherwise isolated knowledge fragments. Early realizations of these important developments will be highlighted.

The Rise of Information Technology and Its Impact on Science

Modern IT might be said to have begun with the telegraph in the mid-nineteenth century or with punch card data processing at the turn of the twentieth century (Bainbridge 2004). However, the computer surely was the steam engine of the twentieth century. It emerged around the time of WWII and has increasingly influenced our technological society since then (Bainbridge 2006). The computer led to the Internet, which has integrated telecommunications into the digital revolution. In the early twenty-first century, the Internet has interconnected billions of people and computers as well as untold amounts of information.

Now the Internet is being augmented by the so-called Internet of Things (IoT), in which billions of currently connected people and computers will be joined by billions of connected devices such as scientific instruments, surveillance cameras, household appliances, and environmental monitors (Pew Research Center 2014).

These devices will contribute greatly to the flood of "big data," which science and society are already coping with. The IoT will accelerate the collection, processing, and communication of digital science data, but it could also increase the amount of non-interoperable data. Oceans of data will naturally connect the continents that represent major fields of science and engineering, thus promoting convergence. But convergence of multiple fields will also be required to create the IoT. For example, Jayakumar et al. (2014) have distinguished five types of IoT, depending upon their power supply needs:

1. Wearable devices such as smartwatches that must go several days between recharging.
2. Set-and-forget devices such as home security sensors that may operate for years without maintenance.
3. Semi-permanent devices such as sensors that monitor bridges and other public infrastructure.
4. Passively powered devices that lack batteries or permanent connections, such as smart cards carried in the user's pocket and activated by a reader machine.
5. Conventionally powered appliances, like smart kitchen microwaves, plugged into a power outlet while perhaps wirelessly connected to Internet.

A particularly promising new related trend is called *distributed manufacturing* from an industrial perspective or the *Maker Movement* from a popular perspective. The movement is a social phenomenon that resurrects traditional crafting hobbies through new technologies like 3-D printers, computer-assisted design, and online social media for sharing creative ideas (Axup et al. 2014). The Maker Movement is potentially far more than a hobbyist fad or an educational tool, as valuable as they can be, because it prototypes a form of manufacturing that could end reliance upon foreign industries and serve human needs better. In future, distributed manufacturing could create most products locally, customized for local cultures and conditions, in relatively small workshops employing local people who learned their skills in the Maker Movement, connected by information technology into the Internet of Things. Many fields of science and engineering must combine to make this vision practical, but absolutely central are computer-based systems for product design, coordination across a diversity of machines producing components from different materials, and management of the nationwide supply chain and local market.

Technology has always been an enabler of science. Early examples include Galileo and the telescope initiating modern astronomy and van Leeuwenhoek and the microscope initiating modern biology. Since the mid-twentieth century, IT has increasingly enabled all of science. The first electronic computers created "islands of computation," which quickly replaced armies of humans operating manual calculators. The most important science application that emerged at that time was the simulation and modeling of physical systems, which is now called computational science. Some observers have called it the *third paradigm* of science, placing it alongside theory and experimentation. Others have called it a new form of theory. Regardless of what it is called, most observers would agree it has had a profound effect on science. An even newer application of IT to science has been called *the fourth paradigm* by advocates (Hey et al. 2009). With less flair, it is also called *data-intensive science* (Agarwal et al. 2011). The IT developments highlighted here are examples of data-intensive science and other data-intensive applications that promote convergence and connections.

Data-Intensive Science

Data-intensive science emerged as computer storage capacities increased and costs decreased. First, it produced "islands of information" around large computers. With this development, huge output files, for example, from simulation runs, could be stored for later analysis. Then, as computers connected to the increasingly high-performance Internet, a "continent of information" was created. However, this continent consisted of heterogeneous data that were (and still are) largely non-interoperable. For the purposes of this chapter, *interoperable data* are those which can be employed together in computer applications. This is a problem in today's IT world because existing databases differ in almost every imaginable way, from having unrelated conceptual schemes for organizing the data to incompatible data storage structures, even just within one field, such as bioscience (Sansone et al. 2012).

Data can sometimes be made interoperable by time-consuming, expensive manual transformations. However, the goal of interoperability is to store scientific data in a form that such transformations can be performed automatically. One step in this direction is to add computer readable *metadata* – data about the data – to each data set. However, the form of the metadata must be sufficiently standardized to enable computer software to find and utilize it. Where interoperability has been achieved, such as with the Human Genome Project, major scientific advances have occurred.

The automatic interoperability of heterogeneous data will be realized when computers "understand" the data well enough to perform any required transformations. A similar understanding of textual information could aid science by greatly improving scientists' access to the articles most relevant to their research. Such an understanding could also advance science by enabling software to automatically deduce new results by combining results found in existing articles. Current computer-based keyword searches of huge databases have been a great step beyond manual searches. However, new IT developments are poised to take this activity as far beyond keyword searches as keyword searches are beyond manual searches.

A data-intensive society is also a defining characteristic in the early twenty-first century. As the World Wide Web was layered on top of the Internet in the early 1990s, the creation of Web pages exploded. Then search engines such as Google were developed to organize those pages to be able to respond to user queries. Those queries have traditionally been accomplished by means of keyword searches. Keywords are "meaningless strings of characters" (i.e., meaningless to computers), but they have been remarkably successful in locating pages that are often of use to persons performing queries. However, a second generation of search engines is emerging at this time. These new search engines can conduct "meaningful" searches; that is, they focus on the *entities* referred to by keywords rather than the keywords themselves. Google's characterization of second-generation search is that the search is for "things, not strings."

Interoperability of Heterogeneous Data

This section will focus on an approach to data management that lays a foundation for interoperability. It is called the *Digital Object Architecture* (DO Architecture) and was developed by Dr. Robert Kahn and his colleagues at the Corporation for National Research Initiatives (CNRI) in Reston, Virginia (Kahn and Wilensky 2006; Hoang and Yang 2013). Kahn was the codeveloper of the TCP/IP protocols, which are the foundation of the Internet, and the DO Architecture seeks to do for non-interoperable data what the Internet did for non-interoperable networks. Because of this analogy, a very brief (and partial) overview of the Internet architecture will be given.

The Internet is a *virtual network*, implemented only in software and riding on top of underlying "real" networks implemented in telecommunications hardware. The underlying networks are in general heterogeneous and non-interoperable. The Internet "stitches them together" with computers called *routers*, each of which is attached to two or more of the underlying networks. Ideally, every component and level of this set of networks needs to be optimized for data-intensive science (Dart et al. 2013).

One of the capabilities of the Internet is to enable the transfer of files from a computer on one network to a computer on another one. The World Wide Web, which has ridden on top of the Internet since the early 1990s, defined a protocol called Hypertext Transfer Protocol (HTTP) that enabled the convenient sharing of human readable information called Web pages (and now other applications such as e-commerce). In a sense, the Web provided for the human interoperability (i.e., information to be read by humans) of homogeneous data (Web pages which have a common format). A goal of the DO Architecture is to provide for *machine* interoperability of *heterogeneous* data. We now proceed to give an overview of the DO Architecture and to indicate how it can provide for such interoperability.

The Digital Object Interface Protocol (DOIP) is the DO Architecture analog to HTTP in the Web. The software of both of these systems can be visualized as an "hourglass," with application procedures in the top half and implementation procedures in the bottom half. At the narrow waist of the DO Architecture hourglass is DOIP, just as HTTP is at the waist of the Web. The Web defines both Web pages and URLs (identifiers) that resolve to Web pages, and the DO Architecture defines *digital objects* (DOs) and *handles* (identifiers) that resolve to digital objects. A Web URL is composed of a computer name followed by a "/" followed by a file name, and a handle is composed of a *prefix* followed by a "/" followed by a *suffix* (the prefix is assigned *to* an organization by the handle authority, and the suffix is assigned *by* that organization, but neither part is intended to be a semantically meaningful name). The DO resolved by the handle system differs from a Web page in that it is the information *about* the data being referenced, not the data itself as it is in a Web page. In other words, the DO resolved by a handle contains *state information* about the data.

Two special types of digital objects are digital repositories and digital registries. All DOs are logically contained in a digital repository, and metadata for digital objects can be placed in separate digital registries or as part of a digital repository. When the handle of a DO is resolved, one of the pieces of information returned is the location of the digital repository that contains that DO.

As was stated above, the Internet can be viewed as a *virtual network*, implemented only in software and relying on underlying real networks implemented in telecommunications hardware. Similarly, the DO Architecture can be viewed as a *virtual database system*, implemented only in software and relying on underlying "real" database systems implemented in database hardware.

Handles identify data independently of the computer(s) where the data may currently reside. With proper management, there will be no "broken links" such as there are in the Web when a page is moved to a different computer. Another difference is that a DO is always *parsable*. That is, it can be "understood" by the software on an accessing computer because it is always in a standard form: a list of type-value pairs. Moreover, the types are also represented as handles and, therefore, can be resolved when the software does not understand them (but some software will be designed to expect and therefore to understand certain type elements).

HTTP laid a foundation for, but did not provide, many of the services that Web users expect today, such as easy-to-create and easy-to-read Web pages (via browsers), search engines to find relevant pages (Google, Bing, etc.), e-commerce sites (Amazon, United.com, etc.), and social media (Facebook, LinkedIn, etc.). Just as these applications have been developed in the upper half of the Web hourglass, many applications can be expected to emerge in the upper part of the DO Architecture hourglass. Because of this design, applications will have a built-in capability to establish interoperability of heterogeneous data. An example of the use of the DO Architecture to facilitate interoperability will be given below.

Creating "Knowledge Graphs" from Scientific Literature

Semantic Medline is a *knowledge graph* created from Medline by Dr. Thomas Rindflesch and his colleagues at NLM. A knowledge graph can be defined as a *graph database*, which is a database in which the connections between the database elements are explicitly expressed (Pujara et al. 2013). That is, the elements are the nodes of the graph, and the relations between the elements are the arcs of the graph. For a convenient example in an overview of Semantic Medline, the team uses the example of *clock genes*, which as the name suggests manage time-related responses and are found apparently in all organisms, from fruit flies to humans (Rindflesch et al. 2011). In this case, the graph is a map of related concepts, which may belong to many different subfields of scientific research. Naturally, there are lines connecting "clock gene" with two specific genes, Cry1 and Cry2, which support sensitivity to blue light and are involved in circadian rhythms that adjust behavior over the cycle of a day. But the graph also connects to some very human problems, including winter depression or mood disorders and even tumor growth. By connecting concepts, a graph such as this accomplishes an effective form of conceptual convergence.

A semantic graph database such as the Semantic Web also has built-in features to represent taxonomies and other hierarchical information structures. A graph can, among other ways, be represented in a computer as a collection of "triples" of the form (element, relation, element). Semantic Medline creates a knowledge graph from the text of the Medline abstracts. In each Medline abstract, there are "key sentences" which describe the results of the article. These key sentences can, in general, be restricted to the simple form subject-predicate-object. One of the contributions of Semantic Medline is a natural language processing module (NLP), which can find many of the key sentences in the abstracts. A related NLM development that is utilized by Semantic Medline is the Unified Medical Language System (UMLS), which is used to solve the *synonym problem* (Bodenreider 2004). That is, it provides for a *controlled vocabulary* which includes a unique identifier for each synonym class. These unique identifiers are used in the knowledge graph constructed from the key sentences. The controlled vocabulary enables the results of different articles to be put into a common language, thereby highlighting article commonalities. The subject and object nouns of each key sentence are nodes in the knowledge graph, and each predicate verb is an arc connecting its subject and object. On the average, three key sentences are discovered by Semantic Medline in each abstract, so 66 million key sentences currently constitute the knowledge graph.

The Semantic Medline knowledge graph can be both browsed and searched. Browsing via a graphical user interface enables an investigator to literally see connections among concepts and tie them back to the relevant abstracts. Graph search languages such as SPARQL enable scientific discovery by connecting isolated facts from the 22 million articles (DuCharme 2013). For example, the SPARQL query,

```
  Select "testosterone", ?relation1, ?x, ?relation2,
"sleep_problems"
  Where {
  "testosterone" ?relation1 ?x.
  ?x ?relation2 "sleep_problems".
  }
```

discovered two articles, the first asserting that testosterone *inhibits* the hormone cortisol and the second asserting that cortisol *causes* sleep problems. This discovery provided the first clue as to how decreasing testosterone in aging men might contribute to sleep problems. That is, no single researcher was aware of both articles.

As this ability to utilize the scientific record for science discovery becomes better understood, it will spread to other disciplines. One reason it has not been widely adopted so far is that the construction of language systems like UMLS is a labor-intensive process. As more automated methods for creating such language systems emerge, this restriction will be alleviated. Assuming that the language systems across different disciplines can be properly articulated with one another, which will not be a simple undertaking given the international scope of science, interdisciplinary science discovery will be facilitated (Frade et al. 2012).

A second system for creating knowledge graphs from biomedical literature has emerged in Europe. Professor Barend Mons and his colleagues at the University of Leiden Medical Center in the Netherlands have developed *nanopublications* (Mons et al. 2011), in which the authors of publications identify and publish the key sentences as they write their abstracts. The requirement for a controlled vocabulary of concepts still exists, but no NLP module is required to find the key sentences. The Semantic Medline approach is very useful for the 22 million extant articles, but for new articles the nanopublication approach could be a viable option – if authors agree to take on the task of identifying their key sentences. Perhaps a hybrid approach will emerge, where Semantic Medline would be used to suggest key sentences to the author who could then accept or modify them.

Knowledge Graphs: Science and Beyond

The "key sentences" described above as subject-predicate-object triples derived from text also have an interpretation as assertions about data, which enables knowledge graphs to naturally combine scientific literature and data into the same knowledge structure (Hebeler et al. 2009; cf. Cho and Kim 2015). This combination greatly enhances the possibilities of discovering new knowledge by mining the scientific record. As a simple example of how triples are used to describe data, consider a table of values where the rows represent experimental subjects and the columns represent specific attributes (e.g., one person per row and attributes such as weight and height in specified columns). In this context, a triple becomes subject-attribute-value, which is in the same "triple form" as key sentences. For example, a triple from such a table might be person1-weight-150, attributing a weight of 150 units to a specified individual human being. A controlled vocabulary representing the row and column names is required as it is for key sentences. Converting tables into triples is easier than converting text, and such conversions of "structured data" has begun to occur. For example, DBpedia has converted the tabular parts of Wikipedia into triple form (Bizer et al. 2009).

Any data table can also be represented as a DO. That is, a handle can be created that dereferences to a DO that contains state information about the table. That state information includes identifying the data as a table and indicating the number of rows and columns and the format of the data values. If the metadata also includes the controlled vocabulary information for the row and column headers, it would be a straightforward programming task to convert any such table into triples for a knowledge graph. At this time, however, the construction of the DO pointing to the data table may itself be a manual task. Assuming the DO Architecture comes into general use, the creation of a DO for a data table could be automated, just as the creation of an HTML version of a document can be automated by a word processing system.

Finally, another possible use of the DO Architecture could be the use of handles to represent entities. As discussed above, UMLS and other entity systems determine the classes of synonyms (the entities) and assign a unique identifier to each one. In the Semantic Web implementation of a knowledge graph, the unique identifier is an International Resource Identifier (IRI). However, IRIs derive from Web URLs and hence at least appear to involve the names of computers rather than the computer-independent DO reference provided by handles.

As mentioned above, the effort to help computers better understand human intentions has moved into the quest for "second-generation search engines." This section focuses on Google's developments as an early example, but other vendors have signaled their intent to develop similar services (e.g., Microsoft announced that its Bing search engine will have a digital assistant called Satori Knowledge Base).

The Google Knowledge Graph and the related Knowledge Vault (Dong et al. 2014) will support three new dimensions for search: answer, converse, and anticipate. First, second-generation search will increasingly be able to answer questions rather than just identifying documents that may contain answers. (There currently exist several "answer engines," such as Wolfram Alpha, with similar goals.) Second, conversing might begin with disambiguation (e.g., "Do you mean jaguar the animal or jaguar the car?") and proceed to supporting additional search depth. Finally, Google can use the accumulated information from other searches to anticipate next search questions (e.g., "Previous searchers for jaguar the animal next searched for…").

As of 2012, the Google Knowledge Graph contained more than 500 million entities and billions of facts related to those entities. These numbers already dwarf the several million entities and 66 million facts that Semantic Medline has assembled. Thus, the "big data" dimension of computer semantics is being accommodated, just as the big data dimension Web search was accommodated by the development of novel "Web organizing" systems such as MapReduce developed by Google.

A Range of Possibilities

A dozen years ago, the Interagency Working Group of Information Technology Research and Development identified a list of grand challenges, long-term scientific advances that require information technology breakthroughs and would benefit humanity. The first priority identified by this team was *Knowledge Environments for Science and Engine*ering, defined through these introductory sections of a substantial analysis (Strawn et al. 2003, p. 12):

Description of the Multi-Decade Grand Challenge

Organize and make broadly available distributed resources such as supercomputers, data archives, distant experimental facilities, and domain-specific research tools to enable new scientific discoveries and education across disciplines and geography

Focus in the Next Ten Years

Understand the needs of scientists and how science is changing (for example, data sets are more complex and teams are more interdisciplinary)

Increase access to computing systems, archives, instruments, and facilities

Build on successful experiments:

- Upper Atmospheric Research Collaboratory (UARC) and Space Physics and Aeronomy Research Collaboratory (SPARC)
- Network for Earthquake Engineering Simulations (NEES)
- Biomedical Informatics Research Network (BIRN)
- National Virtual Observatory (NVO)

Benefits

New discoveries across disciplines (for example, discoveries in one field can apply to other fields)

Establish new fields of science and engineering

Clearly, there has been tremendous progress since this report was published, and we have passed the end of the decade on which it primarily focused. Yet, this grand challenge could legitimately be made again, in essentially the same language, because progress has been a matter of degree, and we can reasonably imagine much more progress in the coming years. The discussion of this grand challenge went into some detail about what the technological challenges were, but its concluding section listed points that could be applied much more broadly (Strawn et al. 2003, p. 13):

Indications of Progress

More users of distributed science and engineering environments

More distributed science and engineering collaborations

More scientists and engineers in remote parts of the country

New tools and applications for more areas of science and engineering

New science and engineering ideas and innovations

Scientists and engineers achieve their goals more efficiently and effectively

More "hands-on" science education in K-12 and undergraduate school

The terms "distributed and remote" directly suggest convergence, and most "new tools and applications" would be valuable for multiple fields of research and development, thereby linking them. Convergence does not necessarily mean uniformity, however. This chapter has stressed the importance of connecting diverse sources of data that may have been assembled in different frameworks but have some commonality of conceptualization or domain. In many ways, human knowledge is far more chaotic that it could or should be, and much of the scientific and engineering effort needs to be invested in mastering that chaos. But an important part of success in that Herculean effort will be recognizing when fundamental commonalities do not exist and diversity must be maintained. For example, even within one field, there may be competing paradigms that would categorize data very differently. But that can be a good thing, because bringing the paradigms together can result in new theory or theories in parallel rather than uniformity (Lewis and Grimes 1999).

A classic example relevant to the topic of this chapter is the constant but incomplete enthusiasm for propositional logic, production systems, or rule-based reasoning throughout the history of artificial intelligence. Alternative exists, such as neural networks of probabilistic methods. It is noteworthy that AI-pioneer Allen Newell (1990) titled his classic book on this topic, *Unified Theories of Cognition*, asserting that human and machine cognition could be explained by the same theories and directly promoting convergence. The general approach is to construct a system of propositions or if-then rules, based on clear definitions and axioms, logically deriving a potentially complex system of statements from rather simple elements. Superficially, this looks like divergence, but it actually achieves convergence of many empirically supported observations by finding a closed set of principles from which their complexity can be derived. Indeed, explanation becomes a form of convergence.

However, as in constructing a factory or a cathedral, much of the intellectual work of science as well as engineering requires assembly of many parts into larger structures. In a historically grounded analysis of theory in physics, Olivier Darrigol (2008, p. 196) describes this balance between divergence and convergence:

> any non-trivial theory has essential components, or *modules*, which are themselves theories with different domains of application. Even in alleged cases of reduction, modules remain indispensable because they play an essential role in the construction, verification, application, and comparison of theories. In this view, the heterogeneity of physical theory is best understood as modular structure; most of its unity rests on the sharing of modules.

Principles such as these can be applied to social science, as well as to physics and artificial intelligence. Barry Markovsky (2010) has applied the same logic to small group theory in sociology and social psychology, even citing Darrigol specifically. As George Homans (1950) pointed out in his classic *The Human Group*, individuals seek gratifying rewards but seldom can obtain them without help. Therefore, they form small groups of cooperating individuals, who come to conceptualize their aggregation as a valuable entity in its own right. Markovsky notes that modular theory requires development of explicit definitions of terms, distinct propositions stating meaningful principles, and logical rules for deriving hypotheses. Just as this approach can build a theory of small groups by assembling principles about individual behavior, principles about individuals and small groups can be assembled to produce rigorous theories of large societies. Within those vast social systems, hypotheses about science may be assembled with hypotheses about commercial institutions to produce a general theory of technological advance.

The fact that commercial search engine vendors are entering the field of computer semantics is a very good signal that the research phase of this field is about to give way to the early adopters phase, as modular theory might deduce. And these commercial systems will contribute to the development of additional systems for science like Semantic Medline, just as science systems will contribute to the further development of commercial systems. In other words, another important public-private partnership is emerging in the dynamic IT industry. Similarly, the emergence of a commercial Internet of Things and the associated cyber-physical systems that are being built on top of it have a strong need for data interoperability, such as enabled by the Digital Object Architecture. Here, too, a public-private partnership is emerging that will serve the needs of both science and society.

The convergence of scientific knowledge is hampered by the size and complexity of science and the scientific record. We must improve our ability to find connections within and among the various science domains if convergence is to proceed unimpeded. As the scientific record, both data and articles, are digitized *and* made interoperable, an important barrier to the convergence of scientific knowledge will be reduced. Systems such as the Digital Object Architecture, Semantic Medline, and nanopublications will be applied to more, perhaps all, science fields, as well as fields beyond the science and technology enterprise, as the Google Knowledge Graph demonstrates. These systems, applications of the fourth paradigm of science, will increasingly contribute to the convergence of knowledge.

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Nanotechnology-Neuroscience Convergence

Jo-Won Lee and Moonkyung Mark Kim

Contents

Abstract

Roco et al. 2013 introduced the convergence of nanotechnology with biotechnology, information technology, and cognitive technology (NBIC) as a main trend in science and technology. They also provided a list of 20 visionary ideas for the next 10–30 years. According to their ideas, in the next 20 years, we expect to have humanlike intelligent robots, smartphones with real-time language translating function, and pocket-sized supercomputers through the advance in the NBIC. To pave the way for this, every computing system should be flexible, mobile, self-programmable, real time, and even self-learning. However, as the miniaturization trend continues following Moore's law, it would be impractical to apply the current nanoelectronics to future computing systems due to enormous energy consumption and technological limits. Accordingly, the architecture and the functions of transistors used in the present computing system need to be improved and inspired by the human brain. Unfortunately, it

J.-W. Lee (✉)
Department of Convergence Nanoscience, Hanyang University, Seoul, South Korea
e-mail: jowon@hanyang.ac.kr

M.M. Kim
School of Electrical and Computer Engineering, Cornell University, Ithaca, NY, USA
e-mail: mkk23@cornell.edu; okebarykim@gmail.com

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is unclear how neural activities in the human brain result in cognitive processes such as learning and reasoning. Nevertheless, the convergence of neuroscience with nanotechnology is expected to bring us closer to building neuro-inspired chips for neurocomputers utilizing some clues on neural activity and structure. In this chapter, we will show various scientific problems and challenges in realizing neuro-inspired chips.

Introduction

According to the Cisco estimates (Cisco's Visual Networking Index Forecast Projects, May 29, 2013), the number of internet users already exceeded 2.3 billion as of 2012 and will reach 3.6 billion in 2017. In addition, smartphones have become an essential part of our lives (Fig. 1 for inauguration photographs of President Obama

Fig. 1 Inauguration photographs of President Obama taken in 2009 and 2013

taken in 2009 and 2013). Smartphones empowered by the Internet offer us access to various information such as map, weather, and traffic and help us manage our schedules. This dramatic change in our lives is mainly attributable to the evolution of computers, which is the most epoch-making invention in the twentieth century and possibly in the human history.

Computers can now assist us in performing many general activities associated with the bank, hospital, government, and school and solve many of our complex tasks such as scientific problems, weather forecasting, virtual nuclear testing, and so on. Thus, our lives are already deeply influenced by computers. As time goes by, we will become more dependent upon it.

However, computers are still inconvenient to use due to their deficiency in reasoning and recognition. Therefore, the demand for machine intelligence is on the rise. The best solution to overcome the current shortcomings of computers is through the convergence of state-of-the-art nanotechnology with neuroscience, which will allow computers to operate more like humans.

Roco et al. 2013 recommended the primary R&D areas for government in the convergence of knowledge, technology, and society (CKTS) as follows:

– Cognitive society and lifelong wellness
– Distributed NBIC manufacturing
– Increasing human potentials
– Biomedicine-centered convergence
– Sustainable Earth systems

These R&D areas, closely related to pursuing human welfare, would be unattainable without the progress of machine intelligence.

Limits of Present Computing Systems

Apple's Siri and Google's Now are the best examples of the voice recognition system since the concept was first introduced in 1968 in the movie *2001: A Space Odyssey*. However, they have some limitations due to the inability of dealing with the continuously changing context of the mobile environment. For example, if you want to make travel reservations using Siri, the smartphone needs to be capable of identifying the best flight and hotel of your choice and the status of the current reservation based on concurrent data. Is it possible for your current smartphone to easily execute these tasks? Smartphones do not have all the necessary expert knowledge to perform them. In addition, the inability of acquiring concurrent data is another limitation since the computational power and data capacity of the supercomputer in the data center cannot match the demand of users from all over the world. Notwithstanding these limitations, voice recognition in conjunction with wearable computer, smartphone, self-driving car, and Internet of Things (IoT) will be the major application area of artificial intelligence (AI) utilizing human-made software.

The advancement of the computer's performance shocked the world in 1997 when the IBM supercomputer Deep Blue with 11.38 gigaFlops (floating-point operations per second: measuring computer performance) defeated the world's chess champion Garry Kasparov. In 2011, IBM surprised us again when IBM's Watson supercomputer with 80 teraFlops beat the champions in Jeopardy, a quiz game. These two remarkable episodes are examples of how machine intelligence could be realized in real life. It would be very convenient for us to have such intelligent systems in hand with the capability of learning, recognition, and decision-making. However, systems like Deep Blue and Watson cannot be applied in other areas due to their immobility. For instance, they cannot drive unmanned cars. Furthermore, they are incapable of understanding semantic contexts or engaging in reasoning and decision-making activities based on collected data from various environments.

A robot is one of the finest applications of AI. Robot scientists have mainly focused on programming the logic for the reasoning and recognition carried out by humans. They believed it would be possible for robots to think like humans by equipping them with sufficient information regarding various human tasks and with logical reasoning power to process the information. So far, these attempts to apply AI in robots have been generally unsuccessful in the past several decades except for some specific tasks, for example, chess and quiz using supercomputers as mentioned earlier. Some may consider everyday activities such as cooking to be easy for robots. However, culinary art requires a lot of creativity with instinct for taste. This instinct has been inherited to humans for generations since the appearance of *Homo sapiens* 200,000 years ago. However, robots lack such instinct due to the differences in the methods for processing input data. Humans learn through their experiences but machines do not have this ability. If science fiction writer such as Isaac Asimov were to come back to life, he would be disappointed to find out that humanlike robot servants have not been developed yet.

Nowadays, we know how difficult it is to achieve intelligent systems which are comparable in performance to human beings. However, in the past, the AI community was overly optimistic on the possibilities of AI. Herbert Simon, a pioneer of AI and a Nobel laureate, made two predictions in 1957: (i) most of psychological theories would be expressed in the form of computer programs, and (ii) a computer would win the chess world championship by 1967. Of the two, only his latter claim was realized after 30 years in 1997. Later in 1965, he insisted again that we would have humanlike machines within the next 20 years, which is yet to be accomplished. Marvin Minsky, another pioneer of AI at MIT's AI laboratory, predicted in 1970 that within just 3–8 years, machines would have the general intelligence of an average human being. Since then, Minsky has dramatically changed his stance and has become critical of his AI community. He stated that "today you'll find students excited over robots that play basketball or soccer and make funny faces at you. But, they're not making them smarter" (Michalowski 2013).

Robots are limited because they only carry out programmed work or input command. Moreover, they lack learning or reasoning abilities. In 1956, AI pioneers, including Simon and Minsky, organized the Dartmouth Conference to discuss how to build AI. They thought that using mathematical modeling and programming, it would be possible to develop intelligent systems to mimic human brains. At that time, solving mathematical problems and playing chess were considered to be some of the most complex and difficult processes that the human brain handle. Thus, AI pioneers were of the opinion that everyday tasks might be readily tackled if these were solved with some modeled rules. In the beginning, the pioneers' AI model seemed to work well as demonstrated by the superior performance of the computer in solving complex math problems in comparison to humans. Completing math tasks requires Boolean processing rather than advanced intelligence. Thus, the computer may excel in them, but not on other everyday tasks. In reality, the realization of AI is not as simple as AI pioneers originally considered.

Nevertheless, over the past few decades, some advances have been achieved toward building an AI system in related disciplines. In neuroscience, scientists have gained considerable knowledge about how interactions of neurons and synapses lead to learning and reasoning. Computer scientists, using supercomputer, have modeled and simulated neural mechanisms to obtain information on the behavior of neurons. Engineers have accomplished remarkable progress in nanoelectronics to emulate neurons and synapses with higher density and less power consumption.

Although current machines are not as intelligent as humans, they are capable of completing specific tasks using supercomputers and software as mentioned above. This success was only possible due to the advances in semiconductor technology following Moore's law for the last 50 years. However, this step-by-step miniaturization trend cannot be continued due to foreseeable technological difficulties within the next 5–10 years.

There are three major obstacles for the miniaturization to increase the density and speed of chips (see Table 1). The first is the unacceptable variation in property parameters and size as the transistor becomes more scale-downed. It is generally accepted that the mass production of integrated chips could not be possible for the transistor size below 5 nm. The second obstacle is the nanofabrication associated with lithography. Extreme ultraviolet (EUV) is considered to be a strong and/or only candidate for the next-generation lithography below 14 nm. It is not yet available for mass production due to the lack of a viable light source. To make the matter worse, there is no next-generation lithography after EUV considering both of the minimum pattern size and the throughput for mass production. Finally, as the transistor size decreases, the chip temperature dramatically increases. Within 10 years or so, the surface temperature of chips will reach that of the sun's surface at 6,500 K without any management for the heat dissipation. A similar situation took place in the 1980s. At that time, bipolar transistor was perceived to consume extensive energy, and thus, it was replaced by CMOS to reduce its power consumption. Therefore, the reduction of power consumption is a major challenge for future computing systems. In other words, energy efficiency fundamentally limits the processing power in computers. No solution is yet to be found to overcome these barriers regardless of the form in the name of beyond CMOS.

Table 1 No further miniaturization for MOSFET

Technical obstacles	Physical reason	When reaching the limit
Variation properties and size	Unacceptable for transistor below 5 nm	After 2020
Heat dissipation	Associated with leakage current, cell density, switching energy, and von Neumann architecture	Already happened
Not ready for EUV lithography below 14 nm	Lack of viable power source to get the necessary throughput	Several times delayed as of 2014 looking for EUV replacements

In addition, the length of switching devices is physically constrained by Heisenberg uncertainty principle. Specifically, 1.5 nm is found to be the physical limit for switching devices based on any materials due to the thermal and quantum perturbation (Zhirnov et al. 2003).

A Necessity for Neuro-Inspired Nanoelectronics for Intelligent Systems

Digital computers are characterized to serially compute input data with fast speed. However, its main shortcoming lies in its large power consumption. For example, the supercomputer operating at several tens of petaFlops (10^{15} Flops) needs several tens of megawatts, but the exaFlops (10^{18} Flops) computer, expected in 2019, requires 1.3 GW (McMorrow 2013). As a rule of thumb, 1 MW is equivalent to the power necessary for 1,000 households. Thus, 1.3 GW is equal to the power for 1,300,000 households, which are roughly 1.5 times the size of Los Angeles, CA.

This large power consumption is related to the von Neumann architecture inherent in the digital computer. In this architecture, memory storing a program and data is physically separated from the CPU. The program and data should continuously move back and forth between memory and the CPU for each calculation. This creates von Neumann bottleneck. Although multi-core computers can process multi-data at a time, they still use the same principle based on von Neumann architecture. It should be noted that the synapses in our brains operate at 100 Hz. Thus, if all the synapses, which is $\sim 10^{15}$ of the human brain, would participate in the calculation, then 10^{17} calculations per second can be performed, which is about 10 times faster than the present fastest supercomputer in the world. In addition, the computation with CMOS ICs is very inefficient at human tasks such as pattern recognition, adaptability, and error tolerance. Thus, emulating the function of the human brain through hardware development could be the first prerequisite to the successful buildup of an AI system requiring a small amount of power consumption.

A number of key differences exist between the computer and the human brain. At present, the highest memory density of NAND flash is 128 Gb, which is around

$10^{11}/cm^2$. Synapse in the human brain is a kind of memory and the density is four orders higher than the NAND. Neuron (soma) is a counterpart to logic and the density is three orders larger than 22 nm CMOS chips ($10^8/cm^2$). Roughly calculating, building 10^9 CMOS/cm^2 is required to reduce the dimension of the transistor by about one-tenth of that (2.2 nm). This is an impossible scenario to implement due to technological difficulties. Operation frequency in our brain is 4–30 Hz, while our desktop computer reaches to 2 GHz level, resulting in the computer being 100 million times faster. However, our brain consumes only about 20 W, whereas the power consumption of the desktop computer is around 350 W. In some tasks like calculation, the computer surpasses our brain, but no computer in the world can reason like humans. Presumably, a robot as smart as humans (100 petaFlops as described above) requires 10–20 MW, which is equivalent to the power generated by a small hydroelectric plant if we use conventional CMOS.

The computer is built from Si and metal, while the human brain is composed of hydrocarbons and aqueous solutions. As mentioned above, the computer is energy hungry, yet poor at pattern recognition, learning, and decision-making. This inferior performance arises from the computer's lack of understanding of the context, and its computation being deterministic, only made by human inputs with synchronous operation in a clock-driven mode. The most fatal shortcoming of digital computer is in its serial data processing using 0 and 1, which is the main cause for its large power consumption.

In contrast, the human brain is very slow but energy efficient with distributed data processing and learning ability and is operating asynchronously in an event-driven and/or stochastic mode. Furthermore, our brain works in a parallel mode using analog data. Consequently, these inherent differences between the computer and the human brain bring about their performance differences: the computer is good at mathematics but poor in adaptation and learning; in contrast, the human brain is good for adaptation and learning, but comparatively poor at mathematics.

Humans have long believed that the capacity for consciousness is the essential, defining characteristic of our species. The computer is the culmination of human efforts to emulate consciousness in itself. Accordingly, the ultimate goal of computer science has been to endow the machine with intelligence, enabling it to function in a manner akin to human logical reasoning and thought. It can be said that God created human being in his own image, while human beings invented the computer to mimic their performance. If that is so, why are computers still inferior to humans at some skills, such as reasoning and recognition? The failure of computers to compete with humans at these tasks indicates that some aspects of human intelligence currently lie beyond the ability of computers. However, this perspective hints at an intriguing question: if we can understand the logic underlying information processing in humans and develop corresponding computer hardware, could it be possible to build a computer that functions similarly to humans?

Two fundamental questions of the human brain remain unresolved. First, we do not fully comprehend how the brain processes and memorizes data at the molecular level. Second, we do not know how this processed information results in our capacities for recognition and inference. In order to grasp these behaviors, we need a detailed map to reveal the activity of neurons and neural networks throughout the brain. The neural system of *C. elegans*, a roundworm, with 302 neurons and 5,000 synapses, has been characterized for several decades, but neuroscientists do not even understand the basic functional details of human neurological structures. For mapping the function of the human brain, scientists have sectioned brains into as thin as possible slices and then stained the sections for observation by optical microscopy, SEM, TEM, and so on. Afterward, the observed images were reconstructed into a 3-D format by a computer. From these images, the neural connectivity has been found to be of a rectilinear 3-D grid with no diagonal connections (Wedeen et al. 2012). This observation yields a very valuable insight that the grid structure can be developed into a 3-D layered crossbar array to create "electronic synapses" in neuro-inspired (neuromorphic) chips. It must be noted, however, that imaging studies of sectioned brain tissue are only possible using cadavers, not living human subjects. In addition to natural deterioration of the brain following death, information could also be lost due to tissue damage during the sectioning process.

An alternate method is to use fMRI to map the brain. However, the resolution is limited to around 1 mm because fat molecules – lipid components of the neurons themselves – block the light, leading to opacity. Recently, (Chung et al. 2013) at Stanford University, have made a major breakthrough in enhancing the resolution to 500 nm – which is 2,000 times better than fMRI – by using a hydrogel known as CLARITY. CLARITY preserves the physical structure of the brain, while simultaneously making its structure more visible by removing the lipids.

Neuroscientists have monitored neuronal activity by implanting electrodes on the brain, but the coverage area of these electrodes is confined to one or a few neurons. The mean area of a neuron in the hippocampus is variable from 250 to 300 μm^2 (Zeidel et al. 1997), and the tip size of the nanoelectrode is less than 0.6 μm^2 for an intracellular recording unit (Lin et al. 2014). Accordingly, only the activity of a single neuron and the interaction of one neuron with another have been well characterized (Houweling et al. 2009). Is it reasonable to contend that we can understand the information processing of hundred billions of neurons only by comprehending the activity of one isolated neuron? This is akin to arguing that on television, we can extrapolate from one or a few pixels, depicting the glint of light on a wine glass, to reconstruct the several millions of pixels that make up a complete episode of Downton Abbey, thereby revealing all potential spoilers for the upcoming season!

A neuron largely consists of four parts: soma, axon, synapse, and dendrite. Axons and dendrites are unique in neurons and are not present in other cells. The soma integrates incoming signals and generates outgoing signals across the axon. The axon sends the outgoing signal to the dendrites of a neighboring neuron. A gap of around 20 nm exists between the terminal of the axon and the dendrite of a data-receiving neuron. This is called the synaptic gap, and thus, the synapse is the connection between neurons. Synapses are known to be responsible for the robustness and massive parallelism of computations of the mammalian brain. The existence of the synapse was verified in the late nineteenth century by Nobel laureates

Camillo Golgi and Santiago Tamony Cajal, using optical microscopy. However, their interpretations based on their observations were diametrically opposed to each other. Golgi insisted that the two neurons must be physically connected, while Cajal advocated that no connection is present between the neurons. Therefore, their respective positions were locked in a bitter tug-of-war until the invention of electron microscopy in 1931 by Nobel laureate Ernst Ruska. In the end, the absence of a connection was found to be correct. This episode powerfully demonstrates that the higher the magnification to which we are able to resolve any structure, the greater the potential for new results to overturn previously accepted results. In this respect, we believe that nanotechnology can contribute profoundly to better understanding neural activity within the brain, which previously has remained unseen. Recently, the importance of the convergence of nanotechnology with neuroscience has been exemplified by the development of the 3-D model of the synapse, as first established by combining observations from electron microscopy, super-resolution light microscopy, and mass spectroscopy (Wilhelm et al. 2014). It is generally true that we can better understand any particular phenomenon in 3-D than 2-D.

The computer remains inferior to the brain at some tasks even if we try to miniaturize the transistor up to the physical limits. Thus, a different approach to circuit architecture is clearly in order. Accordingly, many attempts have been made to emulate our neuronal structures. We could begin to fabricate intelligent machines if we possess even a few rudimentary clues about how neurons process information. In a sense, soma can be considered analogous to digital logic structures, synapses to a kind of reconfigurable memory, and dendrites and axons to metal interconnects within our chip. Furthermore, if we examine the structure of the cerebral cortex in the brain, we come to realize that its layered structure can be emulated by a layered crossbar array, for neuro-inspired nanoelectronics to achieve a density comparable to the human brain.

As recently as 10 years ago, it was very difficult to fabricate a brain-emulating neuromorphic chip, due to the brain's complexity and extremely high density of neurons, even utilizing state-of-the-art semiconducting fabrication technology. Specifically, CMOS-based neuromorphic chips faced major difficulties caused by the variability in parameters such as gate length, threshold voltage, and so on. Furthermore, these variations are large enough to make the chip impossible to control using human-made algorithms. As a consequence, R&D activities on CMOS-based neuromorphic chips have been reduced, and instead, the interest in the digital neuron using a supercomputer has been enlarged. Although this later approach requires enormous power consumption, it has the advantage of producing results with easier programmability.

During the last 10 years, nanotechnology has advanced tremendously, specifically in the area of nanoelectronics. Now, we believe firmly that nanotechnology has the potential to make the goals of artificial intelligence a reality – that we can emulate brain functions such as perception, cognition, and inference. Via miniaturization and 3-D integration, nanotechnology can produce neuromorphic chips with a density relatively close to that of human neurons, while approaching the low power consumption and compact size of the human brain. Furthermore, spike-time-dependent plasticity (STDP) of the synapse, which was definitively demonstrated by (Markram et al. 1997) is known to be a mechanism for the brain's learning. Thus, the realization of STDP is the starting point for the design of electronic synapses for any neuromorphic chips. Fortunately, this STDP characteristic has been emulated in many nonvolatile memories, such as phase change memory (PCM), resistive random access memory (RRAM), conductive bridge random access memory (CBRAM), and so on (Kuzum et al. 2013). Utilizing high-density neuromorphic chips with the STDP property shows great promise for building a computer capable of learning and reasoning since such chips could offer the very high synapse density and low power consumption that are essential for electric synapses in neuromorphic chips. This is called a brain-inspired computer, a neuromorphic computer, or a neurocomputer, which by definition lie within the scope of AI. At present, the development of the neurocomputer is still in the early stages of research.

Uploading Your Brain into a Computer

What developments, which were previously only dreamed of in science fiction, might await humanity in the not-too-distant future if neurocomputers were implanted into the human brain or body and utilized as a platform of brain machine interface (BMI) or brain computer interface (BCI)? One obvious inspiration arises from *Star Trek: The Next Generation*. In that series, Chief Engineer Geordi La Forge, who was born blind, is equipped with a VISOR which directly feeds a very dense stream of information directly into his cerebral cortex, enabling him to "see" not only visible light but radiation spanning the entire known electromagnetic spectrum. The first steps toward this future have been taken in the past 10 years, with the development of prosthetic implants which directly stimulate retinal cells and restore to otherwise blind patients at least a rudimentary ability to detect large shapes, such as the edge of a road and an oncoming vehicle. As BMI technologies become more advanced, we can envision a future where it becomes cost-effective for any person to download an app directly into their brain, to gather and process specialized information, and to guide their work. Brain signals from thinking could potentially control any machine in the world and even yield "telepathic" person-to-person communication by directly connecting both parties to a common neural network.

Storing human memories after death or even downloading all the information from a human brain into a computer for a technologically based "eternal life" has attracted particular attention. This theme was shown in the aptly titled 2009 movie *Avatar*, one of that year's biggest blockbusters. The film portrayed that humans develop software to engineer actual souls for individuals within a local tribe of Na'vi – a humanoid species. By implanting this software on the Na'vi, genetically matched humans could remotely control hybrids of Na'vi bodies and human sprits, called Avatars. A similar concept to Avatar was depicted more recently in the 2014 movie *Transcendence*. In this film, a human consciousness is uploaded into a

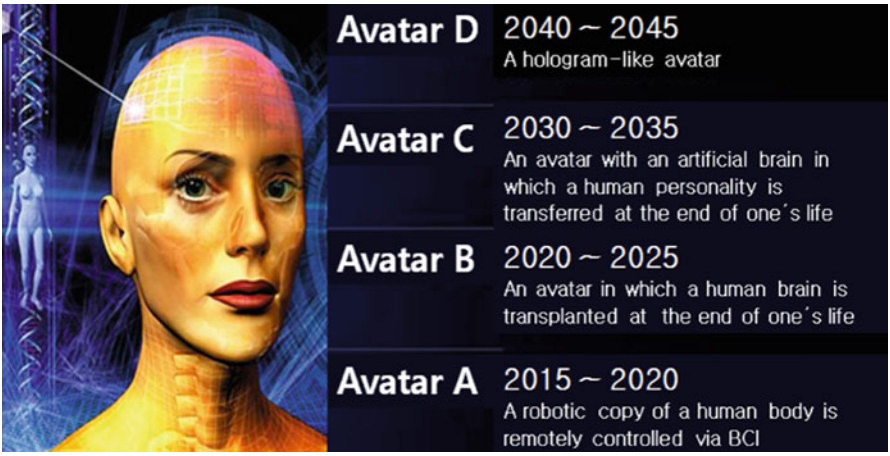

Fig. 2 2045 Avatar Project

computer before dying. Through the computer hardware and the Internet, the uploaded consciousness expands its knowledge continuously, 24 h a day, without need for food or sleep. As a result, this computer gains enormous computation power, transcending the ordinary human ability and bearing an ambition of dominating all living humans.

Although the ideas underlying *Transcendence* may appear at present to lie squarely within the realm of science fiction, their realization may arrive sooner than we think. In February 2011, "2045 Initiative" was announced by Dmitry Itskov, a Russian billionaire, in order to materialize artificial immortality through a hologram conceived in Avatar as shown in Fig. 2 (Upload Your Brain Into A Hologram: Project Avatar 2045, 2013).

Major Neuroscience Initiatives Sponsored by the EU and the US

It is widely declared that the last frontiers of science are to uncover the secrets of the birth of the universe which surrounds us and to understand the neural activity of the brain located between our own two ears. In this regard, the EU and the US have undertaken large, visionary 10-year initiatives to investigate the neural activity of the brain, in 2013. The examination of brain functions is expected to follow two broad, parallel approaches. The first approach, embraced by the Human Brain Project (HBP) of the EU, is to construct the structure of a digital brain through reverse engineering at the molecular level. The second approach is to map various neural functions across the brain, which is the goal of the US BRAIN (Brain Research through Advancing Innovative Neurotechnologies) Initiative. The HBP, with a total funding of one billion euros, aims to model and simulate neural networks using a supercomputer, based on all currently existing data about neural activities. Meanwhile, BRAIN intends to study how each neuron interacts at a molecular level using various probing tools. The two initiatives take quite different approaches, but share the same ultimate goal – to understand the neural functions of the brain.

Mapping the whole brain is absolutely necessary to find the mechanisms underlying various brain functions. This comprehensive map of neuronal connections in the brain is known as the "connectome." A thorough study of the connectome is indispensable to fully understand the mechanisms, which underlie the phenomena of learning, recognition, and reasoning. However, mapping information of the entire human brain is the most difficult challenge because colossal amounts of data are produced from our brain, consisting of 10^{11} neurons and around $10^{14\sim15}$ synapses. It is known that around 2,000 TB ($2{,}000 \times 10^{12}$) of data storage is necessary for the electron microscopy information from one cubic millimeter of brain tissue (Abbott 2013). Thus, more than 1 ZB (10^{21}) is calculated to be the absolute minimum required to store all the mapping information on the human brain. In fact, the total digital data produced by every computer in the world in 2012 is estimated to be approximately 2.8 ZB (2.8×10^{21}), meaning that the storage requirements of even a single human connectome are approximately equal to that of 6 months' worth of data generated by the entire human race.

Conclusion and Future Perspective

It is anticipated that we will be living in a green, intelligent society within the next 10 years (Fig. 3). All of our common devices and their parts will be smart enough to be operated by our voices, gestures, and even brain waves. One major obstacle to attaining this future is that our computer systems are built based on von Neumann architecture, meaning that computations are executed in serial mode, unlike our highly parallel brain. With this architecture, computer technology will never realize the intelligent society that we dream of. Implementing parallel processing through the neuro-inspired chips is the only workable solution.

We certainly understand the neural activity of the brain to some degree. However, our knowledge is nowhere near complete enough to emulate the brain by building a neurocomputer. The human brain has evolved for the last 200,000 years to meet the demands for basic survival: finding food, avoiding predators, breeding, and so on. In contrast, only about 70 years have passed since the first digital computer (ENIAC) was born in 1946. Nevertheless, the authors are of the opinion that the best inspiration for creating a neurocomputer is the approach embraced by the Wright brothers, who made the world's first airplane based on the physics of two fundamental aspects of the flight of birds: how to get lift and how to steer.

Neurocomputing is very difficult to realize at present, but exciting to look forward to in the future. Looking ahead, the neurocomputer would have the possibility of making errors in calculations, much like humans. In this view, complex calculations would continue to be performed by digital computers, but recognition and inference would be carried out by neurocomputers. Within the next

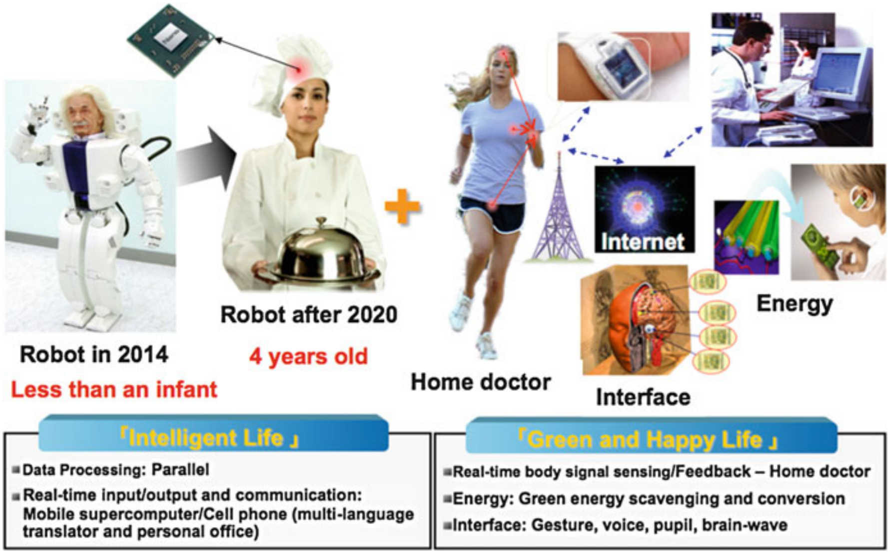

Fig. 3 Green and intelligent society after 10~20 years

several decades, a formidable neurocomputer could become available to us with the speed of present cutting-edge supercomputers and the chip density close to that of the human brain. We can barely begin to imagine what could be done with this awe-inspiring performance. For this dream to come true, systematic approaches are necessary to combine all the nanotechnology-based disciplines with the knowledge derived from neuroscience, computer science, and cognitive science.

Achieving this neuro-inspired computing system will be a long-term marathon, not a 100 m sprint. In the early 1960s, no one thought of the possibility of going outer space. However, humans finally did precisely that, leaving their footprint on the moon in 1969.

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Neurotechnology-Centered Convergence

Zack Lynch

Contents

Abstract

Neurotechnology is used to understand and influence the brain and nervous system for the purposes of improving health, education, entertainment, and information technology. Emerging areas of neurotech development that will create substantial value in the coming decade include therapeutic optogenetic modulation, neuromorphic computing, neurogenomics, brain–computer interfaces, neural stem cells, transcranial electrical modulation, and neurogaming. As these enabling technologies develop and converge, they will make possible completely novel applications including tools that create neurocompetitive advantages; therapeutic restoration technologies; self-learning, hyperefficient neuromorphic computing systems; neuroexperience marketplaces; human

Z. Lynch (✉)
Neurotechnology Industry Organization, San Francisco, CA, USA
e-mail: zack@neurotechindustry.org

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resiliency solutions; neurorobotic interfaces; and many others. Achieving these breakthroughs will require sustained support from both public and private capital sources.

Introduction

Neurotechnology is used to understand and influence the brain and nervous system for the purposes of improving health, education, entertainment, and information technology.

While the primary economic driver of new neurotechnology is the need to develop treatments for brain-related illnesses, we are also seeing the application of neurotechnology across a wide variety of economic sectors beyond therapeutic development. While some of these neurotechnology-enabled applications may appear faddish (e.g., marketing, economics, art), there is a common theme running through them that is profound: how can we use tools that leverage our new knowledge about our brains to make life more efficient and enjoyable (Glimcher 2002; Zeki 2001).

As the application of neurotechnology beyond health grows, neurotechnology will play an increasingly pivotal role in our economic, political, and social lives (Lynch 2004; Giordano 2012; Blank 2013). From accelerating innovation cycle times across existing industries to making entirely new modes of artistic creativity possible, the coming convergence of neurotechnologies offers an opportunity for global economic revitalization and dramatic improvements in individual resiliency (Lynch 2009).

Looking forward, it is now possible to credibly posit multiple new neurotechnology-driven developments on humanity's horizon including applications that create neurocompetitive advantage for individuals, companies, and nations; therapeutic restoration technologies that effectively treat and cure brain-related illnesses; self-learning, hyper-energy-efficient neuromorphic computing systems; the emergence of marketplaces to buy and sell neuroexperiences; new solutions to expand human resiliency for the masses; neurorobotic interfaces that extend our intentions into semiautonomous systems; and many others.

If we are to receive the benefits that these transformative converging technologies can offer humanity, major advances will still be needed across several areas of neurotechnology discussed below, as well as continued progress in enabling nano-bio-info technologies (Roco et al. 2013). Many of these technologies are still at the bleeding edge of development, and in order for them to mature, it is important that they have appropriate levels of funding and political support.

Global Neurotechnology Capital Flows

Neurotechnology applications focused on treating brain and nervous system illnesses include pharmaceuticals, biologics, medical devices, software tools, diagnostic systems, and surgical equipment for the treatment of neurological diseases, nervous system injuries, and psychiatric illnesses. Over two billion people worldwide currently suffer from brain and nervous system illnesses, and the global annual economic burden of brain-related illnesses has surpassed $3 trillion. Brain-related illnesses include addiction, Alzheimer's disease, anxiety, ALS, attention disorders, autism, depression, epilepsy, hearing loss, Huntington's disease, insomnia, mild cognitive impairment, migraine, multiple sclerosis, obesity, pain, Parkinson's disease, posttraumatic stress, retinal disorders, schizophrenia, stroke, traumatic brain injury, and more.

Since 2000, private venture capital funds have invested over $19 billion in promising neurotechnology companies (Lynch 2014). In 2013, the 800 companies involved in the global neurotechnology industry generated $160 billion in revenue with 4 % growth. The revenue for the three sectors in the industry breaks out as follows: neuropharmaceuticals had revenues of $134.5 billion and 2 % growth, neurodevices had revenues of $10.1 billion and 7 % growth, and neurodiagnostics generated revenues of $16.1 billion and 2 % annual growth (Lynch 2014).

In 2013, global venture capital investment in neurotechnology companies (including drugs, devices, software, and diagnostics) was up 12 % to $1.44 billion, while overall life science investing was down 1 % to $6.6 billion. In 2013, the total number of neurotechnology venture capital deals was down slightly to 152 deals, while over 200 different investor groups participated in these financings.

Global basic neuroscience research funding has begun to increase recently with the launch of the European Union's $1.6 billion Human Brain Project and the USA's more modest $200 million a year BRAIN Initiative, both of which have become focal points for accelerated basic research investment. The US National Institutes of Health continues to be the largest funder of basic neuroscience worldwide. It is composed of 27 different research institutes, two of which are focused solely on neuroscience-related research (NINDS and NIMH), with at least 14 more that spend variable portions of their budgets to support neuroscience research. Since 1997, NIH funding for neuroscience has increased from around $2.5 billion to $5.4 billion annually, accounting for approximately a sixth of the NIH budget.

Contributing to the global basic neuroscience funding ecosystem are the European Union, the UK, Canada, China, Japan, and several other countries that collectively invest an estimated $2 billion a year. In addition, billionaire philanthropists and their foundations such as Paul Allen, Howard Hughes Medical Institute, Eli Broad, the Stanley family, and Patrick and Lore McGovern have invested several billion dollars over the past decade in supporting innovative brain research. Importantly, on the translational research front, the pharmaceutical industry invests a massive amount each year on neuroscience drug development, an estimated $25 billion. Meanwhile, medtech and diagnostics companies are investing an estimated $1 billion in trials for new neurodevices and diagnostics for brain and nervous system illnesses.

While the annual investment in neurotechnology for uses beyond medicine remains modest, on the order of a few hundreds of millions of dollars, this does not mean that these applications will not have a broad impact. Today the use of

Table 1 Important areas of neurotechnology development over the next decade with corresponding area of impact

Key area of neurotechnology development	Primary impact arena
Therapeutic optogenetic modulation	Influencing specific human behaviors
Neuromorphic computing	Hyperefficient self-learning digital technology
Neurogenomics	Brain-wide genome-scale engineering
Brain–computer interfaces	Mind-controlled systems
Neural stem cells	Regenerating the brain
Transcranial electrical modulation	Real-time performance enablement
Neurogaming	Consumerization of neurotechnology

neurotechnology as applied to education, entertainment, wellness, and information technology is small, but each of these fields has the potential to impact our lives in important ways.

At the center of the coming neurotechnology convergence are seven enabling technology areas that will be the focus of the next decade of neurotechnology research, development, and commercialization. When considered separately, each of these areas represents critical leaps forward, but more important will be the impact that these technologies have when they converge, opening up new opportunities that will reshape reality in profound ways (Table 1).

Therapeutic Optogenetic Modulation: Influencing Specific Human Behaviors

From its simple origins at Stanford University in 2005, optogenetics has rapidly grown from a single impressive scientific breakthrough into a mission critical tool for researchers across the globe who are trying to understand the neural circuitry of behavior (Boyden et al. 2005). Optogenetic techniques offer ways of inserting genetically modified light-sensitive genes into specific cell types at a particular location in a living brain that can then be turned on or off to modulate behavior. To chart an estimated 86 billion neurons and nearly 10,000 distinct classes of neurons mixed together in the brain, researchers are now using hair-thin fiber optic threads inserted into the brain to pulse light on and off at various wavelengths to modulate specific behavioral circuits in animals.

While breakthroughs in our understanding of neural circuits involved in different behaviors continue, many hurdles remain for those wanting to translate optogenetic research techniques into commercializable therapeutic neuromodulation platforms. Human-focused therapeutic optogenetic modulation platforms face numerous scientific, technical, macroeconomic, regulatory, and clinical hurdles, but the potential payoff of being able to influence specific behavioral neural circuits is enormous (Williams and Denison 2013). With multiple benefits beyond today's electrical neurostimulation systems, optogenetics offers improved precision in the type of cell influenced, thereby reducing potential side effects, and confers the ability to perform simultaneous electrical recording of neural activity during stimulation for finely tuned closed-loop systems (Dai et al. 2013). Advances in several areas, such as the discovery of new light-sensitive proteins that can be silenced noninvasively, are accelerating therapeutic neuromodulatory development (Boyden et al. 2014). The first optogenetic clinical applications targeting the peripheral nervous system are already in development to selectively block pain sensation, to attenuate muscle spasms, and to treat retinitis pigmentosa.

Ambitious national governments have a pivotal opportunity to make leapfrog investments into neurotechnology, which would strategically position them in a leadership role in an area of technology that will have important implications for treating brain-related illnesses, as well as longer-term impacts on human performance enablement (USTC 2014).

Neuromorphic Computing: Massively Efficient Self-Learning Digital Technology

Neuromorphic computing (aka cognitive computing) represents the latest attempt to design brain-inspired computational systems – software and hardware that emulate the architectures, algorithms, and processes used in the human nervous system as an organizing principle for data processing. The goal is to build systems that can be taught rather than programmed and that can autonomously learn how to respond to unanticipated events in an ever-changing world (Williams 2013).

The architecture upon which today's computers are designed is limiting our ability to build massively efficient self-learning digital technology. Today's computers are reaching their limits as they try to solve many complex real-world problems such as real-time learning for autonomous navigation, instant facial recognition, and true voice-controlled systems, each of which requires the real-time input of massive amounts of constantly changing unstructured data to be effective. Indeed, a majority of such data is unstructured (it is not in the form of numbers or tables, but data streams from sensors or video feeds), and despite the economic cost of generating and gathering it, an extraordinary amount sits unanalyzed and wasted.

Looking to go far beyond the binary logic and von Neumann architectures of today's computers, engineers are researching the architecture and function of the human brain for clues on how to design a new computational paradigm that is massively parallel and plastic (the brain is adaptive, modifying its hardware and algorithms based on experience), radically energy efficient (the brain consumes less energy than a light bulb), and computationally robust (the brain can handle more than 50 % noise) (Wong 2013).

The critical challenge on the hardware side is figuring out how to mimic synaptic plasticity, the change in neural connections that occurs during learning and experiences (Crane 1960). This represents a complicated problem in physical space, as there is an incredibly high synapse to neuron ratio of 10,000:1. Neuristors have recently been developed to help solve this problem (Williams et al. 2013).

Neuristors are devices that emulate the signal processing and transmission properties of a neuron. The combination of neuristors and memristors may now provide the necessary components for transistor-less integrated circuits that emulate signal transmission and processing capabilities of brains. In mid-2014, IBM has unveiled a few SyNAPSE chips with the unprecedented scale of one million programmable neurons, 256 million programmable synapses, and 46 billion synaptic operations per second, per watt. IBM said the chip, at 5.4 billion transistors, is currently one of the largest CMOS chips ever built, yet consumes only 70 mW of power by running at biological real time.

On the software side, brain-inspired neural network software architectures, artificial intelligence systems, and deep learning systems are advancing rapidly as Google, Microsoft, IBM, and Facebook attempt to figure out ways to monetize the vast streams of unstructured data around the world (McMillan 2014). What is certain is that programming future cognitive computing platforms will require new software frameworks and training paradigms that will take time for a critical mass of programmers to learn and use to execute successful applications.

The application of neuromorphic computing systems into physical landscapes is leading to the development of neurorobotic systems – robotic systems that are comprised of a controller, a body, actuators, and sensors and whose control architecture is derived from a model of the brain, i.e., cognitive computing architectures and neuromorphic chips (Rohrbein 2013). The key difference between neurorobotic systems and cognitive computing applications is the closed-loop nature of the action (i.e., it will be happening in the physical world). The applications developed from neurorobotic systems will have real-world applicability even in their early stages of development.

Despite the complexity of this effort, recent progress on creating certain components of the cognitive computing system such as neuromorphic chips has been accelerating as heavyweight technology companies like IBM, HP, Qualcomm, Intel, and others funded by DARPA and the European Union's Brain Project are focused on this compelling opportunity. Benefits of neuromorphic computing could lead to many inventions including glasses for the blind that use visual and auditory sensors to recognize objects and provide audio cues; health-care systems that monitor vital signs, provide early warnings of potential problems, and suggest ways to individualize treatments; computers that draw on wind patterns, tides, and other indicators to predict agricultural growth patterns; and systems that monitor global financial capital flows and react proactively to maximize financial outcomes at a variety of time scales.

Neurogenomics: Brain-Wide Genome-Scale Engineering

While advances in genomics have impacted many areas of medicine, only recently have genetic technologies begun to make progress into our understanding of the genetics of brain diseases. Recently completed genome-scale studies with a large number of subjects have benefited from recent technological innovations that have enabled the analysis of genetic variation at unprecedented resolution and scale at rapidly decreasing costs.

Areas that have contributed to this advance include breakthroughs in comparative genomics, gene expression atlases of the brain, network genetics, and their applications to behavioral phenotypes, as well as improvements in the organization and funding of population genomics projects. New diagnostic methods sensitive to picomole and attomole levels have been developed, as well as three-dimensional tracking (at the single molecule level) of protein motors, enzymes, liposomes, and other bionanostructures (Roco et al. 2013).

All of this research has elucidated a fundamental fact that many brain diseases, especially neuropsychiatric illness such as schizophrenia, bipolar disorder, and autism, are massively polygenic in origin – hundreds of genes contribute to the ultimate behavioral outcomes. To make matters more complicated, in the brain, spatial organization (anatomy and connectivity of neurons) and gene expression are critical to understanding how the system functions.

The ultimate goal of genomics research is the development of more effective therapeutics and preventative interventions. This road from gene discovery to actual therapy is difficult even for well-understood diseases. Fortunately, a new generation of genome editing tools including zinc finger nucleases, TALENS, and CRISPR are transforming the neurogenomics landscape. CRISPR, in particular, provides a precise way to delete and edit specific bits of DNA – even a single base pair – rapidly and at a relatively inexpensive cost (Baker 2014). Most importantly, this technology makes it possible to add, edit, or delete multiple specific genes at once, making it possible to change many genes in parallel, from which behavior outcomes can then be observed (Hyman 2014). These new approaches are slashing the time and cost of complex genomics research by orders of magnitude and are providing scientists with the power to rewrite genomes.

In time, CRISPR-driven genetic surgery will be able to correct multiple specific defective genes simultaneously, impacting a wide variety of brain and sensory diseases such as Huntington's disease, aging, hearing loss, and autism, as well as making it possible to modify the DNA of living embryos. The challenge of gene therapy is location – how to deliver enough of the relevant cell to the right location, which makes the eye and ear good early stage candidates because they are accessible and localized.

Brain–Computer Interfaces: Mind-Controlled Systems

A brain–computer interface (BCI) – sometimes called a direct neural interface, a brain–machine interface (BMI), or cognitive-based neural prosthetics – is a direct communication pathway between the brain and an external device. In one-way BCIs, computers either accept commands from the brain or send signals to it (e.g., to restore vision). Two-way BCIs would allow brains and external devices to exchange information in both directions. This type of BCI has not yet been successfully implanted in animals or humans, but progress on this front is accelerating (Donoghue 2002).

The current cutting edge of two-way BCI development is DARPA's $40 million Restoring Active Memory project, which aims to develop and test wireless, implantable neuroprosthetics. As part of the project, researchers at the University of Pennsylvania and UCLA are developing computer models of memory that can understand how neurons code declarative memories – those well-defined parcels of knowledge that can be consciously recalled and described in words, such as events, times, and places. The Lawrence Livermore National Laboratory will manufacture the neural device once a design is established.

The neurodigital interface, the place where inorganic human-designed electronics and organic neural tissue interact, is where the rubber meets the road in these systems. The development of new sensory and stimulatory systems will be required for capturing, recording, outputting, and stimulating of neural signals.

On the neural recording front, the number of neurons that can be simultaneously recorded has doubled every 7 years since the 1950s, currently allowing electrical observation of hundreds of neurons at sub-millisecond time scales (Stevenson and Kording 2011). In humans, the record currently stands at 192 electrodes recording more than 270 neurons at once. Clearly some radical improvements will be required to develop robust two-way BCI technologies. Because electrical recordings have fundamental physiological limits, other methods are under consideration including hybrid systems that combine components of optical recording, embedded active electronics, magnetic resonance imaging, ultrasound, and molecular recording in new ways (Kording 2013).

A plethora of new approaches are emerging to address the complex aspects of the neurodigital interface problem, including flexible nanowire electrodes threaded through the capillary network, carbon nanotube-coated electrodes, ultrathin flexible neural electrodes onto bioresorbable silk protein substrates, neural dust micron-size piezoelectric sensors scattered throughout the brain that use reflected sound waves to capture electrical discharges from nearby neurons, optogenetic techniques for pulsing circuits, new mathematical algorithms to translate action potentials into command signals, direct recording of neural activities into information-bearing biopolymers, CCD cameras attached to multielectrode arrays to improve recording, and nanoporous silicon anti-scarring coatings. It should also be appreciated that noninvasive forms of recording and stimulation have the potential to provide substantial value in the BCI space as well.

Neural Stem Cells: Regenerating the Brain

The brain has extremely limited capabilities to repair itself, but new strategies are emerging to improve the brain's ability to regenerate lost neurons and to facilitate the incorporation of implanted stem cells into an individual's brain circuitry. The first isolation of human embryonic stem cells in the late 1990s and the 2006 discovery that adult cells can revert to a pluripotent state after the activation of particular genes accelerated the field, as human-induced pluripotent stem cells could now be grown in culture and their capabilities explored without creating ethical concerns.

Today companies are using several different pathways to develop stem cell therapeutics, including cell implants which engraft into brain architecture, cells which do not engraft and may be injected intravenously, encapsulated and genetically modified cell implants which act as drug delivery pumps, and small molecule or protein therapeutics which stimulate endogenous stem cells. In each of these cases, there are numerous biotechnical hurdles including the fact that new cells must not only survive under inhospitable conditions but also integrate tightly with existing circuitry to take over lost functions. Such integration may require a "reprogramming" of other parts of the circuit to be successful, and axons may need to grow long distances before finding their appropriate target.

While stem cell research has taken a backseat in the public eye relative to other areas of neurotechnology development in recent years, the potential of neural stem cells to be used as therapeutics holds great promise as breakthroughs in neurogenomics bring additional momentum into the field. For example, researchers have created a miniature human retina in a dish from human stem cells that can sense light, which could help restore vision. Neural stem cell therapy for multiple sclerosis is advancing as researchers seek to overcome the length of time it takes for progenitor cells to turn into oligodendrocytes, the nervous system's myelin-making cells (Chen et al. 2014). In addition, researchers have found a new type of neuron in the adult brain that is capable of telling stem cells to make more new neurons. Other researchers are looking at new ways to induce bone marrow stem cells to differentiate or mature into brain cells. These breakthroughs will further accelerate innovation in neuroregeneration, giving great hope to those who suffer from debilitating diseases.

Transcranial Electrical Modulation: Real-Time Performance Enablement

Research and development into the application of weak electrical currents across the cranium for the purposes of developing noninvasive therapies, as well as new consumer-oriented tools to enable healthy normal humans to perform better, has exploded in the past several years. There are several forms of transcranial electrical stimulation that are being developed which, when coupled with neurosensing systems such as electrical encephalogram (EEG) into a closed-loop system, will prove to be transformative (Dumas 2013). In short, a closed system that can adaptively modulate currents and electrical pulses across the skull will make it possible to optimize their effects and represents a fundamentally new way to both treat patients suffering from a wide variety of brain-related illnesses and improve the performance of healthy normal humans (Yonas 2011). Real-time modulation of electrical signals in the brain with relatively inexpensive devices represents a new way that the average individual may begin to use consumer neurotechnology.

Transcranial direct current stimulation (tDCS) is the application of weak electrical currents (1–2 milliamp) and induced electric fields in the brain on the order of one volt per meter in order to modulate the activity of neurons in the brain. Currently tDCS is being studied for the treatment of a number of neurological conditions including stroke, migraine, and major depression, as well as the improvement of memory and performance in healthy normal humans. When electrodes are placed on the scalp, the current density produced in the brain is exceedingly small, changing membrane potentials only by a fraction of a millivolt. Much of the current is shunted through the skin and within the brain, through the cerebral fluid, thus limiting the effect on neurons. It should be noted that unproven claims about the effects of tDCS abound and that more placebo-controlled trials are warranted.

Transcranial alternating current stimulation (tACS) is a technique designed to change intrinsic cortical oscillations. This technique opens up the possibility of actively synchronizing cortical rhythms through external means, particularly when administered in the "ripple" frequency range (between 100 and 250 Hz) associated with memory encoding. This technique must be used at relatively low frequencies or retinal flashes will be induced; moreover, at higher amplitudes, safety concerns – including seizures – remain. In spite of these issues, active synchronization of cortical oscillatory activity provides particularly enticing possibilities involving stimulation, behavior modification, and alteration of stimulation in real time – especially when implemented as a closed-loop system (Ruffini 2014). Currently, the tACS method is beginning to be used to treat depression, anxiety, and other mood-related disorders.

Transcranial random noise stimulation (tRNS) is yet another variant. This method is like adding "white noise" to ongoing neural activity and is thought to open neuronal ion channels, increasing excitability. There are several potential advantages of tRNS over tDCS: (1) while tDCS can open ion channels once, tRNS can do so repeatedly through multiple ionic influxes; (2) tRNS works around problems associated with stimulation of different sides of a folded cortex, which can lead to effects that cancel each other out.

Studies have also been performed that involve using various drugs to enhance or suppress the stimulation effects of tDCS. For example, applying tDCS in the presence of NMDA receptor and GABA (lorazepam) agonists has been found to facilitate the aftereffects of tDCS (Miniussi 2011). Targeted multimodal therapies wherein pharmacological and electrical stimulation is combined to achieve optimal dose–response relationships represent important and exciting areas of future development in brain stimulation. Combining tDCS, tACS, and tRNS with closed-loop feedback via EEG represents a new way to modulate brain activity in real time for both therapy and performance enablement.

Neurogaming: Consumerization of Neurotechnology

One of the most important trends that will impact the lives of ordinary individuals in the coming decade revolves around the consumerization of neurotechnology and its use in neurogaming. Neurogaming is where the mind and body meet game play.

It is where one's nervous system is integrated into the gaming experience by using new input sensor technologies, output systems, and game design techniques. Neurogames are being developed for a wide variety of purposes including therapeutics, wellness, education, training, and entertainment (Takahashi 2014).

Until recently, gaming has been limited by controller input. In the gaming world this resulted in basic move, jump, hit, and shoot games. Even when gaming was applied to therapeutic and educational games, this also suffered from the same limited keyboard and point-n-click input paradigm. Finally, neurogame developers are creating much more robust lifelike immersive experiences by integrating data from new input devices that track hand gestures and body motion, record and respond to an individual's brain waves via neurosensing devices, react and drive game play with eye tracking and facial recognition technology control play via fine muscle movement sensors, expand emotional integration using heart rate and skin conductance levels, and more – making it possible for creative game designers to build more engaging responsive experiences.

On the output side, neurogame developers are quickly moving away from the flat computer screens and mobile devices that are the dominant output platforms today and instead turning toward new virtual reality platforms, wearable augmented reality technologies, touch haptic sensation systems, multidimensional sounds, and scent creation technologies to design more compelling and realistic experiences.

The convergence of these new input and output technologies makes entirely new experiences to engage our brain and nervous systems in a convincing way. Today we are already seeing the first level of convergence within the neurogaming space as companies develop apps that integrate a few of these core technologies. For example, in the area of entertainment neurogaming, we are seeing the integration of electroencephalography (EEG) neurosensing technology with virtual reality technology from companies such as Oculus VR, in order to bring more closed-loop brain game experiences to market. In other areas, like wellness neurogaming, new apps which improve one's brain fitness, mental clarity, and overall emotional resilience are beginning to reach the market (e.g., Lumosity, BrainBow, If You Can). Already several companies are developing therapeutic neurogames for regulatory approval that are targeted at brain-related illnesses such as ADHD, memory decline, schizophrenia, PTSD, and more (e.g., Akili Interactive, Posit Science, Blue Marble Gaming Company). In addition, educational neurogaming companies are developing programs to engage schoolchildren in an effort to provide personalized accelerated learning (e.g., Curiosityville, BrainRush, C8 Sciences).

While the first generation of these neurogaming technologies is still developed using basic input/output technologies, second generation platforms are beginning to bring together multiple modalities, dramatically improving efficacy and potency, as well as showing their usefulness as new social entertainment systems. The mass adoption of consumer-oriented neurogames will reduce barriers to social acceptability of novel neurotechnologies and act as a major distribution mechanism through which future neurotechnologies will be adopted as they reach a consumer-ready state.

Novel Applications of the Neurotechnology Convergence

Each of the advances briefly described above is exciting in its own right, but the real potential for breakthrough innovation over the next 10–15 years sits at the convergence of these technologies with each other and with other innovations occurring across the greater nano-bio-info technological ecosystem. While trying to forecast the exact product form that will emerge from these convergences is next to impossible, it is possible to begin to confidently predict areas that would benefit from this convergence. Here are several examples:

Creating Neurocompetitive Advantage: The convergence of transcranial electrical modulation with mass market educational neurogaming applications will make possible extraordinarily engaging virtual learning spaces where personalized brain modulation enables individuals to learn languages, mathematics, coding, and other realms of information retention and creativity at an accelerated rate. When advances in neuromorphic computing are then applied to the massive datasets created from these systems, new self-learning algorithms will be able to tailor content to individuals in real time in order to optimize learning. The individuals, companies, and nations who develop and leverage this technology first will have a unique competitive advantage in the twenty-first century.

Therapeutic Neurorestoration: The convergence of brain-wide genome-scale engineering techniques with advances in our understanding of the processes that govern regeneration capabilities of neural stem cells will provide the basis for new therapeutic neurorestoration opportunities for those that suffer from neuropsychiatric and neurodegenerative diseases. The development of a robust new neural coding science as well as the development of rational therapeutic opportunities will benefit greatly from new machine learning algorithms and computational horsepower being developed in the neuromorphic computing sphere.

New Markets for Neuroexperiences: The convergence of entertainment neurogaming environments coupled with transcranial neuromodulation technology underpinned by advances in self-learning neuromorphic computing systems that cocreate new digital experiences with the consumer could unleash a powerful new frontier of value creation for pure digital experiences that could be bought and sold instantly with minimal impact on global physical resources. This is similar to what one would expect in the development of the Metaverse. For example, one could sell virtual vacations complete with emotional stimulation within unique landscapes or one could buy a closed-loop augmented learning system that translates reality in real time into another language to accelerate acquisition.

Enabling Mass Resiliency: A more robust understanding of the underlying neurobiology of neuroplasticity is being formed with each new advance in our basic and applied research methods. Applying this newly discovered knowledge and making it available to individuals in the form of engaging closed-loop wellness neurogaming technologies that can be quickly and easily adopted by consumers will impact human relations in important ways. Examples of resiliency

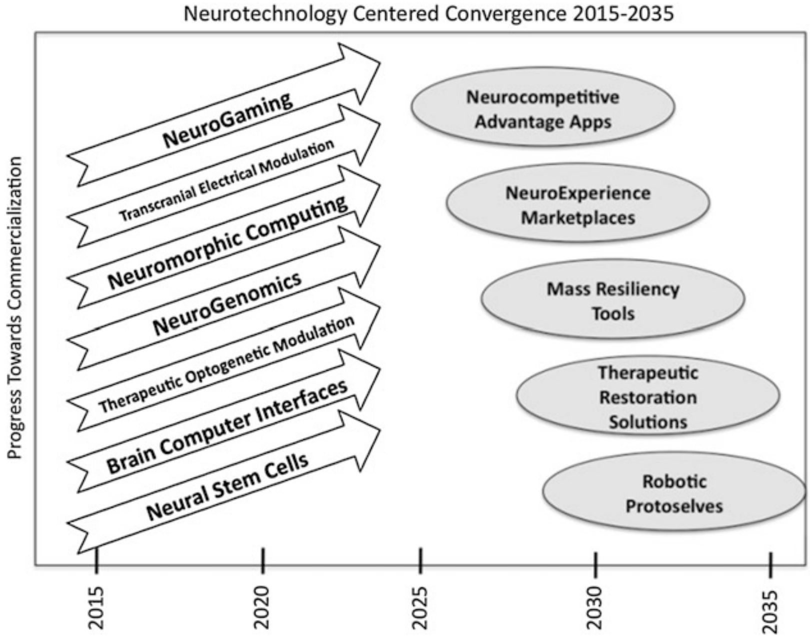

Fig. 1 Seven core neurotechnologies that are emerging from 2015 to 2025 will make possible fundamentally new neurotechnology convergence opportunities from 2025 to 2035

applications would include accelerated meditative states via stimulation, breath feedback systems to improve calmness, and closed-loop rewiring applications to boost empathetic response pathways.

Robotic Protoselves: As advances in brain–computer interface technologies merge with innovation in the neurorobotics arena, we will begin to see the emergence of semiautonomous robotic systems whose key actions are driven by thought-controlled commands. Examples would include assistive systems for the elderly and individuals with disabilities, defensive weapon systems, and systems to support multigenerational space travel (Fig. 1).

Accelerating the Neurotechnology Convergence

As incredible as these potential convergence advances seem, they will not happen in a vacuum. Tremendous amounts of capital will be required to bring this technology into existence. Thoughtful public policy is also essential to ensure that regulatory roadblocks do not stifle innovation in the course of pursuing appropriate ethical boundaries (Lynch 2006). Policy makers should focus on a comprehensive strategy such as National Neurotechnology Initiatives to accelerate neurotechnology research, development, and commercialization.

A robust National Neurotechnology Initiative would:

- Create new funding mechanisms for transdisciplinary team-oriented neurotechnology R&D
- Provide funding to improve cross-coordination of agencies involved in neurotechnology R&D
- Promote tax credits for companies commercializing novel neurotechnologies
- Establish a network of national neurotechnology innovation centers
- Create translational funding mechanisms to speed research to market
- Make support available for jointly funded international initiatives

Moreover, the field of neurotechnology would be accelerated if researchers, investors, innovators, entrepreneurs, and executives focus on the following:

- Convene transdisciplinary meetings focused on accelerating each core emerging neurotechnology with technical discussions on progress toward convergence opportunities.
- Develop new tools for neuromorphic computing architectures which has the potential to accelerate progress in all domains of research, inquiry, and knowledge integration.
- Enhance consumer adoption of neurotechnology by focusing on making neurogaming interfaces as user-friendly as possible using the latest game mechanics and distribution strategies.
- Focus on fundamental neurobiology – the core molecular neurocircuitry of healthy and diseased brains – to elucidate differences and develop treatments and enablements.
- Create tools for noninvasively imaging and interacting with the brain that are spatially and temporally five times more effective.
- Integrate advances occurring in all the nano-bio-info domains as quickly as possible.

Neurotechnology represents the newest set of tools that humanity has developed in our long history of tool making that has enabled more of us live better and live longer in an ever-growing, highly connected global society. Never before in human history have we been so close to having the tools to understand and influence our minds in such a profound way that will help create entirely new industries, inspire modes of thought, and stimulate creative endeavors beyond our current conceptions.

While many conflicts and wars are still fought over natural resources, it is the mind-set of individuals within the conflicting factions that are at the core of many disputes. Unless we nurture the promise of neurotechnology to defuse destructive mind-sets, such disputes will remain stubborn thorns in the peaceful development of our global civilization. This is not to say that we will not continue to face incredibly protracted global problems, for example, the inequitable distribution of natural resources and other sociopolitical issues. But because new tools will shortly be available to deal with seemingly intractable problems in novel ways, we should welcome and promote their development.

Humanity could benefit greatly from more robust ways to emotionally communicate at a mind-to-mind level of bandwidth. This is especially true if we are going to have a chance to empathetically connect in ways that can profoundly change the ethical and moral stances around disputed issues. While advances in other areas of the human endeavor, such as developing efficient clean energy and improving agricultural yields, are also important, there is no other area of technology development that will enable us to directly deal with the most fundamental issue of all: promoting human to human understanding. For the first time in our history, we are at the edge of developing neurotechnological tools that could transform our global society in the most profound way, and the neurotechnology-centered convergence is critical to making this possible.

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Services Science and Societal Convergence

Jim Spohrer

Contents

Abstract

This chapter provides an introduction to the concept of societal convergence from a service science perspective. Societal convergence can be viewed as the next great swing of the pendulum back (1) from increasing individual specialization with reintegration at the societal level (2) to a better balance of specialization and reintegration at all levels of society. Service science is an emerging transdiscipline for the (1) study of evolving ecology of nested, networked service system entities and value co-creation phenomena, as well as (2) pedagogy for the education of the twenty-first-century T-shaped (depth and breadth) service innovators from all disciplines, sectors, and cultures. For the purposes of this chapter, we define societal convergence as the continuous reconfiguration of the

J. Spohrer (✉)
IBM Almaden Research Center, San Jose, CA, USA
e-mail: spohrer@us.ibm.com

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growing body of knowledge (NBIC/CKTS) to ensure depth and breadth at all levels in society while mitigating the "knowledge burden" and maintaining the growth in knowledge as well as improvements in quality of life.

Introduction: Motivations and Goals

What is societal convergence? This chapter provides one possible definition and analysis of societal convergence from a service science perspective. As we will come to see, societal or service system entities are configurations built up from individual cognitive entities, where intergenerational knowledge transfer and knowledge accumulation ("knowledge burden"), both technological and organizational, play a primary role in augmenting capabilities, improving human performance, and improving quality of life. The knowledge burden of a society derives from the need to ensure that the next generation has the knowledge required to run all technological and institutional/organizational systems needed to maintain the quality of life for future generations and continue innovating, thus growing the burden (Jones 2005).

Nano-bio-info-cognitive convergence (NBIC) and the convergence of knowledge and technology for the benefit of society (CKTS) are initiatives that challenge researchers to think more deeply about convergence (Roco and Bainbridge 2003). Convergence fits squarely within the tradition of adding a new layer of discourse that spans multiple disciplinary areas (Gorman 2010). Kline (1995, p. 173) called for the creation of the conceptual foundations of multidisciplinary thinking in order to build better interfaces between the disciplines and better understand the growth of human powers over the past 100,000 years. Kline was especially concerned about the increasing complexity of sociotechnical systems and our species being just one or two generations away from possible collapse, if knowledge transfer to the next generation was disrupted. Kline also was concerned that university leaders needed to find an effective way to incentivize more multidisciplinary thinking within academia, so that graduates would have a stronger grounding in all the disciplines and how they relate to each other and the natural and human-made worlds.

In fact to understand societal convergence, a broad perspective on human history is needed. Service science, which is an emerging transdiscipline, provides one such broad perspective. A transdiscipline borrows from existing disciplines, without replacing them. Like any emerging science, service science provides a new way of thinking and talking about the world in terms of measurements on entities, interactions, and outcomes (Spohrer et al. 2011; Spohrer and Maglio 2010; Spohrer et al. 2007; Maglio et al. 2006). Specifically, a service scientist seeks to measure the number and types of entities, interactions, and outcomes and advance better methods and architectures for thinking and talking about the world in terms of nested, networked service system entities and value co-creation phenomena (Spohrer et al. 2012). These concepts (service systems, value co-creation) are rooted in a world view known as service-dominant logic or S-D logic (Vargo and

Lusch 2004, 2008; Ordanini and Parasuraman 2011; Ng 2012; Lusch and Vargo 2014). In the parlance of S-D Logic, service systems are sometimes referred to as resource integrators, and value co-creation is often exemplified in exchange.

Section "Overview: Societal Convergence" defines societal convergence from a service science perspective, section "Background: Service Science" provides further background on service science as a transdiscipline, and section "Concluding Remarks: Future Directions" concludes with future directions.

Overview: Societal Convergence

The challenge of convergence is gradually becoming better documented (Roco and Bainbridge 2003). The MIT Media Lab has summarized the challenge of convergence in the phrase "we live in a peoplebyte world, with personbyte people" (see 10 min into this video: http://www.youtube.com/watch?v=mwIjcv7OWMo). Every product and institution that makes up our modern world is a packaging of a great deal of knowledge. Even the simplest products, such as a modern pencil, include special chemical processes for graphite, wood shaping, erasers, metal eraser clamp, paints, and more. The specialized tools needed in each of the pencil manufacturing steps are even more sophisticated than the pencil. A smart phone is at an even larger level of complexity. The "app economy" that depends on smart phones is at an even larger level of complexity. Our great-great-great-great-great grandparents lived in a very different world. Our ancestors of just a few hundred years ago had enough knowledge within a relative small network of people to make many of the things they needed to live. The so-called Makers Movement is an indication the pendulum may be swinging back, and local manufacturing skills are returning – however, often dependent on modern technologies such as 3-D printers and robots.

So from a broad historical perspective, the challenge of convergence is of understanding the enormous increase in collective human capability that has occurred over the last few hundred years and which seems to be continuing at an accelerating rate (Kline 1995, p. 174). Nano-bio-info-cognitive convergence, which brings all key disciplines together, has the potential to continue the accelerating rate of augmenting human performance.

However, the challenge is not simply to understand and reap the benefits of convergence, although that is very important, the growing challenge is to address the growing "knowledge burden" that convergence is creating (Jones 2005), or more pointedly, the fact that we are just one or two generations away from collapse, if that knowledge cannot be successfully passed on to the next generation (Kline 1995).

Of course, we can and do use information and communications technologies (ICT) to augment our individual and collective capabilities (Engelbart 1995). However, the augmentations create a reliance on technology (and other formal physical symbol systems, such as organizations and institutions), which simply adds to the "knowledge burden" of society (Jones 2005).

The growth of the "knowledge burden" is reflected in the growth and scale of modern universities (Spohrer et al. 2013; Spohrer 2009). Both the numbers of new disciplines and research centers at major universities around the world are evidences that the "knowledge burden" is growing and convergence is becoming a more urgent issue. However, the major incentive systems of all major universities are still toward more and deeper discipline silos, not toward convergence and reintegration of knowledge from many disciplines into new multidisciplinary and transdisciplinary forms.

For the purposes of this chapter, we define societal convergence as the continuous reconfiguration of the growing body of knowledge (NBIC) to ensure depth and breadth at all levels in society while mitigating the "knowledge burden" and maintaining the growth in knowledge as well as improvements in quality of life. Societal convergence will require the development of new incentive structures that reward a balance between specialization and reintegration of knowledge at multiple levels of society, from individuals to universities to cities to nations. How might this be possible? Fortunately, there is a growing community of researchers working on service science, which offers one possible path to realize societal convergence within the NBIC framework.

In short, societal convergence should make it easier to pass on to the next generation the knowledge to rebuild society, even as the amount of knowledge locked up in each discipline continues to increase. However, to achieve this goal will require rethinking and reframing our views on business and society. One such reframing is described in the next section.

Background: Service Science

Service science draws on a great breadth of academic disciplines, without replacing them. How entities use knowledge to co-create value is intimately tied to all disciplines, which can be thought of as societal fountains of knowledge. As disciplines create knowledge, which is woven into the fabric of society and becomes essential to maintain quality of life, that knowledge becomes part of the "knowledge burden" of that society (Jones 2005). What differentiates service science from all existing disciplines is that it is a transdiscipline, drawing on all and replacing none, with a unique focus on the evolution of service systems and value co-creation phenomena. Service science aspires to provide the breadth for T-shaped service innovators who have both depth *and* breadth of knowledge. Depth can be in any existing academic discipline; appropriate breadth can improve communications, teamwork, and learning rates (IBM 2011).

A "service science perspective," as we will see below, is a way of looking at the world through the lens of service science and S-D logic. A "physics perspective" is a way of looking at the world and "seeing" a world of things made of atoms and forces, but who has ever really "seen" an atom? A computer science perspective is a way of looking at the world in terms of universal computing machines (e.g., physical symbol systems, Turing machines, etc.) and codes (e.g., symbols as both data and algorithms). An economics perspective is a way of looking at the world in terms of actors, supply and demand, externalities, and moral hazards. As we will see below, a service science perspective is a way of looking at the world in terms of an ecology of nested, networked service system entities and the value co-creation phenomena that interconnect them.

Human endeavors, such as "sciences," build on philosophical foundations, and each science must first provide ontology (what exists and can be categorized and counted) new sciences may seem like "stamp collecting" or "counting stamps" to scientists in more mature sciences. For example, Lord Rutherford said, "All *science* is either physics or *stamp collecting*." Service science is still at the stage of counting and categorizing types of entities, interactions, and outcomes), then epistemology (how we know and how others can replicate results), and finally praxeology (actions and how knowing matters or makes a difference). These three "ologies" explicitly or implicitly underlie all sciences; as humans, we seek knowledge of the world and of ourselves and then work to apply that knowledge through actions to create benefits for ourselves and others by changing aspects of what exists (service), in full awareness of our human sensory, cognitive, and motor limits – yet increasingly augmented by our technologies and organizations and augmented by scientifically and imaginatively derived knowledge, of both what is and what might be.

However, "all this knowing" does create a "knowledge burden" which must be carefully managed (Jones 2005). Quite simply, service is the application of knowledge for mutual benefits, and service innovations can scale the benefits of new knowledge globally and rapidly, but all this knowing does create a burden – including the burden of intergenerational transfer of knowledge.

Augmentation layers lead to the nested, networked nature of our world – specifically, as an ecology of service system entities. Value co-creation phenomena (service-for-service exchange) form the core of our human ecology (Hawley 1986). Value co-creation phenomena are also known as win-win or non-zero-sum games (Wright 2001). "Competing for collaborators" drives the evolution of markets and institutions and contributes to both their dynamism/stagnation and stability/instability (Friedman and McNeill 2013). Information technology, Internet of things, big data, etc. are accelerating the ability of service systems to develop and continuously evolve and refine explicit symbolic processes of valuing, which further augment service system capabilities. Alfred North Whitehead, English mathematician, is quoted saying: "Civilization advances by extending the number of important operations which we can perform without thinking of them." Augmentation layers, including technological and organizational augments, contribute to the nested, networked nature of our world and our "knowledge burden." Augmentation layers have many benefits, but they can also "hide" the extent of a societies' knowledge burden.

The mature sciences of physics, chemistry, biology, and even computer science and economics can be used to tell a series of stories – overlapping and nested stories about our world and us. Physics describes the world in terms of matter, energy, space, and time, with fundamental forces well quantified across enormous scales to explain phenomena much smaller than atoms and much larger than galaxies.

Physicists theorize and quantify to tell a story that stretches from before the big bang to beyond the end of time itself. Chemistry describes the world in terms of the elements, molecules, reactions, temperature, pressure, and volume. Geologist and climatologist, born of modern chemists, can tell the story of the birth and aging of our planet. Biology describes the world in terms of DNA, cells, and molecular machinery driven by diverse energy sources. Ecologists informed by modern biology tell the story of populations of diverse species shaping and being shaped by each other and their environments. Computer science describes the world in terms of physical symbol systems and other computation systems, codes, algorithms, and complexity. Cognitive scientists and neuroscientists are today working with computer scientists and others to propose stories of the birth of consciousness, communications, and culture in humans and prehuman species. Finally, economics describes the world in terms of supply, demand, externalities, principles, agents, moral hazards, and more. Economists theorize and quantify to tell the story of morals and markets, laws and economies evolving over the course of human and even prehuman history, and how the world can be in balance one moment and then go completely out of balance the next (Friedman 2008; Friedman and McNeill 2013).

Service science adds to these stories and is an emerging transdiscipline that builds on these and many other academic disciplines, but does not replace any of them. Service science is enormously practical, as national economies and businesses measure an apparent growth in "services" in GDP (gross domestic product) and revenue, respectively. Getting better at service innovation is the practical purpose of service science. Service science is also academic, and like the academic discipline of ecology, it is an integrative and holistic transdiscipline drawing from (and someday perhaps adding to) other disciplines without replacing them. While the basis of service is arguably division of labor and specialization, which leads to the proliferation of disciplinary, professional, and cultural silos, nevertheless service science, as an accumulating body of knowledge, can add some measure of breadth to the depth of specialists. In this sense, service science is holistic and inclusive, every individual can add to her/his breadth as she/he adopts a service science perspective and learns more about how the overlapping stories of other sciences and disciplines fit together into a whole. The nested, networked nature of our world becomes more apparent. As service science emerges, we can begin by "seeing" and counting service system entities in an evolving ecology, working to "understand" and make explicit their implicit processes of valuing and their value co-creation (stable change with many win-win experiences) and co-destruction (unstable change with many lose-lose experiences) interactions over their life-spans.

Service Research History and Community

Because so many disciplines study service, there is a great need for a transdiscipline like service science. Elsewhere we have more fully elaborated the history of service research (Spohrer and Maglio 2010). Over two-dozen academic disciplines now study “service” from their own unique disciplinary perspective, and not surprising each has one or more definitions of “service.”

Because so many professional associations have a service-related SIG (special interest group), journal, or conference, because so many nations and businesses have service innovation road maps, because so many universities have or are starting service research centers, there is a great need for a transdiscipline like service science and an umbrella professional association like ISSIP, which promotes service innovation professional development, education, research, practice, and policy. ISSIP.org (International Society of Service Innovation Professionals) is an umbrella democratically run nonprofit professional association that tries to add value to existing professional association with service-related SIGs, conferences, and journals.

Just as service science draws on without replacing existing academic disciplines, ISSIP draws on without replacing existing professional associations – by design. The ISSIP community is new, but growing. Professional associations are a type of service system that can be designed and evolved, within a population of other professional associations competing for collaborators. This community branch is rooted in IBM’s original SSME effort (IBM 2011; Spohrer et al. 2010). Service science is short for IBM-originated name of service science, management, and engineering (SSME), since service science was originally conceived to be the broad part of T-shaped professionals that complements depth in any disciplinary area with breadth in SSME (IBM 2011). More recently service science has been referred to as short for SSME + D, adding design (Spohrer and Kwan 2009). Even more recently service has been referred to as short for SSME + DAPP, adding design, art, and public policy. The naming of a transdiscipline is especially challenging, and communities can debate pros and cons of names endlessly.

Service Science Foundational Premises

Maglio and Spohrer (2013) have been evolving foundational premises for service science, linking the concept of viable systems to service systems (Barile and Polese 2010):

All viable service system entities dynamically configure four types of resources: people, technologies, organizations, and information.

Put another way, a service system that cannot dynamically configure resources is not viable. The application of knowledge to dynamically configure access to resources for mutual benefits is a fundamental capability of service system entities, and often access to resources (rights and responsibilities) must be earned.

All viable service system entities compute value given the concerns of multiple stakeholders, including customer, provider, authority, and competitor.

Put another way, a service system that cannot compute value given the concerns of multiple stakeholders is not viable. For example, a business must offer something of value to customers, maintain relationships with supply chain organizations (providers), obey any regulations that apply to the business (authority), and in the long run outperform competitors.

All viable service system entities reconfigure access rights associated with resources by mutually agreed-to value propositions or governance mechanisms.

Social and economic actors are resource integrators (Vargo and Lusch 2008). All economic and social actors apply knowledge to integrate resources. Resources can be divided into three categories: market-facing resources (available for purchase to own outright or for lease/contract), private nonmarket facing resources (privileged access), and public nonmarket facing resources (shared access). Access rights fall into four categories: own outright, lease/contract, privileged access, and shared access. Ensuring that nested entities have protected rights and comply with responsibilities is work performed by a governing authority.

All viable service system entities compute and coordinate actions with others through symbolic processes of valuing and symbolic processes of communicating.

Written laws and contracts are relatively new innovation in human history. Computers, spreadsheets, expert decision support system, and electronic trading system are even newer innovations. The transition from purely informal promises (moral codes) to formal contracts (legal codes) speaks to the evolution of service systems from primarily informal to increasingly formal. Viewed from the perspective of computer science, artificial intelligence, and organization theory, people and organizations can be modeled as a type of physical symbol system (Newell and Simon 1976; Simon 1996). Technological and organizational augmentation layers contributed to the nested, networked nature of the service system ecology.

All viable service system entities interact to create ten types of outcomes, spanning value co-creation and value co-destruction.

ISPAR (*Interact-Service-Propose-Agree-Realize*) is an elaboration of the simple four-outcome model with ten outcomes (Maglio et al. 2009). ISPAR includes both service and non-service interactions.

All viable service system entities learn.

If service systems can only apply knowledge in fixed patterns, they will not be able to compete with service systems that learn, adapt, and change to become more competitive.

Research Agenda

Ostrom et al. (2010) proposed research priorities for a science of service. The challenge of societal convergence suggests emphasizing one of these (technology priority) and adding three others.

Technology Priority: Pervasive Force

This research priority deals with the ability of organization to keep up with and incorporate disruptive technologies into service operations and to use advanced technologies to improve service offerings and customer experience. Platforms (smart phones, cloud computing, smart systems, web services, service-oriented architectures), accelerating change (business models, acquisitions), self-service technologies, real-time decision-making (cognitive computing, stream computing), security, privacy, biometrics are important topics related to this priority. Cognitive assistance for all professions is on the horizon (Ferrucci et al. 2010).

Education Priority: Curriculum

Creating curriculum and best practices for teaching and learning service science is an additional research priority. A curriculum that is designed to create T-shaped service innovators with depth and breadth, who have interactional expertise across disciplines, sectors, and cultures, is being requested by leading employers, to improve innovativeness, teamwork, and learning rates (IBM 2011). Several authors have commented on the need for breadth as well as depth to ensure both the growth of knowledge and the ability to prepare the next generation (Boulding 1956; Deacon 1997).

Since service science is a transdiscipline and borrows from so many other disciplines, one interesting proposal for service science curriculum is optimizing the recapitulation of history from a technological and governance perspective (Spohrer 2012). Rapidly rebuilding societal infrastructure and institutions, without the many twists and turns of history, might allow for a compressed, integrated, holistic curriculum (Spohrer et al. 2013; Angier 1998; Arthur 2009; Auerswald 2012). This is also possibly an approach to reducing the "knowledge burden," without reducing quality-of-life measures. Ultimately, service innovations, because they depend increasingly on symbolic knowledge and symbolic processes of valuing, must address the rising knowledge burden and the intergenerational transfer of knowledge challenges (Deacon 1997; Newell and Simon 1976). However, the focus on holistic service systems, such as households, hotels, cruise ships, universities, and cities, may also be important to ensure breadth as well as depth (Spohrer 2010; Motwani et al. 2012).

Policy Priority: Global Simulation and Design Tool

Creating a global simulation and design tool for evaluating alternative governance mechanisms is an additional research priority. Modeling the nested, networked service ecology could also have a profound impact on teaching and learning service science, especially if appropriate pedagogical idealizations can be developed (Spohrer and Giuiusa 2012).

Based on the order of magnitude observation, there is a much larger market for individuals than cities, a larger market for cities than nations. The global simulation and design tool could be used to experiment with policies intended to improve competitive parity between regions at all order of magnitude scales while increasing the speed innovations could spread globally.

Theory Priority: Foundations

To put service science on a more fundamental theoretical foundation, it might be a useful research priority to consider a nested, network service ecology based on something other than the human species. For example, a service ecology based on intelligent machines, with greatly extended life-spans, much faster learning rates, and much larger and denser populations, might be useful for thinking about a service ecology in the limiting case, when constraints on the basic building block service system entity (individuals) are removed. Alternatively, a service ecology with a diversity of species with different physical, cognitive, and social constraints could open up new theoretical directions for service science. Some work on AEIOU (Abstract-Entity-Interaction-Outcome-Universals) framework has begun and greatly elaborated this could be part of an expanded theoretical foundation for service science and other transdisciplines (Spohrer et al. 2012).

Understanding and characterizing the fundamental constraints on species is an important area of research for developing the theoretical foundations for service science. For example, humans have the following constraints:

1. Physical: finite life span
2. Cognitive: finite learning rate
3. Social: finite population size/density

In the last 200 years, life-spans have extended, education levels have risen, and population size and density have all increased. In complex service systems, as fundamental (weakest link) constraints are removed, other constraints emerge to dominate system performance (Ricketts 2007). The mapping of fundamental constraints for other types of service system entities has not been developed yet.

Translating these priorities into a set of grand challenge research questions for service science remains to be done, though there have been some tentative efforts in this direction (Tang 2012).

Concluding Remarks: Future Directions

In this short chapter, we have only scratched the surface, describing how we live in a human-made ecology of nested, networked service system entities – people, families, businesses, universities, cities, states, nations, and more. However, if we are to address societal convergence, there is a need for T-shaped service systems with depth and breadth at all levels in society. Rapidly rebuilding societal infrastructure and institutions, without the many twists and turns of history, might allow for a compressed, integrated, holistic curriculum (Spohrer et al. 2013; Kremer 1993). For example, universities have great depth and breadth of knowledge but still struggle with reintegrating knowledge and properly incentivizing boundary-spanning activities that repackage the whole of human knowledge in a form that can be more readily transmitted from one generation to the next.

The human ecology of nested, networked service system entities has already evolved through several technical infrastructure stages, remarkable in terms of energy, transportation, and communications, which enable great cities to emerge at an accelerating pace (Hawley 1986). Designing alternative viable futures for people in an age of rapidly increasing technical and organizational capabilities presents many challenges (e.g., "knowledge burden") and opportunities (e.g., convergence). T-shaped professionals are professionals with depth and breadth of knowledge across academic disciplines, industry sectors, and regional cultures. T-shapes balance depth and breadth to optimize abilities to compete as individuals and collaborate in teams. Appropriate breadth has the potential to improve innovativeness, teamwork, and learning rates.

In this chapter, within the context of providing a service science perspective on societal convergence, we presented a preliminary bridging framework for analyzing the historical evolution of service system entities to date and exploring the design space for alternative viable futures. Surprisingly, we argue that dealing with the "knowledge burden" of society, which helps people develop the skills to rapidly rebuild societal infrastructure and institutions along alternative possible historical pathways, may open up the largest design space for alternative viable futures. This chapter has implication for those in academics, industry, government, and the social sector interested in a more service-oriented view that balances past, present, and future possibilities.

Finally, over time service scientists working to understand and innovate "societal convergence" must develop and apply relevant frameworks, theories, and models of societal convergence. Ostrom (2009) proposed a specific relationship between frameworks, theories, and models that we adopt and extend. A framework provides shared language to describe real-world phenomena in terms of concepts and qualitative relationships that sharpen shared observations about what exists and how it came to exist (ontology). A theory provides rigor both in terms of measurement methods and empirically testable propositions to expand what is known and how it comes to be known and more efficient ways to arrive at and accumulate knowledge (epistemology). A modern model provides boundary conditions on a theory as well as a computational implementation that can be used to design, engineer, and manage new instantiated systems and realize benefits of theory-based knowledge constructs through appropriate real-world actions (praxeology). Also, we need to keep in mind that at the end of the day, we are debating about experiments to perform on ourselves. Nations are not unlike petri dishes.

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Transition from Inert to Living Systems

Catalina Achim

Contents

Abstract

The transition from inert to living systems has long been a matter of high human fascination and interest due to its cultural significance. Progress in understanding this transition has occurred at a pace related to that of developments in science and technology. The last two centuries shed increasingly intense light on the "evolution" steps that connect the birth of subatomic particles at the beginning of the Universe to intelligent, earthly life. Nevertheless, the complexity of the transformations that constitute each of the steps, of which the origin of life is one, and the fact that the transformations took place long ago make it extremely challenging to elucidate the origin of life on Earth. The human efforts directed to understanding the transition from inert to living systems as we know them include top-down and bottom-up approaches and, more recently, take into account the fact that living systems may take different, unfamiliar forms here on Earth, may be artificially crated, or may appear elsewhere in the Universe in conditions different than those on Earth. Hence, progress in the study of the

C. Achim (✉)
Carnegie Mellon University, Pittsburgh, PA, USA
e-mail: achim@cmu.edu

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origin of life is fostered by a broad range of scientific and engineering disciplines that aim to provide complementary knowledge about the emergence of living systems that converges into a unique picture.

Introduction

The existence of life on Earth makes our planet unique in the Universe, at least for the time being. The human interest in the origin of life can be traced back to the dawn of civilization, as attested by mythology, religion, and philosophy. What life is and how and why the transition from inert to living systems occurred are very complex questions that have preoccupied humans since ancient times. People dealt with these intriguing ideas in a variety of ways, each of which depended on the level of human knowledge, technological stage, and cultural environment. Science and technology led in the last few hundred years to accelerated discoveries relevant to the origin of life. Increasingly sophisticated tools, ranging, for example, from the microscopes built by Antoni van Leeuwenhoek in the seventeenth century to the Kepler space observatory launched in 2007 enabled the discovery and studies of systems ranging in size from subatomic level to molecules, to single-cell organisms, and to planets orbiting in habitable zones of Sun-like stars.

The scientific exploration of the origin of life became purposeful and intense starting in early twentieth century. A search in May 2015 for "origin of life" in the databases of Chemical Abstracts Services of the American Chemical Society, which covers references in chemistry and related sciences published after 1907, identified more than 60,000 references containing the concept of "origin of life" (Scifinder 2007). The US National Aeronautics and Space Administration (NASA) runs an Astrobiology Program that includes the NASA Astrobiology Institute. Centers for research in astrobiology exist in a significant number of universities around the world; there are also nonprofit organizations dedicated to research on problems directly related to the origin of life.

Despite broad interest and the effort dedicated to the origin of life, at present there is no universally accepted definition of life or a precise description of how life originated on Earth. The Merriam-Webster dictionary defines life as "an organismic state characterized by capacity for metabolism, growth, reaction to stimuli, and reproduction" or "the quality that distinguishes a vital and functional being from a dead body" (Merriam-Webster.com 2015). Some scientists question whether it is possible to ever come up with a definition. Nevertheless, a working definition of life is usually based on several properties of living organisms. Specifically, any living organism (1) has a genetic mechanism for the transmission of hereditary information acquired by the individual and possibly its community, (2) has a metabolic system that enables the organism to take in energy and metabolites and use them to maintain a nonequilibrium state, and (3) is compartmentalized, which ensures the spatial coexistence of the machinery for replication and metabolism while concomitantly allowing communication between the individual organism and its environment, which includes other individuals of the same or different species.

The abilities to maintain a dynamic steady state away from equilibrium and to evolve are also critical features that differentiate an organism from nonliving systems. Besides the difficulty to come up with an explanation for the complexity of life, what complicates the tracing back of the origin of life and its subsequent evolution is that they include emergence processes whereby larger entities and/or more complex processes arise through interactions among entities and processes that themselves do not exhibit such properties.

From Physics and Chemistry to Biology and to Life Beyond the Earth and the Present

Organisms make copies of themselves using energy and matter from the environment; diversity and evolution are traits of life essential for survival. While it is clear today that life does not violate the second law of thermodynamics, understanding the thermodynamics of the origin of life and of evolution is a matter of current intense exploration, which may also empower us to possibly discover and create new living systems. The thermodynamics and statistical physics of the living organisms are challenging because they are open systems that exchange matter and energy with the environment and that operate far from equilibrium in an irreversible manner. Schrodinger fostered interest and work on the thermodynamics of life by arguing in his 1944 book "What Is Life?" that an open system could maintain its own entropy low (an organism would preserve a highly organized structure) by increasing the entropy of its environment (the organism would dissipate energy) (Schrodinger 1945). Prigogine, a professor of physics and chemical engineering at UT Austin, set in motion the development of the thermodynamics of open systems in the 1960s. Current models explore the role and importance of energy dissipation in the origin of life and evolution.

Prerequisite for the life as we know it on Earth is the existence of a variety of chemical elements, liquid water, and a source of energy. Hence, relevant to the discussion of the origin of life is how and when these requirements have been met. According to the Big Bang theory, the Universe started more than 13.5 billion years ago (Table 1). The process of nucleosynthesis began within minutes, and atoms beginning with hydrogen, helium, and lithium arrived on the Universe scene about 400,000 years later. In the first 9–10 billion years, as the Universe expanded and cooled, molecular clouds, galaxies, stars, and planets were born. The solar system began its existence 4.6 billion years ago, and, just a "few" millions of years later, the Sun was born as a star followed by the birth of the Earth as a terrestrial planet. If the time between the Big Bang and the appearance of first humans on Earth would be compressed to a familiar January–December, one-year interval, our solar system and then the Earth would come in existence in the first half of September, 9 months after the Big Bang (Sagan 1977). The first forms of life would be born in late September; the oldest fossils found on Earth would date from early October. Mid-November would be the time when eukaryotes, cells with a nucleus, appear followed on December 29 by primates, just 2 days before humans show up for the

Table 1 General timeline from the birth of the Universe to present according to the Big Bang theory and some chemical information

Time from Big Bang (10^9 years)	Years ago (10^9 years)	Event	Nuclear/ inorganic chemistry	Organic chemistry/form of life
0	13.8	Big Bang		
0.5		First-generation stars	H and He	
1	12	Galaxies Later-generation stars	Atoms up to Fe	
		Molecular clouds of nm-μm grains of dust and of gas	~12 minerals in prestellar molecular clouds	
9.2	4.6	The Sun, a star, forms from solar nebula Meteorites Planetesimals	~60 minerals in chondritic meteorites ~250 minerals in planetesimals Solar nebula contained water	Small organic molecules such as acetonitrile, amino acids, and alcohols can be found in meteorites
9.16	4.54	The Earth, a terrestrial plant, forms	~250 minerals	Organic molecules could have been generated on Earth in deep-sea hydrothermal vents or in the atmosphere under UV irradiation or lighting. They could have been also delivered to Earth by meteorites
10–11.3	3.8–2.5			Anoxic biological world Microbes
10.3	3.5			Prokaryotes, single-cell organisms with no inner organelles Typical cell size 1–5 μm
11.1	2.7			Eukaryotes whose cells contain organelles Typical cell size 10–100 μm
11.3–11.9	2.5–1.9		Great oxidation >4,000 minerals	Aerobic biological word
13.8	Current time		>5,000 minerals	10–14 million species of life on the Earth

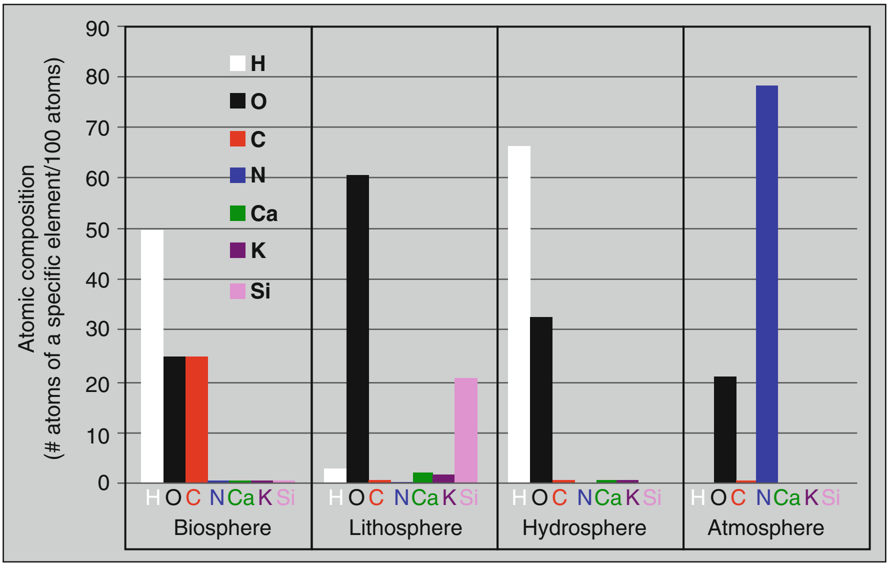

Fig. 1 Abundance of elements in Earth's bio-, litho-, hydro-, and atmospheres based on data from reference (Deevey 1970)

dawn of civilizations. On this 1-year timescale, we are studying the Universe and pondering the origin of life for a much shorter time than the blink of an eye.

At birth, the Earth could have had about 250 minerals and contained water brought about by planetary condensation from dust particles (Hazen 2012). During its subsequent cooling and occasional reheating under the bombardment of meteorites, a variety of minerals could crystallize, increasing the overall number of minerals on Earth to about 1,500 before life emerged. By this time, it was also possible to find on Earth small molecules such as hydrogen, ammonia, carbon dioxide, and methane freed by core geologic processes. Abiotic organic chemistry, carbon-based chemistry, could begin in the Earth atmosphere triggered by UV irradiation or lighting, as well as on the Earth surface and in its Oceans, enabled by thermal energy and light and possibly catalyzed by mineral surfaces. Pioneering experiments in the 1950s by Miller and Urey set off an effervescence of studies that showed the potential of organic chemistry to create from a chemical inventory of small molecules the building blocks of biological molecules, including amino acids, sugars, and lipids, under environmental conditions meant to simulate those possibly existing on Earth at the predawn of life (Bada 2013; Miller 1953).

About 3.8 billion years ago, abiotic chemistry had set the stage for prebiotic chemistry that led to the synthesis of molecules currently present in living structures, such as proteins and nucleic acids. When one compares the abundance of elements on Earth and in biological systems (Fig. 1), it becomes apparent that the abundance of resources was not the determinant of the chemistry and materials science that underlie biology. Instead, physical and chemical processes compatible with the environmental conditions existent on Earth about 4 billion years ago played a critical role in shaping the origin of life.

Living structures or organisms are characterized by a hierarchical organization of complex networks of small and macromolecules on one hand and of chemical and physical processes on the other hand. It is generally agreed that all life on Earth today has one universal common ancestor (UCA), an organism that had a genetic code and a metabolism and lived about 3.5–3.8 billion years ago. Darwin posited the existence of the UCA in mid-nineteenth century in the "Recapitulation and Conclusion" chapter of *The Origin of Species* (Darwin 1859). It is a fundamental premise of the evolutionary theory, which is supported by the similarity of the genetic code and of the key molecular components of all organisms, namely, nucleic acids and proteins. The genetic code is universal too as demonstrated by modern phylogenetics and probability theory. Evolution by variation and natural selection in face of competition fostered the survival, adaptation, and diversification of single- and multicell organisms in a variety of Earth ecosystems.

Presently, it is extremely challenging to find evidence for each of the steps that bridged the existence of the early small organic molecules and the "birth" of UCA due to the intervening billions of years. Nevertheless, it is clear that the dimensions of molecules that enable cellular organization and function must be in the nano-regime (Mann 2012). Proteins with too few residues would lack the globular structure and the dynamics that underlie chemical reactivity. Lipid acyl chains with too few or too many atoms would organize in micelles or in rigid bilayers rather than in the soft, porous membranes of known cells. Hence, macromolecules, self-assembled supramolecular systems, and protocells can be considered the "stepping stones" between the small organic molecules and the UCA of the organisms currently living on Earth (Fig. 2). The exact nature and organization of these stepping stones into one or possibly multiple pathways, which could have evolved in different places on the planet, at different times and on different timescales, is still unknown. Scientists dedicate a huge effort to formulating and testing models for the chemical and prebiotic evolution that cemented the pathways and made one of them "productive," i.e., led to the UCA. (Note that the existence of UCA does not exclude other organisms similar to UCA that have not led to current representatives of life on Earth and have since disappeared.)

Self-assembly, self-organization, chemical catalysis, self-replication, and compartmentalization are physical and chemical processes critical to the transition from inert to living structures. Interfaces between materials in different physical states of matter are candidates for fostering these processes. Macromolecules could have formed originally at solid–liquid, liquid–liquid, or gas–liquid interfaces that fostered self-assembly of and possibly reactions between small molecules. A modern-day chemist or chemical engineer could envision water–mineral interfaces in surface ponds or in deep-ocean thermal vents as abiotic chemical reactors for both organic and inorganic chemistry. Lending support to this proposition is the fact that some modern-day enzymes contain active sites that bear structural and

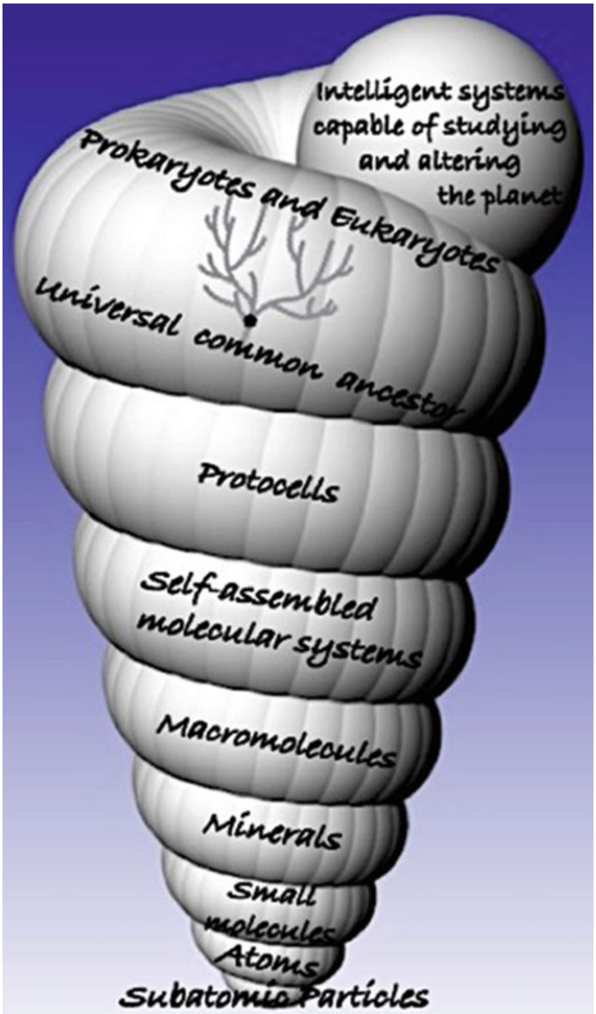

Fig. 2 Cartoon representation of systems of increased complexity on the path from the birth of Universe to intelligent organisms. The bottom-up progression is not meant to represent a deterministic conversion of one type of system into another nor a historical progression

functional similarity to minerals. Minerals can have chiral crystal faces; hence, they could exert also a chiral induction effect in reactions between molecules, thus seeding the synthesis of chiral molecules. Nonliving ensembles composed of one or more types of (macro)molecules that could replicate themselves and be produced by autocatalysis could be winners in the process of molecular evolution. The process by which prebiotic molecules form from smaller organic molecules using external energy could be considered a step on the way to (proto)metabolism.

Metabolism as a mechanism for increasing the size and diversity of the molecular repertoire takes place within living organisms in a synchronous and correlated manner to the genetic mechanism by which information about the organisms is passed from one generation to the next, sometimes even skipping over generations.

The genetic mechanism for information storage and transmission requires energy and the genetic code of organisms is based on molecular building blocks; both energy and molecular building blocks are provided by the metabolism mechanism. In a complementary manner, the genetic code holds the blueprint for the making and the working of the metabolism. Scientists are debating the genetics-first and metabolism-first models for the emergence of cells as well as the possibility of coevolution of increasingly sophisticated metabolism and genetics pathways in which synergy and cooperativity between pathways would lead to increased efficiency, evolution, and selection. Coevolution of the genetic and metabolism early mechanisms could benefit from co-localization of different molecules that support them in, for example, self-organized or self-assembled systems. Alternatively, a molecule that could both transmit information and act as catalyst could play in protocells the roles played by distinct molecules, i.e., nucleic acids and proteins, in the genetic and metabolism mechanisms of extant organisms. RNA, which nowadays supports the translation of DNA into proteins and as ribozyme can catalyze biochemical reactions, represents an example of such a “dual function” molecule that could support the genetics-first model (Gilbert 1986).

All cells in single- and multicellular organisms maintain their individuality and are able to actively communicate with their environment, which may include their peer cells, through a membrane, whose complexity of chemical and structural composition is on par with that of the interior of the cell itself. The questions of how the first delineation from the environment of ensemble of molecules capable of transmitting information and/or catalyzing chemical transformations came about, and how the likely simple proto-membrane evolved to reach the complexity and functionality of the lipid bilayer-based membranes of current cells are likewise central to the origin of life story. Models for various stages of the transition from a primordial soup of organic (macro)molecules to a medium in which these molecules would agglomerate and self-assemble, to a multiphasic environment of vesicles or of mineral-attached, confluent composite films, and onto protocells are being envisioned and tested in relationship to the chemistry they could support (Mann 2012; Monnard and Walde 2015).

The lessons learned by exploring the origin of life on Earth are useful in dealing with broader questions regarding the possibilities of discovering life on other planets and of how unique is life as we know it on Earth. There is no reason to exclude the possibility that the conditions for the transition from abiotic to prebiotic chemistry and on to life could be met on other planets, too. To date, the Kepler Space Telescope has confirmed more than 1,000 exoplanets with a few of them orbiting in habitable zones of their stars (“http://www.nasa.gov/press/2015/january/nasa-s-kepler-marks-1000th-exoplanet-discovery-uncovers-more-small-worlds-in, accessed,” nd). The presence of small organic molecules in space has been unambiguously documented. These discoveries considerably increased the estimated chances that one day life may be discovered elsewhere, a quest actively pursued by the NASA Astrobiology Program. In this quest, having clear bio-signatures of life that can be used in the examination of other planets to find habitable environments is important. These bio-signatures can be based on the examination of the origin of life as we know it or on what is learned from research aimed at creating or discovering minimal or alternative forms of life here on Earth (Blain and Szostak 2014; Stano and Luisi 2013; Urban 2014).

Questions regarding our ability to see or imagine these possibilities preoccupy both scientists asking fundamental questions in fields related to the origin of life and scientists and engineers focused on the future of life here at home and away from Earth. In this respect, bottom-up approaches to piece together the origin of life puzzle from experimental evidence provided by different scientific disciplines meet top-down approaches to create a minimal cell, which would be based on the minimum number of components necessary to sustain life traits. Synthetic biology brings together scientific disciplines and engineering areas to harness and modify biological systems as well as to build new ones for the purpose of creating new biological components or systems (Attwater and Holliger 2014). Many of these efforts are based on the rational modification by synthetic chemistry and bioengineering of the biomolecular machinery found in cells and of the cellular processes that sustain life. In this realm, building a minimal cell in terms of number of molecular components and simplicity of the genetic, metabolic, and compartmentalization mechanisms and creating a living system based on chemistry, including possibly stereochemistry, different from that of biology as we know it can both inform the ongoing quest for the origin of life (Blain and Szostak 2014; Stano and Luisi 2013).

Research on the Origin of Life

The purposeful exploration and use of the environment characterizes many living organisms. Humans use intelligence to take these two activities to deeper and more advanced levels than any other organism. In this context, understanding of the origin of life as we know it on Earth, the discovery of life elsewhere in Universe, and, increasingly intriguing, the possibility of creating synthetic life are all important and fascinating human quests. The work of Alexander Oparin and Haldane in the 1920s could be considered as the starting point of the well-defined and focused effort by scientists from diverse backgrounds to elucidate the transition from nonliving to living structures (Haldane 1929; Oparin 1924).

Science and technology discoveries created sophisticated tools that in turn made possible the study of systems ranging from smaller than 10^{-10} m (e.g., subatomic particles) to those that are farther than 10^{25} m from us. The use of these tools diminished steadily the knowledge and intellectual gap between the birth of the Universe and the current time when life exists on at least one planet, although the gap is far from being closed. In 1938, in the preface to the first English translation of Alexander Oparin's book, *The Origin of Life*, Sergius Morgulis said that "it is true that, if the organic chemist is familiar with wonders undreamed of by the inorganic chemist, the wonders witnessed by the biochemist in his daily tasks staggers the imagination and sharpen the envy of the organic chemist"(Oparin 1953). This statement could be interpreted as an acknowledgment of the increase in complexity

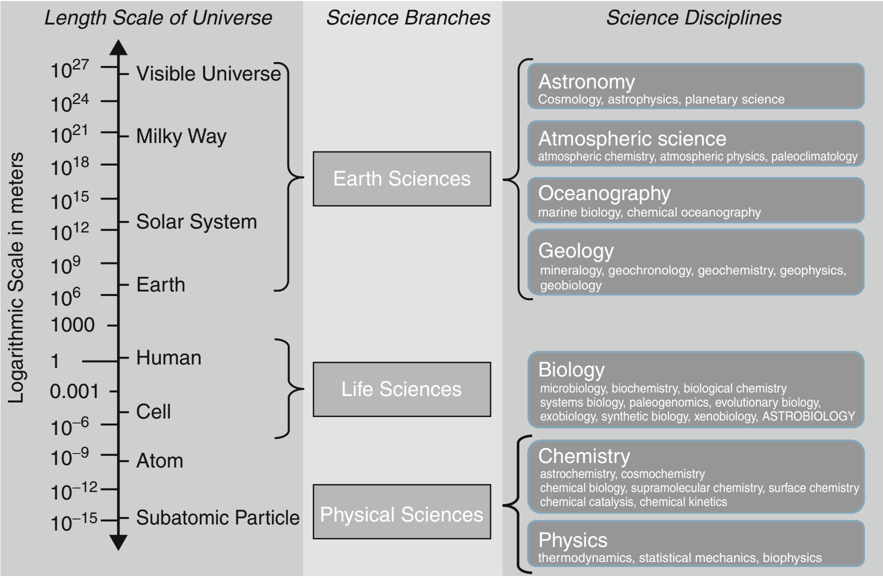

Fig. 3 Selected scientific disciplines and subdisciplines that provide information relevant for the origin of life on Earth (*left panel* of this Figure is based on https://commons.wikimedia.org/wiki/File:The_Scientific_Universe.png. Accessed 23 June 2015)

that relates inorganic chemistry to organic chemistry and biology, although such a view depends on one's perspective and could be challenged. What is clear is that complexity is a property of both the systems that populate the path between the nonliving and living transition and the knowledge being accumulated in the pursuit of the elucidation of the origin of life problem. A consistent effort is made to create a conceptual framework for the continuously increasing amount of knowledge relevant for the origin of life drawn from an increasingly diverse set of science and technology areas. Traditional disciplines, including geology, physics, chemistry, and biology, provide the general framework, with subdisciplines being added as the amount and depth of knowledge in each of these areas increases. Figure 3 shows many of the scientific disciplines that contribute information to the origin of life problem; the boundaries between these disciplines and subdisciplines are not sharp and are being diminished by intense interdisciplinary research. Astrobiology, an interdisciplinary area of science that focuses on the origin, evolution, distribution, and future of life in the universe, could be considered the point of convergence of the discoveries made – and the knowledge accumulated – in the many areas of science it directly or indirectly borders (Catling 2014).

Funded to a large extent by government agencies (e.g., the US NASA), research on the origin of life on Earth, the possibility to originate life in conditions different from those on Earth, and the history of research on origin of life takes place in many laboratories in academia.

Concluding Remarks

Gerald Joyce of the Scripps Research Institute summarized in 1994 a working definition of life formulated based on discussions of the Exobiology Discipline Working Group of NASA: "Life is a self-sustaining chemical system capable of incorporating novelty and undergoing Darwinian evolution" (Deamer and Fleishaker 1994). This definition provides a very general context in which important questions regarding the origin of life on Earth are posed and answered. The origin and evolution of life are complex processes that include emergence steps. Progress in the understanding of these processes, and implicitly the transition between nonliving and living systems, requires and represents the convergence of research efforts made in many related science and engineering disciplines. The research in astrobiology, synthetic chemistry, and synthetic biology is likely to concomitantly shed light on the origin of life on Earth and lead to the discovery of extant new and possibly different forms of life in the Universe or to synthetic forms of life on Earth.

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Unifying Concepts in Physics, Chemistry, and Engineering

Chunli Bai and Chen Wang

Contents

Abstract

This contribution reflects the views on the trends of unification of science and engineering domains motivated by societal needs. The benefits and feasibility of promoting the convergence for advancing society progress as well as creativity in scientific and engineering are discussed, especially with the perspectives from developing economies. The heterogeneity in scientific and engineering disciplines as well as societal priorities should be balanced with systematic analysis during decision-making process.

C. Bai (✉)
The Chinese Academy of Sciences, Beijing, China
e-mail: clbai@cas.cn

C. Wang
National Center for Nanoscience and Technology, Beijing, China
e-mail: wangch@nanoctr.cn

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Introduction

Science, technology, and engineering are inherently mutually related domains of traditional and modern scientific communities. Engineering is generally perceived as the application of scientific knowledge and technology means, with the aim to produce useful entities with high efficiency and reliability. Scientific visions and breakthroughs have stimulated tremendous momentum for technology and engineering advances, contributing to the foundations of modern technology, manifested in the industrial revolutions in history. On the other hand, the advances of science are indebted to the advance of technology breakthroughs enabling unprecedented capabilities to explore unchartered knowledge domains. Common to the efforts in science, technology, and engineering is the everlasting pursuit of capability to obtain knowledge of the physical world and beyond.

Scientific endeavor is inherently associated with engineering by providing the fundamental theoretical basis and principles. Classical scientific concepts are revealed by innovative engineering advances, as well as becoming tangible to general public. The engineering activities dedicated to science and technology become a notable area in the field of engineering sciences. Science is an important source of inspirations to innovative engineering modalities. The complex environments encountered in engineering advances, as well as challenges, provide vast inspirations to fundamental studies understanding the very basics of matter, energy, etc.

The historical manifestation of convergence of science and engineering can be seen from the theoretical discovery of relativity to the atomic energy project in the USA, leading to tremendous applications of nuclear energy in various fields worldwide. The biomedical engineering today is largely associated with the discovery of helical structure of DNA. Semiconductor industry is originated from the breakthroughs in understanding charge transport behavior in matters. In addition, scientific facilities, such as accelerators, observatories, etc., around the world have proven to be the hubs of excellence of both engineering advances and scientific explorations and contributed tremendously to the progress of basic science.

The recent advances in the broad field of nanoscience demonstrate that unification of forces in physics and more general concepts in chemistry and other disciplines offer more essential methods of understanding the nature of materials and transformation in technology. More importantly, integration of fundamental research with engineering methods through system approach, computational methods, and communication has been a remarkable feature in the development in nanoscience and technology and opens new opportunities for manufacturing industries and commercial applications (Bai 2005; RS and RAE 2004).

Conceptual Unification Motivated by Societal Challenges

The trends and characteristics in modern science progress indicate that the increasing integration of basic research and engineering will continuously break through the limitation of human cognition and brings changes to methodology of human thinking into the universal, macro, meso, and micro worlds. The common driving force derived from societal needs forges the mutuality between science, technology, and engineering, representing one of the pronounced characteristics of the so-called mega-science today. Undoubtedly, both developing and developed economies have benefited and will continue to benefit greatly from the unification of science and engineering practices, aimed at different strategic domestic goals and based on different capacity levels.

The revolutions of science and technology in human history have greatly improved the quality of life for vast populations, mostly in the developed economies. However, the industrialization has accompanied numerous disruptions to the environment and resources. Sustainability becomes a central issue if the process of industrialization continues to benefit the rest of the population, particularly the developing and underdeveloping economies. The grand challenges facing these diverse populations provide profound obligations and opportunities for the scientific and engineering communities in general. The unification of science and engineering communities provides a unique platform for scientists, engineers, technicians, and entrepreneurs to join the intellectual resources and material support to achieve maximal societal impact. This observation has been elaborated in a number of comprehensive discussions on the theme of convergence of knowledge and technology for the benefits of society (Roco and Bainbridge 2013; Roco et al. 2013). The envisioned general principles and various characteristic stages of the convergence process aimed at improving creativity, innovation, and social progress present grand and vital challenges beyond technology domains and will engage broad societal sectors.

It is perceivable that while scientific challenges are universal, societal challenges are heterogeneously and diversely reflected among different economies. Particularly, extra effort should be needed for the developing economies to tackle the long-standing societal challenges ranging from environmental to health care that may not be sufficiently supported by imported technologies. While the importance to build up engineering capability in developing economies is generally recognized, the foundation of this process is critically related to the scientific domain which can only be substantiated from long-term support from both public and private resources. This observation echoes the notion on the common social value and goals that motivate the unification of science and engineering. Furthermore, a number of added values can be envisioned from the effort of unification of science and engineering. Education will surely be the one at the top of this list. The future generation of scientists and engineers who could communicate efficiently among their domains of knowledge and expertise will no doubt be more capable of achieving scientific breakthroughs and engineering inspirations. To achieve this goal, the education infrastructure will need to be reevaluated and improved in both developed and developing economies.

For the past three decades, the Chinese government has implemented national strategic plans to promote fundamental research and vital technologies for societal needs, such as nuclear power station, integrate circuitry, broadband communication, digital manufacturing, oil and gas exploratory, water remediation, drug R&D,

manned aerospace and moon exploration, and prevention and treatment of contagious diseases. Seven strategic industries are given high priorities for focused development, including energy saving and environmental technology, information technology, biotechnology, advance equipment manufacturing, advanced materials, and new generation energy vehicles. These national strategic plans have played very important roles to unite the scientific and engineering communities, together with entrepreneurs and industries for developing core technologies that bear broad societal importance. It should be noted that these major efforts have contributed tremendously to promote scientific activities in broad range and prompted significant public awareness for the importance of fundamental science and engineering achievements. As the result of the progress, the national scientific facilities and engineering centers have been greatly improved that will benefit both the domestic and international communities. In particular, the shared research facilities contributed significantly to provide multidisciplinary environment that is critical for improving cross-domain communications which is one of the principles of convergence of knowledge, technology, and society (Roco and Bainbridge 2013; Roco et al. 2013). The multidisciplinary facilities encompassing scientific and engineering domains have been highly recognized in advancing science and technology in both developing and developed economies and will become irreplaceable infrastructures in future advances in convergence of science and engineering.

Public Polices and Mechanisms for Forging the Convergence

The convergence of science, technology, and engineering has been the one of the main driving forces to the modern science. The success of high-tech industries is a remarkable manifestation of scientific achievements. It is foreseeable that the convergence of science and engineering could generate greater societal impacts to the participating economies. The genuinely architectured policies representing the core public interests would be essential to build up the general ecology for science, technology, and engineering among all levels of the relevant communities. Being distinctively different activities, science, technology, and engineering bear respective societal responsibilities and should be supported with respective guidelines and policies. It should be cautioned that due to the respective importance, necessity, irreplaceability, and societal obligations, the national strategic plans and polices should be contemplated, respectively. Particularly important for developing economies is that the balanced support to the respective domains should be carefully planned, coordinated, and properly implemented, considering the heterogeneity in scientific and engineering disciplines, as well as societal priorities. It may be tempting to sacrifice the support to scientific research in exchange for applied and engineering activities under stringent financial situations. However, such tendency would very likely hinder the long-term innovation capability in engineering sector.

Policy-making bodies should be advised on the importance of having related and also distinctively different guidelines for science, technology, and engineering domains. Evaluation of the progress of scientific accomplishments should be reflected mainly by the quality of publications, and while patents will be the main indicator for technology advances, engineering accomplishments should be reflected in the contribution and impact to industrialization and commercial impact. The common elements in the principal policies should reflect the operational characteristics, regulations of activities, evaluation criterions, and projected aims. The national policy can be a strong indication of public priorities in scientific and engineering, as well as a test of the visions of the science and engineering communities. The long-term impact on the societal benefits and the sub-areas in those fields should not be underestimated when debating those policies. It should also be aware that the risks accompanying scientific explorations and engineering innovations should be given serious evaluation in the policy-making process, particularly long-term strategic planning. For this aspect, independent consultation with domestic and international communities could be highly valuable. The benefits of such intercommunity exchanges could reach out much beyond the science and engineering policies to promote understandings among different cultures and social entities. This effort may also serve as an important linkage between developing and developed economies.

The successful mechanisms of the innovative economies provide important reference for the developing economies taking into account their respective needs. Scientists from developing economies, including China, have contributed tremendously and will continue to contribute to the excellence of science in many ways, complementary to as well as competitively among global communities to advance our knowledge frontiers as reflected in substantially increasing number of joint projects and joint publications in recent years (Bai and Cao 2008). The engineering researches, with respective priorities, will significantly increase collaborations with international colleagues, as well as industries. Such progress should also be deemed as a potentially important contribution to the sustained development and improvement of living qualities to this vastly populated country, which is also at the benefits of the international community.

One of the direct consequences of the introducing general principles envisioned in the pursuit of convergence of science and engineering domains may be highly dependent on the organizational effort. In order to generate effective connectivity to achieve advances of integrative approach across human dimensions, existing research infrastructures will inevitably need to be optimized or new platforms may be established according to various stages of convergence-divergence evolution process. The institutional readiness should be keen to the success of public policies and mechanisms for forging the convergence, as well as developing convergence languages among disciplines of different nature.

Distinctive differences may be noticed in the magnitude and distribution of funding among science and technology in developing and developed economies. An example can be found in the overall funding in the year of 2006 according to the statistical analysis of the Chinese Academy of Sciences Comparative Study Group on International Science and Technology (CAS 2009); the funding for basic research was approximately 4.5 billion US$, 14.6 billion US$ for applied research, and 67.7 billion US$ for engineering research, corresponding to 5 %, 17 %, and

78 %. In the same year, the USA appropriated 61.7 billion US$ for basic research, 76.7 billion US$ for applied research, and 210.5 billion for engineering, corresponding to a weight distribution of 18 %, 22 %, and 60 %, respectively. In addition, the funding to basic research in China was 0.056 % of GDP, while the value was 0.471 % in the USA, 0.499 % in France, and 0.395 % in Japan. This comparison is representative of the tremendous disparity of resources in science and engineering for developing and developed economies. According to "American Science and Engineering Index 2014," the total R&D expenditure of China is second to the USA, followed by Japan, South Korea, France, and the UK. However, basic research received only 4.7 % of total R&D in China, compared to over 10 % in other economies. In the year 2012, the funding to basic research, applied research, and engineering are 4.8 %, 11.3 %, and 83.9 % in total R&D. Such differences in funding scenario represent the needs for developing economies to improve the support to basic science in order to maintain long-term sustainability of innovative technology and engineering. The apparent differences in scientific polices may prompt the genuine interests from both academia and administrative branches to develop mechanisms for dialogue and networking. These efforts could facilitate effective management and assessment on the sustainability progress of the convergence of knowledge, technology, and society.

Public Awareness and Support of the Convergence Effort

The engagement of public support is crucial to the sustainable science and engineering activities. Communications are essential not only among the professionals but also toward the laymen who have the key vote on the success of any sensible accomplishments. The efficient and successful communication of science and engineering communities with general public will no doubt benefit all parties. The encouraging achievements in both fundamental scientific research and industrial applications of various engineering advances in China invited considerable public awareness of the important potentials. In addition to the continued endeavors on pursuing excellence in academic research and economical impacts, the growing expectations of meeting societal needs have become evident for scientific and engineering efforts. The multidisciplinary nature of scientific practices presents abundant opportunities for collaborative interests from both various basic researches and technical developments. Notable applications of scientific advances in environmental remediation, public health care, sustainable agricultural development, and so on have been demonstrated.

The scientific advances among both developed and developing economies are closely associated with the expectations from various societal needs. Among many of the tangible impacts, one could observe that science and technology have contributed to generate inspiration for competitiveness of the education, as well as scientific novelties in both developed and developing economies. Such needs in qualified workforce to meet technological and engineering progresses would lead to continued improvements of existing educational infrastructure and foundation of education and training programs in multidisciplinary fields such as nanoscience and technology (Malsch 2008). It has also helped broaden the awareness of science among lay people in developing economies that an important measure of the sustainability of an economy is the capability of core technologies, which are closely related to scientific and engineering activities. The development of core technologies can be associated with not only tremendous economic benefits but also the stability and security of the economic system as well. The acquirement of such core technology cannot be solely dependent from commercially available sources. The dedicated contributions from both scientific and engineering communities pertinent to the economy will be central in the quest of such core technologies by providing key intellectual properties. Such public awareness and support is keen for justification of public resources for promoting scientific and engineering activities in the social system.

Endeavors of Chinese scientific and engineering communities have also made notable progress in delivering keenly needed innovations to various applied sectors. As part of the national commitment to improve the life quality of the society which will benefit over one billion population in China, advances in science and technology are expected to provide the much-needed knowledge reserve and technical support. It is critically important to develop feasible research approaches in order to ensure sustainable public awareness and support. Such approach should provide a balanced consideration of fundamental research versus technological developments and economical gains.

In addition to the continued endeavors on pursuing excellence in academic research and economical impacts, the growing expectations of meeting societal needs have become evident for developing economies. The multidisciplinary nature of science, technology, and engineering leads to abundant opportunities for providing support to improve the quality of life of the general public. On the other hand, the impact of fundamental scientific research may not be measured by immediate economic returns. Even though many fundamental science activities are motivated by curiosity and interests of individuals, they are not directly connected to feasible and immediate applications. The systematic and documented knowledge could form the solid foundation of important technology breakthroughs with broad future impact. Numerous examples have manifested that fundamental scientific research can generate knowledge for making unique and critical contributions to societal needs. Particularly in the situation of public crisis, such as SARS (severe acute respiratory syndrome) in China in 2003, the scholarly expertise from scientific community are the accountable source for providing authentic insight for the general public and authorities. To cultivate original scientific activities, the scientific spirit and ecology should be encouraged and maintained. The conceptually independent and original scientific spirit is also a vital cultural element that could have profound social importance to the general public.

The encouraging achievements in both fundamental research and industrial applications lead to public awareness of the important potentials. The emerging technologies in the areas of national and societal needs are crucial for gaining continued public support as well as identifying key technological breakthroughs.

A successful example of such effort can be observed in the remarkable development nanotechnology in the past two decades (Roco et al. 2011). It should be considered as one of the important responsibilities for scientific and engineering communities to reach out to the general public, rather than being detached, in order to identify the appropriate focuses with finite resources. In particular, keen interests from broad industrial sectors are prominent in China, ranging from health, energy, environment, manufacturing, etc. by reducing the technological barriers. These motivations have been clearly reflected in setting the research priorities at both national and local levels. Considering the restraints in funding capability as well as existing infrastructures, improvised technological solutions for societal needs are essential for promoting science and technology programs in developing economies, as a reflection of the importance of long-term social benefits of research investments.

Collaborative Effort Among Communities

The trends in the convergence of topical fields of scientific and engineering have been clearly manifested. The productive collaborations between scientific and engineering communities are critical to the success of any unification efforts on the basis of common motivations from societal needs and challenges. Considering that foundation of convergence of science and engineering is only at the early stage of generating societal and economic impacts, many grand challenges should be dealt with during this process of searching for technological breakthroughs. The communication among scientific and engineering communities could be vital for developing long-term strategies and road maps in various economies. Such exchanges among diverse academic and engineering interests could initiate substantial collaborations for solidifying the consensus of convergence between these fields. The scope of collaborations could range from identification of strategic priorities, policy-making principles, academic and engineering strengths, relevant educational reforms, etc. The complementarity, as well as competitiveness, associated with the collaborations will be expectedly highly beneficial to the sustainable progress of convergence of science and engineering. This may be particularly important for the developing economies with shared similarities in societal challenges and capacities in science and engineering. The enthusiasm to build the industrial infrastructures with core technologies could facilitate the convergence of science and engineering.

The development of science and technology in China has benefited greatly from academic communications and exchanges between China and international scientific communities. It was widely realized by all participants that international collaborations should be an important segment in building the infrastructures in this area. The strengthened international collaborations can be seen from setting up joint research projects, research groups, bilateral symposiums, etc. In addition, it can be recognized that many investigators in basic research areas have international academic background. The collaborations between international communities are highly productive, setting an excellent example of effective international collaboration mechanisms.

The research community in China and the rest of the world is confronting commonly shared challenges in advancing the scientific and engineering fields. Observable progress in this perspective could be found in the dedicated efforts toward promoting scientific achievements in environmental remediation, public health care, sustainable agricultural development, etc. The efforts in the regime of basic research are complementary at the global scale. Chinese scientists, with relatively limited financial support compared with the developed economies, have contributed notable impact to the international science community. Some achievements are considered important breakthroughs in their respective areas. With the increased attention given to this field, it can be expected that continued contributions from Chinese researchers will be accomplished, with increasingly more innovative findings. In the area engineering activities, China have focused on priorities derived from the national and societal needs, including increasing energy efficiency, developing low-cost drugs and new treatment methods for fatal diseases, etc. These issues are widely concerned from all society domains and scientific community in China and should also strive to make contributions to assure continued public support. It can be expected that the application-oriented research will continue to be encouraged in the future.

Performance Assessment

Appreciable differences of overall performance still exist between developing and developed economies, especially in the area of scientific and engineering domains, as well as industrialization. In both developing and developed economies, societal impacts should be important justifications of public investment in science and engineering. Particularly the improvement of indigenous industries in developing economies should be an ultimate measure of the success of convergence of science and engineering. The fundamental research has continued the momentum of pursuing excellence by dramatic increase of total number of publication and citations which provide an important basis for impact evaluation of various disciplines (King 2004; Kostoff et al. 2007). On the other hand, evaluation emphasis of the engineering success is the quality of the project entity and industrial impact, as well as economical impact.

It should be recognized that performance assessment of an emerging field is a highly challenging task. The multidisciplinary and diverse nature of science and engineering should lead to multidimensional and multilevel evaluation systems. The key elements of the assessment are associated with the expectations from various interests of the society. On the other hand, the scientific and engineering community should have their own set of criterions for their respective disciplines. Different from the well-established fields, the dynamically progressing emerging fields are inevitable to have appreciable uncertainties accompanying the potential breakthroughs. The fundamental and central values of the scientific and engineering fields should be conserved in assessing the emerging fields. Patience and tolerance are needed in cultivating the convergence of science and engineering. Therefore, the genuine assessment of the convergence of science and engineering should incorporate the fundamental values for the perspectives of established fields, and the originality and novelty of the multidiscipline activities should be encouraged and valued. Although the excellence of science and engineering is generally recognized, the social and cultural element could contribute to cultivate uniqueness and originalities in science and engineering. As the result, the enrichment to the established science and engineering disciplines could be a contribution of great value. The introduction of multidimensional and multilevel evaluation systems should reflect the general-purpose principles and dynamic process of convergence described in previous literature (Roco and Bainbridge 2013; Roco et al. 2013) and due consideration of criterions for individual disciplines (King 2004; Kostoff et al. 2007).

Closing Remarks

It has been well recognized that convergence of science and engineering will be accompanied by the evolution process of convergence-divergence. The dynamics of the convergence process could generate innovative and creative divergence that can transform the frontiers of science and engineering. Furthermore, societal progress, such as environmental and energy-related social activities, could have determinant impact on the convergence of science and engineering ranging from technological road maps to national policy. It may be noted that intercommunity collaborations and multilevel communications will be invaluable to develop higher-level cross-domain languages as well as synergistic efforts among science and engineering disciplines. The progress in this direction could expectedly reach out into social domains to foster mutual understanding, appreciation, and respect among economies with diverse cultural origins and distinctive history in both developed and developing nations.

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Part III

Human-Scale Platform

Human-Technology Collaboration

William Sims Bainbridge

Contents

Abstract

The defining feature of the human species has always been that we employ technology to interact with nature. The modern case of human-computer interaction provides five distinct research and development approaches that could be applied to any field of engineering: (1) ergonomics, (2) cognitive modeling, (3) user-centered design, (4) value-sensitive design, and (5) technical culture. The felicitous "symphony orchestra" metaphor for social-technical systems also identifies widely applicable principles: (1) division of labor, (2) a harmony of scientific concepts, (3) the need for significant human expertise, (4) social cohesion of teams, (5) human guidance, and (6) properly defined general principles for decision making. Humanity may have reached a technological watershed at which the basis of much of the economy shifts from physical objects to information, but in any case innovation, will require new collaborations between fields of expertise, in service of human well-being.

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Introduction

Homo sapiens is said to be the tool-making species, yet it could just as well be described as tool-made, since our sociobiological evolution has been shaped by the technologies through which we exploit nature. Stonecutting tools survived from hundreds of thousands of years ago, yet many examples of ancient technology vanished over time, so often we can do little more than speculate, for example, to conjecture that the most important early tool was the bag, allowing a person to carry many other tools, a container that can symbolize convergence of technologies. Consideration of the relationships between tools and their makers over the full sweep of human history provides a background for understanding the dynamics today of the human-scale platform for convergence. This is the set of systems that enable convergence characterized by the interactions between individuals, between humans and machines, and between humans and the local environment. The current moment in human history resulted from the convergence of innumerable factors from our past, and we must now select from a divergence of potential futures, largely determined by human relationships with technology.

The Case of Human-Computer Interaction

A very large number of researchers and projects have in recent decades created a field called human-computer interaction (HCI), which offers many methods and ideas of value in understanding human-technology interaction in general. It should not be assumed that in the future all human-technology interactions will be mediated by electronic information-processing technologies, although current trends seem to be in that direction. Rather, we can draw lessons from this recently emerged field, apply them to other areas, and then consider what ways HCI may be insufficient as a general model. There are at least two very different ways HCI relates to science and technology convergence: (1) in its relevance to the professional practice in these technical fields and (2) as a key factor shaping the convergence of science and technology with society, facilitating both science education and the beneficial use of new technologies.

Consider a stereotypical scientist or engineer doing calculations around the year 1950, using a pencil, pad of paper, slide rule, and printed table of logarithms. Suppose that one step in data analysis or machine design required calculating an area of a rectangle, which could be done longhand, by multiplying the lengths of adjacent sides. The slide rule could give a quick estimate, perhaps accurate to three digits. Familiarly called “slipsticks,” slide rules were carefully made rulers in which one strip could be slid left or right between two others, in this example lining up a mark on the left end of the slider with the value on the stationary part of the ruler that represented one side of the rectangle, then looking along the slider for the number representing the adjacent side, and looking back on the stationary ruler to read out the area. This most common part of a slide rule had two identical logarithmic scales, so that multiplication could be performed as addition.

A multipage table of logarithms could do the same thing but with greater accuracy, allowing the user to calculate multiplication in a simplified form as addition, often through the use of a hand-operated mechanical adding machine. Slide rules also often had scales of trigonometric functions, and the typical scientist or engineer also possessed a printed book of sines, cosines, and tangents. Very few people ever learned the simple yet tedious methods for hand calculating square roots and cube roots or for calculating trigonometric functions, so slide rules and printed tables of functions were essential tools at that historical period.

Today, every civilized person owns a pocket calculator or computer that renders slipsticks and printed function tables utterly obsolete. The user does not even need to know whether the machine contains tables in its memory or calculates each result from scratch, so long as the answer comes immediately upon asking the machine a question. In some cases, a table of empirical data is required, for example, if one wishes to see how much $100 in the money of 1950 would be worth today, taking account of currency inflation. Yet one need never see that table. Online websites provide converters that are periodically updated with new data, and the Bureau of Labor Statistics website tells us that $100 of 1950 money was worth about $715 in 2000 and $989 in 2014.

The most impressive historical example is the Antikythera mechanism, a computer more than 2000 years old, in the form of a complex set of gears used to make astronomical calculations (Price 1974). It is not known how many such devices existed in the ancient world, but they must have been rare and required considerable expertise to operate. Yet now anyone interested in knowing about the positions of solar system objects from day to day can buy the computer-based virtual planetarium *Starry Night* for as low as $50 ($5 in 1950 money), which gets updates from the Internet as well as doing massive calculations inside itself and allowing the user to see the solar system from any position and point in time.

The comparison between a slide rule and a table of logarithms is instructive. Both are approximations of the mathematical functions they represent, but they perform this representation in a different way. In the language of modern computers, slide rules are *analog* devices, in which distance along the edge of a physical object represents magnitude along an abstract scale of real numbers. Log tables are *digital*, representing magnitudes as written symbols following a conventional notation system, typically in the decimal system, to some convenient number of digits.

For some decades, personal computers have functioned internally as digital devices but have used a combination of digital and analog methods for communicating with the human user. A computer's mouse is analog, at least as experienced by the user, moving the cursor across the display screen in a manner analogous to the movement of the mouse across its pad on the desk. The number pad on the keyboard, of course, is digital. Some game players use joysticks with their computers, and a very few users have trackballs rather than mice. Yet the standard combination of mouse and keyboard is physically awkward, and recent mobile devices dispensed with both, using touch screens instead, which can function either as analog or digital inputs, depending on their software. The classical idea of speaking with a computer, popularized in the original *Star Trek* series, has achieved some degree of success in recent years, but remains unreliable.

Given the complexity of the technology and the many ways it can be integrated into human life, researchers in human-computer interaction have developed a number of principles, potentially compatible with each other but often reflecting competing schools of thought. HCI research traditions overlap, following the principle of convergence, and the terminology is not distinct, yet it is useful to identify five approaches that have somewhat different emphases:

1. *Ergonomics* is a long-standing tradition in engineering design that emphasized the physical characteristics of the machine, the human, and the human motions required to operate the machine. In its early decades, ergonomics sought to improve the efficiency of manufacturing production, through *time and motion studies* to optimize human labor (Taylor 1911). More recently, the emphasis became the long-term physical well-being of the human, for example, avoiding work arrangements that would cause repetitive stress injuries. Today, not only are ergonomic principles applied to the design of information technologies, but computer simulation has become a tool for evaluating ergonomics of even such traditional tasks as truck driving and sheet metal work (Faraway and Reed 2007).
2. *Cognitive modeling* focuses on human perception, analysis, and planning during interaction with computers and other technological devices (Olson and Olson 1990). For example, much research focuses on visual search of a computer display to find words or images (Halverson and Hornof 2011). Results can improve the design and layout of computer displays but also provide deeper knowledge about how the human mind works that can be the basis for artificial intelligence systems that emulate it more accurately. For educational purposes and for designing graphic displays of scientific data for researchers, cognitive models can be crucially important to reduce errors as well as achieve efficiency (Börner 2010).
3. *User-centered design* directly involves users of the technology in the process of its development. A project might begin with focus group discussions with potential users and place a heavy emphasis on experimental usability studies as prototypes were being developed. Often, "users" are conceptualized as social groups rather than just individuals, as typically is the case for ergonomics and cognitive modeling. Ideally, the design process is iterative and extensive, cycling repeatedly through five evaluation phases: (1) assess the needs of the community, (2) select a technology plan for sociability, (3) test prototypes, (4) test sociability and usability, and (5) nurture the community (Abras et al. 2004). This approach has some affinity with the recent movement to involve nonprofessional volunteers in research teams, which is called *citizen science*.
4. *Value-sensitive design* seeks to fulfill the fundamental goals of the user or to frame the design in terms of an explicit set of goals that could reflect the needs of any of the participants in the production and use of the new technology. It ideally combines three qualities: (1) conceptualization comparable to a design

philosophy, (2) empirical research on the impact the design actually has on users, and (3) good performance of the technology itself (Friedman 2004). Akin to user-centered design, it gives representative stakeholders a role in the design process (Yoo et al. 2013). Individuals and groups differ in the values they hold dear (Hitlin and Piliavin 2004), and one study of computer games documented a long list of issues about how effectively the systems achieved the goals of different constituencies, including the educational goal to teach new values to the user (Flanagan and Nissenbaum 2014).

5. *Technical culture* defines the conceptual structure and historical tradition that develops a human-centered technology. For example, each computer programming language and operating system is similar to a culture, being a mixture of practically necessary features with logically arbitrary conventions (Rajlich 2004). At the same time, the wider culture provides a context that interacts with the narrower technical culture of the engineers doing the actual development work (Leidner and Kayworth 2006). The four approaches listed before this one give technology developers four clear methodologies to select from or to combine, while this approach seems more passive, observing the social-cultural system that innovates rather than controls it. However, studies that render the assumptions, values, and traditions of a technical culture more explicit may encourage innovators either to embody it more perfectly or to diverge from it in more radical episodes of transformation.

Orchestration

A standard metaphor in discussions of technological convergence is the classical symphony orchestra.. The conductor must coordinate the actions of a large number of human beings, some like the violinists clustered in subgroups and others like the bass drum player taking unique roles. Each player uses a particular piece of technology, a musical instrument of a specific kind, and has gained extensive expertise operating it. While members of the audience may not be aware of the fact, each instrument is historically the result of systematic research in acoustics that could justly be called scientific. The coordination of instruments and players is accomplished most obviously by the human conductor, but the written musical score also plays a role, within the context of the particular cultural tradition to which the piece of music belongs. The performers have worked together for a considerable period of time and thus qualify as a cohesive social group. Each of these points applies in significant degree to other well-organized systems in which humans collaborate with technology and through technology collaborate with each other.

It is said that the first two abstract sciences that made sophisticated use of mathematics were astronomy and musicology. The Antikythera mechanism is remarkable to the point of being astonishing, yet it could not have been built without many years of systematic observation of the planets, in which their changing positions in the sky were noted with some degree of precision. We can thank the

Babylonians for much of the early progress in astronomy, even though the Antikythera mechanism is considered to be a Hellenistic Greek device. The Greeks were pioneers in musicology and acoustics and invented an especially complex precursor of the church organ, the hydraulus. This was a "water organ," and it should be remembered that the Greeks achieved some degree of accuracy in building clocks that operated with water. There were many varieties of hydraulus, typically each having multiple organ pipes just as today's church organs do, but apparently some used a hydraulic device to stabilize the pressure achieved by human pumping actions, so that the sound would be "fluid" rather than coming in a series of pulses.

Much ancient research concerned string instruments, in which the physics of producing sounds at different pitches can easily be studied (Helmholtz 1875). Long before the emergence of modern science, musicologists constructed a simple research device, like a two-string harp, using the same exact material for both strings. Both are tied at one end on a block fastened on a horizontal board, while the other end goes over but is not fastened to a bridge at the far end of the board, hangs down, and is held in position by a weight. Each string has a second bridge in the form of a small block that can be moved along the board, to define what length of the string is free to vibrate when it is plucked. Changing the weight changes the tension on the string, in a precisely measurable manner. This simple device allowed ancient researchers to determine the mathematical functions that define the musical intervals from which scales are assembled. A string that is exactly half the length of another will produce a tone that is an octave higher, so long as the tensions on the strings are the same. As the octave is the ratio 1 to 2, the perfect fifth is the ratio 2 to 3, and the perfect fourth is 3 to 4. With modern string instruments like the violin, the player instinctively knows this, because much of the work is setting fingers of the left hand at different distances along a string to produce different tones.

A grand piano is among the most complex machines devised by human beings, yet dates back three centuries, half that time in about its current form. Harpsichords, which are also complex, are about twice as old (Bainbridge 2012). Neither would have been possible without the invention of wiredrawing technologies that could create highly uniform, strong strings. Humans play both of these classical instruments by striking keys with the fingers, analogous to a computer keyboard, a set of levers constructed in such a way as to minimize noise and arranged in terms of the 12 musical tones per octave but organized to facilitate playing just the seven notes of a traditional scale. The mechanisms of both instruments include an escapement in the part that takes the action of the key and transfers it to the string. In the harpsichord, the escapement plucks the string when the key is depressed, but avoids plucking it a second time when the key is released. In the piano, the escapement hurls the hammer to hit the string, but then prevents it from bouncing to hit the string again. In both, a damper silences the string when the key is released, unless the player tells the machine not to do so. In fully evolved forms of both instruments, the strings achieve much of the range of tones by being in different lengths, but to avoid impractically long strings in the bass, the density of low strings is increased, having a greater thickness, being of brass rather than steel in harpsichords, or even in modern pianos winding a secondary wire around the primary one. Indeed, a full description of both instruments would require many chapters, some of which would focus on the huge variety of raw materials used in their construction and thus on the very elaborate supply chains required to manufacture them.

In performing a piano concerto, the pianist and orchestral conductor are partners in directing the social organization, and the leader of first violins also plays a leadership role, especially when tuning up prior to the performance. Pianos are usually not tuned by their owners, because this is a highly technical task, but by a professional every few months. Violins must be tuned immediately before a performance, by the player, with all violins in the orchestra tuned to the same pitches. Modern pianos are tuned to an equal temperament scale, in which intervals like perfect fourth and fifth are not exact, because mathematically the full set of tone intervals has a complex pattern. But during performance, violinists tend to adjust their pitches closer to the perfect intervals, by exactly where their finger presses on a string. Brass instruments naturally produce a series of pitches in the overtone scale, illustrated by a sequence of ratios 1 to 2, 3, 4, 5, and so forth. The introduction of valves into brass instruments, about two centuries ago, added to their capabilities but did not free them entirely from the overtone sequence. The exception among brass instruments is the trombone, which like the violin can produce any frequency of vibrations within its range.

The point of reviewing these details is to make the very general point that the mathematics of any human-centered technology may start with simple principles, but quickly becomes complicated, having different implications for different tasks within the technological and social system. We could say that the violin and trombone are analog devices, in which the user adjusts the frequency of vibration by directly changing the physical length, while the harpsichord and piano are digital devices. If the instruments are the hardware of an orchestra, the software is the musical score.

Tantalizingly inscrutable fragments of musical score survived from the ancient world, so apparently musicians long sought to write down the music of their songs as well as the words. The dominant form of musical notation today derives from Europe and evolved primarily in the medieval period. In some ways, it is intuitive, for example, in that "high" notes are placed higher than "low" notes on the five-line staff, the notes are written in a linear sequence representing time, and an orchestral score has a different staff for each set of instruments. Yet there are arbitrary elements as well, for example, that adding a flag to a quarter note transforms it into an eighth note and reduces its duration in half. However, this does not mean that musical notation is "unscientific." Mathematical notation is also a mixture of intuitive and conventional principles, as, for example, a summation sign that may be annotated with the range over which the sum should be calculated. Computer programs were traditionally written by humans, but interpreted by computers, and the human readability of programs is a major issue for open-source software projects, in which many humans must read, edit, and expand a program that must run properly on machines.

Cultural conventions exist within the context of the fundamental features of human cognition, and nothing represents the subtleties of this interaction better than the history of written language. As Ancient Egyptian hieroglyphics most famously illustrate, writing began as pictures of objects or actions and then evolved into a more abstract representation of the sounds of spoken language. In the case of Chinese writing, the pictographs lost their visual representational quality, without becoming simply symbols for phonemes. Modern Japanese expresses fundamental contradictions of human nature by combining four different systems: (1) nearly 3,000 *kanji* characters borrowed from Chinese, (2) about 50 *hiragana* characters representing all the different syllables in spoken Japanese, (3) *katakana* similar to hiragana but used for foreign words, and (4) a great diversity of modern symbols introduced from global culture, from Arabic numerals to stylized outlines of human hearts. English speakers should hesitate to criticize Chinese and Japanese for failing to adopt simple alphabets, because they should remember that the spelling in their own language is very far from uniform. More pertinent to the theme of this chapter, hieroglyphics have been reborn as icons on computer screens, suggesting they were not simply obsolete but served particular cognitive functions in the past, as they do again today.

Several competing explanations may be offered about why the written languages of major Asian nations did not become simply alphabetic. One is that human cognition fundamentally involves manipulation of concepts, rather than consonants and vowels. Another is that complex forms of writing confer added status on the educated classes in society. Another is that language functions differently in various spheres of life and the apparent simplicity of alphabets may work best in short-term commercial exchanges, while computer icons facilitate quick selection of a software choice. For science and technology, spoken language is useful but inadequate and must be supplemented with many other forms of documentation and communication. Graphs are visual analogs expressing relationships between continuous variables. As this handbook amply illustrates, conceptual charts are also valuable. A large fraction of patent applications include diagrams of machines. In many sciences, specimen collections are essential, as are research instruments, so physical objects are important for science as they are for engineering.

For two centuries, music theorists have debated the extent to which music embodies the fundamental processes of human thought, having cognitive as well as emotional elements, the development of complex themes over time, and communication as well as expression, relying upon a diversity of technologies (Meyer 1994). Recognizing the complexity of science, technology, and society, any brief list of principles is bound to be at best an approximation, yet six related insights can be drawn from the example of a symphony orchestra:

1. *A division of labor with technological specialization marks every large-scale technological activity*. That is to say, every large-scale human project has the qualities of a system, and thus knowledge of the type of system and its common dynamics would be useful.
2. *Complex social-technical systems depend upon a symphony of scientific concepts*. Harmony between system components, as in music, does not mean unison but compatibility and resonance. If the components had been identical, then

most of them might have been superfluous, yet they could not be dissonant with each other without endangering the system.

3. *Significant human expertise is required in all the domains that comprise the system*. Some of that expertise is required during specific stages of the work, such as a violinist's fingering expertise during the performance and a piano tuner's skills beforehand; thus, the diversity of coordinated contributions is distributed across time as well as space and instrumentation.
4. *A degree of social unity is required of the people working together, but not uniformity*. This cohesion can be structured, in large collective efforts, with subgroups like the second violins functioning as a unit distinct from first violins and suppliers of parts for an aircraft manufacturer dispersed at different geographic locations, yet the people should share common goals and ideally a sense of connection with each other.
5. *Direction in the form of human leaders is essential, but not dictatorship*. As modern theorists in management science have long observed, under most normal conditions, leaders are most effective if they help followers see how doing what the organization needs will also serve their own personal goals (McGregor 1960).
6. *Obeying properly defined general principles is fundamental to creative freedom*. In 1776, the American Declaration of Independence enshrined "the consent of the governed" as a key principle of government, but in 1780 the constitution of the Commonwealth of Massachusetts proclaimed "a government of laws and not of men." In convergence with each other, these two apparently contradictory principles assert that leadership should serve the personal needs of those who are led, yet be guided by abstract principles rather than the personal desires of the leaders. Another way to look at this creative tension is to note that human freedom can flourish best, when humanity has the fullest possible comprehension of the rigid laws of nature.

The Information Civilization

The examples of slide rules and symphony orchestras illustrated very general principles that apply today, yet concerned the technologies of the past. We may well ask how different our current era is from past periods of history, both in terms of the problems we face and the opportunities we may exploit. At each point in human history, it was too easy to be pessimistic, too risky to be optimistic, and too hidebound to be realistic. Imaginative vision is an essential motivator for convergence, so long as we invest the effort required to render its products feasible and judiciously criticize possible harmful unintended consequences (Bainbridge 2007). A good example for human-technology collaboration is the virtual orchestra shown in Fig. 1.

Each of the ten performers depicted in Fig. 1 is both real and virtual, an actual human being operating an avatar in the Internet-based computer game, *Lord of the Rings Online* (LotRO). They are performing in public to an audience of a couple

Fig. 1 An international orchestra playing in Tolkien's middle earth

dozen other avatars, not shown, in the virtual city Bree, in front of the Prancing Pony tavern, a center of informal LotRO social life. The two short avatars in the front are hobbits, and the woman hobbit playing a drum is the organizer and conductor of the group. The person operating her lives in Europe, as do most of the others, but two are in the United States, each communicating through a personal computer. They play music for about an hour, perfectly coordinated by the technology and the human leadership, an online convergence of geographically distributed individuals, and a convergence of technology with the arts.

Although the musical instruments and the performers' costumes are merely images produced by computer graphics, the players needed to do considerable work to acquire them. They also needed to learn the rather complex software system that produced the music, frankly quite separately from the graphics. If the sound of each instrument had been produced where the player was located, it would have been difficult to get the sounds of all ten to fit together, given Internet latency which introduces irregular delays. Therefore, each person in the audience and each player hear music synthesized on their own computers, following a score downloaded and controlled in real time over the Internet. The scores were orchestrated expertly by the conductor and one of the players, using an alphabetic notation system simply called ABC, which also can play music produced by artificial intelligence systems (Oliwa 2008; Cheng 2012).

The orchestra performance was coordinated through a nicely programmed piece of amateur open-source software called Songbook, which required each player to download the right ABC files prior to the performance. The conductor communicated with the players through a private text chat channel built into LotRO, while using a public channel to tell the audience which song came next. She also could talk with her performers through an online voice communication system called Mumble, run separately but in parallel with LotRO. This very successful performance was held in the spring of 2014, and in the summer a LotRO music festival called Weatherstock VI brought together the avatars of fully 487 people.

One may well ask why people would want to play music online and at a great distance from each other, rather than together at the same place. One reason is that the LotRO orchestra consisted of people who loved the *Lord of the Rings* mythos created by J. R. R. Tolkien, a rare but deep cultural orientation. While not strictly speaking a scientist, Tolkien was a scholar of historical linguistics, who perhaps ironically held rather negative views of modern technology. Thus, LotRO is a good example of the interplay between convergence and divergence. Sociologist Claude Fischer (1975) long ago explained that the large populations of big cities allow people with unusual preferences to band together, producing a much greater diversity of subcultures than can be found in low-population areas. These subcultures not only differentiate from each other but interact and thereby produce even more subcultures, hybrids that result from their creative convergence. The Internet is a virtual city with a population not of a million but a billion, thus enabling vastly more subcultures, some of which will take on very real significance in the wider world.

Yet each technology requires some expertise for human beings to operate it, as well as infrastructure investment, so technologies compete against each other to determine which one will dominate in any particular area of human life. Government agencies and corporations experimented extensively with the nongame online virtual world *Second Life* as a venue for group meetings (Bohannon 2011), but most withdrew eventually. One reason was that *Second Life* like LotRO is optimized for use by numerous individuals, interacting more or less equally, at multiple locations, in real time, via low-bandwidth connections. Often a corporation or government agency uses the Internet in three ways quite different from this: (1) connecting two groups situated in the high-bandwidth teleconferencing rooms of two separate branches, rather than many completely separated individuals, (2) broadcasting primarily one-way communications from leadership to the general personnel of the organization, and (3) telecommuting in which individuals contribute their labor asynchronously from multiple locations, including while traveling in the field, with little interaction between them.

Many technologies, perhaps even most, can be used by individuals as well as groups. To continue with the example of virtual worlds like LotRO, which can stand in for many other forms of technology, these environments can be training schools that teach forms of science and engineering to individuals. For example, many future-oriented computer games have the human player interact with robots or other complex machinery that does not yet fully exist here on Earth (Bainbridge 2011b). Consider the *Star Wars* mythos, where two of the prime characters were robots, interacting as partners with humans. The National Robotics Initiative calls such machines *co-robots*, because they collaborate with humans and have a degree of autonomy, without challenging human authority. Many online gameworlds, LotRO among them, allow players using some kinds of avatar to operate *secondary avatars* as well, for example, a hunting bear to help a lore-master in LotRO (Bainbridge 2011a). In the classic but now terminated virtual world, *Star Wars*

Fig. 2 A droid engineer and her creations in a virtual universe

Galaxies, an engineer avatar could collect raw materials, set up component factories, and make a huge variety of robots, as illustrated in Fig. 2.

Every one of the robots in the picture was constructed by the woman engineer avatar standing near the middle. She mined virtual resources from the surrounding environment, set up factories and small production facilities, assembled modules, and in some cases programmed the resulting robots to speak or act in certain ways. A typical battle robot could be given or sold to another player, even if that player's avatar lacked the skills to construct robots, who could then program it to patrol a specific area and give it moment-to-moment commands during a battle. While the system was far from realistic, it did simulate many of the steps required to build real robots and thus had an educational quality.

A debate currently rages over whether robots and other forms of smart technology will erode employment opportunities for humans, especially people who are not especially adept at operating advanced technology (Brynjolfsson and McAfee 2011). The use of simulated robots and other secondary avatars in online games illustrates one of the real-world problems. In undertaking combat missions, often the computer-generated enemies are too formidable for a single player to defeat, but a player with a team of secondary avatars may triumph even without human teammates. Thus, we often turn to machines because human beings are not available to help us, yet getting in the habit of doing so devalues humans. As information technology leverages the abilities of technically competent people, it may reduce the total number of jobs available, especially for people who lack the education or innate abilities to compete in terms of technical competence. Economists have long argued that technological innovation is *creative destruction*, destroying old jobs while inventing new jobs, but there is little reason to trust that the new jobs will automatically be numerous enough to offset the destructive part of the process (McKnight and Kuehn 2012).

Conclusion

The prime antidote to despair is innovation. We must do our best to anticipate unintended negative consequences of new technology, but often the proper response is a mixture of improving the technology and fine-tuning other components in the social-technical system. If world population stabilizes, per capita wealth can increase indefinitely, not by giving each person more food and heating each home hotter, but by providing new cultural services that require human artistic creativity but may use little if any additional natural resources. Playing a three-century-old wooden Stradivarius violin does not require chopping down a living tree, and the energy costs of online communication are more than offset by the reduced need for physical travel. Hopefully, there will be ample employment for everyone who wants to work, in jobs that are interesting as well as useful. This probably requires radical rethinking of the relationships among the arts, humanities, and sciences, indeed using the technology to create entirely new forms of human expression.

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Citizen Science

William Sims Bainbridge

Contents

Abstract

Throughout its history, science has benefited from contributions made by amateurs, but since the creation of Internet an increasing number of important projects have recruited large numbers of ordinary people to their teams, in what is now called *citizen science*. Prominent examples include Galaxy Zoo in which volunteers annotate photographs of distant galaxies and eBird in which bird watchers systematically document their observations out in the field. This phenomenon has become sufficiently extensive that several experts have offered typologies for classifying projects, establishing citizen science as a new research field in its own right. Among the implications for general science and technology convergence is the fact that the nature of expertise may shift, offloading much of the detailed technical knowledge onto information systems, and clarifying theoretical concepts, motivated by the need to integrate into the community many nonscientists, but in consequence also making it easier for a scientist in one field to participate in another. Consideration of citizen social science

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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illuminates how citizen science more generally can facilitate convergence of science with society, guided by fundamental research on how science is understood by nonspecialists.

Introduction

Members of the general public and other nonspecialists are becoming increasingly involved in scientific research, often in the role of long-term volunteers, and progressively acting as partners in the research rather than merely providing free labor. Convergence is central to such citizen science in four ways. First, inclusion of nonprofessionals in research within traditional sciences typically requires innovation in supportive information technology and not infrequently in organization of diverse, distributed teams based on insights from social science. Second, citizen volunteers to a project in one field will often have training in a different technical field, thus being in a position to combine elements from both. Third, citizen science will encourage rationalization of the language, data archives, and abstract conceptualizations employed in the research, thus facilitating more general convergence of that science with others. Fourth, citizen science could become the main mechanism for integrating science into society, thereby rendering society scientific, and harmonizing science with the needs of human beings.

The term *amateur scientist* had become an insult in this era of high professionalization, yet it fundamentally refers to someone who *loves* science. Prior to the expansion of universities and complex industries beginning roughly a century and a half ago, many scientists were amateurs. Galileo, Newton, and Darwin did not earn doctorates in graduate schools. Einstein did earn a doctorate, and calling him a mere patent clerk when he did his decisive early work may unduly romanticize trials and tribulations like those faced by many modern graduate students and postdocs. Given the many opportunities offered first by universities and then by industry and government laboratories, we can assume that most talented young people who want to devote themselves entirely to scientific research can do so in a professional context. However, a much larger fraction of the general public is interested in science than can pursue careers in it, and by investing their labor and often considerable expertise, they not only continue their educations throughout life and take pride in contributing to the advance of human knowledge but also help science converge with society.

The Information Phase Shift

Two citizen science projects are frequently cited as clear examples of the potential benefit to both science and the citizens who volunteer. In the first phase of its existence, Galaxy Zoo enlisted volunteers who classified images of 9,00,000 galaxies, and “These morphological categories are broadly correlated with other, physical parameters, such as the star formation rate and history, the gas fraction and dynamical state of the system; understanding these correlations and studying the cases where they do not apply is critical to our understanding of the formation and evolution of the galaxy population" (Lintott et al. 2011, p. 1). Via Internet and often using handheld devices, "birders' contribute observations to eBird, and "These amassed observations provide scientists, researchers, and amateur naturalists with data about bird distribution and abundance across varying spatiotemporal extents" (Wood et al. 2011, p. 1).

There are many ways to classify citizen science projects, and the most traditional is in terms of scientific disciplines. Galaxy Zoo belongs to astronomy, and eBird to ornithology. But this approach is less than ideal for convergence, not only because a given project may unite several sciences, but also because a project that belongs to one domain may have important contributions to make to completely separate domains. For example, projects differ in whether they *build* versus *buy* the computer software they use to collect, manage, and analyze their data (Prestopnik and Crowston 2012). A well-funded project that has distinctive needs may elect to build the software, but once it exists it may be used in other projects at much lower cost, perhaps adapted somewhat to the new needs which means the original programmers needed to document the source code well. The inheritor projects may be in entirely different disciplines, so long as their data structure and user interface needs are similar.

One way to classify projects is in terms of the nature of the work done by the volunteers. In Galaxy Zoo, the data have already been collected, in the form of photographs; the volunteers interpret the images and annotate the raw data with metadata. The extent to which they are performing scientific analysis, versus merely preparing the data for analysis by professional astronomers, is open to debate. In eBird, the volunteers are collecting the original data, as well as performing about the same other functions as the Galaxy Zoo volunteers. One commonly-used typology begins with five steps in the typical large research project and then categorizes projects in terms of which steps volunteers may participate in (Newman et al. 2012):

1. Defining research questions
2. Collecting and managing data
3. Analyzing and interpreting data
4. Disseminating results
5. Evaluating program success and participant impacts

A related typology goes beyond these steps to ask the circumstances under which a major research project was launched, which largely define or are defined by the role of contributors other than the core team of professional scientists (Shirk et al. 2012):

1. *Contractual* projects, where communities ask professional researchers to conduct a specific scientific investigation and report on the results

2. *Contributory* projects, which are generally designed by scientists and for which members of the public primarily contribute data
3. *Collaborative* projects, which are generally designed by scientists and for which members of the public contribute data but also help to refine project design, analyze data, and/or disseminate findings
4. *Cocreated* projects, which are designed by scientists and members of the public working together and for which at least some of the public participants are actively involved in most or all aspects of the research process
5. *Collegial* contributions, where noncredentialed individuals conduct research independently with varying degrees of expected recognition by institutionalized science and/or professionals

Building on such conceptual models, but primarily comparing large numbers of projects to find clusters empirically, Wiggins and Crowston (2011) developed the following five-category typology:

1. *Action-oriented* projects, which encourage participant intervention in local concerns, using scientific research as a tool to support civic agendas
2. *Conservation* projects, which support stewardship and natural resource management goals, primarily in the area of ecology
3. *Investigation* projects, which are focused on scientific research goals requiring data collection from the physical environment
4. *Virtual* projects, in which all activities are mediated by information and communication technologies, without direct investigation of physical elements
5. *Education* projects, where education and outreach are the primary goals

Action-oriented and conservation projects seem to overlap and will be considered below, because they implicate science directly in public policy debates and even social conflict. Wiggins and Crowston classify eBird as an investigation project, and Galaxy Zoo as a virtual project. In addition to these five categories, they identify two categories of projects that might seem similar to citizen science, but were excluded on the basis of reasonable criteria, which however might deserve reconsideration in the context of convergence.

First, they distinguish citizen science from *open science*, which they define as "open-source like practices in formal scientific research settings." The term *open-source* comes from computer software projects like the operating system Linux that was created by volunteers who shared the uncompiled and documented source code freely so that many people could critique or contribute code (Lee and Cole 2003; Bagozzi and Dholakia 2006). The volunteers whose work was used were technically competent at the level of professional programmers, and the social organization of the project was less hierarchical than most current citizen science projects that clearly distinguish the team of scientists from the citizen volunteers. A new term, *citizen science 2.0*, refers to projects in which the volunteers have greater competence and influence than in projects like eBird and Galaxy Zoo, suggesting that as citizen science evolves and expands into new fields, it may morph into open science.

Second, Wiggins and Crowston excluded several psychology projects in which the volunteers themselves were the objects of study, because human research subjects have not traditionally been considered research collaborators. Here again, as in the case of open science, the boundaries are blurred, more or less from one project to another, and potentially disappearing altogether as citizen science evolves. This potential is especially obvious in personality psychology and the social sciences when studies involve specific human beings over long periods of time, using methods in which judgments by the research subject contribute to the analysis. An early example was the intensive research on personality at Harvard University, chiefly in the 1940s and 1950s, when one of the most influential resulting books focused on just three ordinary citizens (White 1952).

Conceptual Convergence

The heavy and innovative use of information and communications technologies in citizen science projects suggests that computational infrastructure is relatively well developed for that application, setting the stage for a new phase of convergence on the conceptual level. Examples of outdated scientific classification systems are easy to find. Class B of the publication coding system of the Library of Congress includes psychology, but is dominated by religion and philosophy. The subclass to which psychology belongs, BF, includes parapsychology and the occult given that when the catalog was devised well over a century ago, psychic research and spiritualism often presented themselves as sciences of the mind.

The original NBIC report, *Converging Technologies for Improving Human Performance* (Roco and Bainbridge 2003) was assigned to the T category, which covers technology and thus would seem appropriate, but to the TA subcategory which is civil engineering, not really covered in the book, and even the broad T category does not include biology or cognitive science. Classification systems like that of the Library of Congress were an adaptation to the information technology of their day, placing paper-printed books with similar topics on the same shelf of a library to facilitate browsing, or looking through the card catalog in cases like the Library of Congress where users are not permitted into the stacks. The report's full call number is TA166.C69 2003, but it also has two other unique identifiers, the LC control number, 2003048819, and the International Standard Book Number (ISBN), 1402012543. Nobody, not even the editors, memorized these designations, and human beings tend to know a book by its title.

This raises the general convergence question of how much information of what kind needs to be built into the name of a thing or concept, for it to be useful. Today, as all books are migrating to electronic forms, there is no need to decide which one shelf of a physical library each should sit upon. Computerized search engines can find a book in many different ways, for example by title or author. They may *identify* each book by its meaningless ISBN number, but *locate* it by searching a list of keywords or the raw text of the entire publication. Humans may develop their own special purpose tools, for example the Wikipedia page devoted to the NBIC report. This can simultaneously promote both convergence and divergence, as biological and cognitive scientists may classify the report in ways useful for their own fields, but once they find the report they can branch out into the other disciplines and even make use of classification systems with which they were previously unfamiliar.

Many technical terms were derived from the accidental circumstances under which the first example was discovered, or the language of the discoverer (Bainbridge 1994a, b). Neanderthals were named after the valley in Germany where the first skeletal remains of this close relative of modern humans was found; *Thal* means valley in German, and Neander was the name of a revered local clergyman after whom the valley was named. Cepheid variable stars are named after Delta Cephei, the first example studied, in the constellation Cepheus, and of course many constellations were delineated and named in ancient times following principles that have nothing to do with modern astronomy. In cognitive science, this arbitrary naming convention illustrates *exemplar* theories of human cognition, the perspective that concepts are abstractions from specific cases (Conway 1997).

It is said that the universal language of science is mathematics, yet fields differ greatly in how they apply mathematics, and even which branches they find most useful across different subdisciplines. For example, in most of the social sciences, some but by no means all of the work involves statistical analysis, following rules of thumb rather than for most practitioners a deep understanding of the origins of the rules they follow. In the university, a course in social statistics may instruct students about when to use *Pearson's r* rather than *tau* to measure a correlation, and the qualitative logic based on the distinction between real numbers and ordinal scales may be learned, but very few social scientists memorize the formulae for these two very different coefficients, relying upon their statistical analysis software to handle that, let alone ever understand fully how the formulae were derived. That raises the more general principle that technical skills are increasingly being offloaded onto information technologies, a cultural change that may seem worrisome but could facilitate convergence across sciences by reducing intellectual barriers to entry.

In the sciences that emphasize observation of the natural world, classification of phenomena is often central. Consider taxonomy in paleontology and zoology. The author and reader of this essay belong to *Homo sapiens*, while a pet cat belongs to *Felis catus*. The online Integrated Taxonomic Information System (ITIS) created by several agencies of the US government explains that the full classification of kitties is: Animalia, Bilateria, Deuterostomia, Chordata, Vertebrata, Gnathostomata, Tetrapoda, Mammalia, Theria, Eutheria, Carnivora, Feliformia, Felidae, Felinae, Felis catus. *Felis catus* is a genus-species name, and ITIS attributes it to Linnaeus in 1758 who was the key scientist who developed the taxonomic system still in use today. When it was established, the Linnaean system was influenced by an Aristotelian or Christian religious notion that categories of creatures were somehow naturally distinct, even immutable, and the theory of evolution by natural selection would not be developed for a century, while another century would be required before science began to understand how the structure of the DNA molecule determined genetic differences.

The *species* concept continues to be useful, because it identifies a gene pool of creatures that can breed with each other. Yet a widely dispersed species may show great geographic variation, such that individual organisms at the extremes might have trouble breeding if we brought them together. Paleontologists struggle with the concept *chronospecies*, which refers to creatures in the same lineage but from very different time periods, such that their form is markedly different and we can speculate they might not have been able to breed if brought together via an imaginary time machine. For living creatures, we can now sequence their DNA and describe differences much more precisely, although this methodology is developing so rapidly it is hard to predict how far it will go.

The *genus* concept may not be very useful, however, let alone some of the higher-level terms like the catty "Feliformia, Felidae, Felinae." An approach called *cladistics* conceptualizes these classifications as the empirical result of family trees of animals having common ancestors (Hennig 1979). This modern approach does not salvage the Linnaean system entirely, both because common descent is difficult to determine, and because there is no reason to assume that modern species of cats and humans are the result of only a small number of gene pool splits from common ancestors, let alone about the same number. As a practical matter, we could keep the old Linnaean names, but not consider them a scientific classification, then use DNA and other data to constantly update family trees on an open but authoritative archive like ITIS.

Another example is the Unified Medical Language System (UMLS) developed by the National Library of Medicine that began by attempting to harmonize competing terminology systems that had already been developed somewhat independently. Clearly, UMLS is an example of convergence within a field, but a 2004 report said it then contained 2.5 million terms, 9,00,551 concepts, and more than 12 million relations between these concepts (Bodenreider 2004). No human being could possibly learn 2.5 million terms, so in the past experts have specialized. A possible end result of efforts like ITIS and UMLS would be that human scientists learn only very general concepts, and rely upon the databases and information technology search systems to handle the infinitesimal details. That would be a revolutionary shift for many observational fields of science, and one that could facilitate both citizen science and professional scientific convergence, especially if the general terms were not field-specific.

It is not uncommon for innovative scientists interested in two or more fields to borrow a general concept from one and apply it to another, whether as metaphor or as a technically correct description of procedurally or structurally identical realities – *isomorphisms*. For example, Harrison White (1970) applied the concept of mobile electron holes from semiconductor physics to moving job opportunities in social institutions. A well-known but controversial example is the transfer of the gene concept to culture, using the term *meme*, coined by Richard Dawkins (1976). Yes, culture evolves, but does it possess a rigorous structure analogous to DNA that could define memes unambiguously? At a 2005 converging technologies conference in Hawaii, one list of candidate general concepts was suggested, each of which could function usefully in multiple fields, and each of which could be understood abstractly by well-educated ordinary citizens (Bainbridge 2006):

1. *Conservation*: Many parameters of nature are constant, or like the conservation of mass and energy preserve some features even when they are transformed, and this may be true even for complex systems if some manner of homeostasis is in effect.
2. *Indecision*: Some events may be triggered by utterly random factors; indeterminacy is not limited to subatomic phenomena, and information will always be incomplete concerning complex systems.
3. *Configuration*: Most sciences and branches of engineering concern assemblies of units into typical structures, such as the atoms in protein molecules or the people in social networks, and graphing phenomena in spatial representations is a universal mode of human thought.
4. *Interaction*: All systems are dynamic to a significant extent, so many forms of analysis decompose phenomena into subsystems, although the velocity at which these units influence each other varies widely across sciences.
5. *Variation*: Not only do the units in a complex system tend to vary, but their characteristics tend to follow one of a small set of mathematical forms, such as the normal curve, the related logistic curve, or a power law such as the "long-tail" Zipf distribution.
6. *Evolution*: Natural selection tends to reduce diversity while strengthening some form of adaptation, but mutation resupplies diversity, allowing systems to change significantly over time.
7. *Information*: A balance between order and disorder, meaning and entropy, data and wisdom, the raw material of scientific publication and engineering design is ultimately the content of human communication.
8. *Cognition*: The human mind forms cognitive models of reality, which must to some extent mirror the external world, but which cannot be divorced from general human desires, personal past experiences, and the chaotic process by which the human brain evolved.

These principles themselves form a complex system, amplifying or modifying each other, but all widely applicable across multiple sciences. Of course, other such lists can be constructed, and some of these concepts can be criticized. Any final list of general concepts that can validly facilitate convergence of the sciences must itself be the result of extensive scientific study. Traditionally, curricula designed to improve scientific literacy among the general public tended to seek familiar language in which to describe each science separately, but did not attempt to establish a new terminology to unite them (Rutherford and Ahlgren 1990).

Ethical, Legal, and Social Issues

Citizen science raises a very wide range of ethical, legal, and social issues. They could be viewed as interesting challenges that motivate us to understand well how the teams function and how science interacts with the wider society, rather than as evidence that citizen science is undesirable. For example, there are questions about intellectual property rights, whenever a project produces new technology that might deserve patenting, or simply the honor accorded participants on scientific publications that result. Many issues are more obvious in citizen social science, so we can approach them from that direction, but with awareness that once we are fully aware of an issue we may find that it arises in many other scientific fields as well.

Social and behavioral scientists have tended to withhold much information about their research from the human subjects they study, and promotion of subjects to the role of collaborators would violate this longstanding tradition. One reason is that the people under study may adjust their behavior to conform to the researcher's theories, thus invalidating the results (Orne 1962). Another is that information may free the respondents to use the situation for their own purposes, notably to present themselves in a favorable light, what is technically known as *social desirability bias* (Crowne and Marlow 1960). However, especially in cultural anthropology, so-called *native informants* often become very familiar with the goal of the research, even to the point of becoming collaborators in it (Manning and Fabrega 1976). The demand characteristics of a research study, such as the social pressure to find what the team leaders expect, can produce bias in any science. When the focus of scientific research is human beings, there is always the potential for the researcher to merge with the researched, but this can become an advantage rather than a distortion, if the study is designed with the principles of convergence in mind. The key principle is awareness: Understand the human as well as the technical meaning of the research.

While intellectual property rights are typically conceptualized as patents in engineering, in social science they can be conceptualized as privacy. When the Harvard team many decades ago studied a few individuals intensively, their publications concealed the names of the research subjects, but anyone who knew them could recognize them in the research publications, because so many details of their lives were revealed. Today, so-called longitudinal studies, in medicine as well as the social and psychological sciences, collect vast amounts of data about a distinct group of individuals across a span of years. If some of those individuals begin to feel they are partners in the research, and urge that the study morph into citizen science, they not only risk revealing many private facts about themselves, but also starting an avalanche that unravels the privacy protections for the other participants as well.

Consider one of the world's very best longitudinal studies, The Panel Study of Income Dynamics, which has surveyed a sample of American families since 1968, following the same people over the decades and sometimes adding their children as effective replacements when older generations pass away. Housed at the University of Michigan, the PSID has provided the data for over 3,000 scientific publications, in sociology as well as economics, often providing government programs with a needed understanding of the changing conditions of American life, in areas such as poverty and social mobility. The families under study have been protected very well from journalists and others who might exploit them, if their privacy were violated, and they are generally quite loyal participants. A key challenge for any longitudinal study is *sample attrition*, the technical term for when research subjects defect, either refusing to participate any more or simply moving and getting lost to the researchers. This problem has been minimized in the PSID, and careful studies have compared defectors with the continuing sample to see if any regularities in what factors encourage defection might bias the results (Fitzgerald et al. 1998). But imagine what would happen if a few respondents decided the PSID was a citizen science study, set up a blog site to encourage other respondents to go public, and proudly identified which respondent ID numbers were theirs in the widely available dataset. This may never happen, but all kinds of bias might be introduced into the data, even as other participants defected over privacy concerns.

Many future citizen science projects may involve volunteers who are not themselves the subjects of study, but who help collect data about other people. A common example already exists, namely the numerous oral history projects in which volunteers interview members of a community, often elderly ones, to assemble a description of its past (Bainbridge 2014, p. 145). If the volunteers were graduates of a college sociology or urban studies program, working under the direction of former professors, then the research might be community sociology rather than oral history. The chief difference is the use of a theoretical framework, with the development and testing of hypotheses, in the context of an ethnographic case study. This is perhaps the most likely kind of study that could demonstrate the value of citizen social science, and develop methods for dealing with legal and ethical issues, because so much prior work would provide a solid framework.

The relevance for other kinds of science can be illustrated by returning to the Wiggins and Crowston typology of citizen science, particularly their action-oriented and conservation categories. Studying environmental pollution is also studying the behavior of the human beings who caused the pollution (Cooper et al. 2007). Any collective action may have opponents. Any government-sponsored research project may draw the ire of opponents of government in general, or opponents of the currently ruling political party. Opening the doors of a laboratory to welcome citizen scientists also opens the doors to social and political controversy. However, objective scientific research may be the best way to resolve public debates, so its convergence with society may be not only possible but necessary in these times of widespread public discontent.

Environmental protection, including the challenge of global climate change, has been the public controversy most often discussed in Converging Technologies conferences, and a large fraction of government-supported citizen science projects are in this general domain (Bowser and Shanley 2013). The citizen scientists involved in eBird are indirectly contributing to our knowledge in this area, because they help map changing bird migrations as climatic conditions change, and many other environmentally oriented citizen science efforts will contribute in the future. While participants in eBird undoubtedly care about the natural environment, they are not necessarily biased in favor of a particular theory about climate change. Thus, given their background knowledge and research-related interests, they may become valuable opinion leaders in their local communities as the general public struggles to make sense of the objective facts and policy implications of the debate (Katz and Lazarsfeld 1955).

The question then becomes whether citizen science can function effectively outside the discipline imposed by academic institutions and professional scientific organizations. This question may not have a simple answer, and it suggests several directions for research. If the Environmentalist Movement can integrate citizen science into its antipollution crusades, and some of the industries that disagree with the movement can hire their own scientists to provide rebuttals, how can the opposing sides converge to a shared scientific understanding that could guide public policy in the proper direction? Will the development of citizen science eventually lead to a proliferation of scientific schools of thought, not merely one for each field of science, but also one within each field for every nonscientific subculture such as religions, political factions, and historical heritages? In other words, citizen science will have substantial implications for divergence as well as convergence, perhaps not yet predictable in outcome, deserving serious attention.

Public Perceptions of Science

Citizen science has the potential to transform public perceptions of the sciences involved, but its early success depends upon the perceptions that members of the public already have. Thus, one of the roles for social science in convergence of science and society is to chart changing popular beliefs and attitudes, thereby providing a conceptual framework on which to build educational programs and design the organizations that invite citizen contributions. A good dataset for illustrating the current situation is the 2006 General Social Survey (GSS), based on a representative sample of American adults, publically available from National Opinion Research Center at the University of Chicago and the Computer-assisted Survey Methods Program at the University of California, Berkeley.

One battery of eight questions in the 2006 GSS asked, “How important are each of the following in making something scientific?” Table 1 reports the percentages of respondents who assigned each of four levels of importance to eight characteristics of the research, with from 1,775–1,807 answering each one, and the percentages across each row adding to 100 %. It is based on unweighted data, and anyone who wishes may analyze the data while weighting for other variables and also looking at correlations, for example with levels of respondent education.

While few members of the general public expect science to be consistent with religious beliefs, many expect it to be consistent with common sense. They also tend to feel that conventional laboratory and university settings are important, and place a rather high priority on the researchers having a higher degree in the field. These assumptions may need to adjust somewhat, to facilitate citizen science. But the highest importance is given to good intellectual standards: solid evidence, unbiased weighing of the evidence, and independent replication. Naturally, respondents differ in their assessments of various sciences. In answering another battery of questions, only 9.6 % felt that sociology was very scientific, compared with 16.6 % for economics, 48.1 % for engineering, 70.7 % for physics, and 71.6 % for biology.

Table 1 Perceived importance of aspects of scientific research

	Very important (%)	Pretty important (%)	Not too important (%)	Not important at all (%)
It is done by scientists employed in a university setting	42.6	32.4	20.1	4.9
The people who do it have advanced degrees in their field	64.0	29.4	5.1	1.5
The conclusions are based on solid evidence	81.6	15.3	2.0	1.1
The researchers carefully examine different interpretations of the results, even ones they disagree with	74.8	21.5	2.7	1.0
The results of the research are consistent with religious beliefs	11.0	16.6	32.2	40.2
The results of the research are consistent with common sense	40.8	35.6	15.2	8.5
Other scientists repeat the experiment, and find similar results	68.4	27.3	3.2	1.1
The research takes place in a laboratory	42.6	32.4	20.1	4.9

We cannot expect all members of the population to participate equally in citizen science, so social scientists will need to analyze public conceptions in terms of variables such as education that might predict participation. While 47.6 % of 1,276 respondents who lack college degrees believe it is very important for research to take place in a laboratory, only 30.1 % of 511 college graduates expressed this view. Certainly, many kinds of citizen science take place out in the field, or on the volunteer's home computer, rather than in a laboratory. College education correlated with giving a high priority to the three characteristics describing intellectual standards, for example 84.9 % versus 70.8 % on examining different interpretations, and lower priority to the other characteristics, even possession of a higher degree.

Value for Humanity

Science serves many functions for humanity, and several of them can be facilitated by citizen science. Discoveries in fundamental research provide the knowledge necessary for new technological inventions, and public participation can both help make the discoveries and decide whether and in what ways new inventions should be promoted for human betterment. In democracies, public policy requires the consent of the government, and citizens can best play their central role in the political process if they really understand the issues. Documenting the migrations of birds is far from frivolous, providing profound insights on how humanity fits into nature. Classifying images of distant galaxies may have no implications for engineering or public policy, but it does provide the basis for an improved understanding of the nature of the universe. That understanding is of little value if limited to specialists confined to the ivory tower of academia, and science will serve humanity best if it is fully integrated into human culture.

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Collaboratories

Gary M. Olson

Abstract

Most interdisciplinary research projects involve geographically distributed participants. It is well known that such dispersion presents many challenges. The good news is that there are a wide variety of excellent technologies that can help bridge the distance among participants. However, there continue to be many challenges in how to make such projects successful. Fortunately, there is now a large body of research that suggests ways in which the challenges can be overcome. This chapter reviews the challenges and the interventions that can ameliorate the problems.

These days it has become commonplace in almost all areas of human endeavor to work with others who are not in the same location as you. Computing and communication technologies have matured to where it is relatively easy to carry out such activities, though as will be noted shortly, there are still many challenges. In the early 1990s these kinds of technologies began to get widespread attention as a form of infrastructure to support geographically distributed science and engineering. Wulf (1993) described an organization that exploits such infrastructure on behalf of scientific research as "collaboratories" and called them a "laboratory without walls." At that time a research group at the University of Michigan began to both build and study such collaboratories, an effort that has been maintained since. In a volume summarizing much of this work, as well as that of others, Olson et al. (2008a) described collaboratories as

G.M. Olson (✉)
Department of Informatics, University of California, Irvine, Donald Bren School of Information and Computer Sciences, Irvine, CA, USA
e-mail: gary.olson@uci.edu; garymolson@gmail.com

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> . . . an organizational entity that spans distance, supports rich and recurring human interaction oriented to a common research area, and provides access to data sources, artifacts and tools required to accomplish research tasks. [p. 3]

Over time many other ways of talking about such organizations have emerged other than "collaboratory," such as cyberscience (Nentwich 2003), e-Science (Hey and Trefethen 2005), e-Research (Jankowski 2009), and cyberinfrastructure (Atkins et al. 2003). All of these focus on the same core idea: using networked technology to make it possible for scientists and engineers to more easily work together even if they are in different geographic locations. And, ever since Allen's (1977) pioneering work, it is well known that the threshold for describing interactions as occurring at a "distance" is approximately 30 m. So even participants in different hallways, different floors, or different buildings on the same campus face many of the challenges that will be discussed here. Of course, even greater distances incur even more challenges.

In 2000 the University of Michigan group launched the Science of Collaboratories (SOC) project, whose goal was to determine what factors differentiated successful from unsuccessful efforts at creating collaboratories. One component of this project was to catalog instances of collaboratories. This yielded the Science of Collaboratories database, which was populated over time with instances of collaboratories in all areas of science. In a recent update, Olson and Olson (2014) observed that this database had grown to more than 700 entries, covering all areas of science and many levels of scale. Indeed, in that same update, it was noted that such geographically distributed collaborations were beginning to emerge in humanities scholarship as well, facilitated by the same kinds of technologies used in science.

Despite how widespread such collaborations have become, they are still challenging to carry out. Beginning with Olson and Olson (2000), with later updates in J. Olson et al. (2008c) and Olson and Olson (2014), the challenges faced by such collaborations have been summarized in five broad areas, as shown in Table 1. Olson et al. (2008b) and Olson and Olson (2014) contain lots of details about these factors, illustrating them with concrete examples. Another recent review is Jirotka et al. (2013). As several recent reports have shown (Karis et al. in press; Bjorn et al. 2014), these challenges can be overcome with appropriate tools and procedures, which is good news for those who need to engage in such projects. But at the same time many projects struggle with the kinds of issues summarized in Table 1.

As a further aid to helping projects succeed, the Olson group has developed an online assessment tool called the Collaboration Success Wizard (hana.ics.uci.edu/wizard/). This tool is based on the factors shown in Table 1. It contains approximately four dozen questions ("approximately" because its branching structure means that an individual respondent may get a slightly different number of questions). The Wizard is administered to participants in a geographically distributed project. The Wizard comes in three flavors: one for projects that are being planned, one for projects that are already under way, and one for projects that are completed.

Table 1 Factors that lead to success in distance collaborations supported by various technologies

The nature of the work
The more modular the work assigned to each location, the less communication required
The more routine or unambiguous the work
Common ground
Previous collaboration was successful
Participants share a common vocabulary
If not, there is a dictionary
Participants are aware of the local context at other sites
Participants share a common working style, including management
Collaboration readiness
Individuals tend toward extroversion, are trustworthy, have "social intelligence," and are, in general, good team members
The team has "collective intelligence," building on each others' strengths
The culture is naturally collaborative
The goals are aligned in each subcommunity
Participants have motivation to work with each other that includes a mix of skills, they like working together, and there is something in it for everyone – not just a mandate from the funder
Participants trust each other to be reliable, produce with high quality, and have their best interests at heart
Participants have a sense of self-efficacy, that they can succeed in spite of barriers
Management, planning, and decision making
The project is organized in a hierarchical way, with roles and responsibilities clear
There is a critical mass at each location
There is a point person at each location
The project manager:
Is respected
Has real project management experience
Exhibits strong leadership qualities
A management plan is in place
A communication plan is in place
Decision making is free of favoritism
Decisions are based on fair and open criteria
Everyone has the opportunity to influence or challenge decisions
Cultural and time zone differences are handled fairly
No legal issues remain (e.g., IP)
No financial issues remain
A knowledge management system is in place
Technology readiness
The technologies fit the work
The network has sufficient bandwidth and reliability
The architecture fits the need for security and privacy
Communication tools have the richness and immediacy to fit the work
Coordination tools (calendars, awareness, scheduling, workflow, etc.) are sufficient
Everyone has access to shared repositories with sufficient access control

(*continued*)

Table 1 (continued)

Social computing (e.g., micro-contribution systems and social support) is well designed and fits the social as well as work needs
Large-scale computation fits the needs
Virtual worlds are used in appropriate ways
The choice of technologies directly considers:
Speed, size, security, privacy, accessibility, richness, ease of use, context, cost, and compatibility

An individual respondent can request immediate feedback, which is generated automatically, based on that respondent's answers. It points out strengths and weaknesses in the project and for the latter suggests remedies. At the project level, the data are summarized across all respondents and a report is prepared for project leadership. The Wizard has been used for 15 scientific projects involving more than 300 respondents. Some examples of specific projects and the kind of feedback they have provided are covered in more detail in Bietz et al. (2012).

The large sample of collaboratories in the SOC database cover many kinds of science, but it will come as no surprise that many of them involve interdisciplinary efforts to tackle difficult problems. It is now widely recognized that many important science problems require bringing diverse expertise to bear (e.g., Klein 1990, 1996; Derry et al. 2005; Fiore 2008; Stokols et al. 2010; Crowley et al. 2014). While there are some collocated scientific centers and institutes that have been designed for such interdisciplinary efforts, it is much more common that the different kinds of expertise required often reside in different locations.

While the challenges outlined in Table 1 certainly apply equally well to interdisciplinary projects, it is worthwhile enumerating the special challenges that are faced in such work, since it is clear going forward that collaboratories are a key organizational form for such projects.

There is a rich literature on interdisciplinarity and its challenges. The recent edited collection by O'Rourke et al. (2014) has many references to the challenges of such work. Here are some that are based on a discussion by Crowley et al. (2014) in an introductory chapter in that same volume and that echo various key points in Table 1.

First, different fields frequently have their own unique vocabularies. These matters are particularly troublesome when the same words mean different things in different fields. For example, different medical specialties often have different terms for the same anatomical structures, symptoms, and diseases. Even more daunting, the same term can be used in different ways in different disciplines. A project in earthquake engineering revealed that the earthquake engineers and the computer scientists attempting to build tools for them had very different meanings for "system" and "requirements" (Spencer et al. 2008).

Second, heterogeneous mixtures of participants often bring challenges having to do with styles of communication. This is only made more complex by the vast array of technologies available for communication today. Some prefer talking by phone. Others prefer e-mail. Still others like to use web-based conferencing. Users of e-mail also vary in how often they check it and how quickly they reply. Do documents get exchanged as attachments to e-mail or put somewhere in the "cloud"? It turns out the cloud today is very confusing to most (Voida et al. 2013). And emerging social media offer a bewildering array of other ways of staying in touch.

Third, different fields often have quite different practices and priorities. One example is publication practice. For instance, in many fields of computer science, refereed conference proceedings are first-class publication outlets, whereas in many other fields, conference proceedings do not count at all as archival publications. In some fields there may be only a small number of publication outlets that carry sufficient prestige to be worth using. There are also field differences in the construction of coauthor lists, both in who gets included and in what order they are listed.

Fourth, there may be major challenges when the participants in different fields come from different institutions. Universities vary considerably in their support and nurturing of interdisciplinary research. Challenges arise when researchers come from a mixture of universities, companies, or federal labs. How research practices are managed (e.g., human subjects' oversight) can vary. Bennett and Gadlin (2014) have an extensive discussion of such matters and cover five areas that are challenges to interdisciplinary work: institutional self-awareness, organizational trust, leadership, management of differences, and handling of conflict and disagreement.

There are also challenges brought on by the kinds of problems for which interdisciplinary approaches are used. As Crowley et al. (2014) note, such approaches are often used for so called "wicked" problems that "involve nonlinear causal interactions among a multitude of different elements [p. 2]." Domains like climate change, public health, and economic sustainability are difficult ones to work in. Szostak (2014) outlines the many kinds of ambiguity that tend to plague interdisciplinary approaches, often driven by the kinds of problems that are attacked this way. Examples he mentioned include different definitions of concepts, different understandings of conversations among participants, and vagueness that hides inconsistencies. He also describes how these can be handled in productive ways.

Identifying the challenges in geographically distributed interdisciplinary research is an important first step, but it leads to the question of what can be done. Fortunately, the literature has answers based on extensive amounts of research. Here are a few examples of things that have worked.

One of the things learned between the original "distance matters" paper (Olson and Olson 2000) and its later updates (J.Olson et al. 2008c; Olson and Olson 2014) is how important good management practices are. Cummings and Kiesler (2005) studied a large number of NSF-funded projects and reported two distinct findings. First, projects that were geographically distributed were frequently less successful than ones that were collocated. But second, among those that were geographically distributed, having good management separated those that were successful from those that were not.

It has become quite clear that managing a geographically distributed project has many major challenges. In part, this is because good management of such projects requires a much more proactive approach. Out-of-sight-out-of-mind problems can become very serious if proactive oversight of all the participants is not used. This can be particularly troublesome if some of the sites are small, with one or two participants (Koehne et al. 2012). Open and frequently used lines of communication are essential. There are many specific management challenges for distributed projects. Here are some of the more important ones.

A management plan is important. And it is not necessarily the plan that is important, but as Dwight Eisenhower is reputed to have said, “Plans are nothing, planning is everything.” It is interesting that most major funding agencies now require management plans as a part of grant and contract proposals, particularly for larger more complex projects. The chapters in Olson et al. (2008b) contain many specific examples of how large projects have been managed. Some have formal management committees and, in one case, actually hired MBAs with business experience.

It is well known that trust is much more difficult to engender among distributed participants (Tyran et al. 2003). While face-to-face interactions are probably the best way to do this, there are some other options that have been explored (Bos et al. 2002; Zheng et al. 2002), including using richer communication media like video and sharing nonwork, more personal information, though these forms of bridging distance can be slow to develop and remain quite fragile.

Nothing can erode a long-distance collaboration faster than decision-making processes that are invisible or biased. It is important that all involved feel that their interests are taken into account when decisions are made or resources are distributed. This is a key component of the Collaboration Success Wizard (Bietz et al. 2012).

Interdisciplinary collaborations can quickly escalate to involve serious distances that entail time zone differences as well as cultural practices. Minimal overlap in normal work days is a very big challenge. And different cultural practices, which tend to be correlated with increasing distance, can affect things like communication styles or decision-making strategies. Olson and Luo (2007) saw that such cultural differences produced serious strain on large projects such as the large hadron collider in high energy physics. Many Asians were handicapped by being far away from CERN, where the project was headquartered, and did not have access to communication or travel support that would have made interactions easier.

This is where institutional differences can become serious, particularly if intellectual property issues are involved. Olson and Olson (2000) reported attempts at the creation of multi-institutional, interdisciplinary projects that were brought down by lawyers who could not agree on how to handle such matters.

Financial issues are another area where institutional or cultural differences can arise. Olson and Olson (2014) reported on a case involving research among participants in the USA, the UK, and South Africa. In South Africa, money cannot be spent until it is in an account, whereas in the USA expenditures can be made and the funder invoiced. The solution was to arrange a loan in South Africa so money would be in the account, and the US funds were invoiced to pay off the loan.

A project of any complexity quickly generates a large oeuvre of materials: documents, data, practices, and even equipment. Who has what, and how are they shared? How is access controlled? How are such materials kept up to date? Such knowledge management issues can quickly get out of hand when projects are large, distributed, and multidisciplinary.

These management issues obviously touch many of the complexities of doing interdisciplinary research. But there are some other interventions that can also help.

If there are vocabulary issues, it may be important to create a dictionary. Olson and Olson (2000) reported several cases where time invested at the beginning of a project in doing this made things work smoothly later on. One was a large biomedical collaboration, where early on the participants realized they were calling the same things by different terms. Another was a large project on schizophrenia involving participants from many disciplines, where even talking about the same parts of the brain required clear terminology.

If there are noticeable differences in the communication cultures of participants, putting together a document that has a shared understanding about how communication will occur can be very useful. What conventions will be used for responding to e-mail? It can be very helpful for all to at least acknowledge that a message has been received even if a detailed response will be provided later.

Having clearly specified "rules of the road" can be another helpful intervention. In many areas of physics, for instance, there is an important division between theorists and data collectors. And among the latter, there can be a wide array of different kinds of instrumentation specialization. A community of upper atmospheric physicists, with NSF support, developed a document they referred to as "rules of the road." It laid out data sharing and publication practices, among other things. When in a later collaboratory phase their instruments were put on line so that they could access data flows in real time over the Internet, they realized they needed to revise their rules of the road, and they did. A different project attempted to pull together a half dozen different disciplines to study depression, but their attempt at rules of the road foundered as the practices about data sharing and publication were so different and affected participants at different stages in their careers so differently.

It is often useful to give careful thought to the kinds of technologies that will be used for communication and coordination. In Chap. 9 of Olson and Olson (2014), a wide array of technologies were reviewed, and principles for choosing among them were articulated. The four categories of technologies were communication tools, coordination tools, information repositories, and computational infrastructure. Within each of these a variety of specific kinds of tools were described.

The Collaboration Success Wizard is a tool to help with monitoring and ameliorating the challenges in Table 1. There is now a wide array of resources available to assessing and intervening in such distance collaborations. Bennett and Gadlin (2014) list many of these in their Table 17.1, including references to the resources. A couple worth explicit mention are the Team Science Toolkit developed at the National Cancer Institute (www.teamsciencetoolkit.cancer.gov) and the Toolbox

Project and its associated Toolbox Workshops (Looney et al. 2014). In short, resources to help ensure that collaborations work are available. While none of them offer guarantees of success, they all are based on research and experience that moves things in the right direction.

Conclusion

The combination of interdisciplinarity and geographic dispersion definitely presents major challenges for the participants. The extent of these problems, and whether they are unique challenges that may require different kinds of interventions, clearly needs further research. It is apparent in almost any domain of inquiry that such dispersed interdisciplinary projects will only grow, and increase in importance, as both the frontiers of scholarship and the demands of societal problems grow. What we currently know can help mitigate many of the challenges, but given the importance of such projects, constant monitoring of their patterns of success and failure is essential. Mastering these challenges will constitute a most significant accomplishment going forward.

Collaboratories are endemic organizational forms that exploit the emerging cyberinfrastructure, and many of the challenges to making them successful are now well understood. Interventions are available. They provide a kind of organizational resource that can make interdisciplinary projects work (Finholt and Olson 1997). But success will require careful ongoing attention.

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Communication Media

Robert Amant and Thomas E. Horton

Contents

Abstract

The influence of information technology on society is enormously complex and has evolved over time. This chapter examines a few prominent historical visions of how computers would affect human life and human interactions. Taking a view of computers as aids to human decision-making, the chapter continues with a brief exploration of three central questions: What can and should be decided? Who decides? Who benefits? The goal is to provide a sampling of what can be seen as trends toward eventual convergence.

Introduction

In the early 1800s, Charles Babbage described the first plausible digital computer, the Analytical Engine, which gave rise to the first visions of how computers might influence human action. In his later autobiography, Babbage (1864) foresaw that

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R. Amant (✉) • T.E. Horton
Department of Computer Science, North Carolina State University, Raleigh, NC, USA
e-mail: stamant@ncsu.edu

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computers would change the course of science, by automating the tedious calculations earlier scientists needed to carry out by hand. Ada Lovelace, who created the first program for the Analytical Engine, expressed similar thoughts (Menabrea and Lovelace 1842):

> It may be desirable to explain, that by the word operation, we mean any process which alters the mutual relation of two or more things, be this relation of what kind it may. This is the most general definition, and would include all subjects in the universe... A new, a vast, and a powerful language is developed for the future use of analysis, in which to wield its truths so that these may become of more speedy and accurate practical application for the purposes of mankind...

Information technology has changed enormously over its lifespan. Fifty years ago, computers were viewed by the general public and even those knowledgeable about information technology as large, rare, and idiosyncratic machines. Like wild animals, computers would be kept isolated and at a safe distance. But over the years, computers, have become ubiquitous – they're in our living rooms and cars, in our backpacks and purses and pockets, and even inside our bodies in smart medical devices. There are more computers for personal use (including PCs, tablets, gaming consoles, and smart phones) than people on Earth. Their application extends far beyond the sciences; information technology pervades our everyday lives. Computers help us solve problems large and small; they connect us to people and information we need; they help us keep our lives on track. Not all benefits are without trade-offs, however. For example, in the United States, the National Security Agency has come under criticism for data collection in its anti-terrorism efforts; the National Park Service has recently banned the use of aerial drones; espionage has long had an information technology angle. In each of these examples, a balance is being struck.

Broadly speaking, information technology is concerned with data – how we manage it, how we manipulate it, and how we use it. One way to talk about information technology is to break it down along three dimensions: space, time, and distance. How do we store large amounts of complex data while also being able to retrieve it efficiently (space)? How do we use computers to automate complex tasks and computations, so we don't have to do them (time)? And how do we use networks and devices to access data from anywhere in the world (distance)? As basic as these questions are, answers will inform our understanding of the relationship between information technology and society.

This relationship is enormously complex, and we cannot hope even to summarize the topic. Instead, this chapter will examine a few prominent visions of how computers would affect human life and human interactions, for historical perspective. Then, treating computers in the abstract as aids to human decision-making, we briefly explore three questions we believe are central to the relationship between information technology and society: What can and should be decided? Who decides? Who benefits? Our goal is to provide a sampling of what can be seen as trends toward eventual convergence.

A Historical Convergence

In 1945, Vannevar Bush, whose work led to the creation of today's National Science Foundation, wrote a popular magazine article titled "As We May Think" (Bush 1945). In the article, he described a hypothetical memex system to illustrate how information might be explored more effectively than was then possible at the time. His key idea was associative indexing, in which links between different pieces of information would not remain static, as in a library card catalog or the table of contents in a book, but instead could be created on the fly for later recall and review.

He foresaw how lawyers, physicians, chemists, and historians might do their work more easily with the help of a comprehensive and usable system for finding information in this way. Today we recognize his speculations as clear precursors to hypertext and the World Wide Web (Berners-Lee 1989), to the use of semantic networks in artificial intelligence (Quillian 1967) and cognitive psychology (Collins and Loftus 1975), to the digital humanities (Schreibman et al. 2008), and to brain-computer interfaces (Schalk 2008). Remarkably, Bush's article appeared before the first general-purpose electronic computer was even constructed.

A second vision of the future of information technology is due to Douglas Engelbart, who by the early 1960s had begun to publish his thoughts about the potential of computers to augment human intellect to aid us in handling complex situations. He wrote (Engelbart 1962):

> And by "complex situations" we include the professional problems of diplomats, executives, social scientists, life scientists, physical scientists, attorneys, designers – whether the problem situation exists for twenty minutes or twenty years... We refer to a way of life in an integrated domain where hunches, cut-and-try, intangibles, and the human "feel for a situation" usefully co-exist with powerful concepts, streamlined terminology and notation, sophisticated methods, and high-powered electronic aids.

If Bush's focus was on the structure of information and how we might more naturally explore it, Engelbart's vision was broader: assuming that we have rich access to information, computer algorithms might help us make better decisions based on that information. Some peripheral aspects of Engelbart's work are commonplace today: video conferencing, word processing applications, chorded keyboards, windowing systems that can display both text and graphics, and the computer mouse. More generally, we now rely on information technology to make significant decisions, from preparing our personal tax returns to estimating the effects of national economic policy changes.

A third important contribution was from J. C. R. Licklider, whose work would be instrumental in the development of the Internet. In a seminal article with Robert Taylor, Licklider asked (Licklider and Taylor 1968):

> What will on-line interactive communities be like? In most fields they will consist of geographically separated members, sometimes grouped in small clusters and sometimes working individually. They will be communities not of common location, but of common interest. In each field, the overall community of interest will be large enough to support a comprehensive system of field-oriented programs and data.

Licklider and Taylor described face-to-face meetings being replaced (at times) by online meetings, “free and easy” online conversation being critical for cooperation and collaboration, tedious programming tasks being taken over by computers themselves, and the formation of stable, evolving groups of people who might never have met in person. They viewed computers as a medium for interactive communication that could support reasoning and thought, “above all a common medium that can be contributed to and experimented with by all.” Today’s social media, question and (expert) answer Web sites, and cloud computing can be traced back to Licklider’s influence.

These are the most famous and influential early visions of the influence of information technology on society. We see a few common themes. Modern society is complex, but computer systems can help to contain and manage that complexity. Bush wrote of civilization as an experiment and that improved information technology might “push [this] experiment to its logical conclusion.” Bush, Engelbart, and Licklider envisioned different ways in which computers might aid the decision-making of individuals or groups of individuals linked by common interests. Above all is the optimistic view that information technology has the potential to improve our lives.

We also see different emphasis in the visions to some extent related to different facets of information technology. Bush’s vision is concerned, roughly speaking, with space: the storage, and retrieval of large amounts of data. Engelbart addresses time: performing complex calculations quickly enough to inform our decisions or even to make decisions. Licklider’s vision touches on distance, in particular the reduction of large distances (physical and even metaphorical) to those we can more comfortably deal with.

The evolution of visions about information technology and society was accompanied by changes in the way we view computers themselves. Babbage and his contemporaries thought of computation in terms of numerical calculations and algebraic symbol manipulation. This understanding is still prevalent today, in procedural models of computation: a computer executes a set of instructions to accomplish a given task. At the lowest level of abstraction, these instructions include arithmetic and logical operations on small amounts of data, down to individual bits, as well as instructions for reading, writing, or moving data to different places within the computer; other instructions govern flow of control. Machine instructions can be built up into more abstract statements, giving us the high-level programming languages we have today.

This basic model of computation can be seen in modern social science research, for example, in dynamic micro-simulation (Gilbert and Conte 1995). Features of individuals in a society are sampled to create a base dataset (e.g., that a given individual is employed in a specific industry), and probabilities for transitions between different feature values are identified (e.g., the probability of becoming unemployed in any given year). A simulation iteratively updates the samples, generating predictions about how feature values across the society will change over time.

There are other models of computation we may consider as well. One broad family is represented by distributed processing models, including connectionist models and multi-agent systems. Connectionist models have been widely used to model individual problem-solving. In an artificial neural network, neurons are directionally connected to each other; one neuron may have input and output connections to other neurons. A neuron typically associates a numerical weight with each of its inputs, and it applies an activation function that combines its weighted inputs to determine the value of its output. Neural networks have been used to model organizations as well as individuals (Jean-Philippe 2007).

Multi-agent systems encompass a range of different approaches. A multi-agent system typically contains a set of software or hardware agents (e.g., individual programs or robots); these agents make decisions and interact with each other based on locally limited rather than global information; control is decentralized, with agents behaving autonomously or semiautonomously. Multi-agent systems have been proposed as the foundation of intelligence, perhaps most famously by Marvin Minsky in *Society of Mind* (1988). More commonly, multi-agent systems are used as models of collections of individuals, as in a society (Wooldridge 2009), producing predictions and explanations of phenomena ranging from traffic patterns to the spread of specific ideas through a human society. This view of computation, in contrast to the procedural model, is more easily integrated with our view of society, and further is more consistent with the visions outlined by Bush, Licklider, and to some extent Engelbart.

With this background in mind, we turn to general questions about the relationship between information technology and society.

What Can and Should Be Decided?

We begin with an exploration of what should be decided by a society. For example, in an address to prominent computer scientists in the early 1960s, C. P. Snow identified a few of what he considered the most pressing problems of his time: they included the threat of global nuclear war, poverty, and wealth disparity across the world (Greenberger 1962; Snow 1959).

A different approach would be to ask individuals in a society about what they considered important. The company Gallup runs a regular survey of Americans in which respondents answer an open-ended question: “What do you think is the most important problem facing our country today?” In 2014, the most common economic problems mentioned dealt with the economy in general and with unemployment. The most common noneconomic problems mentioned were dissatisfaction with government, immigration, and healthcare. The set of important problems for any given society will not necessarily remain constant, but we may find similarities over time.

One of the reasons for considering computational models of individuals and societies is to establish a common ground for thinking about the relationship between computers and society. Can computers help us solve the problems identified above? Some of them can be cast as problems of resource allocation. As a simple example in healthcare, consider scheduling patients for multiple procedures in a hospital, in which each procedure requires different sets of personnel and equipment. Ideally, it would be valuable to have an optimal schedule that minimizes time and use of resources. Such problems are typically intractable, however. That is, it is not known whether efficient algorithms exist to solve any given instance of such a problem. Further, we have chosen a single, isolated example of a problem; we must imagine that scaling up to the entire healthcare system of a country, or expanding to consider resource allocation in other parts of the economy, would encounter any number of similarly hard problems.

Tractability may not be the most significant challenge, however; we might find that approximate rather than optimal solutions will serve. Other challenges remain in judging whether important problems can be solved. One of the most persistent is the issue of turning complex real-world problems into those amenable to computational solutions. For example, Engelbart's vision of diplomats relying on information technology to help solve problems is still perhaps in the distant future. Snow's problem of poverty is similarly difficult: it is straightforward to imagine a scheme by which wealth could be redistributed, in the abstract, to alleviate poverty, but any practical plan must take into account personal, political, and philosophical differences concerning specific methods and even the motivation for those methods. These factors are very hard to formalize, given the current state of the art in all the relevant fields.

Perhaps the challenges of tractability and problem formalization can be overcome. We will still face a third critical issue of how well our computational representations match the real world. A problem, as represented internal to a digital computer, is an abstraction that we typically intend to capture the relevant properties of some real-world problem counterpart. Problems important to society tend to be difficult to break apart into relevant and irrelevant factors. Further, as George Box (Box and Draper 1987) famously wrote, "All models are wrong. Some models are useful." The structure of a model is important beyond its representation of relevant factors. We can imagine a perfectly predictive model of some social phenomenon in which those factors that are considered causal (e.g., in a statistical sense) are not open to manipulation.

These areas are all under active research today, in computer science, psychology, sociology, economics, political science, and related fields. With progress, we may gain new insight into how to solve important social problems.

Who Decides?

While in the past, worries about the impact of computers on society could be left largely to the computer scientists, these days, thanks to the power and ubiquity of computational devices, their use is of concern to everyone, ranging from individual day-to-day activities to matters of global policy. And (whether they voice it or not) practically everyone in an industrialized society will have their own opinions.

For younger people, social media and the Internet may simply be facts of life. The more cynical among us may question the inclusion of YouTube clips and 3D imagery in our news broadcasts. A politician up for election and caught in an embarrassing video gone viral or desperately trying to retract an ill-advised statement will no doubt have a very different opinion of the Internet than will the candidate from the opposing party. In more authoritarian countries, leaders go so far as to attempt to censor the Internet.

In a broad sense, computers can be viewed as decision-making aids. While completely autonomous systems have been the dream of artificial intelligence for decades, in practice, computer systems require the formulation by human beings of specific problems to solve. If we assume that members of a society must be well-informed enough to participate in the decision-making activities and the resulting benefits of information technology, then what do they need to know? If this question can be answered, then how can people learn what is needed to turn their views into actions?

Snow described the way that good social decisions are made as a kind of Brownian motion, in which vortices form to produce pressure in some area, leading to social or political change (Greenberger 1962). In his view, however, the use of information technology has a potential danger in restricting important decisions to be made and implemented only to those with the knowledge to understand how computers work. One obvious remedy is to make such knowledge more broadly available, and we find several relevant trends in society today.

One such trend is in computer science education, with recognition of the importance of computational thinking. The term was first used by Seymour Papert in the context of mathematics education, as a way to forge ideas that were as "explicative" as Euclidean constructions in geometry but more accessible and more powerful (Papert 1996). Jeannette Wing later popularized computational thinking (Wing 2006), taking it to be "a universally applicable attitude and skill set" developed within computer science but relevant to a wide range of problems outside the field.

As an example of computational thinking, we turn to Alan Turing (1950):

> This special property of digital computers, that they can mimic any discrete state machine, is described by saying that they are universal machines. [C]onsiderations of speed apart, it is unnecessary to design various new machines to do various computing processes. [A]ll digital computers are in a sense equivalent.

With most machines and devices, we naturally think that we should choose the best tool for the job. If that job is an information processing task, however, any computer is sufficient (in practice, any sufficiently powerful, general-purpose computer) because they are all equivalent. Recognizing the flexibility and universality of computers is core to computational thinking.

Another important aspect of computational thinking is the ability to map real-world problems to computational problems – which requires understanding of a range of models of computation, such as the examples of the procedural model and distributed processing models of the previous section, as well as how information can be structured and how algorithms can operate on those structures.

A significant goal of computational thinking is to enable non-computer scientists to recognize situations in which computing concepts are relevant and to apply well-tested techniques effectively. Computational thinking is at the core of new curricula emerging at the university, high school, and even primary school levels in the United States and elsewhere. Computational thinking conveys not only programming skills but an understanding of what computers are capable of in principle as well as in practice. For example, understanding the concept of indirection means realizing how easy it is to include a link to a malicious Web site in an email message, with no obvious visible indication. Understanding the concept of search leads to the recognition that any Web search engine must apply biases (known and unknown, desirable or undesirable) to filter millions of potential hits down to a few relevant dozen.

With a firm grasp of computational thinking, individuals in a society are better equipped to understand when and how information technology might produce change for better or worse.

Another educational trend that has emerged in recent years is massive online open courses or MOOCs. A MOOC typically includes videos, exercises, textbooks, discussion forums, homework assignments, and exams, all available online to students participating in the course. The largest MOOCs have attracted hundreds of thousands of students from countries across the world. The concept is naturally appealing: a low-cost or even free education for almost anyone with an Internet connection, provided by some of the most knowledgeable educators working today. Perhaps inevitably, a significant proportion of MOOCs are in the areas of science, technology, engineering, and mathematics (STEM), in particular computer science.

MOOCs have been proposed by some as a replacement for conventional teaching environments, and it is natural to see them as a potential democratizing force in education. A number of questions remain open concerning MOOCs, however, including their effectiveness compared with conventional classrooms, the difficulty of developing appropriate pedagogical techniques, and their use by a broad cross section of society. The promise remains to be fulfilled.

Yet another visible trend is broad participation in online communities and activities supported by modern information technology. Facebook alone is visited by over a billion users every month (a large majority from mobile devices). Amazon's Mechanical Turk brings work to hundreds of thousands of people, typically very brief tasks that currently require human intelligence. Use of crowdsourcing by researchers in computer science, especially in human-computer interaction and social computing, is growing commonplace. More significantly, Bush's view of a modern society with flexible access to information has expanded; in modern terms, we all have the potential to generate as well as consume content. Participation goes beyond social computing and business applications as well. The idea of "citizen scientists" has reemerged (Silvertown 2009): amateurs who collect field data or help process results to generate, as a group, scientific findings.

The question of who decides in today's society has a much clearer answer than what should be decided: it appears that we are moving in the direction of everyone having the potential opportunity to make decisions with and about information technology.

Who Benefits?

The question of who benefits from information technology in society has come under increasing scrutiny in recent years. Information retrieval and document generation systems have made inroads on jobs formerly held by people working in law, journalism, medical informatics, and even education. In past centuries, workers replaced by automation might have retrained to become operators; today there may be no obvious new positions for displaced knowledge workers. Further, the benefits of such automation may not be uniformly distributed across society but may instead go mainly to the individuals and corporations that own and control the technology.

If we accept that good social decisions are made in some distributed fashion, with a broad base in society, then these trends suggest movement in the right direction. A closely related question is who will benefit from this movement. To the extent that information technology improves the lives of individuals, benefits will diffuse through all of society.

A more difficult issue is the control and ownership of software. The open source software (OSS) movement is another promising trend. OSS is released under a license that denies exclusivity in its use (St. Laurent 2008); someone who obtains an OSS program, free of charge, can read its source code, modify it, use it in another program, and redistribute it under the same conditions. As estimated by lower revenues from proprietary software sales, OSS saves software users billions of dollars each year.

A countervailing movement can be seen in patent law. Cohen and Lemley (2001) give a useful overview of the history of software patents. In the early 1970s, algorithms (like mathematical formulas) were determined not to be patentable, but by the early 1980s patents on programs for applications running on specialized machines were admitted. In 1994 the In re Alappat decision determined that "a general purpose computer in effect becomes a special purpose computer once it is programmed to perform particular functions pursuant to instructions from program software;" this directly reflects Turing's observation. The finding led to the view that programs could be patented.

An explosion of software patent applications followed. Unfortunately, through the 1980s and early 1990s, software patent applications were reviewed "largely by people operating outside their area of expertise" (Cohen and Lemley 2001), granting patents that were sometimes overly broad, sometimes based on obvious previous art, and sometimes simply counterintuitive to professionals in information technology. The result is a complex system in which it is often unclear whether the economic benefits of patents go to appropriate parties and whether innovation is sufficiently supported.

How these issues will be resolved remains unclear, though it is of growing interest among those knowledgeable about information technology.

Conclusion

The historical visions of Bush, Engelbart, and Licklider have to a large extent been met with today's information technology. We have fast and relatively easy access to unprecedented amounts of information; we use information technology not only to inform our decisions but in many cases to make a decision on our behalf; a large proportion of society extends beyond the everyday physical world into cyberspace. Advances in information technology have opened up new variations as well on the themes these visions identify.

We have focused on three questions we consider important in understanding how information technology can influence society: What can and should be decided? Who decides? Who benefits? We believe that thinking about these questions explicitly, in combination, is worthwhile in that it may help us to find new opportunities to improve some parts of our society as well as to prepare ourselves for risks.

The examples that run through this chapter suggest that in some ways we are coming to a converging view of the relationship between information technology and society. Information technology can have a democratizing effect, by bringing information and knowledge relatively inexpensively to very wide audiences; it also makes it possible, at least in principle, for the voices of individuals to be heard more easily. People are becoming more familiar, generation by generation, with information technology, and gradually people are learning about its more theoretical underpinnings, enabling them to make better decisions. Which important problems can and should be solved remains a hard open question.

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Convergence with the Arts

Andy Miah

Contents

Abstract

This chapter examines convergence in science and arts by considering two complementary trajectories over the last 25 years. First, it examines the institutional drivers behind convergence, from the perspective of governance and public value within science. Second, it explores convergence around the methodological practices of artists, which speaks to the complex political economy of knowledge generation, symbolic significance, and biomediated resistance. Finally, it considers the impact of convergence on the future of each area and what might be the opportunities and risks of further convergence.

Introduction

> Artists such as Picasso and Kandinsky took on board the latest scientific developments, while scientists found themselves driven by questions like the relevance of aesthetics to science and what makes a scientific theory beautiful. (Miller 2014, xx–xxi)

A. Miah (✉)
Chair in Science Communication and Future Media, School of Environment and Life Sciences, University of Salford, Manchester, UK
e-mail: @andymiah.net

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Convergence in arts and science can be traced back for centuries, from Leonardo da Vinci's observations of human physiology in the sixteenth century to the development of photographic practice in the nineteenth century. In each case, progress in arts must be understood as having always existed within a wider knowledge economy, in which insights from all kinds of scientific and technological disciplines have shaped the creative practice of artists. This is especially true when looking closely at artists who have experimented with new media (see Reichle 2009). In this respect, more recent discussions about convergence in science and arts would be remiss if they ignored this important historical connection between these fields of inquiry, which, in the past, have enjoyed a closer relationship than may be said of them since the Enlightenment period.

Nevertheless, a contemporary theorization of the trajectories of arts and science may be offered additional to this historical interpretation, which provides insight into a new chapter in this history. As such, this chapter focuses on what has happened over the last 25 years, during which the epistemological boundaries of science and arts have been redrawn again, as a result of two principal trajectories. It examines the UK case in detail, where a series of key indicators of such change within science are apparent and where there is evidence of how this has aligned with the trajectory of new media artists – specifically, bioartists – in their pursuit of working with the materials of scientific inquiry, most notably biological matter itself.

For the sciences, their attention to the arts in recent times can be traced to the rise of public engagement with science and the broader interest in science communication from the science industries. New imperatives to make science more available to the public who are funding research have led to developments in how science is supported, what is expected of scientists as performers of scientific investigation, and what format the means of communication takes. A crucial component of this trajectory has been the rise of modern science festivals, the first of which was born in Edinburgh in 1989 – an event that emerged out of the wider cultural shift toward an event economy. Since Edinburgh's first festival, science festivals have emerged all over the world, and the number of these programs expands even further when including events that do not formally identify themselves as science festivals, such as the recent Pioneers Festival, countless TEDx events, or even science stand-up comedy nights. Beyond the live format, the growth in mediated science communication work is indicative of the ecology of science becoming more integrated within creative practices.

Three years after Edinburgh's first science festival, in 1992, the scholarly journal, *Public Understanding of Science*, published its first issue, which reinforced the importance of the science industries' interest to consider more strategically how it connects with the general public. The journal's launch also made an important contribution to how the academy was starting to theorize public engagement with science, considering different methodological approaches to such work and generating a new cohort of scientists whose research also involved developing sophisticated evaluative tools to assess the impact of their engagement with various publics. Where previously, public engagement may have been seen as a good in itself, worthy of celebration wherever it happens, but of little import to the core drivers of scientific discovery, it was quickly becoming a form of expertise in its own right, subject to critical evaluations, along with developing a desire to advance pedagogically.

From the arts, there has also been a shift in the range of methodological approaches to creating new artistic work, which is more integrated with the science industries. While artists have always drawn on scientific ideas and principles – even using biological matter within their work – a wave of new media artists has emerged recently, who are utilizing the biological sciences to realize work, and this has led to the establishment of the new disciplines of bioart and biodesign. Bioart is redefining how arts is made, where it is made, the range of people involved, and the meaning and value it has within society. In some cases, such creative works offer a commentary on the controversies surrounding late twentieth-century biotechnology, the transgressions associated with genetic modification, and the uncertainty around nanotechnology. Alternatively, bioart may be seen as a critique of how the world orientates itself away from nature in its pursuit of technology and of its inability to resolve the crucial ethical issues that underpin scientific trajectories, but which continue apace, irrespective of public consultation. Alternatively, bioart work seeks to explore the creative potential of new matter – especially matter that is generated through novel scientific practices, which synthesize, adapt, and even create new life-forms – and aspires to break new boundaries of aesthetic potential and new ways of seeing the world.

This chapter articulates these two principal trajectories in full, noting their intersections with wider convergence within the knowledge economy. First, it examines the institutional drivers behind convergence, from the perspective of governance and public value within science. Second, it explores convergence around the methodological practices of artists, which speaks to the complex political economy of knowledge generation, symbolic significance, and biomediated resistance. Finally, it considers the impact of convergence on the future of each area and what might be the opportunities and risks of further convergence.

Converging Institutions

While it is tempting to focus on the methods of different endeavors, when seeking to identify points of convergence, institutional change is an important dimension of documenting convergence across sectors. Indeed, there are specific indicators of convergent practice in how science and arts are produced, which speak to the underpinning shift in each of the practice communities toward each other. One key aspect of this from the scientific disciplines is the rise of public engagement work. Over the last 25 years, one can identify changes to science funding and science policy that have been a catalyst for the production of new science activities, the purpose of which has been to engage a wider public on what science does or can do. The ideological vision behind such funding may be interpreted in at least two key ways.

From one perspective, public engagement funding seeks to bring new scientific discoveries and applications to the attention of a broader public, allowing more people to learn about science, perhaps become interested in it, or even to feel that they have a role to play in shaping its future. From another perspective, science communication work aims to fulfill a democratic obligation, which is predicated on the fact that science is often publicly funded and so should be made available to the public during its development. Each of these *instrumental* interpretations of public engagement with science coheres with the mission of science funders, which are broadly predisposed to promoting the value of science to the public. However, they do not sit neatly with critics – or artists – who want more from public engagement with science, and the emergence of such views is best articulated by examining briefly the three models of public engagement, which have come to define scholarship in this area.

Initially, critics identified the pursuit of educating the public as having the unfortunate consequence of reinforcing a power relationship between the scientific experts and the uneducated public, which rejected the intelligence of the general public and treated them as needing education. On this *deficit* model, the role of public engagement with science is to enlighten the public, with a view to helping them see its value, and to generate further support for its development. Early public engagement scholars criticized this model, arguing instead for a *dialogical* approach to such work, which instead sought to empower audiences so they may contribute to discussions about current issues in science. Yet, even this model was interrogated by theorists, who pointed out that dialogue does not ensure a bidirectional flow of power, nor an ability to assume decision-making responsibilities around science funding decisions, which is the crucial limiting factor in what the public can do to shape its scientific future. In response, critics have argued for an *upstream* approach, whereby dialogue happens before funding priorities have been made by the science industries. The upstream model aims to deliver a more effective democratization of science funding decisions, without undermining the integrity of making decisions about science. In each case, the public engagement model remains an instrumental model; it seeks to create more effectively engaged decisions about the direction of science.

In the UK, various organizations have developed programs of work to advance these models. Notably, the Wellcome Trust, the National Endowment for Science and Technology in the Arts (NESTA, established 1998), and a number of national research councils each have assumed the responsibility to deliver more public engagement opportunities with science. The Wellcome Trust alone provides £10 m for public engagement work annually, supporting a range of activities from film making to digital games creation, and receives applications from broadcasters and arts organizations, along with universities. The public engagement with *research* strategy of Research Councils UK outlines the impetus behind such funded work:

> Relevance, trust, accountability and transparency are the cornerstones of the relationship between research and society. It is vital that the public have both access to the knowledge research generates and the opportunity to influence the questions that research is seeking to address. In enriching citizenship and providing wider perspectives on research, public

> engagement improves the quality of research. It inspires people of all ages, firing the imaginations of our future researchers and feeding the skills and knowledge that are essential to the UK's economy. (RCUK, no date given)

The scope of public engagement work has also expanded beyond the conventional STEM subjects, with social science funders like the Economic and Social Research Council (ESRC) creating a UK-wide Festival of Social Science or any number of AHRC projects, such as digitizing ancient texts and making them publicly available. One key indicator of this general trend to professionalizing public engagement with science is the rise of science festivals, the growth of which may indicate the expansion of public engagement with science and the wider institutional underpinning of funding creative, artistic work around science. Indeed, the rise of science festivals may speak to the maturity of public engagement as an investigative discipline. Taking a sample of science festivals around the world reveals the institutional underpinning of such activity. For example, India's QUARK festival – a university-led festival – receives patronage from UNESCO and the South Asia Youth Environment Network, a UNEP organization. Alternatively, the UK Manchester Science Festival operates under the direction of the Museum of Science and Industry, a common context of a number of other museum-led festivals, particularly in the UK. Also, the Cheltenham Science Festival in the UK has *The Times* newspaper as a headline partner and functions as a platform for new publishers to show their authors and promote new work.

Within the UK, these new resources to support creatively engaged public programs were reinforced by the reformation of the government's research assessment exercise in 2014 – called the Research Excellence Framework. For the first time, this evaluation attributed a percentage of the funding allocation awarded to university researchers on the basis of their impact outside of academia. Where previously academic research was assessed solely on the basis of research, the addition of 20 % dedicated to research impact has been a game-changing shift in UK research culture, providing a quantitative measure by which scientists may contribute time to such work.

These trajectories show how science is getting closer to the realm of creative and artistic practice through the institutional support for funding programs around public engagement with research. Many of the ways in which scientists have articulated their value outside of academia within the REF have been through their impact in the creative sector – either in arts collaborations or media presence. It also reveals how science has become much more aligned with the event economy, the idea that singular events can function as catalysts for political, economic, and cultural investment, typified by such mega events as the Olympic Games or even simply anniversaries. Today, science makers are much more aligned with the importance of staging science, and the production expertise that surrounds such work lends itself neatly to the kinds of skills that also operate around creativity and art. To this end, the next section looks at convergence from the perspective of the arts, to reveal how methodological changes in how artists work are bringing them closer to scientific disciplines.

Converging Methodologies

The complement to institutional change in the sciences is located in the practice of artists who operate at the cutting edge of new media and whose work Miller describes as indicative of a "brand-new art movement" (p. 341). One of the earliest pioneers in bioart practice is the Australian performance artist Stelarc, whose work has consistently inquired into the limits of our corporeality and the trajectory it has taken in a world that is increasingly digitalized and modified by biotechnological conditions. The importance of performance within this historical trajectory is worth foregrounding, especially as performance is also a common thread within the other direction within this analysis – science being performed to a public. As Hauser (2008) notes "Bioart. . .is also attracting the interest of performance artists and those specializing in body art; structural relationships connect the two fields" (p. 90). For example, the French performance artist Orlan undergoes cosmetic surgery to alter her appearance in a way that challenges the commercial industry of body modification. In creating nonstandard modifications to her body, she invites onlookers to consider how else we might imagine our bodies to look, outside of standard notions of beauty that are typical of the fashion industry. Alternatively, John O'Shea's work on *Pig's Bladder Football* envisages the possibility of creating sustainable leisure technology by cultivating football bladders made from his own cell tissues, so as to combat the reliance on synthetic materials.

In contrast, Gina Czarnecki's *Palaces* project considers the wasted biological materials that people discard over the course of their lives, but which may be useful to people for research, repair, or exhibition. In this case, milk teeth donated by children – including teeth from her children – are used to construct a "tooth fairy palace." *Palaces* reveals how bioart need not involve utilizing body modification or technology at all, but simply utilizing biological matter that naturally separates from us. Indeed, Stelarc's early works involved inserting body hooks into his person and suspending himself off the ground. In these cases, one may advance the idea that such work explores principles that have currency in the field of physics, perhaps also the science of pain, but, like Czarnecki's work, biology is not tampered with through scientific manipulation. Nevertheless, such work contrasts with – or may be a precursor to – Stelarc's more recent *Extra Ear* (2008) project, which involves using stem cell technology to create an artificial ear on his arm created from his own tissue. The career of such artists as Stelarc may also be seen has having defined the field of bioart. Thus, while his earlier works may not be seen in this way, they may be explained as steps toward defining a now reasonably clear set of practices that bioartists undertake in their work.

Involving the artist's body or biology within bioart practice seems an obvious new chapter in the history of art. It resonates with the aspiration to locate oneself within the artistic work one produces, enabling the realization of such desires on the most intimate level, as might be said of Stelarc's (1997) stomach sculpture, for instance. It also aligns with a similar trajectory within scientific practice, as the practice of the world's first other cyborg Kevin Warwick may indicate. Warwick's insertion of a microchip under his arm, which has some functional capability, may, on first glance, seem no different from Stelarc's *Extra Ear* project, save for the fact that he may call his work science and Stelarc may call it art. Indeed, the banality of this difference is also well articulated by Eduardo Kac's GFP Bunny, which involved an albino rabbit born via transgenic expression that created a fluorescent quality to its skin. When placed under fluorescent light, the rabbit would glow in the dark. In this example, it is the specific biotechnological practice of transgenesis that defines the work, rather than any broader categorization as bioart. Yet, in this case, the role of the artist in the creation of the work is even more contested, as it appears that Kac had very little input in the creation of the rabbit, which existed as part of a scientific trial. On one level, Kac's contribution was to label the transgenic life form as art, since it was never brought out of the laboratory into a gallery nor brought into existence through any artistic or creative means. Indeed, the genetic scientist behind the project indicates that Alba – the bunny's name – was already in existence and so was not created for Kac's project (Philipkowski 2012).

The act of labeling something as arts may alone be a sufficient act to make it so; one thinks also of Rene Magritte's *Treachery of Images* as a corollary here, instead claiming the life of the rabbit as arts rather than merely accepting its value as a scientific research specimen. In this case, what is intellectually appealing about GFP Bunny is the fact that there was no scope for the artist to have the means that would allow any such artwork to be created. The act of labeling Alba as arts is the most provocative creative assertion available to the artist. In this respect, Kac's intervention may be seen as politically underpinned, as it calls into question the boundaries between science and the wider world, seeking to reveal practice that is common in science, without much awareness from the public. In this sense, GFP Bunny may also be articulated as a medium of public understanding, albeit complicated – and made richer intellectually perhaps – by the fact that a "subject" rather than an "object" is the focus of discussion, as Kac notes (cited in Osthoff 2008).

The utilization of nonhuman species in bioart performance is also a common thread within such practice, and, here, such work invites us to consider how animals are utilized in society and to what reasonable ends they might be put. For instance, in Kira O'Reilly's *Falling Asleep with a Pig* (2009), her performance involves sharing a space with a sheep for some days – spending every minute of the day side by side in a gallery – literally a "companion species" (Haraway 2003). Her work provokes onlookers to consider their relationship to nonhumans and animals, a theme that resonates with a number of controversial scientific possibilities – such as the utilization of pig organs for human transplantation. O'Reilly's performance asks onlookers to consider how they relate to and care for nonhuman species, reminding urban dwellers of the intimacy between shepherds and their flocks that continues to exist, along with foregrounding life within more rural environments. Other artists, such as Catts and Zurr, have scrutinized the need for humanity to farm animals, at a time when environmental activists point out the vast amount of energy needed to sustain one animal life and the harmful gases generated by such life-forms. As an alternative, they have developed *victimless meat* (Catts and Zurr 2008), a new kind of food grown from cell cultures, which has the neat consequence of also attending to animal rights concerns, since there is no sentient life to speak of that is harmed by the consumption of such products.

One other defining aspect of such bioart work is its reliance on other professions to realize the work. In this sense, bioart may be understood as a set of collaborative, hybrid creative practices that disrupt conventional biological boundaries, either through the manipulation of biological matter through scientific or technological means or through situating life outside of its conventional milieu, with a view to enabling some form of aesthetic transaction between the creator and the audience. The term transaction here is admittedly fuzzy but would principally involve work that invites interpretations that have to do with questioning biological boundaries.

In short, the term bioart may be utilized to distinguish any artistic practice that involves the *resituating of biological matter* to create works that are principally forms of artistic practice. While one may argue that many forms of human-centered artwork involve a biological transaction of some kind, or a resituating of biology so as to provoke thoughts about biological transgressions, for present purposes, bioart involves either the physical alteration of biological matter or situating an artist's physical presence within the artwork so as to engage such ideas.

Bioart has been theorized from a number of different perspectives, and scholars have varying interpretations of its significance and role. In some cases, bioart work is preoccupied with imagining a future where the category of the human species ceases to exist – once humanity has transcended its species-typical functions, either through becoming enhanced or by developing new capacities. However, not all work is like this, and some extends from the sci-art discipline of making work inspired, informed, or constituted by some scientific means. As noted earlier in the Wellcome Trust evaluation, bioart – including that which is funded by science – can have subversive capacities, raising questions about the trajectory of science. For example, Dunne and Raby's (2009) *Foragers* imagines how humans may redesign themselves biologically to "maximise the nutritional value of the urban environment," in a world of nearly no resources and an inability for governments to resolve. Alternatively, Michael Burton's (2007) *biophilia* clinic builds on scientist Edward Wilson (1984) and James Lovelock (1989) to consider what kind of attachment people may have to the experience of illness, in a world where all disease has been eradicated. Burton imagines that people would check in to such clinics, just to undergo an experience where they are made more fragile and need to experience the otherwise absent forms of suffering that would describe the future of humanity. In each of these cases, one might conclude that scientific progress is something of an oxymoron, as science pushes us in directions for which we are not prepared or have yet to realize their implications for how people conduct their lives. Indeed, the inadequacy of social, ethical, or political systems to accommodate change brought about by scientific innovation is an enduring thread in bioart practice.

There is also a broader political interpretation to bioart practice, which speaks to its capacity to force society to reconsider what is required of humanity to generate original insights. Artist collectives, such as SymbioticA (Australia), The Arts

Catalyst (UK), and Dunne & Raby, enact a form of biopolitics that is focused on creating collaborative relationships between scientists and artists/designers. An integral part of this praxis has been the infiltration of scientific laboratories by artists, in pursuit of creative expression and the development of new knowledge about the boundaries of biology. Yet, it is not just natural or physical scientists whose work may engage with bioartists. For instance, the work of designers Dunne & Raby undertakes a sociological survey of the future, by working with groups to imagine what kinds of decisions they would make about their lives if certain technological opportunities were available to them. This is true of their *Evidence Dolls*, which involved participants considering how genetic testing would influence their decisions over romantic relationships (Dunne et al. 2008). This work asked people to consider whether the ability to genetically test their potential partners for a range of characteristics would lead to its use as a condition for entering into a relationship.

By envisioning new forms of biological transformation and utilization, artists' ideas become constitutive of the landscape in which debates about biological change take place. However, by utilizing sociological methods, their work demystifies the idea that insights for artistic practice rely solely on individual creative vision. Admittedly, the example may reveal the difference between how artists and designers work, but the crucial point is that bioart often involves similar kinds of consultation and empirical inquiry to inform the work. Equally, a number of bioartists are active within the field of bioethics and regularly write for ethical periodicals. This includes Natasha Vita-More (2010) whose own theorizations on transhuman arts are inextricable from the ethical contexts where decisions about their legitimacy take place. Indeed, on Zwijnenberg (2009) notes that bioartists have "claimed a task for themselves that traditionally belonged to the humanities: ethical reflection on the boundaries of science and art and on other issues involving life and death" (p. xxi).

To this end, bioart, body art, and biodesign also scrutinize contemporary bioethical issues and scientific practice, such as the utilization of embryonic stem cells or the development of transgenic species. However, it is unclear whether all artists intend to resist such processes. Indeed, some are seeking their propagation in order to make their arts possible. For example, Stelarc's own body modifications convey the body's obsolescence in an era of synthetic biology and stem cell regeneration (Smith 2005). The use of stem cells within his *Extra Ear* project is still not the end stage of the work, which next aims to implant an auditory device within the ear and for it to be remotely connected to the Internet, so web browsers can hear what the ear hears, creating a distributed auditory system. If this were not enough evidence of how bioartists may sometimes celebrate the transformative aesthetic potential of biotechnology, then consider Julia Reodica's collection of synthetic hymens, which go beyond genital piercing and tattoo, but which resonates with these similar tribal motifs. This work invites us to consider the role of virginity and its loss in the twenty-first century, a theme that may be interpreted as intimately connected to the biotechnological era, as the contraceptive pill is one of the most transformative technologies of the late twentieth century.

The work of bioartists may be seen as an attempt to disrupt the knowledge economy, as many such artists are not interested simply in their creative means drawing on the work of scientists or revealing its beautiful complexity. Rather, the expectation is that the artist will become co-creator of original knowledge, a genuine research partner in the design and undertaking of scientific studies, to such a degree that some intellectual property over new discoveries or insights may be attributed also to the artist. In this sense, the gradual occupation of artists in labs raises important questions about how society is organized and understands our own humanity. For instance, why do societies privilege scientific knowledge over, say, aesthetic, as is evidenced by the way in which funding is skewed in favor of the former? Would humanity have been better off over the last 100 years or so if it had dedicated more of its resources to the so-called softer sciences, arts and humanities? Would societies have asked different questions or sought different solutions to difficult problems? Admittedly, societies might have produced fewer technologies that would save lives and perhaps would have failed to reduce suffering as effectively as they have through medicine, but then with fewer people on the planet, it might have been more effective at distributing goods more evenly. These are impossibly speculative questions but which nevertheless expose the claim that hierarchies of knowledge systems affect the overall wealth in the world and that the scientific method need not have produced the least amount of suffering in the world.

By implication, one may argue that these collaborative bioart works should also be credited to the scientists involved and, indeed, they often are. While this may beg the question over ownership and the right to commercialize the work or benefit from its syndication in exhibitions or private sale, like all collaborative works, decisions about this are for the artist and scientist to negotiate in advance of and during the collaboration process. There are no fixed rules about who ought to be principal author, but equally it is often true that the scientist's terrain and the artists are distinct enough for all to benefit. Indeed, in the same way that an artist is unlikely to be in a position to capitalize on the scientific work, the same is true of the scientist in relation to the artistic presentation.

Conclusion

As the two trajectories of science and arts have shifted over the years, various tensions have emerged. Involving artists within science communication activity does not always sit neatly with the aspirations of scientific institutions. After all, the US Science Festival Alliance – which sits within MIT Museum – notes on their website that "Science festivals are community based celebrations of the fascinating world of science and technology," and yet not all artists who engage with science support this mission. Similarly, the Wellcome Trust's 10-year evaluation of its funding on sci-art projects notes that its mission was to:

- Stimulate interest and excitement in biomedical science among adults
- Foster interdisciplinary and collaborative creative practice in the arts and science
- Create a critical mass of artists looking at biomedical science and build capacity in this field.

(Glinkwoski and Bamford 2009)

Each of these is sensible aspirations for a science funder, but why should public engagement with science work just be celebratory or aim to inspire, create wonder, and develop interest? What if the science industries, in their unwavering support of science, fail to consider broader societal implications to such work that would lead to circumstances that are less favorable to human flourishing? Arguably, a more compelling mission for science communication is around developing a critical and interrogative public, capable of scrutinizing the, now, advanced capacities of scientific organizations to manage media impressions and control the narrative of public understanding. Indeed, the contribution of artists working within science is apparent in an independent evaluation of Wellcome's sci-art work, which found that

> Artists working on Sciart projects were felt to have acted as a proxy for the public, opening up scientific practices to a wider gaze. By bringing into the public domain new perspectives on the work that was being conducted in laboratories and other places of science, it was suggested that artists were, in effect, acting as the 'public's representative'. A significant aspect of the artists' contribution to 'public engagement with science' was thus as independent scrutinisers – asking questions and provoking insights that might not otherwise be possible, either from the perspective of the general public or from within the scientific community itself. (Glinkowski and Bamford, p. 9)

Early work in bioart has demonstrated the capacity of such interventions, and, in a world where institutionalized media distribution is inherently constrained due to professional codes of ethics and financial interests surrounding such institutions, it may only be artistic works that are in the business of providing these critical platforms. This may explain why some festival directors are gravitating increasing toward artistic works within their program, in part because there is a degree of disenchantment with the scientific mission to use the public realm as a space for championing rather than interrogating science.

This chapter has shown how science institutions are migrating work into the public realm and how artistic practices are moving into laboratories. There is a danger that the two will completely miss each other on the way, where, instead, there is a need for friction and tension to develop more democratically engaged, politically aware, and inclusion participation within both the practices of arts and science. While it is typically artists who seek to make science available to the public through their work, there is also a need for scientists to consider the range of ways in which their practices are creatively informed, so as to challenge conventional epistemological assumptions about what knowledge, discovery, and insight entail.

The common creative process of arts and science provides far more scope for convergence than is typically offered by the manner in which contemporary educational institutions separate them. The wider rethinking of the relationships between these two knowledge systems that I have offered is crucial to embrace, to ensure that work interested in the public understanding of science reaches its potential. To return where we started, there is a need to revisit the history of arts and science and come to terms with the common ground between these different pursuits. As Miller (2014) notes, back in the sixteenth century when Leonardo da Vinci undertook his great works, back then, he "was both artist and scientist, because in his day there was no distinction" (p. 342). This seems ever true again in our brave new world of bioart.

Kuhn's (1969) conviction that, unlike art, science does not seek an audience speaks to a different era where science and arts were more separate or less aware of each other's relevance to advancement in either. It also seems neglectful of the political economy in which science is situated where the audience – far more than just a peer group – must interrogate, scrutinize, question, and support science to legitimize its worth and confirm its importance. This may be a different kind of audience, but I suspect it is no less vulnerable to the possibility of being wondered in a way that today's audiences in science festivals are. Minimally, if one accepts that the progress of science has worth only in the context of human society, then locating science in the public domain, developing thoughtful and strategic approaches to science communication, and ensuring work is done to bring scientists and artists closer together should be treated as an ethical obligation of the arts and science industries. Moreover, one might further assert a moral obligation of society at large to ensure that our pursuit of knowledge and understanding of our world utilizes the most effective tools through which to optimize such opportunities to make sense of science.

Yet, Kuhn makes a crucial point that should guide future work in public engagement with science, which gets to the heart of the present limitations in such work. He notes that "mediating institutions like the museum have no function in the professional life of scientists." It is possible that science festivals and the restructuring of scientific research evaluations, like the UK Research Excellence Framework, which foregrounds the importance of impact beyond academia, have begun to fill this void. However, a lot more work is needed to ensure that this upper limit on the investment a scientist makes on communicating and engaging with the public is not static.

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Co-Robots: Humans and Robots Operating as Partners

The Confluence of Engineering-Based Robotics and Human-Centered Application Domains

Brian Scassellati and Katherine M. Tsui

Contents

Abstract

A new era of robotics research is being driven by pressing societal problems and creating a transformation in the way that we envision human-robot interactions. In this chapter, we discuss three application domains that best capture both the promise and the challenges that this transformation has generated: the effort to build robots that support cognitive and social growth, robots that work in the home doing domestic tasks for users that have no training in robotics, and collaborative robots that work side-by-side to solve manufacturing and assembly tasks with human workers.

Introduction

Robotics is undergoing a transformation that is reshaping research priorities, opening new application domains, and creating possibilities that were unheard of only a decade ago. With its roots in industrial automation, most of robotics had been focused on creating machines that performed repetitious tasks with high precision

B. Scassellati (✉) • K.M. Tsui
Department of Computer Science, Yale University, New Haven, CT, USA
e-mail: brian.scassellati@yale.edu; katherine.tsui@yale.edu

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at superhuman speeds and with minimal downtime. The most salient advances were the result of intersections between mechanical engineering, electrical engineering, and computer science.

Just as personal computers ushered in a new era of computing by shifting attention from highly precise numerical calculations to computation that supported day-to-day activities, the availability (and the promise) of consumer robots has triggered a new convergence of applications, research, and collaborations. Research today centers around human-centered applications, most frequently in which robots are seen not as fulfilling a role independently but rather in cooperation with human partners (Fig. 1). These "co-robots" eschew some of the traditional engineering metrics that were the hallmarks of successful factory automation; instead of pursuing accuracy, reliability, speed, and complete autonomy, they instead are designed to be intuitive to use, to be safe operating in close proximity to people, and to operate semiautonomously in collaboration with a human partner. Advances continue to be driven by engineering-based confluences, but new intersections between robotics and the social sciences, healthcare, psychology, and neuroscience have begun to shape research priorities and application foci.

In this chapter, rather than attempt to provide a comprehensive description of the wide range of new research directions in robotics, we focus on three representative domains that show how the changing confluence of research around robotics is being oriented toward collaborative, user-driven applications. These domains are (1) *socially assistive robotics*, in which robots act as mentors or coaches to encourage long-term behavior change or maintenance, (2) *domestic service robots* that fulfill useful activities within the challenging uncontrolled home environment, and (3) *cooperative manufacturing* which abandons the closed assembly line of traditional factory automation in favor of shared workspaces with collaborative human partners.

Socially Assistive Robotics (SAR)

Perhaps, the most unusual development in robotics is the rapid growth of an application area that involves no physical contact with the user or direct manipulation of the environment. Socially assistive robotics (SAR) puts robots in the role of a therapist, mentor, coach, or guide and provides the user with social or cognitive, but not physical, support (Rabbitt et al. 2015; Scassellati et al. 2012; Tapus et al. 2007). SAR refers to a unique area of robotics that exists at the intersection of assistive robotics, which is focused on aiding human users through interactions with robots (e.g., mobility assistants, educational robots), and socially interactive or intelligent robotics, which is focused on socially engaging human users through interactions with robots (e.g., robotic toys, robotic games) (Feil-Seifer and Matarić 2005). Combining aspects of engineering, health sciences, psychology, social science, and cognitive science, SAR systems are being developed that help to reduce isolation in seniors (Rabbitt et al. 2015, pp. 11–12), support the learning of social behaviors for children with autism spectrum disorder

Fig. 1 Examples of co-robots from the domains of socially assistive robotics (*top*), domestic service (*middle*), and cooperative manufacturing (*bottom*); not shown to scale. (**a**) USC's Bandit provides several types of hands-off guidance, including physical exercise activities for seniors and stroke patients. (**b**) Intuitive Automata's Autom is a personal weight loss coach. (**c**) iRobot's Roomba is a commercially available robot vacuum; appliance robots designed solely for floor cleaning are the most successfully adopted home-use robot. (**d**) Willow Garage's PR2 is capable of various household chores, including folding laundry. (**e**) KIVA Systems' orange drive robots transport warehouse merchandise to inventory station, where human workers "pick" items for order fulfillment. (**f**) Rethink Robotics' Baxter unloads newly vacuum sealed packages from its station at a rotary table while adjacent human workers reload the molds

(Scassellati et al. 2012), and provide first graders with additional one-on-one educational opportunities at school (Short et al. 2014). Much of the drive to construct SAR systems comes from the growing needs of special needs populations, including those with physical, social, and/or cognitive impairments. These impairments can occur at any stage of life, be it developmental, early onset, or age-related. A rapidly aging population, explosive growth in diagnostic rates of developmental disorders, and growing economic inequalities have made personalized care unavailable to many people. The prospect of providing individualized support on demand and at scale to support long-term behavior change has driven these investigations.

While SAR systems do not physically interact with the world, they cannot be replaced with virtual agents; the robot's physical embodiment is at the heart of SAR's effectiveness, as it leverages the inherently human tendency to engage with lifelike (but not necessarily human-like or animal-like) social behavior. Foundational studies in this domain show that compared to virtual agents, physically present robots keep users enrolled in treatment programs for longer periods of time (Rabbitt et al. 2015, pp. 6–7), generate more compliance, cause users to engage in activities the robot suggests (Bainbridge et al. 2011), and even to learn more rapidly (Leyzberg et al. 2014).

An effective socially assistive robot must understand and interact with its environment, exhibit social behavior, focus its attention and communication on the user, sustain engagement with the user, and achieve specific assistive goals (Okamura et al. 2010). The robot must do all of this through social rather than physical interaction and in a way that is safe, ethical, and effective for the potentially vulnerable user. While many of these capabilities have been the focus of robotics research for decades, four topic areas are generally seen as critical to the future development of viable SAR deployments: (1) personalization and adaptation to individual social and cognitive differences, (2) managing autonomy over periods of months to years, (3) constructing models of the dynamics of social interaction, and (4) addressing the ethical issues that arise from automated socially supportive agents. We address each of these in turn.

One of the promises of SAR systems is to deliver enhanced learning and therapy outcomes as a result of personalized interactions tailored to each individual's unique social, cognitive, and physical abilities. Personalized lesson plans from both human tutors and automated tutoring systems have been shown to have a substantial impact on learning gains (Bloom 1984), and this same effect has been demonstrated with personalized robotic systems (Leyzberg et al. 2014). While existing studies in social robotics often focus on a single matching process by which the behavior of the robot is changed to optimize the properties of the interaction at a single moment in time, adaptation and personalization in assistive tasks should ideally treat the goal as an ever-changing target. Computationally, the challenge in constructing such a system stems from the individual differences among users, and that adaptation must occur at multiple levels of abstraction and time scales. At a given moment, robot responses that one user might find frustrating might be optimally engaging to another, or even to the same user under different conditions or at different times. Their responses should also change over time as the user becomes tired, frustrated, or bored. Responses must also vary from session to session or day to day so that interactions remain engaging and interesting. Research in this area focuses on questions such as:

How can we design a robot that adapts to each user's individual social, physical, and cognitive differences? How can a robot utilize patterns of interactions observed with other users (and possibly other robots) to bootstrap its own attempts at interaction?

Certainly, creating robots that can participate in the often complex and subtle aspects of human social interactions is a challenging task. Because of this complexity, many (but not all) SAR systems operate either partially or fully under human control, giving the human and robot roles similar to puppeteer and puppet, respectively. Of course, the long-term goal is to create SAR systems that operate autonomously and can be used without any type of human operator controlling the interaction. Furthermore, the level of autonomy required for SAR systems to succeed, allowing for autonomous operation over months or longer, is a more demanding requirement than those faced by other robotics applications that can rely upon occasional human intervention. The challenge is further complicated by the need for these systems to operate under the complex and unconstrained environments that humans occupy, including homes, schools, and hospitals. Questions that must be addressed in the near future include: Can a robot adapt to the unique demands of complex and dynamic human-centered environments so that it maintains the capability to make appropriate decisions without needing to have perfect perceptual understanding of its environment? Can a robot autonomously determine appropriate motivational and behavioral strategies to maintain a productive working relationship as the novelty of the interaction fades? How can a robot continue to adapt to and autonomously guide its user through successive milestones in order to achieve desired learning or behavior change outcomes over longitudinal time scales?

Assistive interactions are unique among social engagements as they must both support the needs of the engagement itself (by maintaining interest, novelty, and the conventions of social behavior) and guide the interaction toward the long-term behavioral or educational goals of the system. These two aspects can often be in conflict; at times, a good teacher (or coach or socially assistive robot) must sacrifice some of the enjoyment of the interaction, or bend a social rule, in order to promote an educational goal. Huang and Mutlu (2013) recently found some evidence that a robot could make some of these trade-offs by changing its nonverbal behavior, focusing either on improving task performance (recall in a storytelling task) or on improving social engagement by varying the type of gesture behavior used by the robot. Because the socially assistive robot must take an active part in shaping this interaction toward particular goals, the nature of the task and goal representations and the way in which this influence can be applied to shape the dynamics of the assistive interaction represents a core research question for SAR. Researchers address questions such as: What social behaviors and attributes are needed to establish and sustain trust, rapport, and comfort with the user over time to build a successful relationship that continues to provide value? Can we construct representations of interactions that capture not just moment-to-moment activity, but rather allow us to define long-term trends and preferences while maintaining sufficient detail to support rich, complex interactions?

Finally, as SAR systems use social pressure to encourage behavior change, these systems naturally raise safety and ethical considerations. Because these robots avoid physical manipulation and direct contact, the safety considerations differ from those in traditional robotics. Specific physical safety considerations need to be applied when dealing with children and other special needs populations, for example, to protect pinch points and secure small components. Care must also be taken in shaping the relationship between user and robot to ensure that appropriate consideration is paid to the emotional state of the user and the consequences of the robot's actions. Some more pragmatic ethical considerations take into account the inevitable progress of technology, which will render any particular system obsolete well within a user's lifetime, therefore undermining the user's attachment and likely making long-term system operation impossible. As one example of ethics applied to SAR in particular, Feil-Seifer and Matarić (2011) outline the ethical issues of SAR around the core principles of ethics applied to all human subjects research, namely, beneficence, non-maleficence, autonomy, and justice. The first two principles, beneficence and non-maleficence, encompass the SAR issues of relationships, authority and attachment, perception and personifications of the robot, and replacement of human care/changes to human-human interaction. The third principle, autonomy, spans the issues of privacy, choice, and intentional user deception. Finally, justice spans the complex issues of cost/benefit analysis, and locus of responsibility in the case of failure or harm.

Domestic Service Robots

With the advent of robots available as consumer electronic devices for purchase at reasonable prices by the public, domestic service robots have become a popular research area that has the potential for wide-scale economic impact. Domestic service robots are used as productivity tools for household tasks. They must perform their tasks well with minimal intervention and without any expectation of maintenance by a robot technician. The primary challenge for domestic service robots is the real world itself – the home environment does not resemble a well-controlled lab environment. Houses differ with respect to size, layout, and furnishings, and rooms can be cluttered and messy. The complexity of a home is a reflection of the collective needs and desires of each of its residents (Baillie and Benyon 2008). Both consumer electronics market trends and academic analyses of end user needs (see Sung et al. (2009)) point toward two emerging use cases: (1) a general-purpose, dexterous, humanoid robot that is capable of many household tasks (akin to *The Jetsons*' Rosie, the robot maid) and (2) appliance robots – capable of only specific low-level tasks.

Current commercially available domestic service robots are largely appliance robots, for example as catalogued in the 2015 edition of the online *Robot Buying Guide*. Floor cleaning robots have been the most successfully adopted home-use robot with over 110 current and discontinued models of robot vacuums, dry floor sweepers, and wet mops. iRobot leads the consumer electronics robot market and in

2002 introduced the Roomba robot vacuum cleaner (Fig. 1c), a low-profile circular robot with a rotating side brush to sweep dirt into its path and infrared sensing to prevent the robot from falling down stairs and avoid user-specified restricted areas. Over six million Roombas have been sold worldwide as of early 2013 according to *A Roadmap for U.S. Robotics: From Internet to Robotics* (2013 edition). Many Roomba owners and their families treat their robots as more than just appliances; 2 out of 3 Roomba owners named their robot, and 1 out of 3 have brought their Roomba to a friend's house. Researchers have shown that people treat their Roombas as social agents by ascribing gender and personality to it and by verbally greeting and praising it (Sung et al. 2008).

There are a growing number of appliance robots designed to autonomously clean or groom other household surfaces. Lawnmowers robots are the next in consumer popularity; the *Robot Buying Guide* (2015 edition) catalogues over 40 current and discontinuted models of robotic lawnmowers, including Husqvarna's Automower, Friendly Robotics' Robomow, John Deere's Tango, and Bosch's Indego. There are several companies producing pool cleaning robots, including Polaris, Solar Pool Technologies, and iRobot, who also makes the Looje gutter cleaner. Robots for window cleaning (e.g., Ecovacs Winbot, PIRO Windoro, Hobot 168) and air purification (e.g., Diya One, Ecovacs Atmobot and Famlibot) are recent entries to the consumer electronics market.

While appliance robots have had some commercial success, consumer demand and research interests have more naturally gravitated toward the fictional all-in-one, humanoid personal assistants. Researchers and companies alike see the domestic humanoid as a technology-based method for addressing the growing percentage of the population above the age of retirement; a personal assistant robot is placed in the home of an elderly family member, thereby allowing the senior to remain in his/her home and maintain his/her independence and quality of life with the help of the robot (see Beer et al. (2012)). The research community has made steps toward this inclusive vision by designing dexterous mobile robots to autonomously perform elect portions of household tasks under specific conditions (see Smith et al. (2012, p. 1342) for a summary). For example, IRT's Home-Assistant Robot can load clothes into a washer machine, and the Willow Garage PR2 can fold the laundry. The PR2 can also prepare food, such as baking cookies and making pancakes, and CMU's Home Exploring Robot Butler, or simply HERB, can load and unload the dishwasher. This vision has also been the focus of competitions in which research robots must master typical household tasks. Over 100 RoboCup@Home teams have demonstrated their domestic service robot entries in a series of tests set in a realistic home environment or real-world setting (i.e., restaurant, grocery store) (van der Zant and Iocchi 2011). The challenges comprehensively and holistically evaluate a robot's functional abilities, which have included mapping an unknown environment, navigating within it and avoiding dynamic obstacles, recognizing and manipulating an object recognizing a human and tracking him/her, recognizing and understanding a human's speech and/or gestures, and high-level reasoning abilities. However, the challenges of addressing multiple tasks on the same robot in generalized environments still remains largely unaddressed.

While consumers wait for the arrival of an affordable version of Rosie the robot maid, an intermediate trend is emerging – the confluence of smart devices and domestic robots. (see Wilson et al. (2014) for a survey on smart homes and home automation.) In this hybrid approach, homes will have several different appliance robots in order to perform a heterogeneous collection of household tasks. New task-specific robots will enter the consumer electronics market, perhaps potentially to locate misplaced personal items or retrieve fallen objects from the floor (e.g., Dusty concept by the Healthcare Robotics Lab at Georgia Tech). This next generation of domestic robots will be able to communicate with each other and other smart home devices. Researchers worldwide have already begun developing laboratory-based smart homes staffed with robot assistants (e.g., the CompanionAble, Mobiserv, and KSERA projects), and the 2015 RoboCup@Home competition will test the integration of domestic service robots with smart home devices. An embodied social companion-type robot is a likely liaison between the residents and the smart devices and the appliance-based domestic robots; see Fig. 2. Note that one adoption barrier of commercial smart homes has been the coordinated control over the assortment of home automation and smart environment devices (Wilson et al. 2014). It will be imperative for the residents to feel in control over their households and that the domestic service robots understand their preferences, as forewarned by Yamazaki (2006); Cha et al. (2015) corroborated this in the context of a domestic robot assistant helping to organize the kitchen. Initially, it may be preferable for the

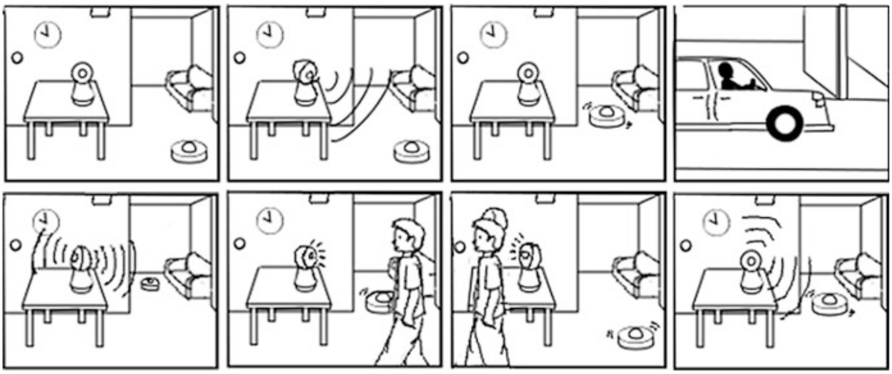

Fig. 2 Example of a companion robot coordinating control over appliance robots and smart home devices. Imagine a scenario in which a robot liaison oversees a network of smart home devices and domestic robots in a condo shared by two roommates. Today, the liaison needs to task the robot vacuum to clean the family room and kitchen. It has learned that the residents are away during working hours, and it is now 10 AM. The liaison confirms that no one is currently home by checking the smart devices in the family room and schedules the robot vacuum for immediate operation. Minutes later, the garage door opening event is detected. The liaison turns up the temperature and recalls the robot vacuum; vacuuming will have to wait until later. As one of the residents passes quickly through the kitchen, the liaison turns its head to follow the resident's movement, trying to announce that there is a new alert. The roommate walks past and leaves the house again. The robot vacuum is redeployed and the alert is reset Image courtesy of Emily Lennon

residents to interact with the robot liaison in order to manually start a robot on its task, or similarly, to explicitly program the robot cleaning schedule. The robot liaison can report back to the residents about successful task executions or outstanding issues that occurred. As residents acclimate to their robotics-enhanced smart home over time, their routines and preferences can be observed; the robot liaison can accordingly suggest changes when the residents are present and/or automatically reschedule their tasks.

Cooperative Manufacturing

Whereas traditional industrial automation focused on speed and precision of repetitive tasks that replaced the need for human workers, a shifting focus to flexibility in the manufacturing process and a revival of the small-scale manufacturer has resulted in an emphasis on constructing robots that enhance manufacturing capabilities by working side-by-side with human workers. Cooperative manufacturing takes the approach that humans should do the tasks that humans are good at (including cognitive planning and fine dexterous manipulation) while relying on robots to do the tasks that robots show superior capabilities (including matching tool ends to parts, handling heavy or dangerous materials, or stabilizing parts). The expectation of cooperation and collaboration between the human and robot teammates may be implicit or explicit in cooperative manufacturing and depends upon the complexity of the task, the capabilities of the robot, and the communication modality between the human worker and the robot. Within this research area, two main applications have been attracting the most attention: (1) automated package handling, and (2) humans and robots sharing workcells.

While much enthusiasm has been shown recently toward using drones, or unmanned aerial vehicles (UAVs), for automated package delivery of pizza and online shopping orders in 30 minutes or less, the reality is that automated guided vehicles (AGVs) – such as carriers, tow units, and forklifts – have been used in warehouses and factories for decades (Ullrich 2015). Large platform AGVs have been used since the 1950s in limited capacities, such as transporting heavyweight payloads such as engine blocks (Wurman et al. 2008). In these traditional roles, human workers and robotic AGVs are separated to ensure safety; if a human worker is present in an area, then the robot must not enter that area.

A more modern cooperative approach can be seen in order fulfillment systems in warehouses. Order fulfillment traditionally has involved human workers who are assigned to zones within a warehouse to batch "pick" items in their zones for several customer orders and convey these items to a centralized packaging station (Wurman et al. 2008). Today, distribution centers utilize fleets of robots to bring racks of merchandise to central packing centers where human workers verify orders and place objects into shipping boxes (Fig. 1e). One human worker packing items at a station may be supported by 5–10 robots, which retrieve pods in parallel and move at human walking speeds (up to 5 km/h). Controlled by a centralized scheduling and planning system, these fleets of robots have been shown in practice to double the productivity of the human workers.

Existing manufacturing facilities are beginning to adopt the practice of humans and robots sharing workcells on assembly lines. According to Tanya Powley's 2014 report in the *Financial Times*, a small percentage of 179,000 industrial robots sold each year are designated for human-robot collaboration; Universal Robots leads this market, having sold 2,500 UR collaborative robot arms from 2008 to 2014. At a Volkswagen automotive factory in Germany, a robot inserts glow plugs into drill holes within the engine's cylinder heads, which are difficult for human workers to reach; the human worker then follows with insulating the cylinder heads. Similarly, *MIT Technology Review*'s Will Knight pointed to BMW's use of a collaborative robot to assist human workers during the final car door assembly in which the doors are insulated from sound and water. The two real-world deployments by Volkswagen and BMW demonstrate tasks in which the human worker and the robot are physically collocated in a shared workcell. However, these tasks are simplistic and discretized such that the robot first completes its subtask and then the human worker finishes the task. It is implied that they are working together as teammates, albeit asynchronously taking turns. The human worker can accommodate the robot, waiting until it is finished inserting the glow plugs or applying the sealant; thus, it is not necessary to model the task and subtasks.

Modeling and recognition of tasks (and subtasks) allow for increased scheduling flexibility, teamwork fluency between the robot and the human worker, and efficiency with respect to throughput (e.g., decreased idle time, decreased task completion time). For example, a robot can act as an assistant by predicting the human worker's subsequent task and providing the necessary tool(s) and/or component(s) (Hayes and Scassellati 2014). Task models can be explicitly programmed as with traditional industrial robot arms or acquired through demonstration (Muxfeldt et al. 2014). The ability to acquire new tasks and skills has opened the possibility of utilizing collaborative robots in smaller manufacturing enterprises (Fig. 1f), as one robot investment can be re-tasked by human workers to a variety of tasks without extensive training or experience. Once the robots are trained, they usually operate alone until completing their task or retraining is needed to accommodate a new part or a change in the process. The wide-scale deployment of these collaborative robots has the potential to radically alter the manufacturing world, as the creation of customized products or the manufacturing of products in areas where labor is more expensive becomes possible.

Currently, there are no real-world examples of human workers and robot manipulators physically working together on the same task, at the same time, in the same place. Traditional robotics approaches are insufficient for realizing this level of cooperative manufacturing. The immediate and low-level challenge is for the robot to robustly detect the presence of a human worker, as opposed to an object or environmental constraint (e.g., table). Subsequently, the robot must be able to detect and track the body pose of the human worker; additionally, it must always be aware of its own pose and trajectory, estimate the human worker's trajectory, monitor for collisions, and stop or adjust its trajectory if necessary. Another low-level challenge is for the robot to recognize the human worker's current action. It must also detect any unexpected behavior by the human worker, determine if its current action should stop, and do so if necessary. Based on the human worker's current action, one mid-level challenge is for the robot to determine the current task or subtask, if more than one exists. Finally, high-level challenges the robot include monitoring task progress, predicting the subsequent actions for itself and the human worker, determining how its current action effects the overall task, and changing if necessary.

Before there can be true side-by-side collaboration between human-robot pairs, many technical challenges need to be overcome. Object recognition, grasp planning, motion planning, and compliant manipulation are all deep and open problems that must contribute solutions to a viable collaborative system. (Frey and Osborne (2013) note that object perception and manipulation is one of three factors preventing the computerization of certain types of human worker jobs.) Beyond improved object perception and manipulation skills, robot manipulators must also be aware of human's physicality, cognitive state, and preferences and factor this into their motion planning. There is hope though that progress can be made with mixed-autonomy systems that rely not on a completely self-sufficient robot but rather leverage the strengths of the human partner to overcome some of the shortcomings of the robotic partner.

Summary and the Future

This chapter has demonstrated the significantly altered trajectory of robotics research from its roots in industrial automation to the dominant domains today that feature robots working in human environments, in concert with human activity, and in order to impact the quality of life of human users. This evolution has been enabled by the convergence of research in human-centered sciences including sociology, healthcare, psychology, and cognitive science. This convergence can be seen in many sub-areas of robotics, including ones in which robots are evolving to coexist with humans, functioning as coaches, assistants, and teammates, albeit for now in limited settings.

In order to function in complex, unconstrained, and dynamic human environments and interact with humans, robots will need cognitive, linguistic, social, perceptual, and motor competencies beyond the current skill level, and this suite of competences must function in concert. The computational and algorithmic demands on these systems are unlike those that led to successful factory automation, and new research methods that utilize methods from converging areas will be needed to create and test these systems. Among the many examples of these transformative applications, techniques that enable robots to easily acquire new skills as they encounter novel situations by generalizing from their prior experiences and applying their existing competences will certainly be essential. Modeling the complexities of human environments, engaging in collaborative and personalized interactions, and developing mechanisms for engaging, useful, and viable long-term interactions are also certain to be critical.

The most significant impact of this transformation in robotics is the range of application domains that could potentially undergo dramatic change. From providing personalized health coaches to educational tutors that supplement the instruction that teachers and therapists can provide, from robots that help seniors to stay independent in their own homes for longer to domestic aids that help manage the interconnected services in the home of the future, and from efforts to bring manufacturing back to small and medium sized enterprises to robots that lend a hand assembling furniture, the potential impact of this new generation of co-robots may instigate wide-reaching changes.

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Figure 1 photos of Bandit and Baxter are courtesy of the University of Southern California and Rethink Robotics, respectively. Photos of the Autom, Roomba, PR2, and Kiva robots are courtesy of Theron Trowbridge (2011), Eirik Newth (2006), Ingo Lütkebohle (2010), and JBLM PAO (2015), respectively, via Flickr (CC BY 2.0). Thanks to Emily Lennon for the illustration used in Fig. 2.

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Distributed Manufacturing

Jian Cao, Kornel F. Ehmann, and Shiv Kapoor

Contents

Abstract

Manufacturing transforms raw materials into different forms or functions through the use of energy and resources. Through this process, new ideas are implemented to create something different from the original shape or function, and values are added to the manufactured goods. The desire to achieve better precision, to utilize less energy, or to simply make cost-competitive products has pushed for innovations in manufacturing processes and system optimization. Throughout history, manufacturing has evolved from cottage businesses to capital-intensive enterprises. It creates good-quality jobs and becomes an indicator for national competitiveness. While manufacturing becomes more geared toward mass production, undesired consequences, such as limited choice and excessive waste, are becoming increasingly more prominent challenges. On the other hand, the demand for point-of-need manufacturing or customized manufacturing has formed a new, yet original, mode of manufacturing, i.e.,

J. Cao (✉) • K.F. Ehmann
Department of Mechanical Engineering, McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL, USA
e-mail: jcao@northwestern.edu

S. Kapoor
Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Champaign, IL, USA

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distributed manufacturing. 3D printing of household items is one example of such distributed manufacturing. In this chapter, the history of manufacturing and its general economic and societal impacts will be discussed first, followed by observations of past and current applications of distributed manufacturing, a discussion on technical enablers and challenges, and finally the projection of the potential impacts and the future of distributed manufacturing from both technological and social perspectives.

Introduction

When human beings started to shape a bone into a tool or a jewelry piece, manufacturing was born. The origin of the word "manufacturing" came in about the 1560s and means "something made by hand," even though water mills were used to assist the grinding of corn as far back as over 2000 years ago as mentioned in a poem by the Greek writer Antipater (Reynolds 2002). The Merriam-Webster (M-W) Dictionary defines manufacturing as the process of making products especially with machines in factories. Specifically, M-W has four ways of interpretation: (a) something made from raw materials by hand or by machinery, (b) the process of making wares by hand or by machinery especially when carried on systematically with division of labor, (c) a productive industry using mechanical power and machinery, and (d) the art or process of producing something. The United Nation uses the following definition for manufacturing in presenting key economic data: "Manufacturing comprises units engaged in the physical or chemical transformation of materials, substances, or components into new products." In this chapter, "manufacturing" is broadly defined as a process or a system that transforms raw materials into different forms or functions through the use of energy and resources.

Initially, manufacturing took place in a *distributed mode*, i.e., people made or created new products for their own use in the house or in the village. This mode of manufacturing, also frequently referred to as cottage industry, remained the prevalent mode of manufacturing until the dawn of the industrial revolution in the eighteenth century. In this mode, craftsmanship was at a premium. Skills were passed mostly within a family or from teacher to disciple. The skills of craftsmanship could be incredibly advanced as demonstrated by fine objects such as the carved olive-stone boat of China's Qing dynasty in the fine collection of the National Palace Museum in Taiwan. This product, made by distributed manufacturing, measured just 16 mm in height and 34 mm in length. Eight figures are carved on the boat; windows can be opened and closed. More than 300 characters of a poem are engraved with exquisite detail on the bottom of the boat. Only one of these items exists. The beauty of this one-of-a-kind object is not just breathtaking and challenging even for modern technology but also, from the technical point of view, exhibits incredible amounts of freedom in creating the design of the object. There was no need for matching replaceable parts; no need for fitting the boat with, for example, an imaginary bridge; no judgment on how fine is fine; etc.

The design and manufacturing freedom, as highlighted above, is not present to the same extent in the *concentrated mode* of manufacturing where products are manufactured at a few concentrated locations, i.e., factories, and then distributed domestically or globally for utilization. Nevertheless, this mode of manufacturing can provide an incredible production volume, such as, for example, the US quarter, with a production volume of over 1.5 billion in 2014. It is of a similar order in dimensions as the carved boat, though no match in terms of intricacy.

The concentrated mode of manufacturing grew out of the industrial revolution initiated in Britain. This took place from the eighteenth to the nineteenth century (~1750–1850). It was a period in which machinery power was invented and applied to form various industries. For example, the textile industry used the spinning jenny, invented by James Hargreaves (1722–1778), for producing multiple spools of yarn and the power loom, invented by Samuel Compton (1753–1827), for weaving to streamline the process of making cloths from cotton, which has been traditionally done by hand in the cottage business, to mass produce. These machines, combined with the steam engine, invented by Thomas Newcomen (1664–1729) and James Watt (1736–1819), had one mission, i.e., to perform a task repetitively and consistently well.

The industrialization movement led to a significant reduction in fabrication costs and time such that ordinary people could afford to own a variety of clothing that was before only possible within the upper classes. Manufacturing output was no longer largely proportional to population. China, for example, who completely missed the first and second industrial revolutions, started to lose its several hundred years of dominance in world GDP in the 1820s. In the 1820s, China had more than 40 % of world GDP and an equivalent percentage of world population, while the USA had about 1–2 % share in both categories. In the 1950s after World War II and the Chinese Civil War, China had merely 6–7 % of world GDP with a world population of 35 %, while the USA had nearly 40 % and 7 %, respectively, according to the Wohlers Report. It was not until the late 1980s when China changed its policy to encourage more free competition and consequently increase manufacturing output that moved the country as a major player in world economy. In 2014, according to the International Monetary Fund, China has 13.3 % of world GDP, and the USA had 22.4 %, ranked as the second and the first largest economy, respectively. Their population percentages, according to the US News and World Report, stood at 19 % and 4.4 % as the first and the third most populous countries.

The desire for maximizing profits and the motivation for being competitive have brought unforeseeable advancements in manufacturing processes and systems. Key concepts, such as standardization and interchangeability, enabled one to decompose a complex product system into smaller modules, which could then be further decomposed and contracted out to suppliers. Such a system encourages one to become an expert in a specific domain and, in many cases, forces product manufacturers to become a commodity manufacturer, where low cost at high volumes is the main goal. One benefit of this concentrated production model is the scale effect, which allows profits to be accumulated and reinvested for further improvements. If it were not for Intel, the largest chip manufacturer with its semiconductor sales in the first quarter of

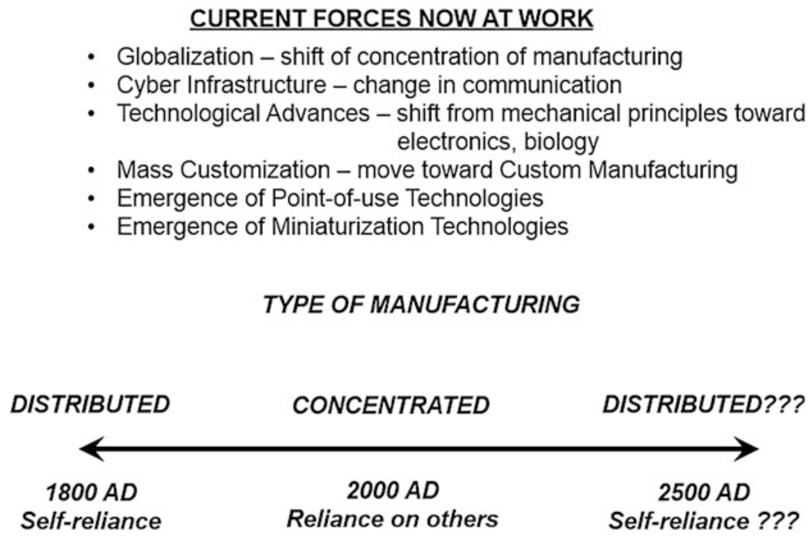

Fig. 1 Evolution of manufacturing mode (DeVor et al. 2012)

2012 over US$11.56 billion, computer products would not be so affordable that 84 % of US households could own a computer according to the 2013 US Census.

While consumers enjoy the affordability coming with mass-produced products in the concentrated manufacturing mode, flexibility is limited in the manufacture of these commodity items as Henry Ford said, “Any customer can have a car painted any color that he wants so long as it is black” (Ford and Crowther 1922). One reason is that an extremely high threshold of capital investment is needed that very few manufacturers can afford. In semiconductor fabrication, for example, a new manufacturing line will cost at least $1 billion, and $3–4 billion is common. Material waste is another issue associated with mass production due to the standardization in packaging and shipping. Rarely can one find the exact quantity that one wants for a specific task, and the solution is to order more and throw away the leftovers. As urbanization grows as the result of the concentrated production mode, a variety of societal problems emerge related to the environment, traffic in urban transportation, stress management, and waste management, particularly, unemployment and crime management if the location is less fortunate in the global competitive market.

The distributed manufacturing mode that coexisted with the concentrated manufacturing mode has started to reemerge and assume a more prominent role in the 2000s largely driven by the needs imposed by mass customization and point-of-need manufacturing and enabled by the fast development of cyber infrastructure, smart devices, and cognitive science as noted in the 2012 article by DeVor et al. (2012) and captured in Fig. 1.

In the rest of this chapter, past and current impact of distributed manufacturing will be summarized in section “Past and Current Impacts of Distributed Manufacturing,” followed by a discussion on the enablers and the challenges facing this mode of manufacturing. Finally, the potential technological, economical, and societal impacts of distributed manufacturing will be presented in section "Enablers and Challenges in Distributed Manufacturing."

Past and Current Impacts of Distributed Manufacturing

The distributed manufacturing mode, rooted in the early developments of the human race, was the dominant fabrication mode before the 1820s. In that era, integration of design and manufacturing occurred at the individual level; real-time process control was applied when the craftsman adjusted the tool angle, for example, based on visual inspection; customization was realized when the customer was physically present for measurement and testing; agility was achieved when consumers and suppliers were within a short distance from each other. With the advancement of industrialization, many of these elements in the entire manufacturing process chain have become separated, e.g., designers separated from manufacturer. However, very recent trends in which integration and convergence of technologies are pursued and realized give distributed manufacturing a rebirth. Three examples will be given below to illustrate the evolution of distributed manufacturing, two in printing and one in chemical production, and its impact.

The first example is associated with the **2D printing** of reading materials. Communication and teaching/learning are integral parts of human development. The original means of spreading wisdom and knowledge was through documents copied by hand. Wood-block printing was invented as a technique for printing, and the earliest surviving example from China was dated before 220 AD (Whitfield and Farrer 1990). The oldest existing print done with wood blocks on paper is the Mugujeonggwang Great Dharani Sutra, dated between 704 and 751 and discovered in Korea. Similar examples, made in about the same period, can also be found in Japan. The technique requires a wooden mold for each article, suitable for mass production as evident in the frequent applications of the technique in materials related to Buddhism. The flexibility of printing came in about 1045 when Bi Sheng invented standard pieces of molds made of clay or porcelain or copper for each Chinese character. Note that the beauty and elegance associated with calligraphy was not reflected in these prints.

Gutenberg in western printing (1439–1457) skillfully integrated metallurgy for making castable metal pieces of individual letters, machine control for creating suitable pressure through a screwdriven mechanism with standardized design for achieving good space control and alignment. The technology delivered a low-cost means for printing books and played a significant role in spreading knowledge and in educating the public in general. Printing technologies have been further improved through etching for creating free-form fine-lined molds and/or through pressure control for creating shades in black–white printing.

The distributed mode of printing took shape after the invention of mold-less or template-free computer printing technologies represented by laser printing and ink-jet printing. Laser printing is a dry printing technology, called xerography, invented by the American physicist Chester Carlson (1906–1968) and engineered to be a successful commercial high-speed laser printer led by Gary Starkweather at the Xerox Palo Alto Research Center. Ink-jet printing, particularly the drop-on-demand type first developed by Epson, Hewlett-Packard, and Canon in the late 1980s, has lowered the barrier in terms of cost for ordinary households or small businesses to own one, so that printing can occur right at home or the office or at the store at the time when needed. It is interesting to note the full cycle of 2D printing over the history of mankind, from distributed to concentrated to distributed, and the technologies associated with it.

The extension of printing from two-dimensional used for paper or book or photoprinting to three-dimensional applications (**3D printing**), cup or shoes or even a car body, is a giant step for distributed manufacturing. In 1892, Blanther of Chicago obtained a patent for creating a three-dimensional terrain map by a combination of 2D contour planes impressed on a series of wax plates (Blanther 1892). It was not until the 1970s that this layer-by-layer technology for making 3D objects received traction for industrial applications when Matsubara of Mitsubishi Motors pioneered the use of photo-hardening materials and DiMatteo of Dynell Electronics (DiMatteo 1976) used it for making a mold that is hard to be made by conventional machining operations.

3D printing is a common alternative term for layer-by-layer additive manufacturing (AM) in which a product is designed digitally, sliced into layers to form a .stl file, and this .stl file is then sent to a machine that builds up the product either by selectively solidifying a polymer resin or by extruding a polymer melt or by melting/sintering metal powders. AM has received enormous attention at all levels, from kindergarten kids to NASA, from artists to dentists (Fig. 2), especially after the establishment of the National Additive Manufacturing and Innovation Institute (NAMII) in 2012, now called *America Makes*. There is also the *Maker Faire* “Make, Create, Craft, Build, Play,” which celebrated its 100th fair at the end of 2013 with 35,000 attendees in Rome and attracted 120,000 people in the 2014 San Francisco Maker Faire and the *Make* magazine (Fig. 3). These movements stimulate the imaginative nature of consumers and bring them to be an inventor.

The third example is about *chemical production*. Small-scale, distributed chemical production is emerging as a powerful development trend in industry. Such distributed production, localized production, and reduced capital investment models run counter to the maxim of “economies of scale,” but they offer economic and safety benefits. As Meredith Kratzer of University of Illinois has noted, “Novel microchemical systems will reduce the need for hazardous reactants, generating them [only] on demand.”

Enablers and Challenges in Distributed Manufacturing

The distributed manufacturing mode *shifts manufacturing capabilities from the hands of the few into the hands of the many*. The line between the creator and user becomes less distinguishable. Instead, technologies from different fields are

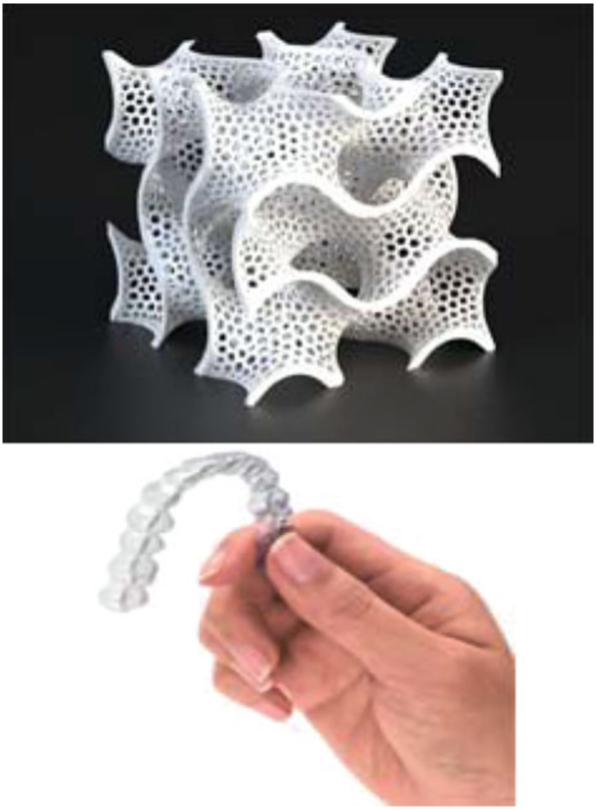

Fig. 2 Sample of 3D-printed products (Top: Image provided by Bathsheba Grossman, Bathsheba Sculpture LLC, http://bathsheba.com; bottom: Photograph courtesy of Align Technology, Inc.)

seamlessly integrated to create a platform in which users can exercise their own creativity to satisfy the needs of mass customization, for example, the creation of patient-specific medical devices or personalized medicine. There are **four key enablers** for distributed manufacturing:

The first enabler is the *autonomous and flexible process* that uses computer numerical control units to control motors or lasers or heating elements and moving stages in a way that external energy can be directed to the desired location at the pre-described energy level. Such units are now commonly integrated with embedded sensors to monitor their functions and are equipped with an easy interface for users to treat them as plug-and-play units. The current move toward "smart manufacturing" or "intelligent manufacturing" is to have unprecedented real-time control of energy, productivity, quality, and costs in manufacturing systems, which lead to the further enhancement of autonomous and flexible processes, one key pillar for distributed manufacturing. Developments in robotics, human–robot interfaces, artificial intelligence, or neurosciences have all played their corresponding roles in moving toward more autonomous and flexible processes and systems.

Fig. 3 Covers of *The Economist* magazine (© The Economist Newspaper Limited, London, Feb 10, 2011) and the *Make* magazine (© Maker Media, Inc, http://makermedia.com, Nov. 2014)

The second enabler is *miniaturization* that reduces the dimensions of functional units to ease their portability and integration and in some cases reduce the difficulty in achieving, for example, a uniform temperature or humidity control necessary for achieving better quality control. For example, a desktop manufacturing (DM) system can literally reside in a room adjoining a hospital operating room, ready to manufacture a diagnostic probe or implant that is tailored to the precise size and needs of the person on the operating table. Such technology can not only significantly reduce healthcare costs but improve the quality of healthcare delivery as well. An example of a similar technology already in use is ceramic dental reconstruction, developed by Sirona Dental Systems. In a single visit, a patient's tooth can be scanned with a 3D CAD system, and a tabletop computer numerical control (CNC) machine tool in the next room can then manufacture a ceramic crown that is immediately put in place in the patient's mouth. Ehmann et al. (2007) conducted a World Technology Evaluation Study on micromanufacturing and found that in 2004–2005, the trend toward miniaturization of machines was already evident in both Asia and Europe, with commercialization of desktop machine tools, assembly systems, and measurement systems well underway.

The third enabler is the *cyberinfrastructure* that changes the way people communicate, the way people describe objects, the way files are shared, and the way knowledge is created. It is now possible for one to use a computer system equipped with cameras to create an object in the digital form using sketches and gestures (Jang et al. 2014). The object created can then be locally printed. It is now possible for one to know the status of a machine locally or remotely over a handheld smartphone device. Cyberinfrastructure is an essential part for safe operation, particularly in the distributed manufacturing mode.

The fourth enabler is the *reduced capital cost* that lowers the barriers for entrance into the distributed manufacturing mode. A \$300 computer laptop in 2014 had more memory and power than a \$2 M computer in 1980 (Amdah 1 470). Some of the low-end 3D printers or laser cutters are now available for less than \$1000 for the consumer market. The cost to access high-speed Internet has also dropped significantly. An estimated 78.1 % of people in US households had a high-speed Internet connection in 2013 according to the US Census Bureau. For industrial usage, the cost of CNCs did not drop significantly, but more functionalities are added to ease process planning and to achieve better quality.

The **five major technical and social challenges** associated with distributed manufacturing described below pose challenges as well as opportunities.

A final product often requires conflicting functional demands, for example, safety and lightweight, which results in the need of employing multiple materials in one single product, i.e., the need for having *multifunctional and multi-material manufacturing platforms*. While 3D printing (additive manufacturing) leads the spread of distributed manufacturing, it is often limited by material choices, size, and throughput. For example, it is extremely difficult, if even possible, to make a functional car hood using 3D printing due to the complex requirements of three-dimensional free-form shape for aerodynamics and styling, high strength for safety, and lightweight for fuel efficiency, in which thin sheet metal or carbon composites are needed. Conventional processes that can meet the above requirements require a significant investment in tooling (millions of dollars), which are not flexible and not suitable for distributed manufacturing. There is a need to develop multifunctional and multi-material flexible manufacturing platforms. Such platforms may be entirely new or may be combining different functionalities of existing manufacturing processes. For example, the combination of robotics (Zeng et al. 2014) and forming technology can have the potential to make functional car hoods in a distributed manner (Malhotra et al. 2012). The potential opportunities in this category can be endless.

Certification of quality or technical specifications is a challenging problem that varies depending upon the manufacturing methods. Take 3D printing as an example; as each part is built individually layer by layer, the consistency and repeatability between parts, the controllability of each layer, and the interaction between layers are all critical to the quality and performance of the final product. A different cooling rate due to the speed of built or the power of the laser utilized will result in a different microstructure, resulting in undesired pores or crystal structure that will affect the fatigue life. Distributed manufacturing usage in a commercial and industrial setting will be the subject of liability and compliance check with safety or environmental regulations. A new methodology for certification, with the integration of predictive modeling, real-time process control/monitoring, high-speed computing, and statistical analysis, will need to be developed and adopted by the community.

The vast growth of technology innovations in the grassroots fashion poses a challenge for *standardization of interfaces*. Distributed manufacturing relies heavily on digital data, digital control, and the cyber-physical interface, i.e., digital manufacturing. The realization of digital manufacturing critically hinges on the ability to securely and easily capture, transfer, and analyze data from production machine tools that possess plug-and-play functional characteristics. An analogy can be made with the standard interface that the PC industry has imposed or the standard programming platform that Apple created to allow everyone to develop “apps” for their specific applications. While many modern machine tools possess sensing and control systems, the data communications and digital interfaces are frequently complex and/or proprietary. The lack of plug-and-play-type digital integration is an obstacle to achieve seamless digital operation of these machines within the distributed manufacturing mode. MTConnect, for example, is an open, royalty-free standard that is intended to foster greater interoperability between devices and software applications.

Just as computers have enabled new forms of crime (identity theft, computer fraud, counterfeiting, violation of intellectual property rights, distribution of pornography), distributed manufacturing also has the potential to be used for illegal purposes, the worry about *dual use*. One can print a functional gun these days. How will society curtail or prevent the use of distributed manufacturing for the production of illegal weapons, explosives, drug paraphernalia, etc.? The answer will not be a single dimensional approach. Technology itself cannot solve the problem, rather, a more inclusive societal approach to embrace the diversity while keeping the technological advantages will be needed.

The distributed manufacturing mode provides the critical link between the designer and manufacturer, between a dreamer and doer. It poses both opportunities and challenges for the *education* system. High Tech High (HTH) founded in 2000 has 5000 students and places a premium on retaining flexibility and agility. As noted by *Newsweek* on September 8 of 2014, the hallway of HTH schools is like “a cross between a science center and a museum of modern art, where the only thing more jaw-dropping than what’s on display is the fact that all of it is created by kids in grades K–12.” The affordable laser cutters, 3D printers and scanners, microcontrollers, and design software have effectively brought hands-on creation to the classroom. The challenge is how to teach students to think thoroughly based on principles of science and engineering, while the temptation of just making it is hard to refuse when it can happen with a touch of a button.

Potential Impacts and Future of Distributed Manufacturing

Convergence of knowledge and technology is envisioned to stimulate an accelerated emergence of highly integrated and flexible manufacturing processes enhanced by the extensive communication capabilities offered by the Internet and by their integration with nanotechnology, biotechnology, and cognitive technologies. Ultimately, these changes may give rise to a fundamental shift in *the way* *manufacturing is performed*, *a combination of concentrated and distributed manufacturing with distributed manufacturing taking a much more prominent share*. Unlike the birth of the computer and of the Internet in which military applications were the driving forces, this shift in the mode of manufacturing follows a grassroots growth approach. Two recent studies from Wohlers Associates showed the industries that used 3D printing technologies in 2009 and 2012. Individual consumer products (electronics + medical) took the largest share, 36.8 % in 2009 and 35.4 % in 2012; and military applications took only 5.2 % in 2009 and 6.0 % in 2012. As the 3D printing technology grows more mature with metal applications, it is anticipated that industrial and military applications will dramatically grow.

The distributed nature of manufacturing and the use of converging technology platforms will alter the path of ***how knowledge is created***. The panel at the recent World Technology Evaluation Study on Convergence (Roco et al. 2014) laid out the fundamental thoughts on how different the paths of knowledge generation could be as illustrated in Fig. 4. For example, school-age students can now create "apps" (applications) for smart phones. New additive manufacturing processes will

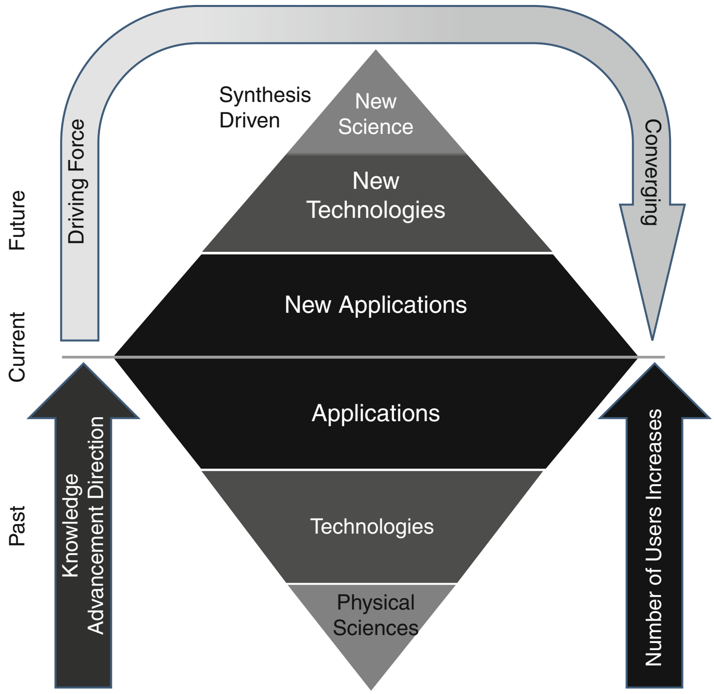

Fig. 4 Schematic of current and future knowledge development and adoption paths. The *right up arrow* shows an increase in number of users as applications increase (Cao et al. 2013) (Convergence of Knowledge, Technology and Society, Implications: Societal Collective Outcomes, Including Manufacturing (2013) Cao, J., Meador, M.A., Baba, M.L., Ferreira, P.M., Madou, M., Scacchi, W., Spohrer, J.C., Teague, C., Westmoreland, P., Zhang, X., © Springer International Publishing Switzerland 2013, with permission of Springer Science+Business Media)

increasingly allow users to locally create one-of-a-kind parts, even from multiple materials, to meet specific needs across a wide range of applications, from aerospace to fashion to tissue engineering; data can be shared in the cloud. The easiness of the user–machine interface will allow the general public to adopt technologies and to invent new technologies, which, in turn, may lead to new scientific discoveries and new sciences, in particular, synthesis-driven sciences. As indicated in the top half of Fig. 4, the driving force for knowledge creation may start from grassroots applications and then broaden to technologies and to converging sciences. This is in stark contrast from how it has been done in the current and past centuries, which is represented as the bottom half of the diamond in Fig. 4. Newly discovered and developed converging sciences will support distributed manufacturing for economic, human-potential, and societal developments.

Unlike the concentrated manufacturing mode in which capital investment is one, if not the critical element for success, the distributed manufacturing mode lowers the entrance barrier and may impact the economic system as well. Crowdfunding is one example of such a move, in which contributions are made individually through the online community rather than through traditional banks or venture capitals. The potential impact of the combination of distributed manufacturing and crowdfunding can be significant, as it unleashes the innovation potentials embedded in individuals. When the ideas being shared over the Internet and distributed made with funding requested from social media, it will certainly shape the traditional economic model and legal practices, such as patent laws, liability laws, environmental laws, etc.

The Internet has already extended the touch of knowledge to every corner of the world. For example, the Khan Academy, an adaptive teaching platform for every user, has over 10 M unique users per month, and Arduino created an electronics prototyping platform that is being used to learn about digital electronics. The distributed manufacturing mode will embrace people with all backgrounds, from simple users in creative arts to makers to sophisticated engineers making it a perfect means for providing education and workforce training.

As the Nobel laureate Niels Bohr (1885–1962) said, “Prediction is very difficult, especially if it’s about the future;” the prediction on the evolution of distributed manufacturing and its future impact laid out above may not be bold enough, but certainly will not be as conservative as what Ken Olsen, the founder and then CEO of Digital Equipment Corporation, said about PC in 1977, “There is no reason for any individual to have a computer in his home.”

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Human Computation and Convergence

Pietro Michelucci

Contents

Abstract

Humans are the most effective integrators and producers of information, directly and through the use of information-processing inventions. As these inventions become increasingly sophisticated, the substantive role of humans in processing information will tend toward capabilities that derive from our most complex cognitive processes, e.g., abstraction, creativity, and applied world knowledge. Through the advancement of *human computation* – methods that leverage the respective strengths of humans and machines in distributed information-processing systems – formerly discrete processes will combine synergistically into increasingly integrated and complex information-processing systems. These new, collective systems will exhibit an unprecedented degree of predictive accuracy in modeling physical and technosocial processes and may ultimately coalesce into a single unified predictive organism, with the capacity to address societies most wicked problems and achieve planetary homeostasis.

P. Michelucci (✉)
Human Computation Institute, Fairfax, VA, USA
e-mail: pem@humancomputation.org; pem@hcinst.org

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Introduction

One could argue that information processing on Earth, and possibly in the universe, began with the emergence of bacterial life three billion years ago (Brasier et al. 2006). Autopoietic life processes are fundamental to the notion of information processing. Reproduction itself requires the ability to process and execute a set of abstract instructions encoded in DNA. Furthermore, organismal survival depends upon the ability to respond appropriately to environmental conditions, which involves sensation, response selection, and consequent action. Even archaic life forms, such as bacteria, possess these information-processing capabilities, exhibiting genetic reproduction as well as movement in response to chemicals (*chemotaxis*), light (*phototaxis*), and magnetic fields (*magnetotaxis*) (Martin and Gordon 2001).

But how does such information processing occur? The entire behaviorist movement of the mid-twentieth century was agnostic to that question, treating the information-processing apparatus of an organism as a "black box," in which one would be concerned only with the environmental input and behavioral output of a system. Eventually, people who wanted to create intelligent machines came along and thought it might be useful to find out what was actually going on inside nature's black box. This led to the birth of information-processing psychology and the subsequent cognitive revolution (Miller 2003), which gave rise to present-day cognitive science.

Cognitive scientists are interested in understanding *how* an environmental stimulus results in a particular response within an organism. Most explanatory models arising from this approach tend to characterize the propagation of information within an organism – in other words, an organism's *internal communication*. More specifically, such models posit that information about an organism's environment is somehow encoded and transmitted to the part of the organism that can activate a suitable response, often with mediating decisional processes. Though bacteria accomplish this via an elaborate chemosensory signaling pathway (Blair 1995), most animals today possess complex networks of specialized cells, called neurons, that serve this purpose. Recent findings, however, suggest that even prior to the evolutionary emergence of neurons, bioelectric signaling occurred among somatic cells, a phenomenon still present in zebra fish (Perathoner et al. 2014). Thus, it would appear that information processing originated and coevolved with life.

This raises an interesting question: What accounts for this coevolution? In other words, what are the adaptive benefits of increasingly sophisticated information-processing capabilities? An answer may be embedded in the following information-theoretic tenet: *in order for something to be informative, it must be unexpected* (Desurvire 2009) *and useful* (Vigo 2012). Expectations, of course, derive from predictions. But where do such predictions originate? In nature, complex organisms, such as mammals, rely heavily on prediction for survival. Anticipating, for example, the attack behavior of a predator could improve evasion. Phylogenetic and ontogenetic processes endow mammals with basic predictive models of their

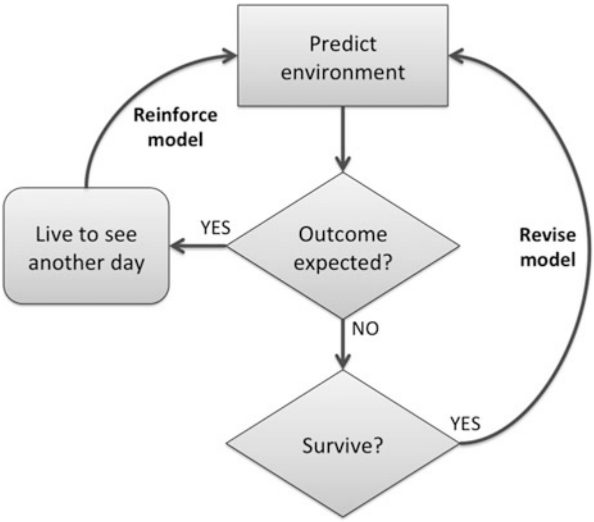

Fig. 1 Experiential learning over the course of an organism's life continually refines its predictive model of the environment

environment. These causal models are then dynamically fine-tuned over the life of the organism via learning. Such learning occurs when an organism experiences an unexpected outcome, which then *informs* the modification of the predictive model (see Fig. 1). When successful, learning results in better predictions. Thus, the ability to develop more complex and comprehensive predictive models of the world can lead to more accurate survival-based predictions under a wider variety of conditions and circumstances. Indeed, cumulative learning is sufficiently critical to the success of an organism that an extensive and growing body of machine learning research exists to emulate this capability in autonomous agent-based systems (Michelucci and Oblinger 2010).

For most people today, the term "information processing" conjures notions of computers and network infrastructure. However, as one considers the future relationship of humans and automated systems, it may be useful to reflect on the biological origins of information processing described in this section. This provides a basis for regarding humans not just as end users of computing systems but also as supercomputers in our own right. Such a perspective liberates us to imagine more easily what might be possible in a future world that is composed of interacting biological and artificial information-processing systems, especially as those lines become increasingly blurred.

Today's Most Advanced Information Processor

The neural circuitry of simple metazoans may limit learning to first-order cause-and-effect relationships. Higher mammals, such as humans, however, exhibit working knowledge of much more complex relationships. Despite technological advancement, the human brain is widely believed to be the most sophisticated information processor in the universe, consisting of approximately 10^11 neurons communicating in parallel over a network of 10^15 dendritic connections (Michelucci 2013a). However, it is not just the raw computational power of the brain that endows it with capabilities that elude our best machine-based systems but rather its complex cognitive architecture. This neurological software, which guides the flow of information in the brain, endows humans with unique abilities such as creativity, abstraction, intuition, anomaly detection, and analytic problem solving, all in service of the most advanced predictive modeling capability known.

Thus far, biological evolution has endowed humans with the intelligence needed for survival, including the invention of powerful technologies. However, some of these inventions have led to intractable societal problems (e.g., climate change, pandemic disease, geopolitical conflict, etc.), the solutions of which exceed the reach of individual human cognitive abilities. These "wicked problems" have no specific formulation, as each problem characterization depends upon a specific solution approach, which exists among an unknown set of possible approaches (Rittel and Webber 1973). To further complicate matters, there is no definitive endpoint; candidate solutions must be dynamic, adaptive, and ongoing. Moreover, wicked problems are multifaceted, often involving multiple systems, such that a solution that benefits one system (e.g., an ecological solution) may have repercussions to another system (e.g., financial markets).

To address these wicked problems and manage the survival risks they pose, we need an intellectual faculty more advanced than human intelligence. That is, we require more sophisticated functional and predictive models of the world and a capacity to employ those models to generate tenable and durable solutions. Because the urgency of this need exceeds the time scale of biological evolution, a viable solution will likely require technological innovation.

One such option would be to build super-intelligent machines that can be used to solve our wicked problems for us. Some believe that creating humanlike cognition in machines, often referred to as artificial general intelligence (AGI), will happen in three steps: (1) map the entire human "connectome," the neural circuitry of the brain, (2) replicate that circuitry using computer hardware and software, and (3) wait until microprocessor speeds exceed the processing speed of the human brain. The culmination of these steps has been referred to as the "technological singularity"(2014), which refers to the moment at which AGI exceeds human intelligence and beyond which we cannot anticipate the impact on civilization (hence the metaphor to the "singularity" construct in physics, which involves a "point of no return").

This approach may not be tenable for two reasons. First, there is wide disagreement among artificial intelligence experts about when the technological singularity might occur (Armstrong and Sotala 2015), ranging from just a few years to beyond the year 2100. Thus, such an event may not be soon enough to mitigate deleterious global processes before they become irreversible. A second reason is that most predictions about the technological singularity are predicated on replicating the human connectome in silico. However, recent evidence (Hansson and Rönnbäck 2003; Tang et al. 2014) detailing the role of nonneuronal cells in brain signaling is emblematic of a fundamental issue with this approach: that a connectomic model of the human brain, which maps the interconnection of existing neurons, along with a functional model of neurotransmission, may be inadequate for explaining cognitive function. Indeed, we are far from having a comprehensive understanding of the biochemical mechanisms that govern brain development and activity. For this reason, developing humanlike cognitive abilities in machines will not depend solely upon processing speed or artificial replication of the connectome, but will also rely upon the realization of a complete and accurate dynamic, mechanistic model of human cognitive processes (Michelucci 2013b).

Human Computation

An alternative approach to building superior intelligence, which may have greater near-term promise, involves directly leveraging human cognition within a distributed information-processing network. As previously described, there are cognitive abilities that remain solely within the purview of humans despite progress in artificial intelligence research. However, there are also tasks much better entrusted to machines than humans, such as counting, calculating mathematical and statistical formulas, and keeping track of events and outcomes. Indeed, the information-processing architectures and resultant capabilities of machines and humans (see Fig. 2) exhibit a striking complementarity that suggests an opportunity for fruitful collaboration.

What if it were possible to engineer systems that combine the respective strengths of machines and humans toward unprecedented information-processing capabilities? Would this endow humanity with a problem-solving capacity sufficient to address present and future societal challenges? Over the past decade, a scientific community has emerged to explore the transformative potential of directly employing human cognition within larger computational systems, giving rise to a field of study called "human computation." Human computation (HC) has been defined generally as the design and analysis of information-processing

Machines	Humans
• Counting	• Inference
• Precision	• Visual Perception
• Objectivity	• Linguistic Ability
• Calculation	• Abstraction
• Persistent Storage	• World Knowledge
• Data Integrity	• Sociocultural Awareness
• Process Execution	• Creativity

Fig. 2 Complementary information-processing strengths of machines and humans

systems in which humans participate as computational elements (Michelucci 2013c). In this definition, the notion of "computation" encompasses the full spectrum of processes that might be applied to the transformation, synthesis, and interpretation of data.

HC systems can be classified at a high level as either naturally emergent or deliberately engineered (Michelucci 2013c). As previously described, information processing is integral to most natural human behavior. When large collections of such behaviors are accessible via the technosocial infrastructure, it becomes possible to extract useful information from such data. In this vein, human computation can manifest as an *emergent* phenomenon. One example of this is financial markets, the aggregate behaviors of which sometimes can be used to predict world events better than individuals, exhibiting the "wisdom of crowds" effect. Another example of emergent HC involves an analytic approach called "query-based syndromic surveillance", which examines trends in online search behavior. Incorporating prevalence measures of semantically relevant Google search terms (e.g., influenza symptom descriptions, influenza terms, influenza complications, etc.) has been shown to enhance influenza forecasting models (Dugas et al. 2013; Ginsberg et al. 2009).

Most HC research today, however, focuses on how to *engineer* goal-directed HC systems, which leverage human cognitive capabilities that still exceed the best automated methods. The HC community has begun to recognize and catalog classes of HC systems toward understanding the success precursors for those systems and improving the repeatability of attendant methods (Greene 2013). To develop a more concrete sense of the use and impact of human computation today, it is worthwhile to examine some of the more prevalent classes of HC systems along with notable exemplars.

As an early success case, reCAPTCHA has become a canonical example of human computation, and in particular, of a *crowdsourced microtasking* system. By embedding reCAPTCHA into their websites, Internet entities can distinguish between legitimate human users and mal-intentioned web crawlers. This is accomplished by making access to site content contingent on the user entering words seen in distorted text images, which today is easier for a human than a machine. In addition to providing a human verification service, reCAPTCHA simultaneously helps curate digital archives by including failed OCR fragments among the examples of distorted text so they can be resolved by the human responses. Thus, in the course of proving their humanness, hundreds of millions of reCAPTCHA users have unwittingly contributed to digitizing a century's worth of archival issues of the New York Times.

"Quid pro quo" systems, like reCAPTCHA (Ahn et al. 2008), compel participation by offering some service (e.g., access to Web content) in exchange for human computation labor. Another system manifesting such reciprocity is Duolingo (Garcia 2013), which provides foreign language instruction during which the users' online learning behaviors contribute directly to text translation services. Thus, Duolingo students have, through their foreign language studies, collectively translated Wikipedia articles from one language into another. The striking observation that Duolingo implicitly trains its own labor market is suggestive of the future potential of HC to become a disruptive economic force.

In contrast to quid pro quo HC systems, crowdsourcing marketplaces (e.g., Amazon Mechanical Turk, CrowdFlower, etc.) provide monetary compensation as an extrinsic motivator. Microtasks, such as tagging photos, completing surveys, or editing documents, are outsourced to a community of active "crowd workers." Remuneration is often predicated on a minimum level of performance and paid in proportion to quantitative contribution metrics, as determined by the micro-task stakeholder, who is typically referred to as the "requestor." Such crowdsourcing marketplaces have been used historically for market research but are also being used increasingly by scientists to collect data, a practice sometimes referred to as *Cyberscience* (Newman 2014a).

Historically, checks and balances in crowdsourcing marketplaces have catered primarily to the requesters. However, in response to concerns about the unscrupulous practices of some requestors, reputation systems such as Turkopticon have emerged to help crowd workers themselves make more informed choices about which projects and project requestors they choose to engage.

Citizen Science is an application of human computation that refers broadly to public participation in the scientific process (Newman 2014a), typically in an online context, but not always (e.g., the Audubon Christmas Bird Count (Ullrich Barcus 2014) and the St. Louis Baby Tooth Survey (Early 2013)). An emerging differentiator between Citizen Science and Cyberscience is that the former seems to necessarily involve an educational aspect, such as participant understanding of the scientific goals and cognizance of how participation contributes to those goals. Irrespective of these potential educational benefits, project instigators are often drawn to the prospect of the tremendous research acceleration that can result from harnessing the power of the crowd. Indeed, most citizen science projects involve crowdsourced microtasking that involves some aspect of data curation that lends itself to human cognition. Moreover, to retain participation, many such projects include "ludic" or game-like elements (Krause 2013).

A pioneering example of online citizen science is the stardust@home project, which began in 2006, in which 30,000 participants used a virtual microscope to analyze millions of digitized images of aerogel to detect nanoscale cosmic dust particles retrieved from the tail of comet Wild 2. To be successful, participants had to learn to use a virtual focuser to visually distinguish particle trails from prevalent aerogel inclusions. Ultimately, the project discovered seven particles deemed likely to be extrasolar particle, the composition of which has suggested revision of existing models of cosmology. All 30,000 participants were included as coauthors on the paper reporting these results in the journal *Science* (Westphal et al. 2014).

Citizen science is being used increasingly in the medical research field (e.g., fold.it, Phylo, WeCureALZ, etc.), particularly by leveraging the analytic ability of humans to exclude avenues of discovery that are unlikely to be fruitful. Since automated solution search methods tend to be exhaustive, they can be computationally intensive and even intractable for certain classes (NP-hard) of problems. Human-based approaches, however, tend to employ world knowledge, abstract reasoning, transfer learning, and intuition to identify a handful of fruitful avenues worthy of further exploration. The fold.it project has gambled successfully on these human abilities, by recasting a complex biomedical research problem into a 3D folding game accessible to nonspecialists. Even though thousands of participants provide puzzle solutions, it turns out that only the very best human-based solutions have exceeded machine-generated solutions and thereby enable new research discoveries. Thus, in contrast to the stardust@home project, which employs a "divide-and-conquer" approach to finding needles of comet dust within a proverbial haystack of digital imagery, the fold.it project uses a "winner-takes-all" model to determine optimal protein molecule configurations. To date, fold.it puzzle solutions have been instrumental in advancing our understanding of the simian immunodeficiency virus (SIV), a close relative of HIV. Fold.it is now setting its sights on proteins implicated in the Ebola virus (Long 2014).

More recently, architects of citizen science systems have taken a greater interest in collaborative discovery, perhaps inspired by the community-based discovery of a new type of "green pea" galaxy due to the inclusion of an online social forum in the Galaxy Zoo project (Cardamone et al. 2009). The Phylo project has created Open-Phylo to allow any disease researchers to upload genetic sequences for crowd-based analysis through the Phylo platform. Phylo's creator, Jérôme Waldispühl, views this new portal as a potential opportunity to use the solution from one Phylo participant as the starting point for another participant toward collaborative solution development.

ReCAPTCHA has been described above as a quid pro quo system, in which a trade relationship exists between each crowd worker and the project stakeholder. Over the past few years, however, a different sort of reciprocity has fueled a class of human computation platforms, in which the community of participants is itself a stakeholder and shares goals with individual participants. In these *virtuous ecosystems*, individual participants contribute information, which is then combined with other users' information and shared back as an aggregate. The platform serves this aggregated information in a form that is easily understood and tailored to the specific needs of each individual, leading to modified behaviors in the real world and often to improved individual results. In some cases, participants will continue to report back new results to the system and perpetuate this virtuous circle. Note that "virtue" in this context refers not to the application domain but rather to the virtue of contributing to a greater whole, which in turn benefits individual participants in ways that encourage further contributions.

One clever and effective example of such a virtuous ecosystem is enabled by an online platform called "Trapster". In Trapster, participants are vehicle drivers who click a button on a smartphone app whenever they see a speed trap along the road. Using georegistration methods, a central server records the location and time of the speed trap observation, which then contributes to a mash-up that reports back to Trapster users the location and recency of any speed traps in their immediate path so they can avoid citations. Ironically, Trapster has resulted overall in improved speed limit compliance, which suggests serendipitous benefits to unintended stakeholders, such as law enforcement organizations and perhaps local pedestrians.

Other noteworthy examples of virtuous ecosystems include PatientsLikeMe and the YardMap project. PatientsLikeMe enables a community of people with certain medical conditions to report regularly about their current symptoms and treatments. The aggregated data is used to provide intuitive graphs and charts showing treatment efficacy tailored to the specific clustering of diseases and symptoms of each patient, based on what has been working for other patients with similar disease and clinical presentation profiles. Ancillary stakeholders are medical research organizations that purchase the anonymized data to develop more effective treatments.

The Cornell Lab of Ornithology's YardMap Project allows online participants to outline any site on a shared aerial map, producing detail maps of spaces ranging from yards or roof garden to a parks or corporate campus and identifying habitat types, individual objects, and practices (e.g., plants, solar roof panels, composting). Users can ask questions about their plants, habitats, practices, and more knowledgeable users can then view the annotated yard maps and provide environmental conservation advice in the integrated social network to facilitate learning and help newcomers to become resources for future users (Dickinson and Crain 2014). Communities also use the platform to work together toward shared goals, such as increasing the percentage of native flora in a neighborhood or enhancing pollinator habitat. YardMap thus generates useful conservation data that can be tied to the Lab's bird monitoring efforts while also serving as a powerful platform for leveraging online social dynamics to influence real-world behaviors that are aligned with users' goals (Dickinson et al. 2013).

Though such virtuous ecosystems manifest a karmic benefit to contributors, it is not difficult to imagine nefarious applications. To better understand such risks, this topic was explored by a breakout team at a recent workshop (Michelucci et al. 2015), who considered applying methods such as cascading social networks to amplify seeds of disinformation (McDonald et al. 2014).

The advent of the Internet removed physical barriers to human collaboration – a brick and mortar meeting room can hold 30 people, but a virtual room can hold 30 million people. This meant that information-processing workflows involving contributions from people, machines, or both could be automated to enable collective innovation and problem solving at unprecedented scales. For example, applying machine-based aggregation methods to such distributed information processing enable a "wisdom of the crowds" effect (Surowiecki 2005), in which the collective answer to a problem exceeds the best individual answer. This effect has been demonstrated from problems ranging from the recollection of order information (Steyvers et al. 2009) (e.g., in what order were these 20 books published) to solving the traveling salesman problem (Yi et al. 2012) (i.e., given a roadmap, what is the shortest path from point A to point B?). It turns out that the specific algorithms and underlying theory used for combining human inputs are critical to the success of these methods (Yi et al. 2012).

In contrast to wisdom of crowd approaches, which tend to be nonsocial and rely on algorithmic approaches to combining human answers, other approaches to collective intelligence seek to enhance human collaboration. Indeed, Francis Heylighen, of the Global Brain Institute, defines collective intelligence as "a group's ability to solve problems and the process by which this occurs" (Michelucci 2013c). Anita Woolley and her colleagues have further explored this notion, by inventing a "group IQ" metric as a way to investigate factors that influence the problem-solving ability of small groups (Woolley et al. 2010). Woolley et al. made the noteworthy discovery that the single most important success factor in group-based problem solving is social intelligence rather than individual IQ. In other words, the individual problem-solving ability of group members is less relevant to problem-solving success than the ability of the group to work together.

NASA's Center of Excellence for Collaborative Innovation (CoECI) has been a pioneer in driving collective innovation, the successes of which have prompted interest in this approach by other US federal agencies, including the Department of Homeland Security and the National Institutes of Health. In NASA's tournament-style challenges, a problem description is provided to a solver community in which prizes are simply awarded to the best solutions. In one noteworthy case, a challenge was posed to improve NASA's ability to forecast solar proton events (resulting from solar flares), which pose radiation hazards to spacecraft and astronauts. Previous NASA and academic efforts could predict such events 1–2 h in advance. The winning solution, provided by a retired radio engineer, could predict such events 8 h in advance with 85 % accuracy (Davis and Richard 2010).

Though not inherently collaborative, such tournament-style competitions can lead to collaboration when mutual awareness prompts teams to combine approaches in order to be more competitive (Netflix prize 2015). Such spontaneous collaboration occurred during the 2009 Netflix Prize challenge, which sought a better algorithm for predicting user film recommendations based on prior recommendations. A $50 K prize was offered to the best solution, but to obtain the million-dollar grand prize, the winning solution had to be at least 10 % better than the existing "Cinematch" recommender system. Two teams were close, but neither exceeded the 10 % improvement threshold required for the grand prize, so they decided to combine their solutions, which resulted in a 10.09 % improvement and a substantially greater monetary award (2015) even when splitting the prize.

Internally, NASA employs a more collective (and less competitive) form of innovation, using third-party platforms such as InnoCentive@work, in which problem solving is driven by an online collaborative workflow process that elicits problem definition, facilitates collaborative discussion, and streamlines solution evaluation. More sophisticated distributed problem-solving approaches are also emerging, such as the ePluribus problem solver, which employs stigmergic (i.e., indirect coordination, such as the scent trails left by ants) methods to enable users to collaboratively blaze solution paths between an initial state and goal state. Within this path-finding context, ePluribus also facilitates problem decomposition into manageable components that can be addressed by users asynchronously and then fuses the sub-solutions from the diverse feedback of many problems solvers into collective solution paths (Greene and Young 2013). Such an approach is potentially scalable to millions of users.

Some might view the ongoing activities of the scientific community as a form of collective intelligence. Indeed, execution of the scientific process and communication of empirical findings are becoming increasingly automated via collaboration platforms, public engagement through citizen science, online journal management systems, experimental metadata capture (Shreejoy et al. 2013), and candidate approaches for connecting these islands of automation within a coalescent framework for collective science (Bücheler and Sieg 2011). Still, today science tends be a sequential process in which a single research team produces hypotheses, methods, findings, and conclusions, which are all published after the study concludes.

One might imagine, however, a platform for collaborative science in which scientific communication coevolves with research and contributions can be inserted by anyone at any stage of the process. Adopting versioning techniques from the software development field, such as branching processes, would permit a single hypothesis to be tested in multiple ways and for the resultant data to itself be subjected to various analyses and conclusions, each giving rise to "version 2" studies, in which new hypotheses are motivated by the version 1 study results, all within a common framework of traceable activities, data, and results. This new form of open research would better play to individual strengths, improve transparency, permit instantaneous knowledge transfer, and facilitate replication. On the other hand, it would pose a new set of challenges, such as how to implement credit assignment. For example, person A would have to be credited for providing a hypothesis, person B for defining methods, person C for improving upon person B's methods, person D for statistical analysis, and so on. Nonetheless, connecting such a collaborative research platform to various crowd-powered systems for data collection and curation could lead to a culture of pervasive participatory science and markedly accelerated scientific advancement.

The collective intelligence approaches discussed thus far entail specific, well-defined methods or processes to achieve certain outcomes. Indeed, our modus operandi for collective intelligence has been, essentially, to insert humans at various stages within an algorithmic process. Human cognition, however, which represents our most sophisticated and capable model of intelligence, seems to manifest multiple levels of abstraction and emergent properties, such as consciousness, arising from its complexity. Indeed, the way we think is decidedly not algorithmic. How, then, might we achieve collective intelligence more closely modeled on human cognition and what might we hope to gain from it?

Marvin Minsky, a renowned cognitive scientist and artificial intelligence pioneer, published a popular book in 1988 called The Society of Mind (Minsky 1988), based on a radical new theory codeveloped with Seymour Papert that the human mind is functionally composed of myriad special-purpose agents and that it is the interaction of these agents that results in high-level cognition. Following Minsky's work, others came along and made specific commitments about the interactions of such agents in various attempts to functionally explain human cognition (see Chong et al. 2009). These cognitive theories, as well as other more biologically inspired approaches, were implemented in software as *cognitive architectures*, which purport to functionally replicate goals, memory, learning, reasoning, and other human cognitive faculties. Today, no single cognitive architecture provides a comprehensive working model of human cognition, but this line of research continues to bring us closer to simulating human intelligence.

This notion of cognitive architecture provides a context for thinking about how one might engineer humanlike collective intelligence. Consider a promising cognitive architecture as a starting point, and for each agent-based system or specialized process within that architecture, imagine substituting a human or human collective that was appropriately specialized by design. Might it be possible in this way to realize a fully cognitive system that does not merely exhibit crowd-based wisdom on a specialized task, but rather manifests collective goals, via executive functions that gather, process, and act on information at massive scales? Though such a *hybrid cognitive architecture* may be a plausible approach for achieving humanlike collective intelligence, it is conceivable that achieving super-human collective intelligence will require entirely new cognitive architectures that maximize synergistic effects among all agents, whether human or artificial.

With the societal introduction of collective intelligence comes the risk of collective psychopathology. Human mental illness (e.g., neurosis and psychosis) can often be recast as information-processing dysfunction (Endres et al.2014), which could also occur in collective information-processing systems (Blumberg and Michelucci 2013). The potential interplay of mental illness in individual human contributors and systemic psychopathology in the human collective remains to be studied. Thus, as we become increasingly dependent upon systems exhibiting collective intelligence, it would behoove us to retain awareness of this potential risk and consider mitigation strategies.

As discussed, collective intelligence research tends to focus on understanding how intelligence emerges from the interaction of many individuals and how to use that knowledge to engineer systems that can solve problems more effectively than their constituent human or machine contributors can solve individually. Although such collective intelligence systems may be used to process real-world data and may themselves be composed of physical systems (e.g., humans and machines), they do not necessarily interact directly with the physical world.

Nonetheless, human-based distributed sensing is an evolving research area in its own right, including such approaches as *collective sensing*, which involves applying statistical methods to aggregated social network data, *people as sensors*, which involves humans in the wild contributing their subjective perceptual experiences via mobile devices, and *participatory sensing*, in which humans use portable sensor technology to acquire objective data from the world (Resch 2013). One clever implementation of participatory sensing is Street Bump, a smartphone app that runs in the background using the device's built-in accelerometers to sense potholes in the road when people drive over them. When a "bump" is sensed, it is reported with GPS data to a central server where it is added to a pothole map that helps inform future roadwork (Carrera et al. 2013). In this example, participatory sensing capitalizes on existing patterns of human behavior and, therefore, does not require any new human activity other than downloading and running the app.

The other two distributed sensing methods described above, *people as sensors* and *collective sensing*, have been useful in crisis relief efforts (Meier 2013). Ushahidi's CrowdMap platform enables the ad hoc creation of a geospatial mash-up, in which users can contribute subjective, locale-specific information to an evolving map. This *people as sensors* platform was employed during the 2010 Haiti earthquake to enable anyone to text their needs to a four-digit code and have that request automatically geolocated on a map. In the wake of Typhoon Pablo, which devastated the Philippines in 2012, *collective sensing* was employed for damage assessment, resulting in the collection of 20,000 relevant tweets. This, however, posed a new problem, which was how to derive actionable information from that social network data. Interestingly, the UN task force decided to use crowdsourcing to analyze the collective sensing data. CrowdFlower, a firm specializing in crowdsourced microtasking, distributes the analysis of those tweets to thousands of crowd workers, who identified any links leading to photos or videos and then assessed the imagery for evidence of damage. Within 12 h, the task force was able to produce a georeferenced damage assessment map with linked imagery, all due to collective sensing and crowdsourced social network analysis.

In addition to amplifying awareness through distributed sensing, human computation also affords an opportunity to be a more effective in the world via coordinated action. Swarm theory demonstrates how local coordination can result in global emergent behaviors (e.g., the V-shaped formation of a migrating gaggle). However, the opportunity for centralized coordination afforded by mediating technology could be used to share locally relevant information with individual actors to improve their efficacy and also to implement more complex activities. WikiProject is an automated tool that seeks to coordinate the online activities of Wikipedia contributors by leveraging the availability of user activity information. By calling attention to the activities of other users who share the same goals, WikiProject attempts to encourage contribution and reduce redundant effort, though perhaps with limited efficacy (Riehle 2013).

While collective intelligence, distributed sensing, and coordinated action, when implemented successfully, are each potentially transformative in their own right, the prospect of combining those capabilities within a unified system suggests a tantalizing opportunity to build a distributed organism that manifests collective agency in the world. Such a "superorganism" would exhibit pervasive awareness through its distributed sensory faculties, reason with an unprecedented degree of predictive accuracy, and implement complex, multi-actor behaviors. This model has evolutionary precedents among the eusocial insect species, which derive survival advantages through locally cooperative, globally emergent collective behaviors. Indeed, a recent comparative analysis of these insect behaviors to open source software development has provided inspiration for new human computation methods (Pavlic and Pratt 2013).

The effects of *organismic computing* were investigated in an online hide-and-seek game to measure the impact of shared sensing, collective reasoning, and coordinated action on group efficacy (Michelucci 2013a). Employing a novel technique, called *simulated augmented reality*, made it possible to test collaborative enhancements that have not yet been engineered. In contrast to virtual reality, which simulates the world in a computer-generated environment, augmented reality superimposes virtual elements onto the real world via pass-through displays. Because augmented reality technology today is still relatively immature, simulating augmented reality in a virtual environment serves as a useful proxy.

The overall benefit of organismic computing on group performance was supported by the study results, as was the central prediction that larger groups would benefit more from organismic computing than smaller groups. These early findings hint at the transformative capabilities that might arise due to organismic computing implemented on a massive scale. Organizational units at every scale, from businesses (Brambilla and Fraternali 2013) to governments, from societies to countries, and even humanity in its entirety could benefit from the synergy, efficiencies, and awareness that might arise through these methods.

Coevolution, Convergence, and Emergence

Organismic Computing, as discussed in the previous section, describes a technological trend toward the interconnectedness of humans across space. To see the complete picture, however, requires us to step back and consider the impact of interconnectedness over time. Smaldino and Richerson describe *cumulative culture* as "learned information and behaviors [that] are reliably transmitted and improved upon" from one human generation to the next (Smaldino and Richerson 2013), pointing out that no single human being knows how to build a modern computer from scratch. Thus, cumulative culture serves as long-term memory for humanity, ensuring that each new generation does not have to reinvent the wheel (or the computer, for that matter). But where does that memory reside?

Along the way, technology itself has improved our ability for cumulative cultural evolution. Though generations long passed may have propagated wisdom and knowledge through storytelling and mentorship, the advent of written communication, and methods to preserve such writing, extended the state space of human knowledge from our minds to the external, physical world. Eventually, we developed abstract symbolic methods for specifying a process, such as a mathematical formula, and even built crude mechanical devices for executing such processes, all the time, carefully recording our methods in writing so that future generations could build on that knowledge. And, indeed, as we became more advanced in our ability to harness the power of nature, we could use that knowledge to replicate these computational processes by routing electrons through semiconductors and even using them to store information. This knowledge has enabled us, through increasingly sophisticated methods, to extend information processing and storage to the external world and increase the fluidity with which such information passes between humans and the physical universe. Thus, the very technology that has been advanced through intergenerational collaboration has been further streamlining that collaboration, thereby accelerating the coevolution of technology and human society in a self-perpetuating process.

The foregoing analysis suggests that the convergence of human systems and technology has led to increasing connectedness among humans over both time and space and that this has been enabled by technology implemented in physical systems. In order to better frame the potential implications of increasingly convergent human systems and technology, it might be useful to first consider a simpler coupling. Imagine a student who is accustomed to adding three-digit numbers in her head, which is not too difficult because most humans can retain that amount of information in short-term memory. Now she is given a more difficult arithmetic problem, which involves adding two 10-digit numbers. Because it is difficult to remember so many digits, the student decides to use paper and pencil to perform the computation. This raises an interesting question: with the paper serving as a state space (i.e., a working memory) for solving the problem instead of activation patterns in her brain, is part of the thinking now happening outside of her brain? Clark and Chalmers have suggested that *epistemic actions*, that is, the employment of external physical constructs to augment cognition, constitute an extension of the human mind (Clark and Chalmers 1998). This view considers the human organism and facilitative physical constructs as a coupled cognitive system.

Extending this notion of a coupled cognitive system to include all human systems at different scales and all physical systems that assist humans in processing, sharing, and storing information suggests a new framework for understanding and anticipating the convergence of human systems and technology.

In this framework (see Fig. 3), the physical universe is viewed as a canvas upon which life processes encode knowledge. Humans are viewed as information processors, aggregators, and actors that serve as intermediaries between the physical state space and the virtual cyberspace, encoding knowledge about the former in the latter and using that knowledge, in turn, to manipulate the former. At its essence, cyberspace can be thought of as an economical representation of information, which

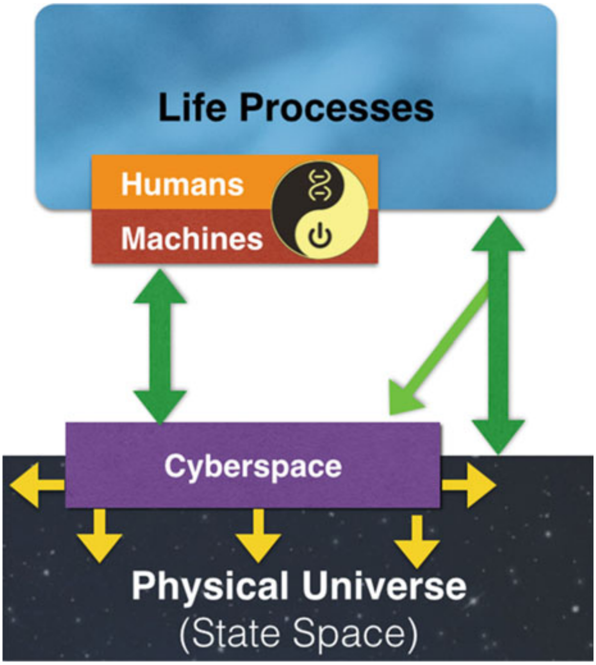

Fig. 3 A cognitive model of the universe

subsists upon a physical infrastructure that provides communication, data storage, and algorithmic computing. In practice, however, cyberspace is the medium within which humans represent, share, and build an understanding of the universe. Thus, as human interaction with cyberspace becomes more pervasive, frequent, and varied, the resultant coupled cognitive system develops a more faithful model of itself.

Today, our shared model of the universe is largely piecemeal, spread across expert minds and specialized communities. To make matters worse, we are flooded daily by petabytes of physical, genomic, social, economic, and other varieties of data. Thus, except for domain-specific computational simulations that exist in isolation, the majority of our knowledge is represented statically, encoded in human language and our data is distributed across heterogeneous repositories. Fortunately, human computation systems such as Wikipedia are improving this situation via collaborative knowledge capture. Furthermore, infrastructure that supports human computation, such as the Semantic Web, promises to enable new human-based discoveries and more usable encodings by linking isolated datasets (Simperl et al. 2013). Over time, we can expect increasingly sophisticated human computation methods to help us leverage our cumulative culture and growing pile of data into cohesive, working knowledge of the world – that is, predictively accurate, dynamic models of the interactions that occur among physical systems including life forms. In fact, these models would be self-reflective, as human contributors would also be modeling themselves and their relationships with other human and physical systems, including the infrastructure upon which the models are built. Ultimately, we might imagine this culminating in a system that is best able to help us predictably influence the world in desirable ways.

The organismic view of information processing described earlier suggests that survival requires an organism to employ accurate predictive causal models of itself and its environment. When this view is applied, in the large, to the coupled cognitive system of life processes interacting with the physical universe, such predictive models become self-perpetuating meta-models. In other words, when life forms collaborate and coalesce, as enabled by technology, to produce a more advanced predictive model of the universe, they are better able to self-adjust and engineer effective interventions that further perpetuate life and more advanced information-processing systems, leading to yet better predictions. Dynamic systems theory would suggest that such a cascading process could lead to a phase shift, that is, a sudden qualitatively different pattern of organization in the life-universe system. One conceivable manifestation of this phase shift is consciousness. Integrated information theory measures human consciousness in terms of the causal impact of abstract information processing on subordinate constituent processes, stipulating a minimal level of connectivity among processing elements necessary for the emergence of consciousness (Tononi 2008). Thus, a sufficient level of information-processing capacity and complexity within the life-universe system may lead to universal consciousness and self-awareness. In such a tightly integrated system, one could imagine the manifestation of collective thoughts that are as transcendent to the thoughts of an individual human as human thoughts are to the simple information processing of a constituent neuron.

Conclusion

Each year, data production increases exponentially. This trend will continue as devices, such as home appliances, become increasingly Web-enabled. The "quantified self" movement alone will result in millions of personalized, sensor-based streams of physiological data captured during exercise. However, in order for data to improve our understanding of the world, it must be informative, which requires both a goal-directed context and an information processor that can extract knowledge that has predictive value. Human computation, in some sense, represents an enabling technology for a new "web of agents" that will help make sense of the massive quantity of data generated by the Internet of Things. Methods such as massively distributed problem solving, citizen science, distributed analysis, and collaborative modeling will efficiently employ human and machine agents in complementary fashion to convert big data into useful information.

The convergence of humans and technology will continue to accelerate due to emerging technologies, such as neural implants and augmented reality, that expand the purview of human experience to more viscerally incorporate cyberspace into a mixed reality. The information ecosystem will rapidly mature with both human and machine-based consumers and producers of information, resulting in coalescence across domains (e.g., social, financial, political) and scientific disciplines. Massively collaborative methods will dynamically embed values that translate into policy and evolving models of governance. Increased automation, such as driverless cars (Newman 2014b), will gradually compel humans to occupy a narrower but more satisfying set of labor categories that play to uniquely human cognitive abilities, such as abstraction, intuition, creativity, and discovery such that contentment occurs even "below the API"(see Reinhardt 2015).

Ultimately, we will find new ways to incorporate nonhuman life processes into our collective models (e.g., mammals, bacteria, viruses). We will develop interfaces at the nanoscale that support the use of microbe-based sensing and information processing. We will develop new ways of propagating and storing information. Over time the physical substrate will become increasingly economical and indelible (see Hornyak 2012) as a state space for accumulated knowledge. Our models will include meta-models describing their own function. Ultimately, the life systems that emerged due to the specific combination of quantum particles and forces that define our universe will be able to collectively describe and understand the mechanisms of their own emergence and through that understanding create new increasingly complex systems, which will in turn produce ever higher-level explanatory meta-models. The affordances of such runaway complexity are difficult to anticipate, but it is conceivable that such a system will become increasingly aware, intelligent, and influential.

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Open Source Technology Development

Kevin Crowston

Contents

Abstract

In this chapter, we introduce the practices of free/libre open source software (FLOSS) development as an instance of the convergence of technological affordances with novel social practices to create a novel mode of work. We then consider how FLOSS software might be used for various scientific applications, perhaps leading to a convergence of current distinct disciplines. We conclude by considering how the technologies and practices of FLOSS development might be applied to other settings, thus leading to further convergence of those settings.

Introduction

Free/libre open source software (FLOSS) is an umbrella term that covers a diversity of kinds of software and approaches to development. We therefore start this chapter by clarifying its focus. Technically, the term free software or open source software refers to software released under a license that permits the inspection, use, modification, and redistribution of the software's source code. FLOSS can thus be

K. Crowston (✉)
School of Information Studies, Syracuse University, Syracuse, NY, USA
e-mail: crowston@syr.edu

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characterized as a privately produced public good (O'Mahony 2003). The freedom to reuse the source code distinguishes FLOSS from other forms of software distribution, such as freeware, where a program is provided for free, but without the source code being available, or licenses that make source code available for inspection but without the right to reuse it (e.g., the Microsoft Shared Source Initiative).

The term FLOSS groups together free software (sometimes referred to as "libre software" to avoid the potential confusion between the intended meaning of free meaning freedom and free meaning at no cost) and open source software. However, there are clear and important differences in the motivation for this approach to software development between the two groups, and the differences are sometimes controversial (Kelty 2008). (See Free Software Foundation (2013) for a detailed definition of free software and Open Source Initiative (n.d.) for a detailed definition of open source software.)

Free software proponents view the ability to view and modify computer source code as a matter of freedom, a basic human right. They thus view proprietary software as immoral, since proprietary licenses cut users off from something they should have. Typical free software licenses (e.g., the Gnu Public Licence or GPL) enforce sharing of source code (requiring it be available to users) and further require that modifications to the source code also be released as open source. This "viral" property means that free software cannot be freely mixed with proprietary software without also freeing that software (though there are technical workarounds).

In contrast, developers who adopt the term *open source* view sharing source code not as a moral issue but pragmatically as representing a better approach to development, by enabling broader participation in development thus improving bug detection, code security, and project productivity. Open source licenses (e.g., Apache or BSD licenses) typically allow licensed code to be used in combination with code with proprietary licenses, thus enabling commercial use of open source software. Similar tensions between moral and pragmatic motivations for openness can be observed in other kinds of open movements, as will be discussed later in this chapter.

FLOSS-licensed software may be developed in the same way as proprietary software, e.g., as in the case of MySQL, which was developed by a company and is now owned by Oracle, but available for use under an open source license. The open source license allows reuse of the code in other settings, for novel purposes and even as the basis for competing projects (called forks): in fact, MySQL now has a community-based fork, MariaDB. However, most FLOSS is developed not by a single company but through an open community process. And despite the differences in philosophy, developers in both camps generally adopt similar open development methodologies, making it sensible to speak of FLOSS development practices.

In some projects, a focal organization may lead the project (Fitzgerald 2006). For example, the Mozilla Foundation leads development of the Firefox browser and Thunderbird mail client, the Apache Software Foundation directs development of

Apache software (e.g., the Apache httpd web server among many others), and the MariaDB Foundation oversees development of MariaDB. A few of these foundations may have resources to employ programmers to work on projects. However, much of the work done by such foundations addresses issues other than development, e.g., maintaining infrastructure, providing a legal framework for the development, providing support to project leaders, or overseeing the general project development approach.

Many FLOSS projects exist outside of any formal organizational structure. Even where there is some kind of organizational involvement, an important feature of the FLOSS development process is that many (or most) developers contribute to projects as volunteers, without direct remuneration from the project, in what has been described as a community-based development (Lee and Cole 2003). Instead of pay, developers are motivated intrinsically by interest in the project or the chance to work on a project of one's own choosing or extrinsically by the opportunity to gain reputation and develop skills.

Recent years have seen an increase in the participation of firms in FLOSS and so in contribution from employees paid to work on FLOSS projects (Lakhani and Wolf 2005) and whose contributions are made available to the wider community (Henkel 2006). However, even employed developers are not paid directly by the projects to which they contribute, so from the point of view of the project, they are still volunteers that have to be motivated (though motivations may be for the corporations providing developers as well as for individuals volunteering their time).

Because of these organizational factors, the teams developing FLOSS are often organizationally and geographically distributed, forming almost purely virtual teams. The teams have a high isolation index (O'Leary and Cummings 2007) in that many team members work on their own and in most cases for different organizations (or no organization at all). Developers contribute from around the world and meet face-to-face infrequently if at all (Raymond 1998; Wayner 2000).

For most community-based FLOSS teams, distributed work is not an alternative to face-to-face: it is the only a feasible mode of interaction. As a result, these teams depend on processes that span traditional boundaries of place and ownership. To span distance, the work of the team coordinated primarily by means of computer-mediated communications (CMC). Often sets of tools are provided together in a "forge," named after the first such, SourceForge, e.g., discussion groups, source code control, bug trackers, issue trackers, and file distribution. Particularly important are systems to share source code and track revisions. These system provide access to the code to anyone but control who can make changes to the released project codebase (e.g., the code that is distributed to end users either in source format or as a ready-to-run binary distribution).

Another common feature of FLOSS projects that can be traced to reliance on volunteer contributors is the skewed distribution of activity across developers. As many developers contribute in their spare time, the amount of time each has available to work on the project varies. Indeed, it can be difficult to say exactly how many contributors a project has, since the difference between "temporarily inactive" and "dropped out" is not always clear.

Developers also vary in what kinds of activity they contribute. The result is a project with an onion structure. Most project have a core of developers with "commit" rights, meaning that they can contribute directly to the code base stored in the source code control system, as well as a set of codevelopers who may write some code, but whose contributions are reviewed by core members before being accepted. An active project will also have a large set of active users who contribute bug reports or other supporting functions such as documentation, translations, or user support.

Community-developed FLOSS thus represents a different approach to innovation in the software industry. The research literature on software development and on distributed work emphasizes the difficulties of distributed software development, but successful community-based FLOSS development presents an intriguing counterexample. Characterized by a globally distributed developer force, a rapid, reliable software development process and a diversity of tools to support distributed collaborative development, effective FLOSS development teams somehow profit from the advantages and overcome the challenges of distributed work (Alho and Sulonen 1998).

Research has identified a number of factors relating to the success of FLOSS development project. Crowston et al. (2012) surveyed the literature to summarize these. Figure 1 shows the resulting framework, with the major concepts that identified in the FLOSS research papers, organized in an *inputs-mediators-outputs-inputs (IMOI) framework.*

Inputs represent the starting conditions of a team, which for FLOSS include member characteristics and project characteristics such as license choice and

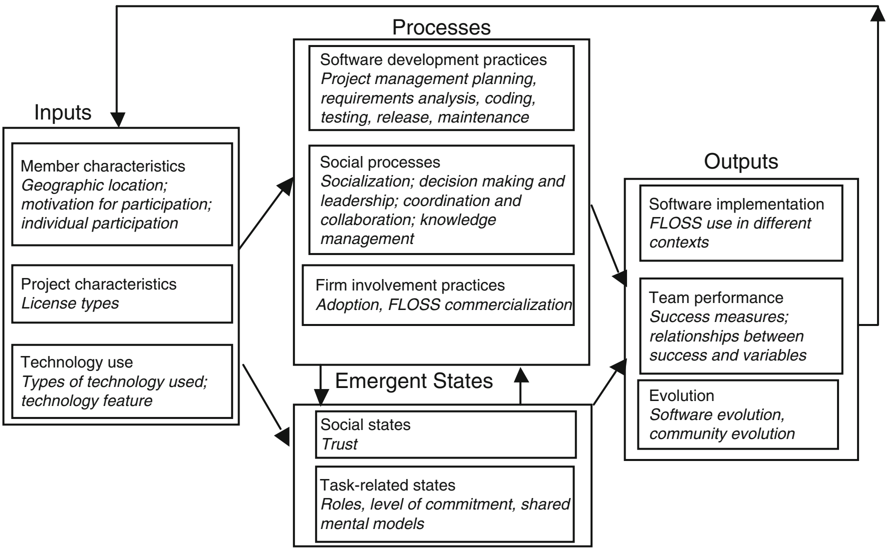

Fig. 1 Constructs and relations studied in FLOSS research (Figure 6 from Crowston et al. (2012)) © ACM. Used with permission. doi:10.1145/2089125.2089127

technology features. For example, developer motivations to contribute are key to the success of projects that rely on voluntary contributions. While a few projects have more volunteers than they can use, most projects have more work to do than volunteers to do it, so attracting and retaining volunteer developers is critical for success. Similarly, firm interest is necessary to attract developers paid by their companies.

Mediators represent factors that mediate the impact of inputs on outputs. Mediators can be further divided into two categories: processes and emergent states. *Processes* represent dynamic interactions among team members as they work on their projects, leading to the outputs. For FLOSS development processes include both software development practices and team social processes.

In terms of the *software processes* adopted, FLOSS development largely resembles any other software development project. However, some software processes do seem to be done in a different fashion in FLOSS projects than in conventional projects. For example, researchers have suggested that requirement analysis is done differently, as requirements are often identified based on interaction with current version and feedback from users rather than from a formal requirement gathering process.

In addition to the development practices, the *social and interpersonal processes* that support the distributed team are also critical. For example, an important social process in an open project is the socialization of new members, as they move from new participants to full members of the community. However, in most open source projects studied to date, the onus of socialization falls on the would-be participant, as few projects have any kind of organized socialization processes, likely due to the general reliance on volunteer developers who do not have time for (or much interest in) socializing newcomers, the vast majority of whom will not turn out to be core contributors (recall the skewed distribution of efforts).

Similarly, studies have found an important role for project leadership, described as "providing a vision, attracting developers to the project, and keeping the project together and preventing forking" (Giuri et al. 2008). Leadership is important because there is low organizational control of volunteer members, and the threat of "forking," while uncommon and discouraged, limits the ability of project leaders to discipline members. In most FLOSS projects, leadership is emergent, meaning that rather being appointed, leaders emerge from the group based on contributions, and often shared, as multiple members of the project contribute to leadership.

The second kind of mediator between inputs and outputs are *emergent states*, constructs that "characterize properties of the team that are typically dynamic in nature and vary as a function of team context, inputs, processes and outcomes" (Marks et al. 2001, p. 357), including social states such as trust and task-related states such as roles, levels of commitment, or shared mental models. For example, the finding of an onion structure in most FLOSS projects suggests the general kinds of roles that emerge, though studies suggest that in most projects, there is a general lack of clearly defined roles leading to considerable role ambiguity. In other words, members, especially newcomers, are often uncertain about how best to contribute. Given the lack of explicit direction, another important emergent state is the degree to which project contributors develop a shared mental model of the structure and functionality of the project to guide their contributions.

Finally, *outputs* represent task and non-task consequences of a team functioning (Martins et al. 2004). Many possible measures of success have been proposed. For example, Crowston et al. (2006) identified seven measures of FLOSS project success: system and information quality, user satisfaction, use, individual and organizational impacts, project output, process, and outcomes for project members. They noted that impacts are often hard to discern and to tie to specifics of the project, leading to reliance on measures more closely tied to the work products.

In addition to the direct link from inputs to mediators to outputs, the IMOI model recognizes that there is a feedback loop from the outputs to the inputs of a project. For example, high-quality (e.g., modular) code (a project output) should make the codebase easier to maintain and so facilitate additional contributions (an input). User satisfaction with the project (an output) is important to retaining developers, while the success of a project (an output) may increase its visibility and ability to attract new developers (an input). Contrariwise, a project that is struggling may find that difficulties in development cause developers and users to leave for more promising projects, thus further complicating development, leading to a downward spiral.

Proponents of FLOSS (in both flavors) claim a number of benefits to users and to society more broadly. The easy accessibility (e.g., zero cost) of software is a benefit to users, though it has been noted that the cost of the software itself is usually a small part of the total cost of adopting a software package. The availability of a system's source code reduces the risk of adoption for users by eliminating the concern that the company providing the software will disappear, taking the code with them and stranding users.

Because of the community's ability to fix bugs and add features, proponents also claim that OSS enables higher code quality. This effect has been summarized as Linux's law: with enough eyes, all bugs are shallow, meaning that bugs can be fixed more quickly than with limited developer base that has time to debug only a limited number of problems, which requires prioritizing bug fixes, even not fixing bugs that affect only a few people. Furthermore, having the code open enables it to be audited, potentially increasing security compared to closed software that is not openly reviewed. However, software being open is no guarantee that it will in fact be audited, as illustrated by the discovery of a bug in OpenSSL, a package that had only a few active developers.

Finally, the ability to examine actual working code can be useful for people learning to program, which can provide a benefit to society. FLOSS is an increasingly important venue for students learning about software development, as it provides a unique environment in which learners can be quickly exposed to real-world innovation, while being empowered and encouraged to participate. For example, Google Summer of Code program (http://code.google.com/soc/) offers student developers stipends to write code for FLOSS projects. The projects also provide mentorship to socialize potential new contributors to the project.

FLOSS in Scientific Research

We turn now to the second topic, namely, the use of FLOSS approaches to develop scientific software and the possible implications of such software for the convergence of scientific fields. Bezroukov (1999) pointed out that FLOSS development resembles academic research in its reliance on intrinsic motivations for contribution, the importance of recognition of contributions and similar funding models. Lots of scientific software is released as open source, consistent with suggestion that programmers have motivations other than payment for their coding. Releasing developed software as open source may also be an expectation of funding agencies. Releasing scientific software in particular as FLOSS is also argued for on the grounds that the tools used to develop scientific results need to be openly available to allow the research process and results to be audited.

Many FLOSS systems are general computing tools, useful across many domains, science included. At the bottom of the software stack are general purpose software such as operating systems (e.g., Linux), networking and programming language compilers or interpreters (e.g., for C++, Perl, Python, Ruby). Also useful for scientific computation is system software for parallel computing (e.g., Hadoop or MPI) and function libraries, both general purpose (e.g., Boost) and for scientific computations more specifically (e.g., SciPy).

Particularly useful for scientific computing are systems for storing data (e.g., databases such as MySQL, PostgreSQL, MongoDB, or Cassandra); systems for performing data analysis, such as the R statistics environment or octave mathematical system; systems for data mining and machine learning (e.g., weka) and for graphics (e.g., gnuplot). Qualitative data can also be processed, e.g., with content analysis packages (e.g., tamsys) or natural language processing software (e.g., GATE). Finally, workflow packages can automate particular sequences of computation in order to improve the repeatability of computations. Some of these tools have an organization or an open source community behind them, e.g., the R Foundation that supports the development of the R statistical package.

In addition, there are many more specialized software packages for analyses in particular domains (e.g., astronomy, biology, chemistry), either standalone or building on one of the above platforms, e.g., statistical analysis in R. For example, the bioconductor project (http://www.bioconductor.org/) provides "tools for the analysis and comprehension of high-throughput genomic data," built on the R system. The Image Reduction and Analysis Facility (IRAF) is a general purpose software system for the reduction and analysis of astronomical data. Packages exist also for the social sciences, e.g., for carrying out social network analysis (e.g., Gephi).

The open availability of tools may promote cross-disciplinary use. Many of the tools are useful across sciences and are a way in which innovations in one domain can be made available to others. For example, statistical techniques implemented in the R package may originate in one discipline but find uses in others. For example, bioinformatics tools developed for the analysis of DNA sequences are being used to analyze process sequences in management enabling management researchers to plot the genealogy of different variations of process sequences.

The research on FLOSS development highlights a number of issues for the development of open scientific software. A key question is the incentive to make something open source. Many scientific software authors are motivated by the need for academic credit rather than pay. This incentive does motivate making the system available, but not necessarily to integrate it with other software packages (Howison and Herbsleb 2013). Furthermore, making a package usable by others requires additional work beyond what is needed to just use the code for personal use. As well, this credit system breaks down if those who use the code do not cite it properly, but such lack of citation is not uncommon as the norms for citing software are still developing.

Supporting users is a significant problem in all of FLOSS, as limited developer time means developers may not be able to provide help to users. Projects often rely on community to answer questions or develop various levels of documentation. A few products may be popular enough to attract commercial companies who can sell services, but many will still be reliant on volunteer support. A further problem is attracting enough developers to keep the software maintained. It is not uncommon for a tool to be developed with grant funding. But when grant runs out, it is not clear who will continue development.

Conceptual Convergence and OSS

FLOSS development has been quite visibly successful and so has inspired or further invigorated many other open movements. A key feature of FLOSS is that the outcomes are open to further use without restrictions. Accordingly, there are many suggestions for making other kinds of products open.

One such movement is the *open hardware* movement. As hardware has a cost, open hardware usually refers instead to making hardware designs openly available, with similar arguments about benefits of access and ability to customize. With developments in distributed manufacturing such as 3-D printing, the gap between designs and objects may be closing, so open hardware may be increasingly interesting and important.

Open access publishing refers to publishing of academic articles and other materials in a way that makes them available to readers without financial or legal barriers to use. Examples include a variety of Open Access journals as well as a variety of institutional or topical paper repositories (e.g., arXiv in physics and related fields). Open access is sometimes mandated by institutional or funding agency policies, e.g., the papers published with support from the US NIH should be made available in PubMed, the NIH's repository. Because publishing does have costs (beyond reviewing and editing that are usually donated by community), it is not uncommon for an open access journal to charge authors for publishing.

Open access may benefit society by speeding use of research results and so the progress of science. It also allows novel approaches to using articles, e.g., machine processing large collections to automatically extract facts and relationships. As with free versus open source software, there is a split in the OA community. A part of the OA movement argues that results of scientific research should be available as a matter of right, sometimes more specifically because taxpayers have already paid for the research by supporting researchers. Others suggest that open access is simply a better approach to publishing because it speeds up the uptake of research results and so the progress of science and are therefore more pragmatic about how it is accomplished (e.g., via author deposit of preprints).

There are ongoing attempts to make other kinds of material open. For example, MIT's Open Courseware initiative provides access to open collections of teaching materials, which can be found in other repositories as well.

Open data means making data collected as part of scientific research or from government administration freely available to support future research, again with arguments about speeding future research, reducing its cost or improving the auditability of research. As in other cases, there is an argument that data created with public funding should be available to the public. There are now many data repositories to support data sharing (e.g., Dataverse, Dryad). However, data are much more diverse than articles and can be quite voluminous, making them problematic to store, index, search, or retrieve. There are also concerns that data by itself may be difficult to understand, with possibilities of misinterpretation or even misuse. Finally, if the data concern human subjects, there are issues of privacy that need to be considered.

Finally, the *open science* movement makes the argument that other products of the scientific process should be openly available. The issues here are difficult, as it is more problematic to share intermediate results that have not been vetted and on which the original authors may still be working.

While the previous set of movements concern the outputs of research, other movements have developed open processes for involving contributors. For example, a handful of publication outlets have applied the open development method used for software for papers. In such a system, authors post papers and the review comments and responses are open.

Citizen science – research projects engaging the public as contributors to science in fields like astronomy, ecology, and even genomics – has recently received increased attention, even though the concept is at least a century old. Broadly defined, citizen science is a form of research collaboration that involves volunteers in producing authentic scientific research. For example, citizen science research might engage volunteers as "sensors" to collect scientific data, as in the eBird project that collects bird sittings from amateur bird watchers and makes them available for research, e.g., to identify the effects of climate or habitat change on bird populations. Other projects involve volunteer "processors" to manipulate scientific data or to solve data analysis problems. For example, the GalaxyZoo project has volunteers classify the morphology of galaxies from space telescope pictures and uses the classified data to test hypotheses about galaxy evolution. Volunteers can potentially be involved in any of the processes of a scientific project. For example, the Polymath Project allows interested individuals (in practice, those with a solid background in math) to take part in mathematics research, by contributing to the proof or discussion of some open conjecture.

Involving volunteers in a project enables a new approach to research, cumulating the contributions of many individuals (Bonney et al. 2014) and taking advantage of uniquely human competencies. To produce sound science, citizen science projects must verify the quality of the research activities and data (Wiggins et al. 2011), which distinguishes them from many other forms of collective content production. Some argue that the public should be involved as well in setting goals for research. However, consideration of motivational implications raises questions about why others would want to be involved if they do not already share those goals.

In addition to its intrinsic merits, FLOSS development has attracted great interest because it provides an accessible example of other phenomena of growing interest. For example, many researchers have turned to community-based FLOSS projects as examples of virtual work, as they are dynamic, self-organizing distributed teams comprising professionals, users, and others working together in a loosely coupled fashion (von Hippel 2001; von Hippel and von Krogh 2003). These features make FLOSS teams extreme examples of self-organizing distributed teams. While the features of community-FLOSS teams place them toward the end of the continuum of virtual work arrangements (Watson-Manheim et al. 2002), the emphasis on distributed work makes them useful as a research setting for isolating the implications of this organizational innovation.

As well, they are not inconsistent with the conditions faced by many organizations when recruiting and motivating professionals or developing distributed teams. As Peter Drucker put it, "increasingly employees are going to be volunteers, because a knowledge worker has mobility and can go pretty much every place, and knows it... Businesses will have to learn to treat knowledge workers as volunteers" (Collins and Drucker 1999). As a result, research on FLOSS development offers lessons for many organizations. Crowston (2011) notes a number of possible lessons for organizations from FLOSS development, e.g., value of making work visible as a basis for coordination and the possibility of alternative approaches to leadership.

Finally, many projects combine both open products and an open process, what are sometimes called *open contribution* projects. A particularly prominent example is Wikipedia. There are similar open communities in which users provide open multimedia contents, e.g., YouTube, MySpace, del.icio.us, Diggit, Twitter, and Facebook. As a related development, given the importance of giving credit as a way to motivate contributions, the field of altmetrics is developing to provide ways to count contributions in different modes.

Conclusion

To summarize, FLOSS technically means simply software released with source code. However, often the process of software development is also open. FLOSS software is widely used, including in science, and FLOSS has parallels of open products and open processes in numerous other domains, particularly in science.

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Participation in Convergence Research

Batya Friedman

Contents

Abstract

Based on established principles and practices, this chapter provides a vision for participation within the convergence research program. To begin, a rationale for broad-based participation beyond the scientific community is established and a succinct characterization of participation provided. Next, dimensions for

B. Friedman (✉)
Information School, University of Washington, Seattle, WA, USA
e-mail: batya@uw.edu

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determining who or what warrants participation, challenges for participation that emphasize process and method, and responsibilities of those conducting research with participants are discussed. The chapter concludes with a discussion of the possibility that participants might say “no” to aspects of convergence and a reflection on responsible innovation.

Introduction

Convergence posits a single coherent system of knowledge and technology for human beings and the natural world. Corralled into a single sentence, the convergence program might be defined something like through a holistic approach that unifies nanoscale technologies with integrated systems and information universes, the convergence program seeks to improve the lives of individual people, societies, and the environment while operating at societal and global scales and accounting for human values. It is a bold and transformative program. And one that fundamentally cannot be carried out by scientists, technologists, and engineers alone. For key to the convergence program are the values, experiences, societies, and natural world in which human beings live and create meaning. Moreover, not only for today’s peoples and nature but also for generations of people not yet born and nature not yet realized.

Any meaningful discussion of convergence must take seriously the scope, scale, penetration, and interaction of the technologies proposed: billions if not trillions (if not more) of sensors under the sea; on the land; embedded in the skies, in people’s bodies, in creatures’ bodies, in public buildings, in open spaces, and in private places; on cars, planes, buses, trams, trains, scooters, space ships, and transportation systems not yet imagined; throughout government agencies, military agencies, educational agencies, religious institutions, corporations, nonprofits, and grassroots organizations; and underpinning global communication and interpersonal connection. All are interconnected, networked, and stored eternally (or so it is hoped). This is the technological landscape in which convergence will be carried out. Others in this volume elaborate on the technical details; this broad technical characterization will suffice for purposes of considering participation.

Given this expansive landscape, numerous questions emerge. How does the scientific community ensure, or at least increase the likelihood, that the convergence program will by and large provide benefit rather than harm? Benefit according to whom? And benefit of the sort that those who live in this instrumented new world would welcome? What standing, if any, does nature have? At the heart of such questions is the recognition of a delicate balance between commitments at some level to a common humanity and natural world and an understanding of a legitimate and deep diversity among peoples’ and societies’ experiences, worldviews, and corresponding values.

Important for a program on convergence, scientists, technologists, and engineers cannot assume a priori that they understand the views and values of the people, cultures, societies, other species, and even the planet that their work will touch, potentially changing forever. To do so risks, at a minimum, a sort of technical arrogance and, beyond that, the very success of the enterprise. For to misjudge what is important to people in their lives and to deliver technical systems that at best ignore and at worst run roughshod over, those concerns is to fall short of the key goals of convergence.

Within this framing, participation by those implicated by convergence is not a luxury. Rather, it is essential for good and responsible innovation and design. Moreover, while important at all levels, such participation is critical especially for the development of foundational knowledge and infrastructure – as what can be built later depends to a good degree on what has been enabled (or not) at these levels. This chapter draws on established principles and practices to provide a vision for participation within the convergence research program. Far from complete, it comprises more a series of signposts (and, at times, precautionary warnings).

Participation: A Succinct Characterization

According to common dictionary definitions, participation entails *the action of taking part or becoming involved in something*. That is a good first approximation.

Going further and with an eye toward the convergence program, such involvement could occur in a variety of ways including but not limited to: being observed, sharing perspectives, sharing expertise, collecting and sharing data, providing critiques, sharing control in the design process, contributing to goal setting, and inspiring change. In some forms, participation can be quite passive. Automatic monitoring of the insulin level and mobility of persons with diabetes as part of a public health intervention is a case in point. Automatically tracking the location and social encounters among people through their cell phone GPS data or among bats through collaring and echolocation to study cross species social networks and community structure are two more cases. In other forms, participation requires more active engagement, such as meetings around climate change with community members to discuss impacts and implications of a proposed instrumentation of a watershed or co-design activities with community members to envision the specific design of that socio-technical system (e.g., sensors to monitor water flow or lack thereof in seasonal creeks, citizen data collection, and reporting of soil erosion and mud-rock flows in rural areas). In some situations, participants may experience their participation as meaningful in which genuine, useful contributions have been made, in other situations as token.

Participation can occur wittingly – that is, by the intent and awareness of the participant – or unwittingly when participants are unaware they have contributed data, shared expertise, provided feedback, shaped goals, or otherwise taken part (Vines et al. 2013). For example, people going about their activities on public streets may unwittingly have their images captured by corporate security cameras, police body cameras, or satellite maps. Or digital device users, who select items from among a set presented to them, arguably may unwittingly be providing feedback about design choices.

In addition, participation may or may not come with the power to influence outcomes. Some forms of participation explicitly attempt to democratize the technical and engineering process and to share control for outcomes among participants. Historically, participatory design was of this ilk (Floyd et al. 1989). Other forms of participation while still engaging rich contributions in terms of observations, participatory data collection, and expertise do so within a structure in which scientists, engineers, and designers retain control over goals, decision-making, design outcomes, and implementation.

Rich traditions in participation and technology design can be found in action research (Hayes 2011), human-computer interaction (Carroll and Rosson 2007; Vines et al. 2013), participatory design (Floyd et al. 1989; Simonsen and Robertson 2013), urban planning (Klosterman 2013), and value sensitive design (Friedman et al. 2006; Yoo et al. 2013), among others. These research and design communities form the backdrop for the material that follows.

Who or What Warrants Participation

Who or what warrants participation in convergence? One way to answer this question is: those who will be implicated by convergence. Yet, given the scope of the convergence program, such participation would be vast. Some tractable means are needed to circumscribe the groups that warrant participation and how to select representatives from among them. The literature on stakeholders from information management and environmental management provides some direction. However, such work typically presumes organizational structures that may not apply to the wide-ranging convergence program. Technologies such as the Internet and cloud computing already press beyond organizational and even national boundaries. How much more so will the technological systems envisioned by the convergence program.

There are numerous dimensions to consider when determining participant and/or stakeholder involvement. Toward providing some pragmatic guidance, here are several.

Direct and Indirect Stakeholders

Value sensitive design calls attention to two broad stakeholder roles, *direct* stakeholders who interact directly with a technology or its output and *indirect* stakeholders who do not touch the technology but are nonetheless significantly implicated by it (Friedman et al. 2006). For example, a convergence system that places sensors (including cameras, GPS, and audio) on wolves in the Pacific Northwest mountains in the United States to monitor wolf migration and mating patterns at a minimum has direct stakeholders: (1) the scientists studying the wolves; (2) the manufacturers of the sensors, cameras, and other equipment; and (3) the wolves, themselves; indirect stakeholders at a minimum would include the ranchers whose land, livestock, and personal data might be captured by the sensors as the wolves travel across their ranches.

Accounting for Generations: Youth, Elders, and In-Between

The scope and depth of the convergence program suggests research and engineering activities that may span decades and may affect different age groups in different ways. Technological interventions that today's elders may find foreign or objectionable may be ready to hand for tomorrow's elders. Engineering solutions that link older and younger people will need to account for the perspectives and preferred ways of interacting for diverse age groups (cf. Yoo et al. 2013).

Accounting for Gender: Men, Women, and Others

However gender is situated with respect to biology and culture, a vast literature documents differences in the lived experiences of men and women as well as points toward other expressions of gender. While gender may seem an obvious dimension that needs to be accounted for, it is still too often the case that western science and engineering research and design work is conducted with primarily male participants, particularly in early stage technical research where foundational decisions are often made about viable directions.

The Artists and Humanists

Historically, artists and humanists have tapped into the human condition, documenting and expressing the depth and breadth of human experience. Eminent biologist E. O. Wilson (2014) argues for the uniqueness and importance of the humanist perspective in his recent reflections on the meaning of human existence. Bringing the perspectives of artists and humanists into the convergence program is one important check on inadvertently engineering dehumanizing technology and solutions.

Vulnerable or Marginalized Populations

Certain populations by virtue of their circumstances, resources, skill sets, and other reasons may be at greater risk than more mainstream populations to experience harms from societal change of the sort proposed by the convergence program. Correspondingly, these groups may also be positioned to experience special benefits. Thus, understanding the situations, perspectives, and values of these groups is critical; their views may surface additional challenges, unanticipated benefits, and previously unidentified harms. Providing any specific list of potential vulnerable or marginalized populations runs the risk of offending groups, either by their inclusion or by their exclusion. Moreover, any list of groups would necessarily be incomplete. A better process might allow for groups to self-identify. That said, naming no groups misses an opportunity to legitimate at least some vulnerable or marginalized populations and to help bring them into the conversation. Acknowledging the former and mindful of the latter, some possible groups include: homeless, immigrants, mentally ill, migrant communities, racial or ethnic minorities, the extreme poor, and victims of domestic violence.

Indigenous Worldviews

Indigenous worldviews point to non-Western ways of knowing and being in the world. These worldviews are important to the groups that hold to them and for the larger human community. Like biodiversity for the natural world, for our cultural world, they are a wellspring of ideas, orientations, beliefs, and ways of being that enrich human society as a whole. If not careful, homogenizing forces within convergence and other science could place the vitality and vibrancy of these worldviews at risk.

Crossing Culture

Whether crossing continents or crossing the street, different cultural groups may have different means of expression, views, perspectives, and ways of organizing human activity. To the extent that activities in the convergence program will cross cultural boundaries, attention to these different cultural perspectives will be essential. Specifically, for participatory activities, attention will need to be paid to culturally situated communicative acts. For example, in some cultures providing direct negative feedback or asking pointed questions would be considered rude, perhaps even hostile; conversely, in yet other cultures, less direct forms of communication might be viewed as obscuring information and uncooperative behavior. Researchers and designers will need to take communicative norms like these into account when designing culturally appropriate ways to obtain feedback from participants.

Power Relations

Among direct and indirect stakeholders, there will be those groups of stakeholders who sit in more powerful positions in society and those who are less powerful. Attention needs to be paid to power relations, both in terms of who is included in participatory activities and how that participation occurs such that those with greater power do not overwhelm those with less.

Religious, Spiritual, and Metaphysical Diversity

People's religious, spiritual, and metaphysical beliefs structure their experience of the social and natural world. A program as comprehensive as convergence will need to be sensitive to different belief systems, including the appropriateness of instrumenting certain natural places or species that are viewed as sacred by some groups.

As reflected in some of the participant dimensions discussed above, the holistic approaches and technical systems of the scope envisioned by the convergence research agenda reach far beyond human beings to implicate other nonhuman entities. Here are four.

Nonhuman Species

Convergence intentionally targets nonhuman species that span a spectrum of sentiency and intelligence – from elephants and whales, to earthworms and ants, to tiny microorganisms, and perhaps beyond. In sorting out participation and on what terms, both homocentric (valuing nonhuman species because of what these creatures offer human beings) and biocentric (valuing nonhuman species in and of themselves and from their own perspectives) orientations are likely relevant (cf. Kahn 1999). How to account meaningfully for the perspectives and concerns of nonhumans remains a thorny question.

Earth

Turning to the planet Earth, similar considerations apply. From both homocentric and biocentric orientations, there may be diverse perspectives for how convergence might proceed. For example, some might view monitoring the oceans to prevent overfishing or delving into the genetics of protozoa to seek a basis for cancer drugs as highly beneficial for humanity. At the same time, some might view certain places – mountains, valleys, or rivers – as sacred and that instrumenting, measuring, and analytically describing such places would defame them. Others such as Edward Abbey (as quoted in Berry 1987, p. 146) argue for the existence of some "absolute wilderness," which "through general agreement none of us enters at all." And still there is the question of in what ways it might be meaningful to ask: "What does the Earth want?"

Social Robots

Other nonhumans are technological entities: social robots or some variant. Such technical systems act with some amount of autonomous agency and often project social cues "as if" they were social others (cf. Reeves and Nass 1996). One question concerns whether these social robots in and of themselves are entitled to moral consideration and, correspondingly, a say in how they participate in a convergence program. Second (and to some extent orthogonal to how one answers the first question), empirical evidence suggests that people who interact with social robots experience them in certain ways as social beings and ascribe certain sorts of moral standing to them. What, then, are the implications of these considerations for the participation of social robots?

Superorganisms

The construct of a superorganism – an organism consisting of many organisms – may be relevant to the convergence program in at least three ways. First and in its most frequent usage, in terms of a social unit of eusocial animals, where division of labor is highly specialized and where individuals are not able to survive by themselves for extended periods of time (e.g., ants). The kind of interdisciplinary work across levels of nature is particularly well suited to a study of eusocial animals in situ and their interrelatedness with other species and ecosystems. Second, one potential outcome of the convergence program may be the discovery that superorganisms are more prevalent than previously believed and, perhaps, even human beings will be reconceptualized as such. And third, extending the construct of superorganism by analogy to distributed cognition, perhaps through new convergence technologies (e.g., brain-brain and brain-machine interfaces, new communication technologies), a brain (or mind) may consist of many brains (or minds), where the division of cognition is highly specialized and where individuals for at least some sorts of cognition are not able to think by themselves but rather think in a collective manner.

Challenges for Participation: Processes and Methods

The kind of world the convergence research initiative envisions – in scope, breadth, instrumentation, and integration – has few counterparts in modern-day society. Moreover, for large-scale technological change, it is notoriously difficult to predict the actual impacts and ways in which new scientific knowledge, technology, and infrastructure will be appropriated. Writing, aqueducts, the printing press, and the Internet are cases in point. Looking backward, for any of those technologies, it is hard to imagine what sort of participation from stakeholders would have been helpful in setting goals for developing and implementing those technologies. Looking forward with respect to convergence requires recognition of similar challenges and limitations.

Turning now to explore five practical challenges for realizing participation.

A first challenge entails who initiates participation. Typically, in research and design endeavors, the scientists, engineers, and designers involved in the project initiate and invite participation from groups they have targeted for specific aspects under study and development. Such processes make good sense as those developing the science and technology know a good deal about when and where participant input would be useful. The discussion above provides some brief guidance for stakeholder dimensions that scientists, engineers, and designers might consider taking into account. That said for a project of the scope of convergence with the potential for significant impact on people's lives, it seems both prudent and responsible to put in place additional processes by which stakeholders – groups or individuals – could initiate participation and have a say in how that participation might be structured. Moreover, the possibility for stakeholder-initiated participation lays the foundation for shared responsibility among scientists, engineers, and designers and those who will benefit or be harmed by the outcomes of the convergence work.

Sampling and recruitment entail another challenge: once stakeholder dimensions have been determined, which specific individuals or entities are invited to participate and how will their participation be solicited. Different kinds of participation at different points in a project may lend itself to different sampling and recruitment methods and processes. Scientists and engineers should follow best practices for the particular methods and processes employed. Though convenient to recruit participants from those nearby – in one's workplace, laboratory, or field site – given the diversity of stakeholders, researchers should be cautious in doing so. The literature is chock full of examples in which participants were selected from among research teams or those nearby only to discover later critical blind spots in the resulting theory, methods, science, and designs (e.g., airbags primarily developed and tested on western men roughly 5 f. 10 in. in height and 160 lb in weight initially resulted in a design that was less safe for smaller-sized people, including small women, people of Asian descent). For convergence research, researchers will need to be alert to representativeness with respect to gender, geography, online access, instrumentation, and many of the other dimensions sketched above.

A third challenge entails barriers to participation. What if scientists, engineers, and designers of convergence were to invite participation from a wide range of groups and individuals through diverse processes and methods (as suggested above), and no one comes? This highlights some form of mutual responsibility, where meaningful, not overly burdensome opportunities for participation exist and at least some individuals and groups take up those opportunities. Scientists, engineers, and designers can do numerous things to make participation attractive to participants – that is, to remove barriers to participation. Among them are: building in some form of direct benefits for participation (e.g., for genetic health applications this could take the form of free testing or free access to resulting software); making data collection as undisruptive as possible (e.g., collecting data in the background through sensors or other digital devices, providing opportunities to provide short responses in situ, holding workshops during the lunch hour close to people's places of employment); providing ways for participants to contribute to science that captures their imagination (e.g., citizen science models that give participants a sense of ownership in the scientific enterprise); ensuring privacy and anonymity as needed (e.g., collecting only aggregate data from individuals who are especially concerned about privacy); covering financial costs incurred for participating (e.g., travel costs); and providing financial or other material compensation especially when a good amount of time or inconvenience is required.

Unwitting participation entails a fourth challenge. Many aspects of the convergence program rely on pervasive, unobtrusive, automatic data collection that is embedded in the background. Entities that enter into these physical and virtual spaces may unwittingly become participants contributing data without their awareness or their consent. Moreover, from the scientific perspective, if participants know that data is being collected about them, that knowledge may influence their behavior in important ways. Further, the sheer number of potential participants may make obtaining consent pragmatically difficult. That said, while some might wish to argue that data collected about activities in public or as part of commerce – be it physical or virtual – is fair game, some unwitting participants may not share this view. Some individuals may value the ability to be out in public, engaged in commerce, civic life, communing with nature but otherwise left alone. These and other hard questions around how to manage responsibly unwitting participation need to be engaged.

In order to account for human values, convergence research will in some way need to engage with participants to garner their insights about the potential benefits, harms, and value implications. Thus, a fifth challenge entails the need to help participants envision the sort of future that could result from convergence. Here, the issue is not so much predicting the future, as it is being able to envision a range of potential futures so that participants can express their views and values about those various alternatives. A few useful methods for this purpose from which to build include: Delphi, Envisioning Workshops, Futures Workshops, and futures prototyping through film, scenarios (such as pastiche scenarios, value scenarios), and simple models. Many more can be found in the urban planning, participatory design, value sensitive design, and action research literatures. That said, none of these methods have been developed to specifically foreground the implications of widespread sensing technology of the scope and scale proposed by the convergence research program. Thus, adaptations of these methods or entirely new methods will likely need to be developed. Moreover, the new methods will need to help participants envision the implications for widespread sensing data that can be merged and analyzed in real time and then reused and recombined in diverse ways at various points in the future.

Responsibilities for Conducting Research with Participants

The particular policies, practices, and norms about what constitutes ethical research reflect not only the laws, customs, and understandings of the society and government of the time but also the type of scientific activities being undertaken. From this perspective, the vast technical scope, breadth, and integration of the convergence research initiative likely will challenge the scientific community's current understandings for how to apply established (at least within a western worldview) key elements of ethical research – respect for persons, beneficence, and justice. Consider that the research community is only now beginning to grapple with the ethics of conducting research with big data. The convergence program will make the current amounts of data seem small. Measurements will be made on increasingly smaller time scales with increasingly broader geographic regions and increasingly greater precision. Many of these measurements will occur in the background, potentially without the awareness of those about whom the data is being collected – unwitting participation. In addition, the convergence program fundamentally is about a holistic and unified theory for human society and the natural world. Thus, the interconnectedness among data sets potentially will be huge. Anticipating those future connections at the time of data collection may be difficult if not impossible, and the impacts of that connectedness unknowable in advance.

Some critical questions that will need to be addressed are:

- How will the scientific community and potential participants from diverse communities, cultures, and nations come to a shared understanding about what constitutes ethical research with human and other participants in convergence research?
- How will institutional review boards for ethical research become educated about the convergence program and its potential for benefit as well as harm?
- What existing best practices can be adapted for collecting, storing, securing, maintaining, reusing, and repurposing data for holistic analyses? Where these come up short, what new best practices will need to be developed?
- What existing best practices can be adapted for obtaining genuine informed consent from participants, particularly in situations in which data is collected pervasively, automatically, and in the background? Again, where these come up short, what new best practices will need to be developed?
- Given how difficult it likely will be to anticipate the outcomes of interconnected, holistic convergence research, it may become increasingly important for participants to be able to withdraw their data from a collection should they desire. In those instances, what administrative and technical processes will be needed?

These questions only begin to tap the surface. As scientists and participants gain greater experience with the actual practices and implementation of convergence research, other issues and considerations likely will emerge. Alertness to these emerging conditions is paramount.

What if Participants Say "No" to Convergence?

For participation to be meaningful, the views and values of participants must have clout in the scientific, engineering, and design process. This means to some degree sharing control with participants. At the smaller and less controversial levels, this means input from participants could be used to better understand problem spaces, address usability, and functionality constraints and in evaluation processes. Taking participation further, it could be used in problem framing and goal setting: to understand and support individual, family, organizational, societal, and global goals. All of the above presume that at some level, participants have agreed to and embrace the convergence program. But what if participants in reflecting on the goals, processes, and expected outcomes of one or more aspects of the convergence program say, “No, not that for my society – that is not the kind of world I want to live in or want my children to live in.” Then what? How is the convergence program to be respectful of participants’ deeply held values and choices, should those be at odds with the program’s directions (cf. Baumer and Silberman 2011)? For example, some individuals who highly value privacy in public or fear misuse of tracking data by governments or corporations may object to living in an environment instrumented with sensing devices that capture data on their physiology, activities, whereabouts, and other aspects. Or as another example, individuals who choose to live closely connected to the natural world may object to a research program that at its core seeks to sense and monitor the natural world closely and does so in the service of controlling nature. These worldviews and others like them may be in opposition to the convergence agenda. Should circumstances like these arise; how will scientists, engineers, and designers have the tools and skills to generate ways forward that respect these views? What boundaries can be set? What power relations checked or put into place?

A Final Reflection on Responsible Innovation

Hannah Arendt, Wendell Berry, Josef Rotblat, E. O. Wilson, and numerous other intellectual and scientific leaders in various ways have raised the issue of a potential mismatch between human beings’ scientific and technological capabilities and our moral ones. The risk, of course, is that our scientific and technical prowess vastly overreaches our capacity to make moral and ethical use of that knowledge and those technologies. As convergence pushes forward on expanding our scientific knowledge and technical prowess in deep, interdisciplinary ways that cuts across matter from the very small to the galactic, this is an issue the convergence program must grapple with. A legitimate question at all times must be as: is this particular knowledge or technology one that human beings – as individuals and societies’ have the moral capacity to use well? Moreover, this and related questions belong not only to the scientific community but also to the global public. For participation writ large: such questions should be part of an explicit on-going public debate about responsible innovation.

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Personalized and Interactive Literature

Michael Mateas and Noah Wardrip-Fruin

Contents

Abstract
Interactive and personalized narrative – two aspects of interactive storytelling – are familiar as a pair of science fiction visions. The Holodeck, from *Star Trek*, imagines real-time, plot-defining interaction as a protagonist in an immersive virtual world. The Illustrated Primer, from Neal Stephenson's *The Diamond Age,* instead imagines a computerized book which automatically writes custom, multimedia stories for its owner, indirectly contextualizing and commenting on the owner's current life situation and challenges. Neither of these visions yet exists, and some believe that interactive storytelling is an inherently flawed concept. Nevertheless, interactive storytelling is experienced by many people every day. This is most common in computer games but is also experienced through a wide variety of other forms, from hypertext fictions to live performances. Researchers, designers, and authors continue to make progress by focusing on the specifics of particular fictional genres and tropes. This has produced a flowering of approaches and research directions, which are already indicating ways in which interactive storytelling will transform our key experiences of fiction. This chapter focuses on three of these experiences: empathy,

M. Mateas (✉) • N. Wardrip-Fruin
Center for Games and Playable Media, University of California, Santa Cruz, Santa Cruz, CA, USA
e-mail: michaelm@soe.ucsc.edu; nwf@soe.ucsc.edu

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curiosity, and responsibility. Empathy includes our experiences of identification, theory of mind, and social simulation with fictional characters. It is already changing as players, for example, struggle to complete gameplay challenges that mirror those of characters within a game's fiction. It promises to shift further as it becomes possible to, for example, radically customize fictions to facilitate identification with particular characters. Curiosity includes our experiences of speculating about plot developments, character motivations, and the significance of fictional themes. It is already changing as interaction allows audiences to not only speculate but manipulate, investigate, and enact strategies within fictional worlds, receiving feedback that shapes their understandings of the world and what the fiction's systems make possible. It promises to shift further as fictions are developed with a much wider range of possible audience actions and system responses within the key areas of fiction (rather than in the simulation of, e.g., physical movement or resource flows) and as fictions are able to actively reason about means of engaging audience curiosity. Responsibility is an experience that traditional fictions have struggled to create, with both radically experimental and traditional storytellers working to produce experiences that result in audiences reflecting on their own patterns of thoughts, actions, and complicity with the actions of others. Interactive experiences seem to promise an easy way to address this, because audiences choose and take actions. But we are only beginning to see this happening, as research efforts produce fictions that give audiences a broader range of meaningful choices within the key interpersonal action. Future developments in these areas are expected to produce fictions that are more emotionally engaging, that help us make sense of our lives, and even that contribute to positive behavior change – necessitating the development of knowledge about the impacts of the powerful new art forms that emerge, as well as new ethics and aesthetics of interactive storytelling. A product of the convergence of computer science and the humanities, cognitive science and literature, engineering and art, new interactive and personalized approaches to narrative offer insights into future applications of science and technology, as well as into the fundamentals of human nature.

Introduction

Imagine having your own private storyteller. Like the best of literature, film, and theater, your storyteller will sometimes tell you stories with well-drawn, complex characters exploring deep psychological and moral themes, sometimes stories with exciting plot twists and edge-of-the-seat, heart-thumping action and sometimes cerebral stories with puzzle-like plots. But unlike traditional story forms, your private storyteller can change the story in response to your reactions, letting you take a role in the story, or take into account your higher-level direction about the flow and structure of the story. Further, your private storyteller knows what is happening in your life, your current worries, joys, preoccupations, likes, and dislikes and creates stories just for you given your current life situation. This dream of interactive and personalized narrative is a common trope in science fiction, with interactivity exemplified by *Star Trek's* Holodeck and personalization exemplified by Neal Stephenson's *The Diamond Age: Or, a Young Lady's Illustrated Primer*.

The Holodeck – first introduced as the "recreation room" in *Star Trek: The Animated Series* in 1974 and given the name Holodeck in the pilot episode of *Star Trek: The Next Generation* in 1987 – is a room in which a synthetic, physical reality is projected. People using the Holodeck step into a projected storyworld typically as the protagonist, interacting with characters and driving the plot progression through their actions. Much research in interactive narrative has been driven by this vision of first-person storyworld interaction (Laurel 1986; Bates 1992; Murray 1997; Crawford 2004). In contrast, Neal Stephenson's novel *Diamond Age* imagines a computerized book which automatically writes custom, multimedia stories for its owner. The book's goal is to help a child develop into an actualized adult who can effectively pursue their own vision within society. Continuously sensing the world of its owner, it generates custom stories designed to foster self-development given what's currently happening in its owner's life. Unlike the Holodeck, in which the computer controls the other actors and directs the scene, here the computer is more like a novelist, with important roles within the story played remotely by human actors recruited by the book over the network (referred to as "ractors" within the novel). Putting these two visions together, there emerges a model of a computer-based private storyteller that can be a real-time writer, director, and actor, with appropriate interfaces supporting player interaction. In this chapter we describe future directions for *interactive storytelling* grounded in an examination of the current state of the field, using this term to refer to both within-story interactivity and personalization (which can also be seen as a form of interactivity).

But before diving into a description of the future, it is important to understand the pessimism that often surrounds discussions of interactive storytelling, particularly among game designers and researchers. Since games as a media form seem to be distinct from stories, it may seem strange to examine arguments about interactive storytelling made by people writing and thinking about games. However, game-based storytelling is by far the dominant cultural form of interactive storytelling. In fact, most people will only have experienced interactive storytelling in games. So we have this interesting contradiction – games are the dominant form of interactive storytelling while simultaneously games and stories are seen as being deeply contradictory forms.

Within game design circles the game vs. story dilemma is often posed starkly. Games are about interactivity, providing players with systems within which they make their own choices, within which they choose their own destinies. In contrast, stories flow under direction of an author, with characters fulfilling their destinies by traversing preauthored plot progressions. To the degree that a game contains a story, it removes interactive freedom from the player. This problem is sometimes seen as a failure to underwrite narrative events with a simulation. Narrative events are rather triggered parasitically on top of the nonstory simulation (typical game simulations include combat, resource management, and spatial exploration) that actually processes player actions and provides incremental feedback. The player is thus unable to develop mastery and sophistication with respect to their interaction with the story, running counter to the fundamental affordances of games as a medium.

An academic version of this same debate, termed the ludology vs. narratology debate, dominated the game studies community in the early and mid-2000s (Wardrip-Fruin and Harrigan 2004; Juul 2005). The academic version of the game/story dilemma was often established definitionally. The standard narratological definition of narrative is that it consists of a *story* composed of an ordered sequence of objectively occurring story events, a *focalizing narrator* who is telling the story (potentially out of order) from a particular subjective point of view, and a *discourse* which is the subjectively described out-of-order presentation of the story made by the narrator to the narratee (reader/viewer). Starting with this definition of a story, games are found to be inconsistent with narrative; the player is composing a sequence of events through her actions rather than experiencing already-composed events through a focalizer, with the strong distinctions between authors, narrators, and narratees breaking down. Thus games, while they might sometimes contain stories, are not themselves stories and should not be viewed primarily as a storytelling medium.

So on one side we have a vision for interactive storytelling in which computers become personalized storytellers, offering deeply interactive and personalized narratives. On the other side we have games, which arguably provide the deepest form of interactivity yet found by underwriting interactivity with complex dynamic systems. Yet many game designers and scholars remain deeply ambivalent about (and sometimes outright hostile toward) the potential for games as a storytelling medium. And at the same time game-based storytelling is undergoing a renaissance. Commercial storygames are exploring complex themes such as guilt and responsibility (e.g. *Spec Ops: The Line*, *The Walking Dead*). The two major North American venues for independent games, Indiecade and the Independent Game Festival, both recently added narrative award categories in response to the wave of exciting storygame experimentation taking place in the indie community. And the Game Developers Conference, the largest worldwide gathering for game developers to discuss their craft, has recently added a Narrative Summit to their schedule. So how do we make sense of these contradictions? How is progress in interactive storytelling possible?

The most common rock upon which discussion of interactive storytelling founders, and the biggest impediment to progress, has been a common insistence on a single universal theory of interactive storytelling, typically backed by a formal definition of narrative. Many arguments in game research and design start with a formal definition of narrative, such as the narratological story/discourse model described above, and draw conclusions about what is and isn't possible to achieve based purely on definitions. Research in technical approaches to story generation and experience management sometimes starts with overly simplistic universal definitions, such as that a narrative is a causal sequence of events, and then have difficulty creating systems that support engaging story experiences with the cultural sophistication and interest found in noninteractive story forms.

Attempts to "solve" the problem of interactive storytelling through formal definitions and universal theories mistake the nature of the challenge. Interactive storytelling is not a well-posed formal problem amenable to solution by the rational application of appropriate definitions and problem-solving methods but rather a *wicked* design problem, in which the attempt to create interactive stories changes our understanding and definition of what an interactive story is (Rittel and Webber 1973; Mateas and Stern 2005). It is through creating interactive stories that we discover the variety of ways in which narrative pleasures and affordances are changed and enhanced through interactivity. Progress therefore requires a grounding in concrete narrative genres, traditions, and tropes. Specific narrative traditions, such as action movies or the German bildungsroman, and specific tropes, such as unreliable narrators and love triangles, provide detailed guidance on narrative structures and progressions that lead to specific audience effects. And this is how the creators involved in the current flowering of interactive storytelling are making progress, by ignoring the deadlock brought about by attempts to build universal theories, and engaging in the research and creation, engineering and craft required to build upon and experiment with specific narrative traditions, inventing new possibilities for interactive storytelling.

As this suggests, interactive storytelling is a deeply interdisciplinary endeavor. It requires technical work – and future progress will require deep technical innovation – but it cannot be guided solely by the methods and values of engineering. The genesis, guidance, and evaluation of interactive storytelling projects requires knowledge about story form, construction, experimentation, and critique that is the domain of the arts and humanities. This deeply interdisciplinary character is something that interactive storytelling has in common with other forms of *computational media* that are already transforming how we present ideas, learn, interact socially, and entertain each other (Wardrip-Fruin and Mateas 2014).

In this chapter we look at the future of interactive storytelling from a similarly interdisciplinary perspective, referencing fictions and research from a range of traditions, some of them (such as game design and the psychology of fiction) already explicitly interdisciplinary themselves. We examine this future primarily through the lens of the different kinds of audience responses interactive storytelling can produce. Rather than focus on technical agendas and story taxonomies, we focus on the key experiential categories of empathy, curiosity, and responsibility. These are shared with traditional narrative but can become radically transformed and expanded in interactive form. In the last section of this chapter we present future directions for interactive storytelling based on these experiential categories.

Empathy

One of the key experiences we have with traditional fictions could be called *empathy,* to think and feel what characters within the story are thinking and feeling. The traditional dramatic qualities of identification, catharsis, and emotional closure are part of empathy. Interactive storytelling can produce this experience in the traditional ways – and also can alter it.

One aspect of empathy is fiction's activation of our "theory of mind" – our thinking about what other people know, think, and feel and how they might react to that. As Lisa Zunshine argues in *Why We Read Fiction,* fictional narratives "rely on, manipulate, and titillate our tendency to keep track of *who* thought, wanted, and felt what and *when*" (Zunshine 2006, 5). Interactive stories currently do this using the traditional tools of fiction, such as the cinematic "cutscenes" that play out in many video games.

For example, consider a popular game such as *Uncharted 2: Among Thieves. Uncharted 2* builds on the narrative tradition of action movies, using character relationships and situations, as well as cinematic techniques, common to such movies. Let us look at a particular cutscene that builds on the tropes of love triangles and the romantic tension between ex-lovers. The main character (Nate) stumbles upon a reporter (Elena) and her cinematographer (Jeff). There is some physical action, such as when Jeff tackles Nate before realizing he's not a threat, and some dialogue exposition, such as when Nate learns that Elena is in the area tracking a war criminal named Lazarevic. But the real action requires the player to use theory of mind to understand – based on clues in their physical action, tone of voice, and expressions – what the characters are thinking. We see Nate and Elena's surprise to find an ex-lover in the war zone. We can see Nate being evasive with Elena because he is in pursuit of the same goal as Lazarevic. And we see Elena's anger when she realizes she's been deceived by Nate – as his current partner, Chloe, arrives and says they have to keep going if they want to stay one step ahead of Lazarevic – as well as Chloe's amusement and Elena's discomfort at the romantic tensions between the three of them.

Another way of putting this is that, as Keith Oatley argues, fictions are prompts for "social simulations" we run in our heads (Oatley 2011), for imagining what is going on in the heads of others, what that might feel like, and what might happen next. And interestingly, this seems to impact how we experience the rest of the world. Raymond Mar has shown that the more fiction people read, the better they are at emotion perception and social cognition (Mar et al. 2006). Geoff Kaufman and Lisa Libby have shown that when we strongly identify with fictional characters we don't just see from their point of view – we can take on their experiences as our own, and this can influence our future behavior (Kaufman and Libby 2012). In understanding the cutscene described above, a player is bringing the same mental machinery of social simulation to bear as she would in noninteractive narrative.

However, there have been no comparable studies exploring the considerable new possibilities for empathy afforded by interaction in interactive storytelling. Interactive stories not only prompt simulations in our heads but are on some level simulations themselves. Most of the physical action in *Uncharted 2,* for example, takes place not in cutscenes but interactively. When we play the game, Nate jumps, climbs, runs, shoots, and takes other actions under our control. In other games, we control other types of simulations – perhaps of the flow of resources (in a game like *Civilization*) or even of the tempo-driven performance of a quartet (in a game like

Rock Band) – though currently most games with strong characters focus on physical simulation. Just as with our internal social simulations of fiction, we imagine possible futures of these simulations, thinking about what might happen next, as the following section of this chapter will discuss. And we also struggle with the simulation. It presents *challenges,* which are embedded in the fictional world, presented as experienced by the characters. We work, through our control of the characters, to try to overcome them.

For example, in *Uncharted 2,* Nate and Jeff are established in somewhat adversarial roles. Then Jeff is shot in the gut. He's bleeding and needs to be taken to safety. It's Nate's job – and therefore the player's – to carry him. Within the physical simulation of the game, the player is not allowed to use many of the actions she is accustomed to using – no running, no jumping, no climbing, no two-handed weapons. Thus the physical simulation challenge given the player mirrors the narrative challenge given Nate, making the player feel the same sense of fear, challenge, and accomplishment as the fictional character. After the player has successfully carried Jeff through the dangerous area, in a cutscene Lazarevic arrives and executes Jeff, making the hard-won victory meaningless.

Interestingly, at this point, some players feel genuinely angry with Lazarevic. This is certainly not because he is a well-drawn villain in the terms of traditional fiction. (He's closer to a cardboard cutout.) Rather, it is because there is something compelling, in ways we are only beginning to understand, about fictional worlds that are driven by our interaction. We are "sutured" to most fictional worlds quite loosely, while interaction can interpellate us into the world, making the feelings about what happens there more personal. In this case the fictional character Nate feels outrage at Jeff's execution. And the player shares this outrage more viscerally than she would purely through the mental simulation of traditional fiction; the player is outraged because their actual real-world accomplishment has been nullified in a manner mirroring the fictional events of the story.

This brings us back to empathy, and particularly to Kaufman and Libby's work on experience taking. One striking thing about their research is that they found the design of the fiction is actually quite important. For example, they studied students just before the 2008 primary election, having them read different versions of a story about a student struggling to vote, and found that students identified noticeably more strongly with the protagonist of a story who went to the same university as they did (rather than another nearby school). They also found that, while the reported intention to vote was very similar after reading the stories, 65 % of readers of the highest-identification story voted, but only 25–43 % of those reading other voting stories (Kaufman and Libby 2012). Researchers Jorge Barraza and Paul Zak have found a neurochemical mechanism for such effects, showing that stories can cause the release of oxytocin, a neuropeptide associated with empathy and trust (Barraza and Zak 2009). Experimental subjects displayed more empathetic behavior, such as donating money to a stranger, after seeing an emotional story. Subsequent studies found that areas of the brain associated with theory of mind and empathy are activated as people experience a story. Interactive storytelling will continue to build on these effects, discovering new approaches for creating empathy.

Curiosity

Another of our key experiences with fiction is *curiosity.* This is perhaps most obvious in genre fiction. We form hypotheses about who committed the murder in a mystery. We imagine how the hero can possibly succeed against overwhelming odds in a thriller. We wonder what the consequences will be when speculative fiction posits new technologies and social organizations. But as Zunshine and others argue, the hallmark of literary fiction is a similar sort of curiosity, about interior thoughts and feelings, and about their consequences.

And just as with empathy, interactive storytelling can create the experience of curiosity using fiction's traditional approaches. Consider *Shade,* by Andrew Plotkin. *Shade* is an example of *parser-based interactive fiction*, the descendent of the text adventure (Montfort 2003). The player reads textual descriptions of the world and takes action by typing commands. *Shade* draws on the conventions of the short story and the trope of the unreliable narrator. At first the situation seems simple – the unnamed main character (controlled by the player) is in their apartment getting ready for a trip to a desert rave. We can explore the apartment, satisfying our curiosity about what will happen if we look in the mirror (we see shadowy space beyond the mirror rather than our own reflection) or turn on the kitchen sink (nothing comes out; apparently it hasn't worked since we moved in). We can make progress on getting ready, by following the steps on our list – but things don't go as we expect. For example, we can try to vacuum up the sand on the floor, but more of the sand just spreads around.

As this sense of strangeness grows, *Shade* foregrounds three kinds of curiosity that are important in interactive storytelling. The first is curiosity *in the storyworld,* as we wonder what is going on and what will happen next. The second is curiosity *about the storyworld,* as we wonder what *Shade* is about and how to interpret its themes. These are both standard types of curiosity about fiction. But *Shade* also prompts a third curiosity *about the interaction,* as we wonder about the system, what commands will be accepted, and how they will be interpreted. This third curiosity is interesting in part because it changes our experience of the first two.

For example, at a certain point *Shade* suggests that the main character is hungry. We interpret this suggestion, become curious about what will happen if we (the character we are identifying with) attempt to eat, speculate about what objects in the storyworld might enable eating (and where they might be), and then become curious about what actions that we can take through the system might allow us to test our speculations. As we search the apartment, we find crackers in the cupboard, which might confirm our speculations. But when we pull off the stuck box top, white sand sprays out. This is a surprise, but then a revelation – one that informs our ideas of what is going on (the first level of curiosity) and what the story is about (the second level). We discover that the narrator in *Shade* is unreliable, that the view of the world we see through the narrator's eyes does not reflect what is really happening in the storyworld. By the end of the experience it becomes evident that the apartment is a hallucination, that the narrator has already gone to the desert rave, become lost, and is dying of thirst in the desert.

It's a more powerful revelation because it comes not just through our reasoning but also through our action.

In other words, curiosity *in action* enables experimentation, through which we can build an interpretation of the fiction and a model of the system, so that our actions can both reveal and shape the story. This can happen when we identify with a character we control – as in *Uncharted 2* and *Shade* – but identification is not required. For example, in *The Sims* and its sequels we often control a multicharacter household, operating from a somewhat remote "God's eye" perspective. Even though we are unlikely to identify strongly with any of these characters, we are still very curious about the interaction, about the possibilities of the underlying system.

Further, simulation is just one way that interactive storytelling can engage our curiosity. The tradition of literary hypertext fiction has particularly foregrounded the creation of complex fictional structures (nodes, links, and maps) that engage our curiosity in interpreting their shapes and our location within them (Hayles 2008). Storygames embed story elements in an explorable storyworld to piggyback narrative on curiosity-driven spatial exploration. Rather differently, the tradition of alternate reality games (ARGs) – which disperses a fictional experience through everyday communication channels, physical locations, and even live performances – engages our curiosity about what is inside and outside the fiction, and how interaction is possible.

Responsibility

Conventional fiction excels at producing experiences of empathy and curiosity – but these are not the only ambitions of fiction's creators. One experience that creators have struggled to produce in many ways, from the experimental drama of *Mother Courage and Her Children* to the realistic narrative of *The Jungle,* is one that we might term *responsibility*. For example, a film like *The Bicycle Thief* works to raise the question of our responsibility, specifically of our complicity in systems that produce crushing poverty. A more contemporary work like *The Wire* connects this to systems of policing, education, and politics in modern U.S. cities. Many audience members empathize with these fictions' characters and are curious to learn what will happen to them. But when it comes to questions of responsibility, creators face – perhaps inevitably – the fact that their audiences did not, in fact, carry out any of the particular acts that these fictions portray (even if they have carried out analogous acts, or acts that support the systems that produce the suffering portrayed). It is hard to get people to feel responsible.

We might think that interactive media forms, such as games, can address this easily. By definition, they open possibilities for the audience to take action. But in many games, the possibilities for action are strictly delimited. A player of *Uncharted 2,* for example, has two choices: to carry out some version of the actions currently required by the game (e.g., climbing a particular wall, fighting a particular enemy) or to cease making progress in the game. In other games, such as *The Sims,* the choice of actions is much broader. But the characters often feel like playthings, rather than people, in part because of their simplicity (they are defined by a small set of traits and they seek to satisfy simply constructed resource needs, such as food, rest, and cleanliness) and in part because the underlying system has few ways to put them in narrative situations that would evoke our empathy. It is not uncommon to set Sims on fire, or drown them in swimming pools, or deny them the ability to urinate, and the games in the series are designed to respond amusingly.

Of course, there are exceptions, and these can be telling. For example, "Alice and Kev" – a playing of *The Sims 3* told through a screenshot-heavy blog by Robin Burkinshaw – manages to convey an engaging story about poverty and homelessness (Burkinshaw 2009). Burkinshaw sets up Sims without resources, or the means to acquire them, and then lets the simulation of *The Sims 3* make most of the decisions. The results are compelling because the underlying simulation is all about resources, providing many ways that characters can try (and fail) to get their needs met, and many ways for other characters to respond – for example, community members ostracizing Alice because she smells bad, police picking her up when she sleeps where she's not supposed to (especially after curfew). There aren't many meaningful actions for the player to take, but Burkinshaw's nonaction continually raises a compelling question: "Why are you letting this happen?" And this, of course, is also the question that poverty and homelessness asks of all of us.

But if we want to move toward interactive stories that evoke responsibility in action (not just inaction) and that allow us to take those actions in areas beyond the movement of resources and physical objects, we need approaches that allow for a wide variety of actions in the areas that are key to fiction. One such key area for fiction is social relationships, and researchers in the academy and industry have been creating new AI frameworks (sometimes discussed as "social physics" engines) to explore its possibilities (Evans and Short 2014; McCoy et al. 2014). These frameworks have enabled experimental games, such as *Prom Week* and *Blood & Laurels*.

Such games typically have casts of characters involved in high-stakes social interaction – whether it will determine who goes to the high school prom together or who will be the next emperor of Rome. There is a wide range of social actions available for players to take within these fictions. They may feel empathy with a character's situation, identifying with them in a way that makes them want to take an action. Or they may be curious about how one character might react if a second character takes some action with a third character. The underlying social simulation enables the creation of a fiction, based on the audience member's actions, that reflects insights gained through these kinds of engagements with the storyworld. Further, the game's responses actually teach the player something more about how the storyworld works – who different characters are, what the nature is of different situations – which can inform future actions. And this combined ability does seem to evoke a sense of responsibility from a variety of audiences. Reviewers approaching these from both game perspectives and story perspectives have written about the dawning realization that manipulating the characters feels wrong, that negative strategies aren't the only way to accomplish things, and about feeling bad about themselves when reflecting back on their actions.

The experience of responsibility with interactive storytelling is not about making players feel bad about themselves. But that reviewers felt this way, after adopting relatively negative strategies for dealing with interactive characters, shows that interactive storytelling approaches can evoke responsibility – they felt genuinely responsible for the stories created through their play. Further, it shows that responsibility opens up new opportunities for self-reflection (another key experience pursued by some creators of fiction). The further development of the technologies, designs, and writing techniques of interactive storytelling will create new opportunities for evoking the experience of responsibility.

Future Directions

There are a number of exciting future directions for creating new, augmented versions of the key experiences of empathy, curiosity, and responsibility in interactive storytelling.

Within existing technologies, creators will continue to develop new rhetorical strategies for creating these experiences. This will involve new ways of juxtaposing interaction with story events and themes, as we saw in the *Uncharted 2* example of Nate carrying Jeff to safety to develop empathy, or varieties of environmental storytelling where the story is communicated through environmental interaction as we saw in *Shade*. There are interesting opportunities to play these experiential categories off against each other. For instance, curiosity-driven interaction in a physically simulated story environment can be used to trigger story events that the player then feels responsible for, since their own curiosity is what caused the event to happen. Of course this sense of responsibility may evaporate on replay when the player discovers that the event is rigged to always happen as the experience progresses, and that the only way to not make it happen is to stop playing. This highlights a limitation of nonsystemic approaches to interactive storytelling, where the underlying simulation doesn't support a generative space of story events and outcomes. Systemic approaches open up radical new possibilities for creating these story experiences (Riedl and Bulitko 2013).

The impact of empathy effects could be even greater by moving beyond dominant simulation types such as physical action and resource management toward simulations directly supporting identification and empathy. Simulations of character motivations, emotion, and social interaction can underwrite interactive choice of the actions pursued in the fictional world, rather than being limited to completing prescripted sequences. This allows a player to get to know fictional characters through their own unique interaction strategies, developing deeper senses of both empathy and responsibility.

Systemic story approaches will also facilitate the experience of curiosity *in* storyworlds. Current interactive stories don't have a mechanism for reasoning about what the player already knows, given what they've seen, and what knowledge to reveal next about the storyworld in order to most effectively generate and satisfy curiosity. A systemic approach that supports the dynamic withholding and discovery of knowledge avoids the problems of the two standard approaches: a fixed order in which players gain information about the story (decreasing responsibility) or a fixed partially ordered progression (resulting in some story progressions with a less compelling generation and satisfaction of curiosity than others). Systemic approaches similarly enhance the experience of curiosity *about* storyworlds, where explicit modeling of revelations and their relationship to themes allows a dynamic ordering of revelations given the particular interaction path of players; this also creates a deeper experience of responsibility. Finally, systemic approaches support curiosity about the narrative as a system. In many interactive stories, aspects of the physical world are simulated, but the narrative itself is not. Though preauthored story knowledge and events can be attached to physical world actions, the possibility space of the story isn't itself underwritten by a simulation. As character motivations, reactions and desires, social interactions among characters, and possible plot progressions are simulated, the narrative system itself becomes a source of curiosity-driven exploration. One way to understand this is to consider the common practice of players posting videos of their gameplay on sites such as YouTube and Twitch. In the current state of interactive storytelling, story progression is not a big motivator for posting such videos. Because the character interactions and story progression are fixed, every player effectively sees the same thing, so there is nothing for one player to learn about the story from watching another player. Instead, it is the systemically supported aspects – such as combat, resource management, and the unique gameplay challenges that can be created with generative methods – that motivate players to share their own unique strategies and approaches and watch videos of other players to learn theirs. It is "systems curiosity" which supports this kind of video sharing. We will know that systemically supported story has arrived when character interaction and story progression become a common driver for video sharing. We already see the initial example of this with *Façade* (Mateas and Stern 2003), the first fully realized interactive drama, which, 10 years after release, still has an active community of players sharing gameplay videos on YouTube.

As discussed above, a few interactive stories are starting to use simulations of social interaction to deepen a player's experience of responsibility. As story simulation techniques improve along the lines described in this section, this may also lead to the resolution of tensions that exist between these categories in traditional storytelling, particularly the tension between empathy and responsibility. Some writers and theorists, such as Bertolt Brecht, have seen empathy as counter to responsibility (Brecht 1964). Story structures that engender deep identification and empathy are seen as "turning off" an audience's ability for critical reflection, where critical reflection is seen as key to having an experience of responsibility. The traditional approach for countering this is to break the narrative frame by, for example, directly addressing the reader or audience. This pulls the audience out of the story, bringing back critical reflection, but at the expense of empathy. Systemic story approaches can support a cycle of reflection and engagement in which players are within a storyworld but also reflecting on the story system to decide what actions to take next. Augusto Boal's Forum

Theater, which emerges from the Brechtian tradition, is a noncomputational example of this (Boal 1979).

Going back to the two science fiction visions which started this chapter, much of the discussion has so far focused on the Holodeck vision. However, there are also future directions that move toward the construction of a real-life Illustrated Primer, personalized narratives that help us understand ourselves and the world around us.

We will see the development of radically customized and personalized narratives for creating positive behavior change and well-being. This represents the convergence of three directions in information technology: the quantified self-movement, technologies for well-being (Calvo and Peters 2014), and story generation (Gervas 2009; Wardrip-Fruin 2009). With the growth of cheap sensors, wearable technologies, and cheap storage and processing, it has become possible for people to apply data science to their own lives, to search for correlations and patterns in the physiological and activity data of daily life. There is also a growing concern for using information technology to promote well-being, to facilitate positive behavior change. The generation of customized narratives becomes a way to connect the two. New kinds of story generators will be developed which, given patterns and correlations found in the data of daily life plus desired behavior changes specified by individual users (e.g., stress reduction, the reduction or elimination of bad habits, etc.), generate stories which make use of empathy effects to facilitate the desired changes.

The generation of personalized narratives will also help people make sense of and satisfy their curiosity about the real world. With near-instant access to a constantly changing deluge of information, we have difficulty seeing the big picture and drawing lessons from all this information. Stories are how we come to develop an intuitive understanding of the mechanisms and interrelationships of a complex world, where we try out alternative courses of action and project possible futures. Data-driven personalized narratives will help turn data into wisdom. For example, personalized narratives could place complex news events in historical context while helping users to empathize with different points of view, or present hypothesized explanations for correlations discovered by data analytics, priming intuitions about possibilities for action and future questions to pursue.

Finally, laboratory research, building on studies of the reader effects of traditional narrative, will begin studying interactive storytelling to more deeply understand the differential effect of the enhanced experience of empathy, curiosity, and responsibility enabled by interaction. This complements design and technology experimentation by revealing the mechanisms and quantifying the effect size of different design strategies for interactive storytelling. Such research will also aid the development of media literacy programs. Current media literacy programs provide children and adults with skills for navigating our media-saturated environment, for being able to skillfully interpret the rhetoric of various forms of advertising and to make use of a variety of media forms to express their own messages and stories. As interactive storytelling becomes a more common element of the media landscape, its potential for even larger emotional and media effects will require new forms of media literacy and ethical engagement with this powerful medium. A product of the convergence of computer science and the humanities, cognitive science and literature, engineering and art, new interactive and personalized approaches to narrative offer insights into future applications of science and technology, as well as into the fundamentals of human nature.

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Virtual Meetings

Walt Scacchi

Contents

Abstract

This chapter reviews and examines virtual meetings (VM). VM are meetings where participants are distributed across physical space or time yet seek/act as virtually colocated in a commonplace. Computer-mediated VM are the common form or mode of interest. Many millions of people regularly engage in such meetings worldwide, most often in small groups with others known to them. This chapter focuses attention on two different recurring forms of such meetings: VM conducted through online documents or artifacts that may be stored, accessed, or transacted via their associated systems and repositories and VM where participants employ computer-rendered avatars in immersive virtual worlds to denote their presence, identity, and ability to interact with other avatars through online media or experiences.

W. Scacchi (✉)
Institute for Software Research, Institute for Virtual Environments and Computer Games, University of California, Irvine, Irvine, CA, USA
e-mail: wscacchi@gmail.com; wscacchi@ics.uci.edu

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Introduction

Using online artifacts as informal documents, people act to communicate to others unknown or invisible through the networked media they author. In this form, the world of free/open-source software development (FOSSD) projects is a primary example of online venues where remote participants interact and collaborate through online artifacts, most often without any face-to-face meetings. Similarly, via meetings in virtual worlds using avatars, persons control their avatars in ways visible to other people through distant views of their remote avatar puppetry. People who play multiplayer online games, like *World of Warcraft, EVE Online, League of Legends,* and others, routinely meet and interact with other players (some familiar, some unknown) from remote locations in order to play the game together. But it is common for people to work together in virtual worlds that sometimes act like games, while some multiplayer game play resembles complex workplace activities, like planning team-oriented game combat or competition (Bainbridge 2010).

In both forms of VM, participants meet for any of a wide variety of purposes through computer-mediated environments, rather than face to face. Additionally, both may provide different kinds of affordances that enable or inhibit the various VM purposes. But in either form of VM, the perceived/actual distance among participants can matter, whether in space, time, place, or cultural practice (Olson and Olson 2000). Initially, this distinction was employed to help categorize online technologies and work practices that were either local or remote (space) and synchronous versus asynchronous (time) (Shneiderman and Plaisant 2006). This formulation of the space-time distribution of VM however did not readily tease out what affordances facilitate, constrain, or inhibit VM participants' ability to enact routine or new ways of collaborating, transferring knowledge, making decisions, or enacting behavioral outcomes. Subsequently, Olson, Olson, and others (Olson and Olson 2000; Olson et al. 2008) examined how scientists and others collaborate at a distance through information technologies and found that workplace conditions and local cultural practices also matter and also found that group communication requires common ground for mutual understanding; communications that are tightly coupled or that entail ambiguous evaluation by the participants may exclude those unfamiliar; collaboration benefits from the readiness of participants to work together; participants who come ready to use online VM technology will be better prepared for collaboration; and differences in participant time zones, native culture and first languages, and trust mediate or undermine the effectiveness of VM. However, it is unclear whether VM practices in FOSSD projects or in multiplayer computer games and persistent online virtual worlds (CGVW) are best explained by these characterizations or whether there is more to be surfaced from the examination of VM practices in such online environments. This is part of what will be addressed in this chapter.

Overall, we are well informed to recognize that VM are not without their challenges and successful use or practice cannot be readily assumed. However, socioeconomic pressures and technological advancements may encourage their adoption and routine use. As such, attention in this chapter focuses on examining how the two alternative forms of VM facilitate or complicate socialization, knowledge transfer, decision-making and rationalization, and practical action outcomes.

Topics not addressed in this chapter include whether VM: have agendas; are planned and structured versus unplanned and improvisational; enable different participant roles in attending or contributing; employ explicit means for assessing the efficacy of meeting processes or outcomes; whether using smartphones or tablets by coworkers gives rise to new kinds of VM types or outcomes; whether there is robust encryption or cybersecurity capabilities; and the like. All of these issues merit serious study and careful explication, but are beyond what we address here. Similarly, meetings that primarily employ only phone/voice conferencing, videoconferencing, or Web-based conferencing are not in focus, though they are all widely used. But when these communication modalities intersect with the two VM forms in focus, we examine their relevance, mediation, or affordances in support of social interaction through online artifacts or through avatars.

VM Through Online Artifacts, Artifact Systems, and Repositories

Can people meet and collaborate at a distance within documents or online artifacts? Increasingly, the answer is yes. More people are acquiring and practicing the skills of how to do so with growing frequency. Such capabilities are enabled through technological affordances like Internet access, Web-based systems, and social media. People are learning how to collaboratively read, write, and edit online documents using services like *Google Docs*. However, many kinds of online artifacts look and function less like formal documents and more like intertextual multiparty communication streams or genre ecologies (Bazerman 1994; Spinuzzi 2003).

Online artifact systems that enable instant messaging, threaded discussion forums, e-mail transactions, Web page viewing and navigation, personal/group timelines, video tutorials, subscription news feeds and tweets, file sharing and versioning, and others are all becoming virtual online places where people meet, communicate, decide, and rationalize what to do and how to do it (cf. Scacchi 2010a). Clearly, these are diverse media for communication and social interaction, and how one works or is used for meetings is different than the others. Yet as interactive social media broadly construed, they serve as online spaces/places where dispersed participants can communicate, collaborate, coordinate action, cooperate, or express conflicts and competitive positions. Further, it is common that sustained groups, communities, or enterprises adopt intertextual collections of some of these informal media as a genre ecology for routine online work that supplement or displace the role of formal documents within the organization of work (Orlikowski 2000; Scacchi 2010a). To help explain this, we use the domain of FOSSD projects, which span from small-group efforts to global multinational communities where people work to develop, deliver, and share complex software systems, but rarely meet face to face to collaborate their work activities or outcomes.

In many global FOSSD projects, there is widespread reliance on shared informal software development artifacts that serve as both the workspace and workplace for FOSSD activities – artifacts found in project discussion forums, in persistent Internet Relay Chat (IRC) channels for instant messaging, in project Web pages (content management systems), and more (Elliott et al. 2007; Scacchi 2010a). More succinctly, collaboration in FOSSD projects happens within and across online software artifacts that are enabled (and constrained) by the underlying artifact repositories that are organized and managed using different storage schemes. This occurs in part because FOSS developers are often loosely coupled and governed through informal online artifacts and tool usage protocols (e.g., in build and release activities that are coordinated and synchronized through software version management systems like *CVS, Subversion,* or *GitHub*) (Scacchi 2010a). So this helps to surface that online artifact repositories that underlie and afford the usage of related online artifacts are a critical part of the sociotechnical infrastructure that enable seemingly sparse artifacts become situated as online work places. Said differently, collaboration between spatially and temporally dispersed FOSS developers is enabled through persistent, informal artifacts that are stored, shared, and updated within or across online repositories through end-user system interfaces.

Lastly, massively open online courses (MOOCs) are emerging as scalable VM spaces for classroom/lecture-style education and training. Many MOOCs offer online, Web-based access to video lectures/tutorials traditionally presented in academic classroom settings, along with links to online reading materials, quizzes/exams, and student discussion forums. However, MOOCs also serve as a common modality for sharing and socialized articulation of knowledge, rather than just as a venue for communicating informational knowledge through prerecorded (or live) broadcast lectures. Whether MOOCs are effective for learners or what affordances and experiences make them most effective remain open questions at present. But as the costs for higher education grow to create barriers for entry, along with exponential growth of the global demand for underserved communities to gain open access to higher education resources, socioeconomic demand for MOOCs is likely to continue to expand. This in turn points to the likely growth in empirical studies that seek to identify the ways and means that afford (a) better production and delivery of MOOC artifact content; (b) better pedagogical rubrics that configure selected online artifacts, systems, and repositories as different learning genre ecologies; and (c) better preparation of students for online collaboration as a self-managed learning mode.

VM Through Avatars in CGVW

Recent analyses of persistent online virtual worlds (e.g., Bailenson et al. 2008; Bainbridge 2007; 2010; Boellstorff et al. 2012; Bohannon 2011; Pearce 2009; Scacchi 2010b), as well as emerging ventures commercializing emerging CGVW technologies, reveal that a diverse, growing set of sociotechnical affordances (i.e., new ways and means for net-centric, decentralized collaborative work) are supported and being used in practice by user communities dispersed in space and time. This section identifies and summarizes what such studies and analyses of CGVW have found across ten categories, though none of these categories should be viewed as necessarily more important than the others:

1. *Group presentation, communication, conferencing, and interaction* – VM can incorporate a sense of place at a distance. Such places may be rendered as graphically modeled meeting spaces where participants will gather to interact and exchange information, coordinate and plan follow-up activities, etc. Many utilize 2D/3D graphically modeled spaces to mirror conventional meeting rooms or classrooms. Integrated software services include support to import and display preexisting slide presentation decks, static images, or embedded media players for video/audio content, each of which may be sourced from online media content repositories (e.g., *Slideshare, Instagram, YouTube, Pandora*, or local media). In this way, such VM attempt to provide visual appearance of places familiar to people (see Mirrored worlds and memorialization below), along with online desktop computing applications. More capable systems also provide the ability to visualize and interactively manipulate 3D-modeled objects for meeting participants to view and manipulate, also described below. However, online 3D meeting place designers need not limit the appearance, function, or affordances they provide to those that only mirror the everyday physical counterparts, as the potential to design VM that are not limited to the meeting place physics and thus accommodate new modes of presentation, conferencing, or interaction. Some of these are highlighted later.

   Next, *graphic chat rooms,* especially those rendered as 2D Web-based graphic worlds, are the most common kind of VM for avatar-based social interaction. Commercial services provided to enable VM are now dominated numerically by those focused on young people as end users. Virtual worlds like *Club Penguin, Webkinz, Habbo, Whyville*, and a few dozen others report more than 1–10+ million sustaining online users clustered in the 5–17-year-old, English-speaking demographic. Some further report more than one million unique users per month. In VM in these worlds, end users meet to chat, hang out, engage in virtual dating, play games, dance, and more generally with others who they do not know in person in the everyday world. Those that target younger users 12 years or less in age also provide antipredator safety monitoring and online chat services that employ content filtering (e.g., cannot ask/disclose personal information), restricted chat vocabularies, or preformed dialog expressions. On the flip side, the use of restricted discourse universes enables multi-language translation, which in turn allows participants to meet and chat with others around the world with whom they may not be able to talk to due to first-language differences. Young people in these VM thus can learn and practice cross-cultural interactions in a reasonably safe, online manner. Finally, it is worth noting that when young end users grow up with regular VM experiences, it may well be the case that these users will come to rely on such VM as part of the cultural practices within their online social world and workplaces.

Overall, 3D VM systems are often promoted as a means of displacing participant travel costs and burden (including travel time and related travel contingencies) while seeking to embrace end users who are comfortable with a sustained online presence (Bainbridge 2007; Bohannon 2011). This is one of the practical outcomes they may realize. However, 3D VM also represent an alternative to currently available solutions for conventional online conferencing and meetings provided by *WebEx, GoToMeeting*, and *Skype*, all of which do not rely on the use of interactive or animated avatars to denote a user's presence in a VM. VM avatar systems enable end users who may have restrictions on physical or social mobility due to age, safety, or other concerns. But young users are growing up in online worlds where VM are socialization places to go with things to do with others that they may otherwise not be able to engage.

2. *Training, education, rehearsal, and learning* – There is growing interest in the use and efficacy of virtual world simulators to support corporate training, academic education, and student learning. When multiple users can concurrently participate in the simulated worlds, they may be able to enact simple/complex behaviors to understand how best to use/service a simulated device. Example projects include small-group problem solving within informal science education for students in primary and middle schools, as have studies in corporate settings in the team-training adult technicians in service operations and diagnostic procedures been explored, as have many others (Scacchi 2010b; Scacchi 2012). In such examples, the abilities for groups to play, discover, try-fail-revise, rehearse, and then commit to an action plan are all elements of social action that build from socialization, knowledge transfer, and rationalized decision-making arising from VM experiences. Similarly, the availability of simulated laboratories where experiments with materials that are costly and difficult to manage in the everyday world are modeled in 3D as animated objects that can be engaged and manipulated via avatars also points to future learning environments for academic subjects that lack laboratory support (Scacchi 2012).
3. *Identity role-playing, team building, and other social processes* – When users utilize avatars to denote their interactional presence within a virtual world, many may elect to try out other personas and visual identities. These post-human representations of individuals afford the ability to try to be someone else or someone different from their everyday world physical appearance and social identity. Many successful multiplayer games offer preformed characters that vary by gender, in-game role, and role-based skills for players to choose for game play. However, other role-playing modalities can be supported in CGVW. For example, people who may have limited physical abilities, such as being bound to a wheelchair, can enact an online social identity through an avatar that can walk, run, and fly and therefore exhibit protean virtual abilities (Bailenson et al. 2008). Similarly, for awareness or diversity training, some organizations utilize role-identity reassignment plays, whereby a senior manager may take the role, identity, and virtual appearance (and sometimes gender or ethnicity) of clerical staff members, and vice versa. Such virtual identity enactment also

affords role-play with participants who may be spatially, temporally, or culturally distant. In addition, the awareness/diversity distance may be playfully engaged and interactively traversed in ways that the participants may be uncomfortable to try when in the physical presence of other participants, while the identity-play distance manifest through interactive avatar puppets also provides safe ways to overcome perceived authority distancing from others. Finally, playful team challenges can place user avatars in precarious virtual settings (e.g., in a large rowboat that must ferry supplies across a raging river), who must collectively act to achieve shared goals (crossing the river safely without loss of supplies). In this way, multi-avatar VM can be used to train or help people discover new ways on how to work together to achieve shared goals in the presence of challenge, different roles and authority relationships, and risk. It also affords safe engagements through potentially low-cost and fun means. But such capabilities do assume the willingness and competency of participating users in the workplace to be somewhat facile in their use and control puppetry of avatars that operate and interact within a virtual world. Over time, such skills may become more widespread, especially in younger generation workers who have experience in multiplayer online games.

4. *Mirrored worlds and memorialization* – Many people invest significant amounts of personal time and effort to develop and perform with in-game characters or avatars within a virtual world. Sometimes these experiences spans months to years, as well as a variety of online cultural experiences and rituals (Pearce 2009). To no surprise, these people become vested in their online games or virtual worlds as a place where they play, interact, collaborate and plan, emote, and empathize with others in recurring online meeting places. Sometimes, VM occur in online places where game characters or avatars hang out, socialize, form online personal/intimate relationships, create memorials sites or sacred grounds, and more. Other times, the virtual place is invested and socialized through ways and means that actively seek to replicate physical places in the everyday world. As these online places are situated within remote computation servers that may be administratively controlled and operated as online services by third parties, then these external parties may choose when and how to transform or terminate these online places for financial business reasons (e.g., inability to operate profitably). When such online places are made inaccessible or unavailable to vested end users, collective effort of the virtual survivors to immigrate and reestablish a similar or alternative place in a somewhat related online game or virtual world emerges (Pearce 2009). Similar efforts at preserving the memory of those who have passed on, or to reanimate personas of famous people as avatars that can be interactively engaged in situated discourse or interaction, are motivating the establishment of VM places where these "spirits" can be engaged. Whether or not this creates opportunities or affordances for virtual immortality is less the issue, but it points to ways and means by which game players and virtual world enthusiasts may act to develop VM places where they can encounter and interact with others long gone. Finally, we may expect to see

the development and provision of augmented reality device interfaces for VM participants who relish further immersive, replicated world experiences for their virtualized cultural heritage.

5. *Multimedia storytelling and avatar control/choreography* – Many participants find their situated work/play experiences memorable in ways they desire to share with others unable to be there and then. Alternatively, some have observed the interaction of in-game user characters and non-player characters (NPCs) can constitute a kind of online/cinematic storytelling that in turn can be improved and refined through (postproduction) use of video editing software. Avid enthusiasts focus on learning and practicing how to control online avatars as virtual actors who enact stories or screenplays using VW locations as theatrical sets for acting. Consequently, many stories portray avatars in group/VM situations where their remotely controlled interaction enacts socialization processes, knowledge transfer, decision-making, and consequential behavioral outcomes. Games like *The Sims* were among the earliest to embrace this mode of game play system usage, by providing online repository services for publishing game-based stories that could be both read as literate media and reanimated through replay of the story within the game. Hundreds of thousands of such stories have been produced and published, and some stories have been viewed or played by comparable numbers of participants. Elsewhere, the practice of recording high-performance game play sessions ("speed runs") to document a player's claim of game play accomplishment gave rise to the practice and software technology called *machinima.* Millions of machinima videos now populate social media sites like *YouTube*. But what machinima and game-based storytelling demonstrate is that people can learn and practice the art of VM as a theatrical modality. Similarly, it demonstrates that VM can be designed and recorded for pedagogical purposes, for entertainment, or as an embodiment of new media literacy in forms that traditional media and organizational practices may be unable to readily realize. Once again, we may anticipate such efforts are likely to be embraced by a new generation of end users who are comfortable and accomplished with play-working in CGVW.
6. *Product prototyping and review* – VM that embrace a vision for the future that utilizes virtual reality (VR) technologies for end-user interaction and gesture-based control sometimes stress value of shared affordances for interactive creation, manipulation, and editing of interactive 3D object models to support new product development. In such VM, end users may be engineers, project managers, subcontractors, and others who come together as a small group that is most likely geographically dispersed, but working under time constraints that demand rapid turnaround. Major automobile manufacturers are known to employ such VM capabilities to help reduce the cost/time for development and integration of components or subsystems that will become physically embodied elements of new cars, as a result of iterative prototyping, review, and refinement of 3D model placeholders. This in turn implies the need for subcontractors (e.g., small- to medium-size manufacturers or large volume product suppliers) to acquire VM-compatible computing systems so that they can readily exchange

new product design specifications, simulation or testing results, and manufacturing capacity or supply chain performance indicators. Furthermore, the rapid growth of interest in "do-it-yourself" object making and small-lot manufacturing will help stimulate interest in the practice of new product development via product prototyping, redesign or reconfiguration, and user review through small-group VM. These VM capabilities may eventually be engaged through Web-based services or mobile devices. These capabilities may also be blended with new product demonstration and sales or even with prospective customers at trade shows or in focus groups.

7. *New product demonstration, customization, or selection* – VM places can serve as new product showrooms. This may often be well suited for the everyday sales and promotion of physical objects, especially those that traditionally may not fit within a smaller showroom, due to the size of the object, or those ready for advanced sales due to their status as virtual product mock-ups. Such showrooms may be used to showcase, demonstrate, and acquire objects like commercial airliners, cruise ships, hotels and office buildings, hospital and surgical suites, custom homes, heavy equipment, concert hall or stadium seating, and even new automobiles, motorcycles, bicycles, or personal rapid transit pods. Retail store sales of personal items like clothes and fashion accessories may also be supported through walk-up, on-demand user experiences with "interactive mirrors" that utilize augmented reality features to provide product overlays on the person(s) trying on or contemplating object purchase, perhaps also with VM of remote friends or family members chiming in through online chat. The physical objects being showcased or offered for sale often feature modeled and simulated interactive controls for simulated user experience, thus affording "try before you buy" user interactions with object features or controls while protecting new product inventories from shrinkage or damage. Another common capability that VM new product showcases feature is the ability for customers to specify product customizations (e.g., exterior color, interior finishes, upgraded accessories) that can be readily interchanged or reconfigured on demand by the customer, salesperson, or sales team. But such capability also affords the product vendor to defer product manufacture cost and time until a completed sales transaction triggers an order to build the customer configured project. This can be especially important when product manufacture entails assembly of subsystems that are sourced through global supply chains.

   Overall, these VM-based product experience or encounters allow for customer walk-through, simulated user experience from first-person views, and final product feature specification prior to manufacture, delivery, or first use. Consequently, it is not surprising to expect a growing diversity of new products marketed and sold through VM may be delivered and experienced through Web-based or mobile devices, as well as for those devices populating an Internet of Things.

8. *Game development and/or modding* – Networked multiplayer computer games represent a global multibillion dollar industry. Game development firms may be large multinational enterprises, reconfigurable networks of small genre-specific

game-making studios, or ad hoc communities of enthusiastic players who seek to modify or extend their favorite games when the game product is accompanied with a game software development kit (SDK) for use by end users. This last category enacts VM to support the game play/modding activities outside or independent of commercial studios. Web-based portals like *ModDB* and *Steam* offer online artifacts that support modder VM, much like they can support FOSSD projects. Game mods are often subject to intellectual property licenses that assert that community development mods are free (cannot be sold for fee), open source, and redistributable to those with licensed copies of the original game (Scacchi 2010c). However, many game players organize ad hoc VM within the game itself so as to situate their comments or suggested modifications within the virtual world (game level) where they may be most visible to other players during play activities or can be demonstrated using in-game player avatars.

Through such ways and means, game modders embrace and practice VM that accommodate all of the preceding VM affordances and capabilities, and many do so outside of formal enterprises (Scacchi 2010c). This may be another reason why formal enterprises value and recruit avid game players/modders as potential employees, because of the VM expertise that they can bring to a firm. Finally, the actions of game modders within games also reveal the shortcomings of the SDKs they employ. Specifically, SDKs are separate from the interactive game world during modding activities, so it is uncommon for game mod developers to watch, observe, share, and review a prototype mod while it is being developed, rather than wait for a preview release. While this might seem like a small issue, it does help reveal that within avatar-based virtual worlds like *Second Life* or *OpenSim,* where participants can interactively modify their world in real time in the presence of others, it is clear that SL and OpenSim are not recognized as compelling game play platforms; thus, game development and modding does not typically happen in VM hosted on such virtual world platforms.

9. *Sociotechnical process discovery* – As academic researchers engage in empirical studies of VM activities and practices in different organizational settings, there is interest and research into articulating what kinds of scientific knowledge or practical action can best be enacted through VM. This raises questions for how best to study and discover what recurring processes and informal work practices arise through the ongoing use of VM in the workplace. Different research studies perform ethnographic or virtual ethnographic approaches to discover sociotechnical processes emerging within VM work or play activities (Boellstorff et al. 2012). Others are interested in studies with large quantitative data sets that arise through data mining of low-level user events/transactions through avatar interactions with one another, with NPCs, with situated virtual objects, and subsequently through VM (Seif El-Nasr et al. 2013). In either research modality, what is of concern is how best to study VM where dispersed participants interact with one another through avatars, what they do, what kinds of decisions they make, and what consequences follow (Bainbridge 2010). However, it is also noteworthy that avatar-based VM may afford new ways

and means for discovering the dynamics and configurations of different sociotechnical interaction processes that are realized through avatar interaction. For example, at this time, we see relatively little practice of multisite or global software development projects utilizing avatar-based VM and instead see online artifact-based VM almost exclusively. Why this is so is unclear and understudied.

10. *Enabling human behavior transformation* – Can people modify, adapt, or transform their individual or group identity, or their behavior, through interactions within a VM? This is an open research question that is being explored in the realm of games for health and VR-based educational experiments. In the world of games for health, people who may be subject to health challenges that are mediated by lifestyle choices (e.g., obesity, diabetes) or the result of injury (stroke, traumatic brain injury, Parkinson's disease) may seek for new ways and means to improve their quality of life through social interactions in online virtual worlds or through active game play. Many informal pilot studies and formal clinical studies reveal that participants can not only learn healthy lifestyle habits but also acquire and enact new active behaviors that they previously did not perform. In such online settings, participants most often engage other characters or NPCs, who may be adaptively controlled by the underlying game design or guided by skilled therapists working at a spatial or temporal distance. Consequently, participants interact with others through recurring VM that are supportive to the needs of patient-participants, which in turn can help people to learn how to better self-manage their chronic care needs or to accelerate patient recovery and rehabilitation. These patients consequently are observed to accomplish and embody personal transformation which improves their quality of life, at least for some period of time (long-term behavioral transformation studies are yet to be performed or reported). These game-based VM for personalized health care are likely to garner more attention as affordable health care is sustained as a national priority. Tele-rehabilitation experiments with personalized game-based therapies that accommodate the participation of remote therapists, health care providers, and extended family members are thus an emerging form of VM-based health care we may expect to see in the future.

    Avatar-based VR experiments with the classroom of the future have begun to demonstrate that accelerated learning results can arise for students. In one set of studies, the physics of student avatars was experimentally manipulated so that every student could sit front and center in the virtual classroom where students get the best attention from the teacher (avatar) while being minimized to the distraction of other nearby students (Bailenson et al. 2008). Such perceptual experience is readily supported through user-specific (client-software) views into a virtual world or VM, something that cannot be easily achieved with a conventional physical classroom. Beyond this, studies also reveal that when students personalize their avatar in a protean or "superhero" manner, they learn to be more convivial and socially supportive (Bailenson et al. 2008) versus when they adopt avatars they personalize for competitive or "first-person combat" play in multiplayer games. As such, we may expect to see more studies that seek new ways and means for improving the productivity, learning, social skills, and negotiation outcomes of people who work through custom tailorable avatars that interact within VM.

Discussion and Conclusions

A diverse collection of lessons or insights can be observed from the review of "Virtual Meetings" affordances presented in this chapter. VM can be realized and enacted through online text-based artifacts, 2D graphic meeting rooms, or persistent 3D virtual world meeting places. When complex work activities are focal, as is common in globally dispersed FOSSD projects, text-based online artifacts and associated repository systems are the most commonly used. When younger participants learn to meet and socialize online, 2D graphic chat rooms with managed discourse practices currently dominate. Finally, when users are accomplished game players and virtual reality enthusiasts, then persistent 3D CGVW are viable places to meet. But all accommodate different practices for socialization, knowledge transfer, decision-making, and behavioral actions.

Different tools and techniques are both required and afforded for use in VM. But these sociotechnical interaction capabilities require different kinds of supporting infrastructures to enable their sustained online use to global communities of potentially millions of people who as end users want to meet and interact with others in small-group VM. Community repositories for FOSSD projects like *GitHub* host millions of shared software project and artifact spaces that are almost exclusively textual and infrequently graphic or 3D. 3D CGVW are presently well suited for playful online interactions through avatars, but are much less frequently engaged for routine organizational work practices, though some inroads are appearing through new production design and demonstration, and identity role-play experiences. Training and educational applications that foster VM are primarily based on utilization of passive media that can be readily packaged for broadcast and assessment, more so than for innovative learning experiences that are still experimental at this time.

VM offer the potential to embrace entirely new kinds of VM experiences. Meeting rooms and associated supporting media content need not be limited to mirroring what can be done in the everyday world. Instead, they can embrace new experiences such as where each participant is self-identified and appears in protean form that is self-perceived to be positioned at the meetings center spot, embraces its readiness to collaborate using online artifacts and services at hand, and does so all within a world that is not limited to physics of conventional meeting room places.

New devices that sense or monitor the physical environment or personal information/data space of end users working within an Internet of Things may afford new ways and means for experiencing VM. The continued growth and diffusion of mobile devices like smartphones and tablets as portable personal computing/media platforms seems to suggest that new kinds of VM will appear, though it is unclear what form they may take (text-based vs. 2D vs. 3D vs. app-specific hybrids) or which will be most effective in different kinds of local/global VM.

Finally, there is need for growing recognition that new generations of younger end users will grow up skilled and ready for VM practices. Transcultural VM experiences of young people may anticipate a future where VM usage is a necessary element of workplaces and learning systems.

Overall, VM are both exciting and boring venues for online socialization, knowledge transfer, decision-making, and behavioral action. What determines whether such VM are fun, playful, or tedious depends on the capabilities and experiences that are readily afforded for different user-skill demographics, so that what works well for one community or group may be cumbersome and frustrating for others. So it is unlikely that we can identify emerging patterns of success or failure in enabling online collaboration practices that will be universal, but we do recognize that both successes and failures are common. What remains to be determined is how best to design, organize, practice, and continuously improve/adapt the VM genres so that we can readily recognize when we are working or playing within a productive or unproductive one.

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Part IV

Earth-Scale Platform

The Earth-Scale System

Bruce Tonn and Dorian Stiefel

Contents

Abstract

To effectively deal with global-scale issues requires an appreciation of earth-scale integrated systems; both natural and anthropogenic. Exponentially increasing change within anthropogenic systems, driven by seemingly manic creative destruction, complicates efforts to understand natural and anthropogenic systems interactions. This is a wicked problem that must be tackled by organizations dealing with global problems such as climate change and pandemics and by those who are worried about human-level issues such as personal identity and population changes. Converging knowledge is necessary for understanding these problems and identifying solutions, as is foresight that captures individual and global implications.

B. Tonn (✉)
Department of Political Science, University of Tennessee, Knoxville, Knoxville, TN, USA
e-mail: btonn@utk.edu

D. Stiefel
Baker Center for Public Policy, University of Tennessee, Knoxville, Knoxville, TN, USA
e-mail: btonn@utk.edu

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Introduction

"Spaceship Earth" is at once an apt yet misleading metaphor for understanding the essence of earth-scale integrated systems. On one hand, the metaphor communicates the need to care for earth life's only reasonably inhabitable home, a never-ending task. To achieve this task requires dedicated attention to all of the earth-scale systems that support life on earth. From this perspective, earth is a platform for study and for solutions that operate across integrated systems.

On the other hand, the metaphor also conjures the archetype of an actual spacecraft that is technologically advanced, has integrated and reliable systems and whose functionality is well understood and predictable. Failure of spacecraft systems and subsystems can lead to loss of life, and therefore, such eventualities are taken seriously. Failures are mitigated by backup systems and redundancies. Standard operating procedures are developed to detect and respond to system failures. All spacecraft systems and subsystems are exhaustively tested to detect and rectify glitches, although experience suggests that it is impossible to completely eliminate catastrophic risks.

Though the sentiment underpinning the metaphor of Spaceship Earth is compelling, Spaceship Earth hardly resembles an archetypal spacecraft. Indeed, life on Spaceship Earth is more like this: Once the spacecraft enters space, the astronauts begin to change everything about the spacecraft except its external dimensions. The astronauts decide that the craft needs to move through space faster, so they devise, construct, and install a new propulsion system. Likewise, the air and waste recycling systems are deemed substandard and are likewise replaced with newer versions. Of course, every aspect of the information technology system is found lacking, so they print new computer hardware, rewrite the operating systems, and completely redesign all of the major software applications and user interfaces. To simply label the resulting technologies as under-tested beta versions would be quite generous. All of this change happens without a plan, without certain knowledge that the changes would be beneficial, without consideration of the interactions between and among subsystems, and without extensive and definitive testing before implementation. The risks to the spacecraft and their lives are palpable but are overridden in the astronauts' minds by their stronger belief that technological change and progress are always good (in the long term).

This metaphor highlights an important distinction between anthropogenic and natural systems. The former seem to be changing at an exponential rate, whereas change in the latter is sedate by comparison. Theoretically, this is not a problem for humanity as long as it is understood that the natural systems are the life-support systems and ought not to be compromised by anthropogenic change. Change is a given, even within the natural systems, and the changes in these systems occur at scales and speeds that differ over several orders of magnitude, thereby creating flows and turbulence that can be destabilizing at least and catastrophic at worst. Interactions between the systems need to be understood.

It also must be understood that anthropogenic change can also help protect our planetary life-support systems. The emergence and convergence of nanotechnology, biotechnology, information technology, and cognitive (NBIC) science promise enormous societal and earth-scale sustainability benefits (Roco et al. 2013). Optimists can point to advanced technologies that reduce energy demand, emissions of greenhouse gases, air and water pollution, and industrial wastes. Water supplies and quality are being improved, food is being grown in more environmentally friendly manners, and applications of synthetic biology to reduce species extinction are gaining adherents. Humanity and our life-support system can benefit from having these types of technologies sooner than later.

Convergence of Knowledge Is Necessary

Thus, a major challenge for humanity is how to manage the natural, integrated life-support systems of planet Earth with the creative destruction that underlies modern economies (Schumpeter 1942) and changes the anthropogenic system. New ideas and objects constantly replace the old. Among many entrepreneurs, creative destruction, also known as technological disruption, is the explicit goal of their efforts ((Really) Creative Destruction: 2013 MIT Technology Review 2013), even though this turbulence could unwittingly damage planetary life-support systems. The genesis of creative destruction can be found in human's innate needs for expression and creativity (Adler 2015), which may be why creative destruction appears to be accelerating (Davis and Meyer 1999).

Managing natural and anthropogenic systems and their interactions is a wicked problem as defined by the contradictory knowledge, the number of people, the high costs, and the interconnections with other problems (Kolko 2012). It requires not only an understanding of systems (Meadows 2008) but also of the system of systems in which multiple concepts and models are considered simultaneously. Given the earth-scale of the challenge, the entirety of human knowledge needs to converge not only to understand each system but also to understand interrelationships between systems and the cascading actions and reactions between and among systems. Convergence of knowledge is also needed to support foresight, with the goal of assessing potential futures that, at the very least, ought to be avoided. In short, management of integrated earth systems must be ethical and moral and also must satisfy obligations to future generations (Tonn 2009).

These types of convergence for scientific expertise and forecasts are part of scientific inquiry. For example, the Intergovernmental Panel on Climate Change (IPCC) is a transformative organization because it embraces this challenge (Tonn 2007). Periodically, all human knowledge related to climate change converges on the IPCC team. In its assessment reports, the IPCC synthesizes and distills this knowledge for use by scientists and decision-makers across the globe (e.g., IPCC 2014). The reports draw on a plethora of disciplines, including, inter alia, atmospheric science, oceanography, terrestrial ecology, climate science, meteorology, civil engineering, planning, economics, energy science and engineering, agricultural science, and forestry. To forecast climate change, integrated earth-scale systems are detailed in individual climate, economic, and emissions models, and then the models are tightly coupled to produce the requisite outputs. Researchers from many disciplines have compiled extensive records of past climate change to assist in validating the climate models. The reports are designed for use by a complex and integrated system of climate change decision-makers that literally involves every level of government as well as the profit and nonprofit sectors and concerned individuals worldwide.

Science and technologies also converge to support policy options to mitigate and adapt to climate change. The most notable examples fall within the energy production and carbon capture and sequestration areas. These include new composite materials for wind turbines and photovoltaic cells, smart grid technology, and a host of energy storage technologies. The biotechnologies of the NBIC equation are well represented through research and development projects in biomass and microbial energy solutions. The cognitive aspect of NBIC is also represented through applications of behavioral economics, social marketing, and energy consumption behavior. Forecasts are developed through technology assessments (e.g., market penetration of energy-efficient vehicles, lights, appliances, etc.) and dedicated energy market simulations (e.g., the National Energy Modeling System developed by the United States (US) Energy Information Administration).

Internationally, convergence of knowledge as seen from a system of systems perspective extends well beyond climate change examples. Numerous international bodies require the effective convergence of knowledge to understand the issues and to coordinate global-scale response to these issues. For example, the United Nations recently published a set of 17 global Sustainable Development Goals (SDGs) (United Nations Department of Economic and Social Affairs 2014). The SDG program is a follow-on program to the Millennium Development Goals (MDGs) program, although the SDGs are much broader than the MDGs and include, for the first time, social goals (e.g., ending poverty, achieving gender equity), environmental goals (e.g., protecting the oceans and terrestrial systems), and economic goals (e.g., building resilient infrastructure). The goals encompass every issue in this book, yet simply listing the goals and over a hundred and fifty strategic targets belies the complexity of the integrated systems that encompass the real-world aspects of the goals. To measure progress toward achieving these goals requires a whole earth monitoring system and a convergence of human knowledge to understand the integrated earth-scale systems that are both the causes and solutions to the problems.

The World Health Organization (WHO) deals with the threat of pandemics. To be successful, the WHO must understand, inter alia, agriculture, animal husbandry, rural and even urban cultures pertaining to both, the etymology of viral diseases, viral mutation, transference of viruses from hosts to other organisms (e.g., between birds or between birds and humans), international travel, treatments, and vaccines. Economics and production processes need to be considered as well as culture with respect to risk mitigation and perception.

The World Bank strives to end extreme poverty and promote shared prosperity by providing financial and technical assistance. To be successful, the World Bank must understand, inter alia, micro- and macroeconomics, all industries, domestic and international finance, domestic and international politics, enabling science and technologies, environmental protection and impacts, and the roles of the related international organizations such as the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the United Nations Environmental Programme, the International Energy Agency (IEA), and the General Agreement on Tariffs and Trade (GATT). As in the WHO example, the World Bank also must consider culture with respect to risk mitigation and perception.

Benefits of Convergence of Knowledge at the Human Level

Even at the human level, an integrated systems perspective is required for understanding and action. Theoretical benefits of convergence of knowledge at the level of the individual include wellness and human development, productivity and economic development, societal sustainability, empowered individuals and communities, human knowledge and education, and an innovative and equitable society (Roco et al. 2013). These benefits are accrued by leveraging earth-scale natural and anthropogenic systems to converge knowledge and, conversely, by converging knowledge to leverage earth-scale natural and anthropogenic systems.

For example, consider the human-level issue of personal identity. Identity is who you are and is, in part, expressed by culture. Interwoven in one's identity are the groups individuals feel that one belongs to – gender, community, nationality, and ethnicity. Identity is what makes one special. People can feel alienated, lost, and rootless without a strong identity. The social psychology of identity can lead to unrest and even violence.

Thus, identity is a problem in modern society. Globalization, information technology, and social media ensure that virtually no cultures or communities are isolated. No one group of individuals is assured that any positive aspect of their identity is indigenous to themselves. Feeling special by being different is no longer a reliable aspect of identity. For example, American urban hip-hop has found its way to such diverse places as Australia and Yemen, resulting in consternation in one case (Is the white, female Australian rapper diminishing the identity of American hip-hop?) and pride in the other (Yemeni youth find creative expression within the chaos of national collapse). With cultural cross-fertilization and contamination, individual identity becomes uncertain and ill defined.

If identity aspirations are unmet, it is easier to feel downtrodden. As technological changes outpace the adaptability of cultures and individuals, to protect identity, one can expect conservative notions, rebellion against change, and extremism, and sometimes terrorism, in response. Drug abuse or alienation and loss of sense of self also are possible. Anxieties about personal futures, wealth, and well-being combine with anxieties about the life-support system also contribute to the Gordian knot of human psychoses. Thus, to deal with the very important issue of identity requires a system of systems perspective and the convergence of knowledge.

On the other hand, because of globalization and social media, individuals who may feel their identities constrained by the socioeconomic circumstances of their birth now have enormous opportunities to find or create new identities that are better suited to their true natures. The problem these brave individuals face is finding groups of like-minded individuals that share their identities and can affirm their internal sense of self.

Population change is another example of intimate human behavior that requires system of systems thinking. Fertility rates have declined substantially around the world. This is due to a number of factors, including a reduction in infant mortality, spread of birth control technologies, and advances in gender equity in education and employment. Reductions in population growth have major benefits for the global environment through lower than expected demands for energy, food, water, and virgin materials.

Unfortunately, many social systems were designed decades ago under the assumption of continued population growth rates and shorter lifespans. As a result, many societies are aging rapidly, some too fast to support social safety nets such as Social Security in the USA. In Japan and many European countries, the birth rate is below replacement levels. From a system of systems perspective, this situation can cause hardships in many countries, as demographics, health care, economic production, and many other social systems react with turbulence. Changes in economic and even military power could ensue. Thus, the very human-level decisions regarding having children have system of systems implications that can only be understood with convergence of knowledge.

Foresight Must Inform the Solutions

The benefits of convergence of knowledge are clear but achieving that convergence and those solutions requires foresight with a system of systems perspective. For example, it is important to foresee droughts and the domino effect of its implications. A drought in the American West could reduce cattle stocks, which could spur expansion of cattle farming in South America, which could put even more development pressure on Amazonian rainforests, which could have negative implications on efforts not only to mitigate climate change but also to protect engendered species and ecosystems. Advances in fusion energy, high temperature superconductors, and batteries for electric vehicles could change the face of electric power systems and drastically reduce demand for coal and petroleum, which could in turn have major international relations implications, especially in the Middle East. One can spin endless scenarios of these kinds.

Good foresight requires the study of system of systems. Individual systems can be studied from the perspectives of traditional academic disciplines, in which case more often than not the systems that define the discipline are isolated for in-depth study from the system of systems. To consider the previous example, social scientists could descriptively study personal identities within a community system and explain from sociological psychological principles the types and frequencies of identities observed. However, the evolution and change of identities over time probably could not be explained robustly without reference to a set of integrated socioeconomic, technological, and even climate systems that incorporate past, present, and future considerations.

In turn, futures of any meaningful global social, economic, environmental issues cannot be assessed without an integrated knowledge of systems and a convergent approach. The field of futures studies (Bell 2003), it can be argued, is one of the first to fully embrace the concepts of integrated systems and convergent approaches. This is because in order to envision potential future worlds, futurists weave together trends emanating from many national and global mega-systems, including trends in areas such as economics, politics, society, technology, and the environment (Schwartz 1996). The most insightful and plausible scenarios express the essential relationships between integrated systems. Relative to the example, the future of identity is best addressed through an assessment of the most important driving forces acting on and within a set of integrated systems, including globalization, world cultures, media, politics, technology, and the global environment. Futures of population change likewise can be best addressed through such a process, again including attention to globalization, culture, law, etc.

Capturing the human-level implications of global trends is possible with foresight. For example, impacts on identity are getting deeper. Using foresight to understand impacts to identity in this new world requires combining knowledge of psychology, sociology, and social psychology with trends in economic homogenization on one hand and exponential technological change on the other, the emergence of new cosmologies based on mash-ups of science and religion, and existential threats posed by climate change. Technological diseases such as the fear of interacting with people in a face-to-face situation (syncrophobia), becoming addicted to the immense flow of real-time information about everything (psychominpencemania), and psychological dissonance about one's self caused by increasing catalogs of personal images and videos over time (chronoschizophrenia) are likely to increase (Tonn 2005). Extremism affects individuals even as creativity might increase or decrease feelings of well-being. Amid these impacts, humans continue to need foundational sustainability, resilience, food, water, love, species protection, and mitigation of existential risks of human extinction. Global mental health, then, is another system that requires foresight in particular and convergent thinking in general.

In the quest for understanding and improved foresight, no system should be ignored, even seemingly inconsequential ones such as global sports. Viewing global sports in system of systems perspective, one can argue that international sports competitions can in some sense be a more peaceful substitute for war. Sports also have the potential to yield implications relative to human interactions, identity, technologies, and societal stability. What does personal achievement mean in international sports in a world where performance-enhancing drugs are regularly used? What does success or failure of national sporting teams mean to national identity and even to international relations? How do international sports relate to personal identity?

When identity and sports are combined, identification with sports clubs and teams may overshadow other sources of identity, such as family, neighborhood, profession, or even ethnicity. This could be positive or negative. Such identification may be a compensating factor in more mobile societies and in situations where heroism in the mythic sense is in short supply in other areas of life. Strong identification in sports persists despite Theseus' paradox, for the players, managers, owners, venues, and even the uniforms are consistently being replaced by pieces that may have no logical ties to the fundamental identity of the teams themselves. If there is some truth to this observation, is identity becoming an increasingly shallow personal construct, and if so, what might be the global mental health implications?

Capturing the global implications also is possible with foresight. For example, innovation in the world of ten billion that is expected by 2050 could have major implications for the meaning of life as individuals deal with environmental and existential concerns, internalize the implications of substantial space exploration, and address the related astrosociological issues. Global self-sufficiency becomes feasible as space travel becomes more inexpensive because of space elevators, ensuing easy access to the resources of the moon, Mars, and asteroids. In turn, advancements in space will demand new funding models for space travel and colonization. Is humanity equipped to engage in the collaborative behavior needed to achieve these goals?

Back on earth, the barriers to entry in some economic sectors are getting steeper. The costs of developing a new jet engine, for example, are becoming exorbitant because of an expensive convergence of materials science, design, advanced manufacturing techniques (e.g., additive manufacturing and water-jet cutting), and extensive reliability testing, not to mention the increases in knowledge necessary to understand global economics and global demand for planes and world oil. Years of testing are needed to move an engine from concept to prototype to testing to regulatory approval. Do the benefits of convergence to produce these truly sophisticated technologies outweigh the fact that only a handful of entities around the world will be equipped to produce them?

International trade economists have long promoted globalization to take advantage of efficiencies of the law of comparative advantage: Countries that are best, say, at growing bananas should grow bananas. Countries that are more suited to growing wheat should grow wheat. Countries that are more suited to manufacture jet engines should do that. This is an orderly view of globalization.

The more recent incarnation of globalization is much less orderly and it takes a global systems perspective to understand why. In an increasing number of economic sectors, barriers to entry are quite low, thereby negating to a large degree natural comparative advantages and our ability to foresee where new and disruptive technologies will be created. For example, in addition to the well-documented low barriers to entry in the information technology sector, decreasing costs of biotechnologies are significantly reducing barriers to energy in genetic engineering fields and even in the emerging field of synthetic biology. New low-cost approaches to space technologies could fuel growth in human space exploration or could teach us more about how humans inhabit our own planet.

This new world of globalization is driven by a rich mixture of factors: differentials in wage rates across countries, differentials in regulatory costs, existence and costs of infrastructure and transportation systems, workforce skills, and access to the creative class (Florida 2002). Comparative advantage is now frequently created by the agglomeration benefits stemming from communities of entrepreneurs such as in Silicon Valley in California or Boston, Massachusetts, where start-ups are legendary. However, because of low barriers to entry and the free movement of human capital and intellectual property across the globe, entrepreneurship and the attendant technological change are diffusing across the world. While this may take shape differently in China than in India because of cultural differences, fundamentally, waves of creative destruction are already rippling from these countries and also from Western Europe, Korea, South America, and even Israel (Senor and Singer 2010). System of systems-based foresight is a necessary approach to understanding each of these scenarios and to identifying the individual and global implications.

With system of systems thinking, foresight can inform inputs for public decision-making. Capturing governance and risk implications requires convergent thinking in order to develop new approaches in general and for societal risk mitigation in particular. This requires more than sustainability in which the natural and anthropogenic systems appear to assume stable operating situations and require only minor improvements. This also requires more than resilience to major natural disasters and other potentially catastrophic events or even adaptability or learning (Argyris 1976). It requires an integrated system of public policy goals. These goals should integrate concepts such as sustainability, resilience, and adaptability with equity concerns. It requires an integrated system of ethics regarding current and future generations, encompassing acceptable levels of risk to individuals from environmental threats in the near term (e.g., 10^{-6}) to acceptable levels of existential risk over the very long term (e.g., 10^{-20}) (Tonn 2009).

Effective and equitable public policies require the integrated efforts of multiple levels and scales of government, spanning local to regional to national to international. Nongovernmental organizations and profit-making firms also need to be integrated into the systems of risk identification and reduction. These governance systems need to be self-organizing in the sense that progress is dependent on all of the actors to engage with each other, assess situations, evaluate options, make decisions, and change behaviors, all with appreciation of their place within the system of systems (Senge 1990). Additionally, numerous institutional arrangements are required for the synthesis of knowledge and practice of foresight, much like the IPCC's role with respect to climate change.

All of the stakeholders must learn over time, such as through a process of double-loop learning (Argyris 1976) wherein the outcomes of policy decisions are evaluated rigorously as are the values that guided the decisions initially. Learning how to improve governance can be fostered through experimentation, although learning how to design effective and ethical experiments involving humans and our governance systems is a wicked problem in its own right. Diversity feeds experimentation yet may result in more uncertainty in the short term. Much time may be needed both to implement and evaluate experiments, given that governance effectiveness would need to be evaluated over a rich set of situations and contexts. As a whole, then, what does society gain from this system of systems knowledge at an earth-scale level?

Reflections from the Future

These examples confirm that system of systems thinking is more critical than ever. Rhizome models, for example, allow us to map system of systems as sets of causes, effects, and influences. This is best understood in the context of the Internet where users are interconnected and a single point of origin cannot be determined because it does not exist (Dreyer 2012). Allowing multiple concepts and concepts simultaneously in our thinking allows us to understand science and technology development; how NBIC is allowing innovation worldwide; how the Internet is accelerating market penetration rates; how big data analysis is facilitating niche marketing and increasing concerns over the protection of privacy; how technology is impacting governance and international relations (Schmidt and Cohen 2013); and why the chicken crossed the globe to the benefit of human civilization (Lawler 2014).

System of systems thinking facilitates simultaneous thinking about social, technological, economic, environmental, and political system of systems. Societal systems are empowering, with benefits and uncertainties for identity, as addressed above. Technological systems are distributed and intertwined. Economic systems drive affordability of solutions and our overall resilience to major shocks to the overall natural and anthropogenic systems. The environment is part of the natural system, but it also promotes environmental values, resilience, and the quest for identity as self-sufficiency demands access to local energy, water, food, and the comparative sustainability of resource use among populations (Rees 1992). Political gridlock, if not complete failure of nation states, leads to more local self-sufficiency and opens capacity and opportunity for new nongovernmental organizations.

In turn, these systems require knowledge and consideration of comparative advantage, fluid culture, shifting power, and influence from national governments to transnational firms to nonprofits to wikinomics, the noosphere, and common minds across the world (Kurzweil 2005). Contrary to the globalization of identity, identity becomes focused on self-achievement and community. As needed, identity and communities interact with life-support systems for resiliency but with the potential interactions of the integrated social and economic systems to increase household production, decrease the need for salaried employment and income, and decrease monetary income, which reduces income taxes. Reductions in income taxes reduce government revenue and also contributions to Social Security, causing both to be reimagined; employment shifts from firms to households or nonprofits; macroeconomic policies designed to control money supplies to spur consumption also need to be reimagined as do the meanings of unemployment and the role for governance in political systems.

To understand and leverage these natural and anthropogenic system of systems, much less the interactions, convergences, and cascading effects, requires foresight. This gets easier as all stakeholders demand a self-sufficient world that is more predictable with respect to its system of systems interactions with the global life-support system. Regardless, more modeling approaches will help our collective understanding of where humans are and where humans might be headed. Advanced agent-based models (Gilbert 2008) and integrated state, time, and agent-based models (cf. Campbell et al. 2005) running on increasingly more powerful computing platforms are especially important in this context. Modeling systems within systems also may depend on new forms of sentience if humans are to fulfill our obligations to future generations.

Because the global-scale issues facing Spaceship Earth require an appreciation of earth-scale integrated systems that are both natural and anthropogenic, humans must apply convergent thinking with foresight to understand and solve our problems: Convergence of knowledge is necessary to understanding the earth-scale systems that make up Spaceship Earth.

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Astrosociology (Social Science of Space Exploration)

Jim Pass and Albert A. Harrison

Contents

Abstract

Discussions concerning science and technology convergence too often ignore the social sciences. This is not the case here, as the focus is on a relatively newly emerging and increasingly relevant social science field. Astrosociology is an interdisciplinary and multidisciplinary field that promotes and represents convergence of the physical/natural sciences and the social/behavioral sciences on all matters pertaining to humanity's interests and activities in space and the consequences of these activities for people on Earth. While political science and economics have sustained a strong interest in space, interest on the part of anthropology, sociology, and several fields of psychology has been low. Also, with the exception of selected space science research areas including astrobiology, the search for extraterrestrial intelligence, and the protection of the Earth from asteroids and comets, the receptivity of physical and natural scientists to inputs from the social and behavioral sciences has been low. Increasing synergy

J. Pass (✉)
Astrosociology Research Institute, Huntington Beach, CA, USA
e-mail: jpass@astrosociology.org

A.A. Harrison
University of California, Davis, CA, USA

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between the "hard" and "soft" sciences requires increasing interest within both the social and behavioral sciences and encouraging receptivity on the part of physical sciences. This chapter emphasizes the need for convergence, the barriers to convergence, and potential approaches to reduce these barriers. Achievement of unprecedented levels of collaborative synergy is possible with increased levels of sustained convergences. This is possible by increasing social science literacy among the public and "hard scientists" and developing win-win research projects that accommodate varied interests and goals. SETI, astrobiology, and planetary defense serve as specific examples of successful convergence efforts, though they involve social scientists in relatively small numbers. These examples demonstrate both the limited successes and the largely untapped potential of the social sciences to contribute to space education and research.

Introduction

Since the dawn of the space age in 1957, contributions from social scientists have not kept pace with hard scientific and technological developments. Economics and political science have made ongoing contributions, but research and application from other fields including anthropology, sociology, and many areas of psychology have been somewhat sporadic and intermittent. Much of the good work was accomplished in the past by individuals alone, and among several social scientists for specific projects and publications, so no coherent collaborative effort remains intact long enough to move the theoretical and empirical work forward on a sustained basis. No body of literature can reach adequate development and recognition unless interdisciplinary and multidisciplinary efforts become formalized and sustainable.

Each field within social science has benefitted from pioneers. In anthropology, Ben Finney has had a long-term interest in space-related matters including reducing the divide between the physical and social sciences (Finney 1992). Along with physicist Eric M. Jones, he forever united space exploration and settlement with the search for extraterrestrial intelligence (SETI) in their coedited volume *Interstellar Migration and the Human Experience* (1984). More recently, we find seminal work by Jack Stuster (1996, 2004, 2005). Recently, anthropologists have begun studying "new space" activities on the part of visionaries, entrepreneurs, and others to increase private enterprise in space (Valentine 2012).

In sociology, B. J. Bluth (1983) made significant early contributions to understanding psychosocial adaptation to spaceflight, and though many of her writings were never published, her achievements are summarized in Connors et al. (1985). Extensive writings by William Sims Bainbridge (1991) also come to mind, as does the work of Alvin Rudoff (1996) and Diane Vaughan (1996). One of Rudoff's questions – where is sociology? – still rings loudly in our ears. Pass (2004c) has termed space as sociology's forsaken frontier.

In psychology, while hard-core research at the human-machine interface has been continuous, NASA's interest in personality, social, and organizational psychology gained traction only after astronauts reported difficulties on extended duration missions on the Russian space station Mir (Harrison and Fiedler 2011a, b). NASA cut "soft" psychology from the space program before the Mercury flights ended. However, in anticipation of post-Apollo flights, psychiatrist Nick Kanas and psychologist William E. Fedderson (1971) outlined psychological and social issues at the individual, group, and intergroup levels. This provided a model for many researchers who followed, and Kanas went on to a long and distinguished career involving collaboration with Russians. Robert Helmreich (1983) is among the leaders who sought to reinstate neglected areas of psychology into the US space program, and psychiatrist Patricia A. Santy (1994) and the interdisciplinary team of Connors et al. (1985) later joined him. In 2001, Harrison (2001) wrote a book called *Spacefaring: The Human Dimension* that made a clear and concise argument for the need for social science involvement.

There were other pioneers, but the number of social scientists involved in space-related matters was, and remains, small. Thus, the promise that social science holds for illuminating and guiding our entry into space is still largely unfulfilled. The problems are twofold.

First is the issue of igniting interests within the social sciences. This is difficult because it is not among the traditional research areas nor is it, particularly at this moment, a hot research topic. With occasional exceptions, academic publications do not appear in mainstream journals; indeed, they may appear in journals such as *The Journal of Rockets and Spacecraft*, *The Journal of the British Interplanetary Society*, *Acta Astronautica*, and *Theology and Science* that are unknown to social scientists. It is difficult to generate involvement in a research area that has a meager and difficult-to-find literature base and does not have the support of top leaders of the field. It may be difficult, too, because, traditionally, some of the most promising space-related topics have a science fiction ring.

Second, there is the problem of engaging interest and receptivity on the part of the "hard" scientists and engineers (and their administrators). For many – not all – hard scientists, past personal experience, standard practice, and intuition suffice. Input from the social sciences is unwelcome if it costs extra money, delays a launch, or somehow interferes with management prerogatives. As for envisioning our future in space, anthropologists and sociologists were bypassed in favor of Utopian visions promulgated by rocket men such as Konstantin Tsiolkovsky, Hermann Oberth, and Wernher von Braun. Oftentimes, these inspirational visions have strong religious and ideological themes mixed with assumed advances in technology (Harrison 2007, 2013, 2014; Launius 2012). People often fail to recognize that space exploration and settlement is more than a strictly scientific activity, largely because the human dimension of space receives too little attention.

Definition, Scope, and Relevance of Astrosociology

Astrosociology represents an effort to (1) increase interest among social scientists, (2) boost receptivity to social science inputs on the part of physical (and natural) scientists, and (3) thereby expand the level of synergy produced by all the many participants in the ongoing drama of humankind's entry into space working together. Astrosociology focuses on the relationship between space and society/ humankind (Hearsey 2011). Astrosociology is the scientific study of *astrosocial phenomena*: the social, cultural, and behavioral patterns related to outer space (Pass 2009).

While it may be tempting to assume that astrosociology applies only to humans living in space, and thus consider it an unneeded field that is still well before its time, it is already applicable to those on Earth, as it has been for decades. Astrosocial phenomena will loom in importance in terrestrial societies as human activities in space exert more subtle and blatant influence on individuals, groups, organizations, and societies. Thus, rather than a premature effort, astrosociology is planting its roots at the beginning of a long and potentially hazardous beginning of forays beyond the Earth (Pass 2004a). Moreover, we know very little about the effects of astrosocial phenomena, even in terrestrial societies.

By moving beyond a few scattered efforts, we can, to consolidate gains, achieve new insights and make collaboration among traditionally different disciplines an accepted and hopefully routine part of all space-related efforts and social science transitions. Convergences among the various social science, physical science, and natural science disciplines and fields are vital for fostering future advancements in space and understanding resulting effects on Earth, including a spacefaring future (Pass 2004b; Pass and Harrison 2007). We have much to draw upon. These include drawing on sound theory and research, preparing for unintended consequences of well-meaning ventures, and urging the alignment of technological and cultural change. For example, the development of space societies requires an approach similar to urban planning in order to maximize the livability factor within the isolated human ecosystem.

Even the acceptable uses of technologies – or what sociologists call *material culture*, coined by sociologist Ogburn (1922) – possess positive and negative social and cultural characteristics. For example, what are the acceptable uses of nuclear power? What are the unacceptable applications? Not everyone agrees that this type of power source is acceptable when launching spacecraft from terrestrial spaceports. Decisions about how best to use potentially harmful scientific discoveries and technological viewpoints require ethical decision-making and that requires study by social scientists. Such efforts require long-term commitments. In the absence of interdisciplinary education and research, the gap between technology and culture could grow catastrophically large.

In our assessment, researchers in the physical and natural sciences show a greater degree of sustained collaboration than do their peers in relevant areas of social science. We see major collaborative efforts in biotechnology, nanotechnology, artificial intelligence, robotics, and future energy technologies, just to name a few. Nothing like this exists within the social sciences to an extent that is even close to the taken-for-granted realities enjoyed within the physical and natural sciences. Without a much greater impact by social scientists, the potential for space migration and the salvation of humans on Earth remain less certain. However, increased involvement on the part of the social sciences and improved collaboration with the physical sciences is not enough. We need a shared, holistic understanding of space exploration, settlement, and related areas. The future of space education and research must identify and exploit areas of compatibility that can result in convergence with the physical and natural sciences wherever possible. This can result in new forms of synergy beyond what is possible among the physical and natural sciences alone, providing new insights, methodologies, and new directions in research and education.

STEM

STEM stands for the “hard” sciences, technology, engineering, and mathematics. This acronym identifies the major focus of NASA and the core curricula of a growing number of new programs in academia. The “S” in STEM has historically favored the physical and natural sciences, as if the social sciences represented something fundamentally different, something somehow unscientific or at least less scientific than the “hard” sciences. Even the label “soft sciences” implies that the scientific method, rigorous theory building, and unbiased empirical investigation are less applicable to human behavior or, worse, that human behavior is not subject to scientific laws. This is a purposefully constructed overstatement of the average position of natural and physical scientists in order to illustrate the point that the concept of science is too often exclusive of social science when it comes to space issues. Yet this status quo involving the exclusion of the social sciences includes its own built-in limitations.

Originally advocated by the Rhode Island School of Design (2014), STEAM is an effort to add the arts to the STEM agenda. There is nothing wrong with this approach per se, but it does not go far enough because it leaves out the social and behavioral sciences as well as the humanities. The arts can contribute to space research, such as making a habitat livable rather than just survivable through the construction of appealing artistic works and comfortable architectural surroundings. However, the social sciences can offer much more than the arts alone.

To be fair, projects that involve collaboration between scientists from both branches of science have occurred in the past including work on committees and projects, publications, and other forms of research efforts. However, it is also fair to point out once again that these interdisciplinary efforts have tended to be short-lived rather than the persistent efforts that can ensure long-term advancements. This is problematic, as it generally results in small developments. While short-lived efforts can bring about new ideas, discoveries, technologies, and scientific applications, typical interdisciplinary efforts end too soon, and thus the synergy that may have developed dissipates too quickly. The promise of ongoing convergences lies in formal, long-term multidisciplinary campaigns, with continuing efforts to create new interactions among scientists within each branch of science and those between the two branches. In the area of space education and research, the dearth of research on astrosocial phenomena means that much more collaborative work is required that can benefit humankind in both known and unknown ways.

Thus, temporary cooperation cannot continue if humankind truly seeks to live permanently in extraterrestrial ecosystems, for example. The physical environment characterized by contributions from the STEM subjects is a necessary element of survival and even potential prosperity, but it is not a sufficient condition. Human beings, who must live within the confines of those space ecosystems, must have both physical *and social* environments that support survival (Pass 2011). One cannot foretell the exact convergences that arise when the two branches interact formally and sustainably, yet one can reasonably expect that new breakthroughs increase chances of survival. Planning from the early stages of any program or trend will benefit humankind most profoundly when all types of scientists and scholars work together toward a common goal on a continual basis.

Successes

Developments in astrobiology, SETI, and planetary defense illustrate that highly collaborative research is possible. Here, we find collaboration among social scientists and humanists and between these fields and physical and natural scientists. Although relatively few social scientists are involved, the success of this collaboration gives rise to hopes for similar successes in space exploration and settlement and other achievements pertaining to humankind and space on a much more widespread basis.

Astrobiology studies the origin, distribution, and future of life in the universe and hence touches upon great questions of human existence, long considered the province of philosophy and theology (Blumberg 2011; Dick and Strick 2005). Where did we come from? Are we alone in the universe? What will become of us? NASA's astrobiology program, as set forth in the NASA Astrobiology Roadmap, combines physical, biological, and social sciences and recognizes enormous implications for society (Des Marais et al. 2008). As such, astrobiology provides fertile grounds for astrosociology. Central topics include the origins and evolution of life, the search for life and its precursors beyond the Earth, environmental ethics, establishing ourselves as a multi-planet species, and protecting ourselves from global catastrophes and extinction-level events.

Because of astrobiology's far reaching implications for humanity, NASA's Astrobiology Roadmap spurred a parallel effort now known as the "societal roadmap" (Race et al. 2012). Based on workshops drawing participants from a wide range of disciplines, the societal roadmap identifies five areas for exploration. These are:

1. The range and complexity of societal issues related to how life begins and evolves
2. Astrobiology's implications for the significance and meaning of life
3. Relationships of humans to life and environments on Earth
4. The potential relationships of humans with other worlds and types of life
5. Life's future on Earth and beyond

The societal roadmap underscores the importance of anticipating new discoveries, including how people with different worldviews are likely to react to them (Race et al. 2012). What might be done to communicate new findings to diverse audiences? Will the public accept or reject these new discoveries, and, if accepted, how will they incorporate them into existing cultural and subcultural narratives? What impact might they have on space entrepreneurs and industrialists? What kinds of social change might we expect? How is it possible to turn new findings into building blocks for understanding discoveries that are yet to come? The societal roadmap provides a useful resource for researchers at the juncture of astrosociology and astrobiology.

SETI, the scientific search for extraterrestrial intelligence outside of our solar system, began in 1960 when theoretical calculations and advances in technology prompted Frank Drake to initiate a radio telescope search in 1961 (Drake 2011). Search strategies seek indicators such as a focused radio beam, a pinpoint of light, or an artifact, which are indisputable products of nonhuman technology. Among SETI researchers, the astrosociological component is known as “the cultural aspects of SETI” or CASETI. John Billingham provided much of the leadership here. He was an aviation and space physician who, after his shift to SETI, became a strong advocate of interdisciplinary research (Billingham 1998; Billingham et al. 1999; Harrison 2013). Billingham was fond of saying that we need to apply all of the “gray matter” that we can to SETI, and he hoped that by attracting to SETI, the top scholars in various disciplines, others within the discipline, would follow suit.

As defined by Billingham (1998, p. 711), CASETI includes “all thinking about ETI [extraterrestrial intelligence] going back to the classical era, the immediate [consequences] of detection, and indeed the science and engineering of SETI as set in the context of human activity.” Within a year of Drake’s first search, the National Science Foundation sponsored an interdisciplinary workshop at the National Radio Astronomy Observatory, and within the first 10 years, SETI had recruited scholars from anthropology, archeology, linguistics, history, and sociology to join the conversation. Based on workshops held at NASA – Ames Research Center in the 1970s – a comprehensive report on SETI included commentary on religion, societal responses, and the kinds of studies that might be done in preparation for contact (Morrison et al. 1976). By the 1990s, CASETI had become a regular part of annual International Astronomical Federation conferences and were featured in special issues of the peer-reviewed journal *Acta Astronautica*, but very little seems to have made it into premiere social science journals. Over the years, the cultural aspects of SETI have been the focus of many conferences and have surfaced in new venues, including regional sociology meetings and national anthropology conventions. There is a relatively abundant and growing interdisciplinary literature including overviews (Harrison 1997, 2007; Michael 2014; Michaud 2008; Tough 2000) as well as more specialized fare (Traphagan 2014; Weintraub 2014), though convincing more social scientists to participate remains a critical challenge (Harrison 2011a). The SETI Institutes’ Douglas A. Vakoch has edited several truly multidisciplinary books (Vakoch 2011, 2013a, b, 2014; Vakoch and Harrison 2011). The significance of studying SETI (and astrobiology) utilizing scientists and scholars from both major branches of science becomes clear when one considers the implications of detecting extraterrestrial life in any form and how such a discovery could alter societies and their cultures in ways not totally predictable based on today's incomplete data (Harrison 2011b).

Astronomers, planetary scientists, and other physical scientists involved in the protection of the Earth from asteroids and comets (planetary defense) have shown remarkable interest in contributions from social scientists including them at planetary defense meetings held on an intermittent basis. This acceptance is evident in the International Academy of Astronautics Cosmic Study Group's report on *Dealing with the Threat to Earth posed by Asteroids and Comets* edited by Ivan Bekey (2009). Here, we find chapters on organizing for the task, behavioral factors and planetary defense, and policy implications. The science agenda includes identifying potentially hazardous near-Earth objects, calculating and recalculating orbits to estimate when (and to a lesser degree, where) they will strike, and inventing and deploying devices to deflect or destroy the object. The societal agenda includes promoting international planning, performing risk assessments that take subjective assessments and emotions into account, and preparing for warnings and evacuations, an initial emergency response, and long-term recovery efforts (Race et al. 2012).

It is not entirely clear why astrobiology, SETI, and planetary defense embraced social science from the start while the early space program was resistant to involving social science. Quite possibly, cold war politics and the goal of beating Russia to the Moon worked against social science. The space program was highly organized and controlled, the time schedule was tight, and anything that portrayed NASA or the astronauts in an unfavorable light were, from an administrative point of view, threats. Social science research had the potential of revealing a flawed organization or preventing serious imperfections in the astronauts. From the start, astrobiology, SETI, and planetary defense became as international efforts. Whereas the great Moon race was a win-lose contest between American and Soviet ways of life, astrobiology, SETI, and planetary defense offer a superordinate goal, on the whole, a win-win activity. NASA is highly involved in astrobiology and planetary defense (not SETI), but is not hegemonic and welcomes international participants. Perhaps this open approach reduces the potential damage that could have resulted from the broad-based consultation and interdisciplinary activity. In any event, successful astrosociological research requires taking the vested interests of organizations and participants into account.

Areas of Future Astrosociological Education and Research Efforts

Astrosociology has gone through a number of growing pains, though it has managed to move forward. Most of the first 10 years of development focused on introducing the field to the space and social science communities and on making the case for its relevance and thus necessity. In 2008, the incorporation of the nonprofit organization known as the Astrosociology Research Institute, or ARI, in California became a reality. Its mission remains the development of astrosociology as an academic field, though on a much more formal basis. Furthermore, over the last 3 years or so, the transition to the pursuit of educational and research-oriented actions has accelerated.

Astrobiology includes a strong educational component that bodes well for the future aimed at scientists and technicians, social scientists, humanists, and the public. This is intended to build solidarity across interest groups, increase interdisciplinary and multidisciplinary activities, and smooth the course of our progress in space by minimizing unpleasant surprises or "unintended consequences" (most of which can be foreseen and dealt with if the right skill mix is involved). Thus far, this educational component includes:

1. Implementing efforts to incorporate astrosociology into existing social science and humanity programs and disciplines, as well as those that integrate the field into STEM programs
2. Providing information, resources, and new developments via the ARI website
3. The *Astrosociological Insights* newsletter
4. Publishing the new free online peer-reviewed *Journal of Astrosociology* (JOA) scheduled for introduction in early 2015

Rigorous theory building and credible research efforts must characterize the future of astrosociology's development. Original astrosociological research remains the last area that still needs considerable development, which will become a high priority starting in 2015. One of the goals is to build a permanent astrosociology community so that interdisciplinary science can continue as space increasingly affects humans who remain on Earth and those who decide to migrate beyond. This research community, we hope, will be self-sustaining long after the Institute passes from the scene, if that should occur.

The social sciences and sociology, in particular, have accumulated more than 200 years of empirical findings, a great many of which are relevant to the relationship between space and society. Borrowing existing theoretical concepts and reviewing relevant research findings represents a good start. Moreover, new astrosociological research could add much to the STEM approach, again to achieve a more holistic understanding of how astrosocial phenomena integrate with terrestrial social forces and how it affects social conditions and influences social change. Astrosociology can serve as an impetus for a new paradigm that unites all the social science and STEM disciplines in new ways so that all scientists interested in space research can collaborate to accelerate progress in several dimensions of social life.

The human dimension affects spaceflight, settlement, resource exploitation, and other related matters whether the humans involved are in space or on the surface of the planet Earth. Even those not directly involved benefit. Even those who openly criticize space programs as wastes of human effort and funding enjoy space program applications as they voice their objections often over calls from the cell phones while avoiding severe climate conditions that they learned about from their weather apps based on data analyzed from overhead satellites. Astrosocial phenomena are pervasive in our cultures, subcultures, societies, and everyday lives, and we need to recognize them as such.

Conclusion

We have illustrated some of the historical difficulties inherent in getting unlike-minded scientists to cooperate so that scientific and technological convergences are more likely to occur. We also provided several examples regarding the tremendous potential successes that convergence activities can bring about if all types of sciences from both branches of science participate. The future of space exploration cannot reach its greatest potential if social science participation and acceptance remain at their current levels.

Technological and scientific progress as the future unfolds depends on convergences among fields and disciplines, especially those that have rarely cooperated in the past. Natural and physical sciences have made tremendous breakthroughs on their own, and perhaps even greater ones through interdisciplinary efforts within the traditional "hard" branch of science that focuses on space. Moreover, societal leaders, ethics experts, and social scientists have decided or at least influenced how new scientific and technological advances were to be used. However, the level of focus on how astrosocial phenomena affect individuals, their social groups, cultures, societies, and the international community has remained surprisingly inadequate. The creation of the field of astrosociology addresses this inattention so that a formalized effort focuses on this void (Pass 2006) and on this astrosociological frontier that social scientists have scarcely investigated.

The status quo reveals relatively very little input from social scientists regarding space-related matters. Nevertheless, the future of space education and research depends on increased convergences. It will prove increasingly valuable as humankind moves farther away from the planet Earth. What most people – including all brands of scientists and scholars – too often fail to take seriously is the fact that outer space already affects societies and the lives of their citizens on a daily basis, and this influence will only grow stronger over time if science and technology continues to advance at even a moderate pace. Societies will continue to benefit in yet unforeseeable ways as long as space remains relatively important among policymakers, universities, and corporate leaders, not to mention the public.

The timescale of this advancement, should it continue, will depend largely on the level of resistance to new scientific and technological breakthroughs on a number of different fronts. Some resistance will occur even against announcements to pursue particular courses of research that appear to benefit humankind and society, and thus future social movements may develop aimed at disrupting others' plans. Cultural lag is a common structure feature of any society, which occurs when inevitable technological change in the (physical) material culture outpaces nonmaterial culture (ideas) causing resistance (Ogburn 1922), as various subcultures possess conflicting agendas and priorities. To be sure, a large segment of the population possesses various levels of distain for space exploration and especially new technological advances. This give-and-take dynamic process is part of a convergence-divergence process (Roco and Bainbridge 2013). Nevertheless, it remains possible to transcend what humankind currently considers as "normal" progress, as history has shown.

What can convergences accomplish in the area of outer space education and research? The general theme of this chapter, then, focused on two distinct types of convergence strategies. First, cooperative ventures among social scientists within the single branch of social science fields and disciplines require much greater action. As a starting point, however, a much larger proportion of social scientists must take space issues more seriously and pursue astrosociological education and research. Convergences within the social sciences can yield heretofore unattainable outcomes, to be sure, but they will still be limited. It is probable that this type of formalized interdisciplinary pattern must reach a certain threshold for the second type to become prevalent. Indeed, informal pilot programs and ventures will probably be required to move this trend forward.

The second type of convergence becomes possible by moving beyond the fields and disciplines within either of the two branches of science. When adding the social sciences to the traditional approaches dominated by the STEM subjects and thus introducing astrosocial phenomena to the equation, social and cultural forces become much more prominent and central to the scientific investigations carried out. Traditional approaches to space education and research, and those focusing on astrosocial phenomena, when purposely tied together, can offer new insights into both (1) how humans can better live with each other in confined extraterrestrial ecosystems and (2) how humans on Earth can take better advantage of terrestrial environments and resources. The latter type of scenario most immediately benefits humankind, though over time, both benefit human beings wherever they happen to reside.

The future is wide open, and new convergence strategies can accelerate humankind's progress in science and technology beyond what is possible by either branch of science alone. A higher level of collaborative synergy is possible. New forms of collaborative synergies involving all sorts of combinations of scientific fields and disciplines centering on outer space issues have begun, to be sure, but they remain in their infancy and still lack enough input from the social sciences to result in truly unanticipated developments. Indeed, the design of the field of astrosociology resulted as an attempt to bring the social sciences into the space age. However, one of the more important targeted outcomes focuses on providing a rallying point for convergence-based advancements to become possible and more mainstream. With this in mind, it is safe to state that humankind is just beginning to take advantage of scientific and technological convergences that may well transform the world, with important contributions focusing on astrosocial phenomena firmly established as a new dimension of space education and research.

However, it cannot be overstated that this is only possible if scientists purposely work toward new convergences within their own branch of science and, more importantly, work toward convergences with those in the other branch. As such, natural and physical scientists should read this chapter, and perhaps surprisingly to many not familiar with astrosociology, social scientists should to do so as well. Otherwise, the human dimension of space will continue to fall under the radar of the space community, resulting in inevitable one-dimensional analyses, thus slowing progress in space exploration as well as resulting in poor management of the Earth's resources and its environment. Once again, it must become clear to all that astrosocial phenomena affect human beings, their societies, and their cultures, wherever they may be, even within the confines of the Earth's atmosphere and magnetic field.

Acknowledgments This chapter is dedicated to my co-author and dear friend Al Harrison who passed away shortly after finishing his contributions to these chapter contents. He was both as a kind person and a major contributor to space education and research from a social scientific perspective. As our first Advisor, Dr. Harrison was a great supporter of astrosociology and the Astrosociology Research Institute (ARI). In fact, he was a pioneering researcher in astrosociology long before it was established! His input greatly improved the quality of this chapter.

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Demographic Transition

William Sims Bainbridge

Contents

Abstract

For a century, a key component of social scientific understanding of sustainability on Earth has been the theory that human population growth would gracefully adjust toward stability as the entire world became technologically modern. However, today this theory is in serious doubt, and it is equally plausible to argue that population will grow to natural limits set by starvation and warfare, or that it will shrink to a less violent human extinction. Many current policy debates are affected by these uncertainties, in such areas as national defense, immigration, education, and health care. Only the convergence of social and biological sciences, assisted by contributions from many other technical fields, will achieve a proper understanding of the complex systemic processes involved to identify the most humane and effective policies. Thus, convergence of science and technology will be required to achieve beneficial convergence of all human beings into a single healthy and prosperous society.

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Introduction

Among the most vexing problems facing humanity are those that relate directly to how many people can comfortably live on this planet or on any particular continent or national territory. A classical perspective called *demographic transition theory* asserted that somehow the birth rate would naturally adjust until world population was stable at a level that was sustainable economically and environmentally, but in recent years all of its assumptions have been called into question. Additionally, the issue of population policy is implicated in political disputes about immigration, health care, public education, and many other sensitive matters. At the extreme, rhetoric can become racist and sexist, and rational scientific debate can be silenced.

The goal of this chapter is to outline the legitimate scientific questions in a way that connects demographic dynamics to other processes of significance for a range of sciences and technologies, thus considering demographic transition as a form of convergence. Ideally, the populations of the world will come together in a way that ensures the survival of all the diverse peoples. But that cannot be achieved without clearheaded consideration of the barriers to consensus that exist, and of the ways in which population debates have turned ugly in the past.

Theories of Natural Equilibrium

For more than two centuries, a rather gloomy theory has cast long shadows over demography, called *Malthusian* after its early advocate, Thomas Malthus (1798). It holds that human population will increase until it hits absolute natural limits, at which level starvation, disease, war, and the more subtle symptoms of poverty would halt any further increases. Variations exist within Malthusianism, for example, warfare in competition for scarce resources may do its grim job too well, reducing population below its natural maximum. Or, the aristocratic classes may hoard some of the resources, causing poor people to starve, and also keeping the total population below the limit. If that were not sinister enough, a modern elite could claim with at least the semblance of logic that a higher fertility rate among themselves would serve biological evolution, ensuring a higher rate of reproduction by people with superior genes, and a lower rate among inferior people. To say the least, these are not pleasant thoughts, and a more optimistic alternative would be welcome.

Malthus was writing just as the Industrial Revolution was having its full effect, and the following decades seemed to refute his theory because the economy of his native England grew faster than the population, resulting in greater health and widespread prosperity. Despite occasional economic recessions, prosperity in advanced nations tended to increase, for three reasons: (1) Raw materials from the entire world had become available, and residents of the United States and Canada would do well to remember that earlier in history their lands were economically significant as sources of raw materials for English industry. (2) The consolidating capitalist economic system, for all its faults, did a good job of investing in profitable capital facilities, from mines to factories to distribution systems. (3) Science and technology advanced rapidly, moving ahead of population growth.

All three of these points connect to science and technology convergence. During the Industrial Revolution, the valuable raw materials came from extractive industries, including copper, iron, coal, and oil. Today, nanotechnology can provide raw materials not by digging them up from underground at remote locations but by assembling some of the atoms that exist all around us into engineered structures, such as carbon nanotubes. Convergence of economics and the social sciences may be able to refine and expand the capitalist system so that it can function better globally and with improved control of income inequality. More generally, continued progress in science and engineering will require active convergence, not merely uniting all the fields but assembling them into the equivalent of an engine of continued progress. In recent decades, there has existed considerable debate about how many human beings the ecosystem of the Earth can support, given the uncertainties about the untapped stocks of natural resources and the question of what helpful technological or social innovations remain to be achieved (Cohen 1995).

As was true two centuries ago, human well-being depends upon whether the curve of technical and social progress stays ahead of the curve of demographic increase. The fact that additional technical progress is clearly possible does not assure us that it will be achieved fast enough. In the wake of the Industrial Revolution, the spread of industrial technology and improved agriculture seemed to trigger a population explosion which remained a concern (Ehrlich 1968). In the middle of the twentieth century a general social theory emerged, often called *Functionalism*, that asserted societies tend to adjust their norms, values, and institutions to achieve a good deal of stability – *homeostasis* – not merely because they hit physical limits but as the result of beneficial social feedback processes. This was a convergent theory, and the social scientists who contributed to it came from sociology, cultural anthropology, and a diversity of other areas.

Within Functionalism, a perspective on population trends emerged called *demographic transition theory* (Davis 1963). In its simplest form, it considered human history in terms of three periods. In ancient days, human life was precarious, and a very high birth rate was needed to offset a high death rate and achieve stability in the size of the population. The second period roughly followed the Industrial Revolution, as medical and economic advances reduced the death rate, while the birth rate remained high because it was sustained by traditional cultural institutions. Therefore, the size of the population expanded rapidly. But this middle period was marked by demographic transition, because gradually the culture adjusted and the birth rate reduced as well. In the third period, which many nations may have entered decades ago, both the death rate and the birth rate are low, and again, as in ancient days, the size of the population is stable, although much higher than it had originally been.

This theory of demographic transition relates to convergence in several ways. Without technological progress across many fields, neither the birth rate nor the death rate could decline below their traditionally high levels. Obviously, effective methods of contraception gave families a degree of technological control over the production of children, but these methods are varied and depend upon a variety of medical advances as well as social customs. Conditions in the wider economy, themselves largely technology dependent, shaped the decision process within families, for example, the reduced need for children to work on farms or to provide for their parents once they enter old age. Similarly, death rates are shaped by public health as much as by medical treatments, and the quality of both depend upon the advance of scientific knowledge and the growth of economic prosperity. It was not enough for discoveries and innovations to arise in multiple separate fields simultaneously, but also they needed to diffuse across occupational and geographic boundaries, in the process of which they influenced each other in the manner of science and technology convergence.

One of the early ways in which this transition was conceptualized was in terms of *cultural lag* (Ogburn 1922). Partly because diffusion of innovation takes time and partly because culture changes slowly as norms are transmitted in modestly altered form from one generation to the next, customs are slow to catch up with material realities. Social scientists like William F. Ogburn nearly a century ago especially pointed to the significance of the changing role of women in society. In ancient days, with high rates of infant mortality, there was no alternative but to require women to devote all of their most vigorous adult years to bearing and raising children. They also played economic roles, but within the household, not merely cooking but making clothing and many other things used in daily life at home. When infant mortality rapidly declined, the need to give birth to many children did as well. Simultaneously, in the context of society-wide technological progress, much of the homework traditionally done by women, notably manufacture of clothing, was taken over by factories. One interpretation of these shifts was that women's status in society actually declined initially, and many societal customs needed to be changed after considerable lag before women could achieve equal roles with men in the world outside the home. Other interpretations can be suggested, but clearly the demographic transition was connected to a vast number of other changes going on in human society, with the potential to cause or aggravate many problems, in addition to the benefits it offered.

Explosion Versus Collapse

The most serious criticism of demographic transition theory has concerned whether it is really the case that human society is so finely tuned in terms of cultural and institutional factors to achieve stable population numbers after effective birth control technologies were introduced, rather than experiencing a total collapse. This is not a new issue, and the pioneer in this area of demography, Warren S. Thompson, was quite aware of it when he contributed an article titled simply "Population" to the *American Journal of Sociology* in 1929. At that time, he used statistical data to suggest that different societies seemed to show three different patterns: (1) In some countries, people were not yet able to limit the birth rate voluntarily, and the expected drop in the death rate had not really yet occurred either. (2) In other countries, birth rates were slowly coming under control, but death rates were declining more rapidly, so the population explosion associated with early stages of the transition was to be expected. (3) In the final group of countries, the transition was far advanced, but it was unclear whether contraception would lead to stability, or to inexorable population decline.

That last possibility, severe population decline, was a very active topic of discussion early in the twentieth century. Thomson himself had written about it in 1917 using the provocative but then current term *race suicide*, a phrase made popular by President Theodore Roosevelt, otherwise considered one of the most progressive leaders of his day. The term originally referred to concerns expressed by descendants of the earlier Anglo-Saxon and German immigrants to the United States that their own groups' birth rates were too low to keep up with the influx of immigrants from southern and eastern Europe, whose own birth rates seemed higher. Ideally, this topic should be an exclusively scientific discussion, but it became highly politicized, quickly connected with racism and anti-immigrant hostilities.

An amalgam of science and elitism briefly surged, often called *eugenics*, which argued that public policy should discourage reproduction by "inferior" people. The fact that Nazi ideology adopted this idea in the harshest manner imaginable discredited not only the political misuse of demographic science but some of the legitimate scientific questions as well. Recently, social scientists have expressed concern that sinister popular sympathy for eugenics might be resurrected by modern genetics, for example, because it is now possible to determine the distribution of genes of interest across the large so-called races or smaller ethnic groups (Phelan et al. 2013).

The rise of demographic transition theory soothed the debate, half a century ago, because it seemed to imply that all the population issues would be solved once all societies on the planet completed the transition. In the following section we will consider the dynamic balance between groups within society, and this section will take the wider view on the global prospects for demographic transition. Consideration of some very recent demographic data will best anchor this discussion. Table 1 gives the key statistics for the two dozen most populous nations, all those with over 50,000,000 population as of April 11, 2014, as estimated by the US Central Intelligence Agency and reported on the Internet for anyone to peruse in its *World Factbook*.

To be sure, all the numbers in Table 1 are estimates, and reporting the population of a nation with an apparently precise number like 1,355,692,576 for China can be misleading. Yet the CIA uses standard demographic methods working with statistics reported by the nations themselves, and other sources of such statistics are unlikely to be superior. One of the columns of figures can be interpreted as a prediction, but need not be, namely, life expectancy. The *Factbook* explains, "Life expectancy at birth compares the average number of years to be lived by a group of people born in the same year, if mortality at each age remains constant in the future. Life expectancy at birth is also a measure of overall quality of life in a

Table 1 2014 population estimates from *The World Factbook* of the CIA

Nation	Population	Median age	Life expectancy	Birth rate	Death rate	Migration rate	Growth rate
China	1,355,692,576	36.7	75.2	12.2	7.4	−0.3	4.4
India	1,236,344,631	27.0	67.8	19.9	7.4	−0.1	12.5
United States	318,892,103	37.6	79.6	13.4	8.2	2.5	7.7
Indonesia	253,609,643	29.2	72.2	17.4	6.3	−1.2	9.5
Brazil	202,656,788	30.7	73.3	14.7	6.5	−0.2	8.0
Pakistan	196,174,380	22.6	67.1	23.2	6.6	−1.7	14.9
Nigeria	177,155,754	18.2	52.6	38.0	13.2	−0.2	24.7
Bangladesh	166,280,712	24.3	70.7	21.6	5.6	0.0	16.0
Russia	142,470,272	38.9	70.2	11.9	13.8	1.7	−0.3
Japan	127,103,388	46.1	84.5	8.1	9.4	0.0	−1.3
Mexico	120,286,655	27.3	75.4	19.0	5.2	−1.6	12.1
Philippines	107,668,231	23.5	72.5	24.2	4.9	−1.2	18.1
Ethiopia	96,633,458	17.6	60.8	37.7	8.5	−0.2	28.9
Vietnam	93,421,835	29.2	72.9	16.3	5.9	−0.3	10.0
Egypt	86,895,099	25.1	73.5	23.4	4.8	−0.2	18.4
Turkey	81,619,392	29.6	73.3	16.9	6.1	0.5	11.2
Germany	80,996,685	46.1	80.4	8.4	11.3	1.1	−1.8
Iran	80,840,713	28.3	70.9	18.2	5.9	−0.1	12.2
Congo, DR	77,433,744	17.9	56.5	35.6	10.3	−0.3	25.0
Thailand	67,741,401	36.2	74.2	11.3	7.7	0.0	3.5
France	66,259,012	40.9	81.7	12.5	9.1	1.1	4.5
United Kingdom	63,742,977	40.4	80.4	12.2	9.3	2.6	5.4
Italy	61,680,122	44.5	82.0	8.8	10.1	4.3	3.0
Burma	55,746,253	27.9	65.9	18.7	8.0	−0.3	10.3

country and summarizes the mortality at all ages." The four rates are expressed per 1,000 population. Demographers often use more complex birth rates based on the number of women in the typical child-bearing years. But for present purposes, comparable rates are more intuitive. The migration rate is the net of in-migration minus out-migration, and the growth rate can be simply calculated from the other three, sometimes with a discrepancy of 0.1 because of rounding errors.

Some of the technologically advanced nations have higher death rates than birth rates: Russia, Japan, Germany, and Italy. Of these, only Italy has sufficient immigration to offset low fertility. A key complicating factor is the age distribution of the population, and low birth rates today can produce old populations with even lower birth rates tomorrow. For example, the fraction of the US population under age 18 declined from 25.7 % in 2000 to 24.0 % in 2010, as the percent age 62 and older increased from 14.7 % to 16.2 % (Howden and Meyer 2011).

Fertility differences across nations have often been attributed to their religious traditions, and the Roman Catholic Church is widely believed to encourage high birth rates, but Italy's situation seems to refute this theory. Demographers have suggested that Islam supports especially high birth rates (Keyfitz 1987), but the table shows that both Turkey and Iran have moved close to Mexico, suggesting that all three may eventually approach the low-fertility pattern found in many parts of Europe, as the result of increased prosperity, education, and many other trends associated with advanced technology.

Migration can be conceptualized as a major demographic form of societal convergence, and it is interesting to note that among large nations, the United States and United Kingdom have the highest net immigration rates, after Italy. Canada's is actually higher than any of these three, fully 5.7 per 1,000 population, although with a population around 35,000,000 Canada was not included in the table. One may speculate that something about Britain and its two prominent former colonies is especially conducive to cultural convergence. Many technologically advanced nations, the United States among them, currently experience heated political debates about immigration. Yet for nations with low birth rates, immigration may be the most effective way of sustaining the size of the population.

Purely as an intellectual experiment, it is easy to run the changing birth, death, and migration rates forward, extrapolating into a hypothetical future what the population of a nation might be. One study using 2007 data on the nations of the European Union predicted that only one of them would not eventually go extinct, France (Bainbridge 2009). Germany would reach zero population in 1,100 years, the United Kingdom in 1,825 years, and Italy in "only" 900 years. Of course, long before these dates of national death were reached, immigration would have increased, whether peacefully or by military invasion, and a combination of cultural shifts and government pronatal policies might have reversed the demographic decline.

One of the most thoughtful demographers, Nathan Keyfitz (1982), expressed serious doubts about long-term predictions of population growth or decline, but so long as we do not place much confidence in simple extrapolations like this, they can highlight issues that must be studied more deeply. A superficial but reasonably logical reading of the table is that many large nations are still growing rapidly through fertility, and for the foreseeable future the population decline in some nations could be offset if they were more open to immigration. Population explosion up to the Malthusian limits still seems likely, and collapse of the entire human population seems remote. Avoiding Malthusian disaster depends upon true human convergence.

Inequality Versus Justice

Nationalist and racist versions of eugenics seem not merely evil, today, but ignorant. The genetic diversity represented by all peoples of the world as a convergent gene pool is a highly valuable resource. A gene from Uganda may combine with one from Patagonia to produce a desirable characteristic that may improve the length and quality of life for all descendants who possess both genes. Yet there is much to debate about differential fertility within each local population. In 1994, *The Bell Curve* by psychologist Richard Herrnstein and political scientist Charles Murray ignited huge controversy, when it asserted that the statistically normal distribution of intelligence (the bell curve) was largely genetically determined. This book is over two decades old, and its data older still. In addition, the authors imprudently used apparent race differences to make some of their key points, when race may not really be at all relevant to the most important scientific and policy questions (Wilson 1978). Certainly, in the past, scientists have sometimes been too quick to adopt incomplete or invalid measures of human intelligence and other attributes that vary across individuals (Gould 1981).

However, the convergence of cognitive science, genetics, and other fields is consistent with the hypothesis that many characteristics considered to be virtues are significantly shaped by biological inheritance. For purposes of this discussion, we need not make any assumptions about how these characteristics vary geographically around the globe, or how they correlate with membership in large-scale human groups, merely that they vary across individuals in any society. These characteristics are also inherited to some degree nonbiologically through parenting and schooling. Both forms of inheritance take on significance for demographic transition, when we consider the fact that fertility varies significantly across social classes and other divisions in society.

For better or worse, some versions of Malthusianism imply that traditional societal elites had a reproductive advantage in competition against the poorest classes, at the very least that their prosperity reduced infant mortality, thus increasing the chance that a child will reach adulthood and produce more children. In feudal societies, polygamy, whether formal or informal, may similarly have increased the net fertility of upper-class males. In modern societies, we rightly believe that children of all social classes deserve good health and education, which greatly reduces the demographic disadvantages of poverty. But as a practical matter, the best-educated classes may be more rigorous in employing birth control, including simply delaying fertility until later in life, thus having less time to produce children.

Education and fertility are but two variables in a complex social system, a fact that renders scientific research on cause-effect relationships difficult. For example, if a couple produces many children, each child tends to achieve less educationally and professionally (Crenshaw et al. 2000). Demographers tend to refer to this as the *quantity-quality trade-off*, although that term may seem too pejorative. One factor is that when a couple has many children, less time and other resources can be invested in each one. An entire research tradition focuses on the achievements of first-born children, who at least early in their lives are the only children in their household, and attend school before they have many siblings. However, quality-quantity trade-off research has a problem in that the personality, culture, intellect, or conceivably even genetics of the parents may be the ultimate cause of high fertility and low attainment. A few studies comparing families to which twins are born do support the hypothesis that quantity directly reduces quality, because couples do not choose to have twins. This problem may be more acute in societies with poor systems of public education, in which more of the burden falls on parents, so it could be reduced by worldwide economic convergence. Indeed, research indicates the problem is worse in a developing nation like China than in a developed one like Norway (Li et al. 2008; Kravdal and Rindfuss 2008).

Cultural and technological changes over the past 60 years may have exacerbated the problem. Arguably, higher education has become more important as a path to occupational success, while the cultural restraints that supported the self-discipline required to achieve educationally have weakened. This is most obvious when adolescent sexual behavior is studied, as early sexual experience correlates negatively with educational attainment, especially when pregnancies result (Frisco 2008). This is usually considered from the standpoint of the sexually precocious adolescents who suffer lower occupational success as a long-term result, but it also can be considered from the standpoint of the adolescents who delay sexual experience in favor of education to the point that they may have fewer children.

Convergence Challenges

If the demographic transition, as traditionally conceptualized, is completed worldwide, a number of adjustments must be made, but which transformation, decided through which decision process, remains unclear. At the very least, considerable social science research is required to determine rigorously what challenges must be met, applying which innovations from science and technology, and which cultural changes as humanity converges into one global society. For example, the middle to late stages of demographic transition, marked by expanding populations but somewhat moderate birth rates, enjoyed a *demographic dividend*, because an unusually large fraction of the population was in the working years of life, thereby raising productivity (Reher 2011). After completion of the transition, larger fractions were elderly, retired, experiencing increasingly poor health requiring costly treatment.

This chapter of the Handbook cannot authoritatively recommend the policies that should be adopted, both because we lack the solid science on which to base such policies and because any serious changes to current laws and institutions require very broad consensus to be both effective and ethical. However, this Handbook is intended to offer a very wide range of ideas about how to achieve a better future through convergence, so a few ideas here can at least stimulate thought.

For years, advanced nations have struggled with the issue of when and how should workers retire, an issue that has myriads of human consequences. In the United States, at least officially, the age at which one *may* retire has been decoupled from the age at which one *must* retire. Superficially, this seems to increase the individual freedom of workers, supported by regulations against age discrimination. But in an era in which both innovation and globalization cause creative destruction, ending old kinds of work while creating jobs of new kinds, many older workers lose their jobs not because they reach mandatory retirement age but because the job itself disappears. As a practical matter, they may not be qualified to get one of the new jobs, or in subtle ways that no regulation can effectively prevent, may be unattractive to employers.

One of the painful issues associated with mandatory retirement is the question of whether older workers are less productive yet because of seniority are often paid more than younger workers, so forcing them to retire could be good for the employer. The fact of the matter may vary by occupation, because some kinds of work may place greater emphasis on the extensive experience that many older workers possess. Or, in technical fields, retaining workers longer requires fewer to be trained. One logical solution for occupations in which older workers are less productive is to pay them less, or at least not to pay them more, and indeed younger workers need high enough salaries to afford to have children.

Japan is one of the nations in which mandatory retirement has been debated most extensively (Clark and Ogawa 1992). And at least for a time, major Japanese corporations had a custom that buffered the effect of mandatory retirement for their best workers. Especially when the Japanese retirement age was 55, major corporations would help some of their favorite people get adequate jobs in related but smaller companies, such as suppliers, with requirements and salary appropriate to the work abilities of seniors.

Ideally, we can imagine a universal government-corporate partnership that with a high success rate placed older workers in satisfactory if less remunerative jobs, after they lost the original employment they were best prepared for, or voluntarily retired. At the risk of oversimplification, work demanding physical strength may be especially unsuitable for older workers, yet people who have always had manual labor jobs may be poorly prepared for white-collar jobs. It would be too facile to say that late-life education can solve this problem, yet certainly it can help. Traditionally, many social scientists considered laborers to be the oppressed working class, yet in a modern social democracy, they may retire earlier and be supported by highly educated people with physically undemanding jobs who stay employed to a much greater age. Any such ironies that prove to be true need to be met with creative solutions, rather than merely result in dysfunctional resentment.

Any program that would retrain older workers and place them in new jobs would need to incorporate science and technology convergence in every aspect of its design. Most obviously, jobs would need to be identified or even created that the particular seniors could learn to do, given their prior work experiences and current physical condition, which requires innovative thinking about technology. Consider, for example, truck drivers. It is plausible, if not certain, that many kinds of long-distance truck driving job will have vanished in a decade, given the progress in self-driving robot vehicles, and we can wonder if the same will happen eventually for local delivery trucking. These jobs have a strong physical component, if they are not exactly manual labor, but they also require technological expertise and complex direction-following. Could former truck drivers take jobs in information service industries, where they deliver specially tailored information over the Internet to customers? If the trucking industry continues to operate as it currently does with many drivers, could retired truck drivers take on Internet-based service jobs that currently are going to young people or to workers in other nations?

In varying degrees, many nations have profertility tax or benefit policies, among which one might count any tax benefits married couples may receive, as well as tax deductions for having children. More direct are government subsidies such as the family allowances in Israel, which have indeed been shown to encourage fertility (Schellekens 2009). Senior demographer Paul Demeny (2011) has suggested four "utopian" policies that could be adopted in the event that the Functionalist theory of demographic transition failed, and fertility fell below replacement level, leading to severe economic problems on a course toward extinction. Each of these is admittedly controversial and requires strong government action, thus violating the values of many contemporary citizens:

1. Adjust democratic voting to offset the current power of elderly voters, for example, allowing parents to vote on behalf of their children, or weighting each person's vote in terms of their likely life expectancy at their current age.
2. Considering parenthood to be a job, and paying parents the equivalent of what they could earn in the workplace, if they chose instead to bear children, perhaps also screening applicants in terms of some criteria for good parenting abilities.
3. Adjusting public support for elderly citizens, such that those who were parents of more children would be paid higher Social Security benefits in old age.
4. A mandatory 2 or 3 year social service requirement could be instituted, analogous to the old military draft, either for all young adults or only for immigrants, perhaps with an exemption for parenthood.

Since Demeny is among the most respected demographers of his generation, his ideas can be taken as provocative stimuli for thought, however radical they might seem. Indeed, such policy changes cannot be considered seriously without a much better scientific understanding of the human demographic, cultural, and economic system. Notably, Joseph Lee Rodgers (Rodgers et al. 2008) and a team of coauthors explicitly employed scientific convergence, using the synonym *consilience*, to study the connection between fertility (age when bearing first child for women) and education in data on Danish twins. They found that purely genetic models did a poor job of explaining patterns in the data. However, they argue that social science has wrongly resisted consilience with the biological sciences, and in studies of demographic transition only a proper combination of social and biological sciences can produce accurate results. *Behavioral genetics* need not focus narrowly on the fertility of couples but can play a key role in developing complex system models of human social organizations more generally (Ilies et al. 2006).

Conclusion

A postmodern version of demographic transition theory might claim that after the transition further scientific and technological progress is unnecessary, even destabilizing. Yet it seems unlikely that the demography of an intelligent species can achieve homeostasis without using its intelligence, unless it falls into the dire circumstances described by Malthusianism. One thing Malthus failed to note, although we cannot fault him because he wrote so long ago, was the fact that the very technological progress that rendered his theory false for two centuries would become very dangerous once his theory became true. If there are still poor nations on our globe by the end of the current century, they will have the power to destroy civilization and the instability that may unleash their fury. Only the convergence of humanity, enabled by the convergence of science and technology, can find a way to achieve population stability simultaneously with peace, prosperity, and justice.

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Global Risk Assessment

Ortwin Renn

Contents

Abstract

Risk governance refers to a complex of coordinating, steering, and regulatory processes conducted for collective decision-making involving uncertainty (this article relies an on an updated and modified version of a book chapter (Renn 2014)) (Rosa et al. 2014). Risk sets this collection of processes in motion whenever the risk impacts multiples of people, collectivities, or institutions. Governance comprises both the institutional structure (formal and informal) and the policy process that guide and restrain collective activities of individuals, groups, and societies. Its aim is to avoid, regulate, reduce, or control risk problems.

O. Renn (✉)
Environmental Sociology and Technology Assessment, Universität Stuttgart, Institut für Sozialwissenschaften, Abteilung für Technik- und Umweltsoziologie, Stuttgart, Germany
e-mail: ortwin.renn@sowi.uni-stuttgart.de

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Introduction

Risk governance refers to a complex of coordinating, steering, and regulatory processes conducted for collective decision-making involving uncertainty (this article relies an on an updated and modified version of a book chapter (Renn 2014)) (Rosa et al. 2014). Risk sets this collection of processes in motion whenever the risk impacts multiples of people, collectivities, or institutions. Governance comprises both the institutional structure (formal and informal) and the policy process that guide and restrain collective activities of individuals, groups, and societies. Its aim is to avoid, regulate, reduce, or control risk problems.

The general process of making and implementing collective decisions – governance – is as old as the human species itself. It encompasses the traditions and institutions that are the vehicle and outcome of these decisions and has a long past. Until very recently, the broad change embedded in the idea governance devolved into a much narrower idea, one referring to the administrative functions of government bodies and formal organizations.

Recent events have changed all that. Entirely new forms of coordination and regulation have emerged in response to rapidly changing societal conditions, such as globalization. The focus of this article is hence on global risk governance, not national or regional risk management. Boundaries between the public and private spheres, boundaries between formal governmental bodies and informal political actors (especially NGOs: nongovernmental organizations), and boundaries between markets and business interests and the regulatory needs of society all are blurred. At the same time due to the growing recognition of the increased scale of collective problems, the domains of sovereignty shifted upward to supranational bodies. Owing to these and other changes, the idea of governance has been re-elevated to its original – broad – scope (Rosa et al. 2014). A number of key events are responsible for that elevation. Among them is a general rejection of the word “government” in favor of “governance” in postmodern thought on political and economic institutions. Others include the adoption of governance in the official parlance of the European Union. Still more specific actions include the prominent place (including its own title) the term holds in the prestigious independent organization in Geneva, Switzerland: the International Risk Governance Council (IRGC 2005, 2007).

This governance framework established by the IRGC provides guidance for the development of comprehensive assessment and management strategies to cope with risk. The framework integrates scientific, economic, social, and cultural aspects and includes the engagement of stakeholders. The concept of risk governance comprises a broad picture of risk: Not only does it include what has been termed “risk management” or “risk analysis,” it also looks at how risk-related decision-making unfolds when a range of actors are involved, requiring coordination and possibly reconciliation between a profusion of roles, perspectives, goals, and activities (Renn 2008, p. 366).

The shift from government to governance signals a crucial change in the process of how collectively binding decisions are being made: from traditional state-centric approaches, with hierarchically organized governmental agencies as the dominant locus of power, to multilevel governance systems, where the political authority for handling risk problems is distributed among separately constituted public bodies (cf. Lidskog et al. 2011). These bodies are characterized by overlapping jurisdictions that do not match the traditional hierarchical order of state-centric systems (cf. Skelcher 2005). They consist of multi-actor alliances that include traditional actors such as the executive, legislative, and judicial branches of government, but also socially relevant actors from civil society. Prominent among those actors are industry, science, and nongovernmental organizations (NGOs). The result of the governance shift is an increasingly multilayered and diversified sociopolitical landscape. It is a landscape populated by a multitude of actors whose perceptions and evaluations draw on a diversity of knowledge and evidence claims, value commitments, and political interests (Rosa et al. 2014). Their goal, of course, is to influence processes of risk analysis, decision-making, and risk management.

For making the IRGC model akin to global context conditions and dynamic-adaptive management practices, Klinke and Renn (2012) proposed some alterations to the original IRGC risk governance model, because it appeared too rigid and standardized for being applied to complex technological risks. They developed a comprehensive risk governance model with additional adaptive and integrative capacity. The modified framework suggested by Klinke and Renn (2012) consists of the following interrelated activities: pre-estimation, interdisciplinary risk estimation, risk characterization, risk evaluation, and risk management, monitoring, and control. This requires the ability and capacity of risk governance institutions to use resources effectively (see Fig. 1). Appropriate resources include:

- Institutional and financial means as well as social capital (e.g., strong institutional mechanisms and configurations, transparent decision-making, allocation of decision-making authority, formal and informal networks that promote collective risk handling, and education)
- Technical resources (e.g., databases, computer software and hardware, research facilities, etc.)
- Human resources (e.g., skills, knowledge, expertise, epistemic communities, etc.)

Hence, the adequate involvement of experts, stakeholders, and the public in the risk governance process is a crucial dimension to produce and convey adaptive and integrative capacity in risk governance institutions (Pelling et al. 2008; Stirling 2008).

This article features the risk governance process as designed by the IRGC and modified by Klinke and Renn. It will introduce each stage (pre-estimation, interdisciplinary risk estimation, risk characterization, risk evaluation, risk management, and communication/participation) and points to the application of each stage for global risk governance. Finally, this chapter will conclude with some basic lessons for risk governance in the field of technological risks.

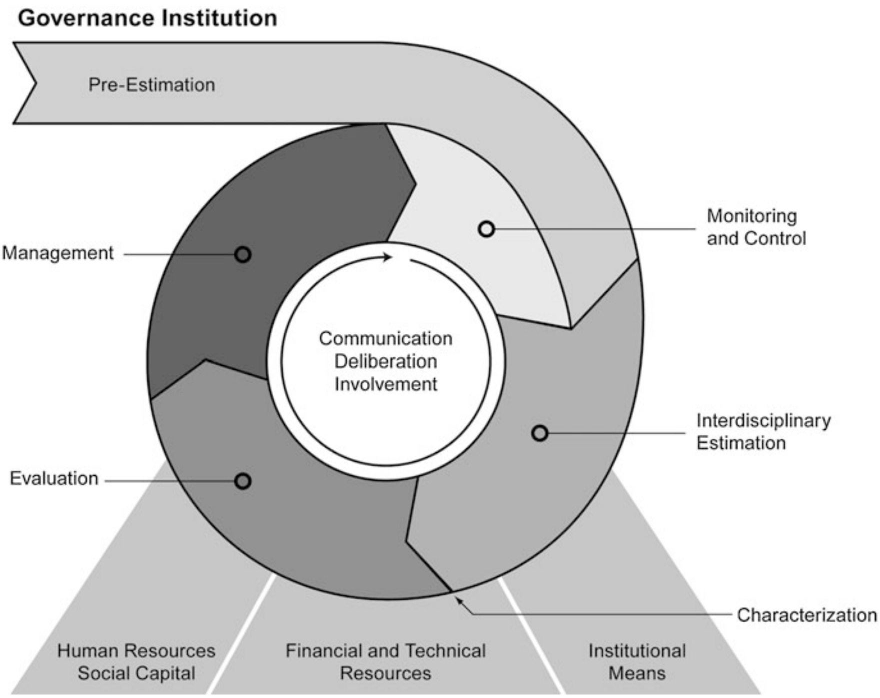

Fig. 1 Adaptive and integrative risk governance model (The adaptive and integrative risk governance model is based on a modification and refinement of the IRGC framework (IRGC 2005). It has been published in Klinke and Renn (2012))

Pre-estimation

Risk, while a real phenomenon, is only understood via mental constructions resulting from how people perceive uncertain phenomena (Rosa et al. in press). Those perceptions, interpretations, and responses are shaped by social, political, economic, and cultural contexts (IRGC 2005, p. 3; OECD 2003). At the same time, those mental constructions are informed by experience and knowledge about events and developments in the past that were connected with real consequences (Renn 2008, p. 2f.). That the understanding of risk is a social construct with real consequences is contingent on the presumption that human agency can prevent harm. The understanding of risk as a construct has major implications on how risk is considered. While risks can have an ontological status, understanding them is always a matter of selection and interpretation. What counts as a risk to someone may be destiny explained by religion for a second party or even an opportunity for a third party. Although societies over time have gained experience and collective knowledge of the potential impacts of events and activities, one neither can anticipate all potential scenarios nor be worried about all of the many potential consequences of a proposed activity or an expected event. At the same time, it is impossible to include all possible options for intervention. Therefore, societies always have been and will always be *selective* in what they choose to be worth considering and what they choose to ignore (IRGC 2005).

Pre-estimation, therefore, involves *screening* to choose from a large array of actions and problems that are risk candidates. Here, it is important to explore what political and societal actors (e.g., governments, companies, epistemic communities, and nongovernmental organizations) as well as citizens identify as risks. Equally important is to discover what types of problems they identify and how they conceptualize them in terms of risk. This step is referred to as *framing*, how political and societal actors rely on schemes of selection and interpretation to understand and respond to those phenomena that are relevant risk topics (Nelson et al. 1997; Kahneman and Tversky 2000; Reese 2007). According to Robert Entman (1993, p. 52 [emphasis in original]): "to frame is to *select some aspects of a perceived reality and make them more salient in a communication text*, *in such a way as to promote a particular problem definition, casual interpretation, moral evaluation, and/or treatment recommendation* for the item described." Perceptions and interpretations of risk depend on the frames of reference.

Framing implies that pre-estimation requires a multi-actor and multi-objective governance protocol. Governmental authorities (national, supranational, and international agencies), risk producers and opportunity takers (e.g., industry), those affected by risks and benefits (e.g., consumer organizations, local communities, and environmental groups on behalf of the environment), and interested parties (e.g., the media or experts) are all engaged. They will often debate about the appropriate frame to conceptualize the problem. What counts as risk may vary greatly among these actor groups.

It is therefore essential in any risk governance cycle to start with the frames of those who are involved in the issue. If these frames are not taken seriously, the risk governance effort may create major controversies and conflicts right from the beginning. Once frames are ignored, it is very difficult to develop a risk assessment and management strategy that is supported and accepted by all the major stakeholders.

Interdisciplinary Risk Estimation

The interdisciplinary risk estimation comprises two activities: (1) *risk assessment,* producing the best estimate of the physical harm that a risk source may induce (including all scenarios that could compromise the safety of the facility under review), and (2) *concern assessment*, identifying and analyzing the issues that individuals or society as a whole link to a certain risk. For this purpose, the repertoire of the social sciences, such as survey methods, focus groups, econometric analysis, macroeconomic modeling, or structured hearings with stakeholders may be used (Renn et al. 2011).

Why are two types of assessments needed in risk governance? For political and societal actors to arrive at reasonable decisions about risk and safety in the public interest, it is not enough to consider only the results of risk assessments, scientific or otherwise. In order to understand the concerns of affected people and various stakeholders, information about their risk perceptions, their behavior in crisis situation, and their worries and concerns about the direct consequences if a crisis situation evolves is essential and should be taken into account by risk managers.

Interdisciplinary risk estimation consists of a systematic assessment not only of the risks to human health and the environment and but also of related concerns as well as social and economic implications (cf. IRGC 2005; Renn and Walker 2008). The interdisciplinary risk estimation process should be informed by scientific analyses, yet, in contrast to traditional risk regulation models, the scientific process includes not only the natural sciences but also the social sciences, including economics.

In 2000, the German Advisory Council on Global Environmental Change (WBGU 2000) suggested a set of criteria to characterize risks that go beyond the classic components probability and extent of damage. The Council identified and validated eight measurable risk criteria through a rigorous process of interactive surveying. Experts from both the natural sciences and the social sciences were asked to characterize risks based on the dimensions that they would use for substantiating a judgment on tolerance to risk. Their input was subjected, through discussion sessions, to a comparative analysis. To identify the eight definitive criteria, the WBGU distilled the experts' observations down to those that appeared most influential in the characterization of different types of risk. In addition, alongside the expert surveys, the WBGU performed a meta-analysis of the major insights gleaned from existing studies of risk perception and evaluated the risk management approaches adopted by countries including the United Kingdom, the United States of America, the Netherlands, and Switzerland. The WBGU's long exercise of deliberation and investigation pinpointed the following eight physical criteria for the evaluation of risks:

1. *Extent of damage*, or the adverse effects arising from an accident or the occurrence of a damaging event – measured in natural units such as deaths, injuries, production losses, etc.
2. *Probability of the event occurring and probability of the extent of damage induced by the event* (relative frequency of a discrete or continuous loss function).
3. *Incertitude*, an overall indicator of the degree of remaining uncertainties inherent in a given risk estimate.
4. *Ubiquity*, which defines the geographic spread of potential damages and considers the potential for damage to span generations.
5. *Persistency*, which defines the duration of potential damages, also considering potential impact across the generations.
6. *Reversibility*, the possibility of restoring the situation, after the event, to the conditions which existed before the damage occurred (e.g., restoration techniques including reforestation and the cleaning of water).

7. *Delay effect*, which characterizes the possible extended latency between the initial event and the actual impact of the damage it caused. The latency itself may be of a physical, chemical, or biological nature.
8. *Potential for mobilization*, understood as violations of individual, social, or cultural interests and values that generate social conflicts and psychological reactions among individuals or groups of people who feel that the consequences of the risk have been inflicted upon them personally. Feelings of violation may also result from perceived inequities in the distribution of costs and benefits.

Subsequently, the UK Treasury Department (2004) recommended a risk classification that includes hazard characteristics, the traditional risk assessment variables such as probability and extent of harm, indicators on public perception, and the assessment of social concerns. In addition to the eight criteria listed above, the Department made an extra effort to define criteria for measuring concern. The list of concerns includes:

- Perception of familiarity and experience with the hazard
- Understanding the nature of the hazard and its potential impacts
- Repercussions of the risk's effects on (intergenerational, intragenerational, social) equity
- Perception of fear and dread in relation to a risk's effect
- Perception of personal or institutional control over the management of a risk
- Degree of trust in risk management organizations

When applied to technological risks, the phase of interdisciplinary risk estimation includes four major steps:

- First, there is a need to develop scenarios that include plausible sequences of accidents or other pathways of harm (pollution, waste production).
- Second, these scenarios need to be augmented with assumptions about human behavior that one can expect in such situations including crisis identification, crisis management, domino effects, perception-driven responses, and human errors. It is important that these behavioral components are integrated into the technical analysis because the interaction of both the technical and the human sphere creates the combined threats to human health and the environment (IAEA 1995).
- Third, each scenario needs to be assessed according to its probability of occurrence within the uncertainty ranges in which these estimates are embedded.
- Fourth, these scenarios need to be tested for stakeholder and public concerns with respect to their consequences and its implications. There may be equity violations involved or special symbolic meanings affected.

These four steps of generating knowledge and insights provide the data and information base for the next step: risk evaluation.

Risk Evaluation

A heavily disputed task in the risk governance process concerns the procedure of how to evaluate the societal acceptability or tolerability of a risk. In classical approaches, risks are ranked and prioritized based on a combination of probability (how likely is it that the risk will be realized) and impact (what are the consequences, if the risk does occur) (Klinke and Renn 2002; Renn 2008, pp. 149ff). However, as described above, in situations of high uncertainty, risks cannot be treated only in terms of likelihood (probability) and (quantifiable) impacts. This standard two-dimensional model ignores many important features of risk. Values and issues such as reversibility, persistence, ubiquity, equity, catastrophic potential, controllability, and voluntariness should be integrated in risk evaluation. Furthermore, risk-related decision-making is neither about physical risks alone nor usually about a single risk. Evaluation requires risk-benefit evaluations and risk-risk tradeoffs (Graham and Wiener 1995). If the benefits and potential substitutes were not included in the assessment phase, this needs to be done in the evaluation phase. Judgments about risk tolerance require a comparative review of alternatives and benefit-risk ratios. So by definition, risk evaluation is multidimensional. In order to evaluate risks, the first step is to characterize the risks on all the dimensions that matter to the affected populations. Once the risks are characterized in a multidimensional profile, their acceptability can be assessed.

Furthermore, there are competing, legitimate viewpoints about evaluations over whether there are or could be adverse effects and, if so, whether these risks are tolerable or even acceptable. Drawing the lines between "acceptable," "tolerable," and "intolerable" risks is one of the most controversial and challenging tasks in the risk governance process. The UK Health and Safety Executive developed a procedure for chemical risks based on risk-risk comparisons (Löfstedt 1997). Some Swiss cantons such as Basel County experimented with roundtables comprising industry, administrators, county officials, environmentalists, and neighborhood groups (Risko 2000). As a means for reaching consensus, two demarcation lines were drawn between the area of tolerable and acceptable risk and between acceptable and intolerable risks (Fig. 2). Irrespective of the selected means to support this task, the judgment on acceptability or tolerability is contingent on making use of a variety of different knowledge sources; in other words, it requires taking the interdisciplinary risk estimation seriously.

Looming below all risks is the question of what is safe enough, implying a normative or moral judgment about acceptability of risk and the tolerable burden that risk producers can impose on others. The results of the risk and concern assessment can provide hints over what kind of mental images are present and which moral judgments guide people's perceptions and choices. Yet the decision what is safe enough and which risk is tolerable or acceptable is a political decision that needs public legitimization.

With respect to technological risks, the judgment of acceptability or tolerability is usually related to three issues: *occupational safety*, *routine emissions of waste into air soil or water*, and *accidents with sudden emission of energy and/or*

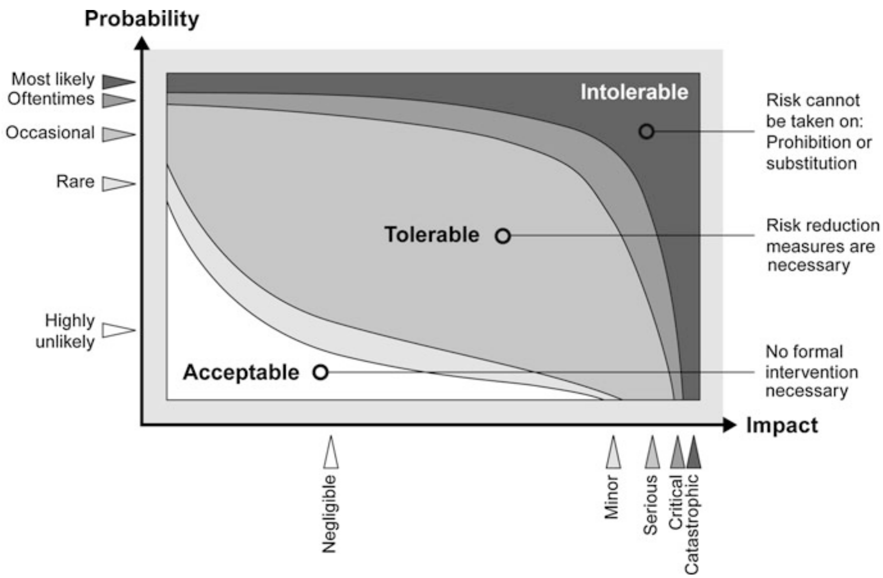

Fig. 2 Areas of acceptable, tolerable, and intolerable risks (Adapted from Renn 2008, p. 150)

material. For all three aspects of technical risks, there are normally regulatory standards that need to be adhered to. For sudden events such as accidents, often deterministic (safety provisions) and probabilistic (safety goals) standards are in effect; for controlling emissions, maximum tolerance levels for certain time intervals (daily, yearly) are specified (Aven and Renn 2010). In addition, regulatory agencies can issue flexible standards based on ALARA (as low as reasonably achievable) or BACT (best available control technology). Regardless of what methods for standard setting are applied, it always involves political judgments about the tolerability of statistical losses (in terms of lives, health, environmental damage, and money). These judgments need to be legitimized in an open and democratic process. This will be further discussed in the section on "Risk Management".

Risk Management

Risk management starts with a review of the output generated in the previous phases of interdisciplinary risk estimation, characterization, and risk evaluation. If the risk is acceptable, no further management is needed. Tolerable risks are those where the benefits are judged to be worth the risk; further risk reduction measures are not necessary but can be accomplished by voluntary measures. If risks are classified as tolerable but not as acceptable, risk management needs to design and implement actions that render these risks either acceptable or sustain that tolerability in the longer run by introducing risk reduction strategies, mitigation strategies, or strategies aimed at increasing societal resilience at the appropriate level

(Renn 2008, pp. 173ff.). If the risk is considered intolerable, notwithstanding the benefits, risk management should be focused on banning or phasing out the activity creating the risk. If that is not possible, management should be devoted to mitigating or fighting the risk in other ways or to increasing societal resilience. If the risk is contested, risk management can be aimed at finding ways to create consensus. If that is impossible or highly unlikely, the goal would be to design actions that increase tolerability among the parties most concerned or to stimulate alternative course of action (van Asselt and Renn 2011).

Risk management is based on different regimes, i.e., the set of rules and standards that govern the handling of the risk in a specific regulatory context within a country or culture. The main goal of these regimes is to ensure robust regulatory results. Robust regulation is highly dependent on how risk managers and regulators deal with three major challenges: complexity, uncertainty, and ambiguity (Renn 2008, pp. 187ff.; Renn et al. 2011). Complexity refers to the difficulty of identifying and quantifying causal links between a multitude of potential candidates and specific adverse effects. Uncertainty denotes the inability to provide accurate and precise quantitative assessments between a causing agent and an effect. Finally, ambiguity denotes either the variability of (legitimate) interpretations based on identical observations or data assessments or the variability of normative implications for risk evaluation (judgment on tolerability or acceptability of a given risk). Based on the distinction between complexity, uncertainty, and ambiguity, one can distinguish four risk management routes (Fig. 3).

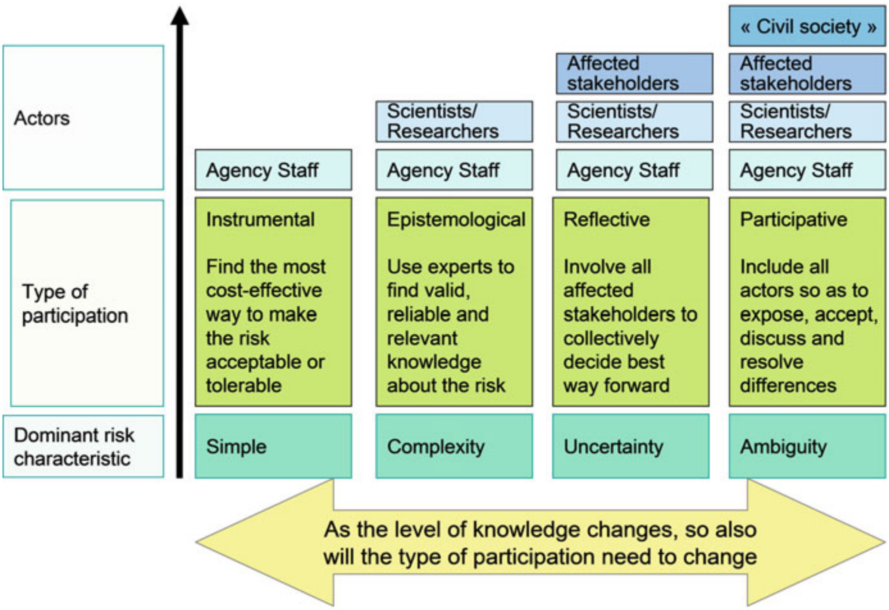

Fig. 3 Relationship between stakeholder participation and risk categories in risk governance (Adapted from Renn 2008, p. 280)

The easiest task is to deal with simple, linear risks. Simple does not mean small or negligible. It refers to the assessment and evaluation process. If the risk is well known to the actors if there is hardly any uncertainty and ambiguity, the risk management strategy to take is to assess the risk-benefit ratio and develop measures that move the risk into the acceptable area of the risk evaluation diagram. The risk management actions are straightforward and include technical standards, safety manuals, and routinized monitoring.

In a case where scientific complexity is high and uncertainty and ambiguity are low, the challenge is to invite experts to deliberate with risk managers to understand complexity. Understanding the risks of oil platforms may be a good example of this. Although the technology is highly complex and many interacting devices lead to multiple accident scenarios, most possible pathways to a major accident can be modeled well in advance. The major challenge is to determine the limit to which one is willing to invest in resilience.

The third route concerns risk problems that are characterized by high uncertainty but low ambiguity. Expanded knowledge acquisition may help to reduce uncertainty. If, however, uncertainty cannot be reduced (or only reduced in the long run) by additional knowledge, a "precaution-based risk management" is required. Precaution-based risk management explores a variety of options: containment, diversification, monitoring, and substitution. The focal point here is to find an adequate and fair balance between overcautiousness and insufficient caution. This argues for a reflective process involving stakeholders to ponder concerns, economic budgeting, and social evaluations.

For risk problems that are highly ambiguous (regardless of whether they are low or high on uncertainty and complexity), route 4 recommends a "discourse-based management." Discourse management requires a participatory process involving stakeholders, especially the affected public. The aim of such a process is to produce a collective understanding among all stakeholders and the affected public about how to interpret the situation and how to design procedures for collectively justifying binding decisions on acceptability and tolerability that are considered legitimate. In such situations, the task of risk managers is to create a condition where those who believe that the risk is worth taking and those who believe otherwise are willing to respect each others' views and to construct and create strategies acceptable to the various stakeholders and interests. But deliberation is not a guarantee for a smooth risk management process. Lidskog (2008) argue that complexity and ambiguity are grounds for continuous conflict that is difficult if not impossible to resolve. The reduction of complexity simultaneously implies reducing the number of actors as relevant or legitimate participants. The resolution of ambiguity requires a broad representation of all actors involved in the case. So it is difficult to find the perfect path between functionality and inclusiveness (Renn and Schweizer 2009). In any case, a prudent response to this inherent conflict is to invest in structuring an effective and efficient process of inclusion (whom to include) and closure (what counts as evidence and the adopted decision-making rules) (Aven and Renn 2010, pp. 181ff; Renn 2008, pp. 284ff).

Risk management for technological systems requires *technological*, *organizational*, and *behavioral measures* for reducing risks that are not regarded as acceptable in the first place (Hood et al. 2002):

- Technological measures relate to the inclusion of active and passive safety devices, inclusion of filters and purifiers, and waste handling technology.
- Organizational measures include emergency and contingency plans, guidelines for daily operations and safety checks, monitoring requirements, and provisions for assuring accountability and competence.
- Behavioral measures extend to all educational and training efforts to improve personal performance, increase sensibility for safety issues, and strengthen the feeling of responsibility and accountability among the staff (safety culture).

The historic record about technological accidents and failures has shown that both the integration of and the compatibility between technological, organizational, and behavioral measures were often the main reasons for the events that lead to accidents and disasters (Cohen 1996; Hutter 2010).

Within the phase of risk management, monitoring and control play a major role in sustaining high safety levels. Risks often occur as a consequence of relaxed inspections, incomplete or insufficient monitoring, and overconfidence of the staff. Often accidents are caused or aggravated by mere lack of oversight. It is contested in the literature whether monitoring and control should be performed by the operator of technical facilities (with random inspections by the public authorities) or closely observed and enforced by public authorities. In recent times, the idea of public-private partnership (joint responsibility) has also been raised and recommended as a potential solution to this question (Sikor 2008).

Risk Communication and Participation

Effective communication among all relevant interests is one of the key challenges in risk governance. It is not a distinct stage (in contrast to how it is often treated in the risk literature), but central to the entire governance process (IRGC 2005). Positively framed, communication is at the core of any successful risk governance activity. Negatively framed, a lack of communication destroys effective risk governance. Early on, risk communication was predicated on the view that disagreements between experts and citizens over risks were due to the lack of accurate knowledge by citizens. The solution was sought in the education and persuasion of the deficient public (Fischhoff 1995). Implied in this solution was the belief that an educated public would perceive and evaluate risks the same way as experts. However, this deficit model has been subject to considerable criticism. For one thing, increased knowledge often elevated citizen concerns about risk, creating an even greater diversion between them and experts. For another, as Pidgeon et al. (2005, p. 467) phrased it, “One of the most consistent messages to have arisen from social science research into risk over the past 30 years is that risk communication. . .needs to accommodate far more than a simple one-way transfer of information. . .the mere provision of ‘expert’ information is unlikely to address public and stakeholder concerns or resolve any underlying societal issues.” Third, research on risk controversies has demonstrated that in general the public does not always misunderstand science. Furthermore, experts and governments may also misunderstand public perceptions (Horlick-Jones 1998; Irwin and Wynne 1996).

The important point to emphasize is that risk communication and trust are delicately interconnected processes. And there is a large volume of literature demonstrating the connection between trust in the institutions managing risks and citizen perceptions of the seriousness of risks (Earle and Cvetkovich 1996; Löfstedt 2005; Whitfield et al. 2009). Communication breakdowns can easily damage trust. At the same time, communication strategies that misjudge the context of communication, in terms of the level of and reasons for distrust, may boomerang – resulting in an increased distrust (Löfstedt 2005).

Communication strategies proliferate. Communication refers to meaningful interactions in which knowledge, experiences, interpretations, concerns, and perspectives are exchanged (Löfstedt 2003). In the context of risk governance, exchanges among policy makers, experts, stakeholders, and affected publics are of special interest. The aim of communication is to provide a better basis for responsible risk management. Its aim is to also enhance trust and social support (Poortinga and Pidgeon 2003). Depending on the nature of the risks and the context of governing choices, communication will serve various purposes. It might serve the sharing of information about the risks and possible ways of handling them. It might support building and sustaining trust among various actors where particular arrangements or risk management measures become acceptable. It might result in actually engaging people in risk-related decisions, through which they gain ownership.

However, communication in the context of risk governance is not simple. It is not just a matter of having accurate assessments of risks. It is not just a matter of bringing people together. It is not just a matter of effective communication. It requires all these features and more. Also required is a set of procedures for facilitating the discourse among various actors from different backgrounds so they can interact meaningfully in the face of uncertain outcomes (Rosa et al. 2014).

Proper communication features multiple actors. The US National Research Council report (Stern and Fineberg 1996) is an important milestone in the recognition of the need for risk decision-making as an inclusive multi-actor process. It also was a germinal precursor to the idea of risk governance with its emphasis on the coordination of risk knowledge and expertise with citizen and other stakeholder priorities (cf. Jasanoff 2004; Stirling 2007).

One key challenge to risk governance is the question of inclusion: Which stakeholders and publics should be included in governance deliberations? The inclusion challenge has deep implications. Contrary to the conventional paradigm where risk topics are usually identified by experts, with the analytic-deliberative process underpinning risk governance, public values and social concerns are key agents for identifying and prioritizing risk topics. Inclusion means more than simply including relevant actors. That is the outmoded practice of "public hearings" where relevant actors are accorded a fairly passive role. Inclusion means that actors play a key role in framing (or pre-assessing) the risk (IRGC 2005; Renn and Schweizer 2009; see also Roca et al. 2008). Inclusion should be open to input from civil society and adaptive at the same time (Stirling 2004, 2007). Crucial issues in this respect are as follows (see also Renn and Schweizer 2009): Who is included? What is included? What is the scope and mandate of the process?

Inclusion can take many different forms: roundtables, open forums, negotiated rule-making exercises, mediation, or mixed advisory committees including scientists and stakeholders (Renn 2008, pp. 332ff; Rowe and Frewer 2000; Stoll-Kleemann and Welp 2006). Due to a lack of agreement on method, social learning promoted by structured and moderated deliberations is required to find out what level and type of inclusion is appropriate in the particular context and for the type of risk involved. What methods are available? They all have contrasting strengths and weaknesses (Pidgeon et al. 2005).

A focus on inclusion is defended on several grounds (Roca et al. 2008). First, one can argue that in view of uncertainty, there is a need to explore various sources of information and to identify various perspectives. It is important to know what the various actors label as risk problems and which most concern them. Here, inclusion is interpreted to be a means to an end: a procedure for integrating all relevant knowledge and for including all relevant concerns. Second, from a democratic perspective, actors affected by the risks or the ways in which the risks are governed have a legitimate right to participate in deciding about those risks. Here, inclusion is interpreted as not just a means but also an end in itself. At the same time, inclusion is a means to agree on principles and rules that should be respected in the processes and structures of collective decision-making. Third, the more actors are involved in the weighing of the heterogeneous pros and cons of risks, the more socially robust the outcome. When uncertainty is prevalent, there is no simple decision rule. In that view, inclusion also is a way to organize checks and balances between various interest and value groups in a plural society. Inclusion thus is intended to support the coproduction of risk knowledge, the coordination of risk evaluation, and the mutual design of risk management.

The task of inclusion is to organize productive and meaningful communication among a range of actors, who have divergent interests but complementary roles. The cumulative empirical analyses suggest that providing a platform for the inclusion of a variety of stakeholders – to deliberate over their concerns and exchange arguments – can help to de-escalate conflicts and legitimize the final decision. Nevertheless, however careful the establishment of the platform and the decision rule about inclusion, there will always be some disappointed actors in society (Beierle and Cayford 2002).

Conclusions

This chapter has described the genesis and analytical scope of risk governance in a global context. It argued for a broader, paradigmatic turn from government to governance. In the context of risk, the idea of governance is used in both a descriptive sense and a normative sense: as a description of how decisions are made and as a normative model for improving structures and processes of risk policy making. Risk governance draws the attention to the fact that many risks, particularly pertaining to large technological systems, are not simple; they cannot all be calculated as a function of probability and extent of damage. Many risks embed complex trade-offs of costs and benefits. Risk governance underscores the need to ensure that societal choices and decisions adequately address these complicating features within an increasing interconnected global world. However, conventional risk characterization typically treats, assesses, and manages such risks as if they were simple. This practice has led to many failures to deal adequately with risks. The thesis of this article has been that the risk governance framework advocated in this chapter provides an adequate and practically proven concept for dealing with complex, uncertain, and ambiguous risk problems and could serve as a role model for future regulatory reforms aimed at improving the robustness of the risk management performance.

In a pluralistic society embedded in a global economy and ecology where the pressure to legitimize political action is always high, the process of developing and locating potentially dangerous technologies such as nanotechnology or synthetic biology often encounter widespread skepticism and deep distrust. More than in other policy arenas, decisions on risks must be made plausible to a wider audience (i.e., based on intuitively understandable reasoning) and depend on trust in the major actors involved, the respective industry, and the regulatory agencies. Hence, risk governance can only be successful if there is an intense, communication-oriented dialogue with the major actors and the interested public. The larger the number of individuals and groups that are impacted by a technology development or deployment, the more likely it will be that conflicts will arise. These conflicts deal with issues of risk acceptability or tolerable risk levels as well as notably equity issues such as a just distribution of risks among the affected population and, even more important, the distribution of benefits. If equity issues are ignored or not given due attention, people tend to amplify their experience of risk and lower the thresholds of tolerability as an expression of their discontent with the process rather than the resulting risk. Hence, the timely and mutual participation of social actors in managing risks and crisis is both technically appropriate, as they may bring important local knowledge to the decision-making process and democratically imperative, as the distribution of risks and benefits demand a legitimate key for designing a fair risk-benefit sharing initiative. Effective participation helps technology providers, users, and political decision-makers to secure greater legitimacy in citing processes, thus contributing to the democratic culture of a country.

Risk governance is not simply a timely buzzword, but a disciplined argument for a paradigm shift. Paradigms and reforms do not just shift in the abstract, but also shift in practices. Such fundamental transitions are not easy. Yet, the global context conditions of human actions in a multi-actor decision-making framework make such paradigm shifts inevitable.

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Linguistic Convergence

Magdalena Bielenia-Grajewska

Contents

Abstract

The aim of this contribution is to draw readers' attention to the notion of linguistic convergence and its implication for the modern world. The chapter starts with the definition of linguistic convergence and the presentation of the *Multidisciplinary Hexagonal Model of Linguistic Convergence* created by the author of this work. The next part of discussion focuses on the function, theory, discipline, as well as level and type perspectives of linguistic convergence. Other aspects presented in this contribution are causes and effects of linguistic convergence. The chapter finishes with the perspectives of linguistic convergence, taking into account the growing role of neuroscientific research.

M. Bielenia-Grajewska (✉)
Intercultural Communication and Neurolinguistics Laboratory, Department of Translation Studies, University of Gdansk, Gdansk, Poland
e-mail: magda.bielenia@gmail.com

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Introduction

The twenty-first century is shaped by a number of factors, with language being a crucial determinant of the modern reality. Language does not exist in a vacuum but constantly responds to the changes taking place in the near and far entourage. Consequently, language not only determines the environment but is also shaped by it. The growing importance of boundarylessness and the increasing presence of fluidity are among the key notions underlying modern reality. As Leibold et al. (2005, 15) state:

> . . .since the late 1980s a major turning point in the world's economic, political, and social history has occurred. The walls seem to have collapsed – between nations, between industries, between sectors of the economy, between organizations, and between functions inside an organization. Linkages networks and symbiosis are becoming the order of the day, as evidenced in the increasing incidence of alliances, mergers, joint ventures, cross-functional project teams and communities of practice. Inside organizations, enterprises are realizing the value of interdependencies, rather than differences and independencies, through initiatives such as simultaneous development process, concurrent engineering, agile manufacturing and resource management networks; and outside organizations the need for value system management (as opposed to value chain management), and business ecosystem influencing are now starting to be realized.

Thus, the processes that can be observed nowadays are rather of converging character, overcoming differences and forming common backgrounds for effective organizational dialogue. The feature highlighted in the quote is also of importance in other types of situations that will be discussed in the coming sections, devoted to the place of language in different types of convergence determining the modern reality. Another reason for the growing interest in the linguistic convergence is the focus on culture and language in the life of individuals as well as the performance of organizations.

The causes for this situation are diverse and many. First of all, individuals and organizations operate in a multilingual reality. Due to the diminishing barriers in terms of geography and technology, people have the opportunity to interact with speakers from other countries far easier than in the previous century. Additionally, the mobility does not only concern individuals but also business entities, with more and more corporations operating worldwide. Another important factor is the dichotomy of globalization versus "glocalization" that is represented in the search for pan-national approaches, of mostly converging character, and simultaneously, in the craving for individualism represented at the local level, mainly visible in divergent attitudes.

The linguistic aspects of these phenomena are to be observed in, among others, the growing role of global languages, such as English, and the increasing importance of dialects and jargons. As Roco et al. (2013) state, several societal changes can be expected in the coming years. First of all, new industries and new jobs connected with the interfaces in the spheres of economic, societal, human, technological, and terrestrial activities will be created. Secondly, convergence will lead to even more intensive creativity, innovation, and economic productivity and the development of a common domain for interactions. Moreover, it will stimulate lifelong wellness and human development, by offering complex healthcare and education services. Thus, the aim of this chapter is to discuss the place of linguistic convergence, being not only the determinant influencing the complex processes characteristic of the twenty-first century but also the phenomenon that is shaped by the broadly understood environment as well as other types of convergence.

Definition and Comparison

Linguistic convergence is understood as the integration of language and nonlanguage elements that can be observed at macro, meso, and micro levels. Discussed from the entity level, linguistic convergence is perceived as a language-related phenomenon characterized by the similarity of linguistic representations (e.g., of syntactical, semantic, or textual types) as a result of language contacts. Linguistic convergence can also be defined by taking into account the approach to convergence presented by Roco et al. (2013) who state the importance of *higher-level languages* (*multidomain*, *convergent*) that rely on knowledge and achievements of different disciplines and constitute of terminology and concepts being common in different areas of study. As illustrated in Fig. 1, the phenomenon of disciplinary convergence can be conceptualized in terms of six subprocesses: media, cultural, technological, economic, legal, and geographical convergence.

Media convergence is connected with the amalgamation of available information and communication technologies, resulting in digitized content and the primacy of Internet in communication. Another type of interdisciplinary assimilation can be *cultural convergence*, represented in the concurrence of elements stemming from different cultures. Cultures as such can be understood in different ways, being the representation of communication in ethnic, national, hobby, or professional communities. To focus on the issue of national culture and its relation to convergence, one may quote different typologies used in cross-cultural management, such as the ones proposed by Hofstede, Gesteland, or Trompenaars and Hampden-Turner (detailed discussion on the mentioned typologies in, e.g., Holden 2002) to discuss how the approaches may change when individuals are exposed to different cultures and how a national culture evolves due to the contacts with those having different worldviews.

Analyzing the social sphere, *linguistic convergence* may accompany liminality and may be connected with the results of rites of passage (e.g., Van Gennep 2004) that facilitate one's incorporation into a new social situation. In addition, convergence as such is an element of social contacts; consciously and subconsciously people imitate interlocutors since similarities in verbal and nonverbal behavior stimulate effective communication. It should also be stated that languages are also an important element of cultural convergence. Moreover, linguistic convergence coexists with nonlinguistic convergence visible in using haptics, proxemics,

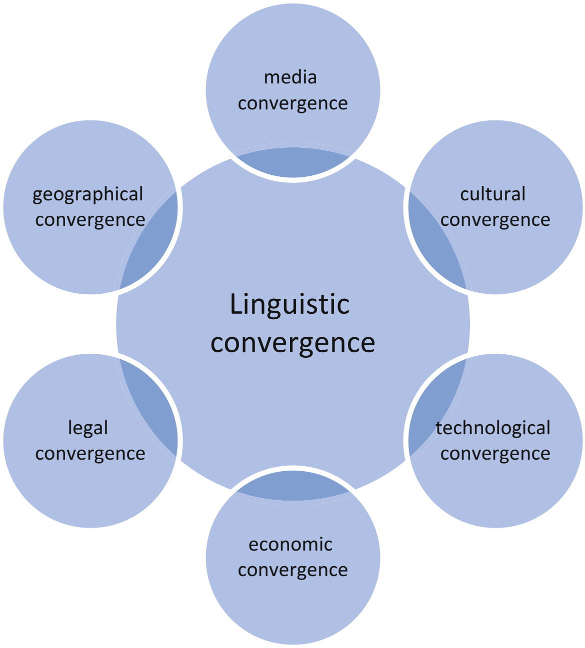

Fig. 1 Multidisciplinary Hexagonal Model of Linguistic Convergence (created by the current author)

and chronemics to strengthen the usage of linguistic repertoire. Convergence is also connected with the change of individuals' role in modern life that results from the technological development.

Technological convergence can be defined as the assimilation of functions of different tools so that the technologically advanced apparatus can perform similar tasks. Due to the current technological assimilation, personal involvement in organizational activities is more participatory than it was in the past. An example can be the notion of *prosumer* who not only purchases products but also creates the market. Due to the growing influence of technology in the life of both individuals and organizations, people have the opportunity to express their points of view in a synchronous and asynchronous way and, consequently, change the way products or services are tailored to the needs and expectations of the target audience. In addition, technological convergence is represented in augmented reality that links real world with virtual world.

Economic convergence is represented in assimilation taking place among organizations, individuals, products, and economic reality. In economics, convergence is often associated with catching up, and it is used to discuss the progress made by less-developed countries in comparison with the developed ones. Another application is within the eurozone, with convergence criteria determining the adaptation of national economic reality to the eurozone area, concerning, e.g., the countries that plan to use the euro currency. As far as convergence in marketing is concerned, it is visible in the products having diversified functions in the same time. An example can be a smartphone that offers not only calling options but also searching the web, writing emails, using GPS facilities, checking the pulse, etc. It is also connected with technological convergence since many functions are offered within one tool. Moreover, economic convergence is also accompanied with convergence at the linguistic level, being represented by conducting communication in a simultaneously complex and compressed way to cover all the features and expectations of a given tool as well as being efficient in order to make a promoted product interesting and worth purchasing.

Legal convergence typically involves making legal systems similar, as in the European Union or pan-national organizations. Linguistic convergence accompanying legal regulations is visible in the unification of legal terminology. The last element – *geographical convergence* – is linked to any type of assimilation or adaptation taking place on a given geographical territory, and linguistic forms of expression follow territory-related changes. It can be represented in the inclusion of villages in urban areas or the membership of cities or countries in international organizations. Moreover, Roco et al. (2013) discuss the notion of *societal convergence* that is connected with the participation of society in different stages of converging knowledge, application, and opportunities for development. Convergence supported by the society leads to advancements in the sphere of sustainability, economic productivity, human development, and national security.

The Functional Perspective

The functional dimension of linguistic convergence can be studied by taking into account how linguistic convergence determines the processes of adaptation, identity creation, and divergence, taking into account both standard and crisis situations. An example of adapting to the environment is represented in the concept of *calibrated linguistic identity* (Bielenia-Grajewska 2012b). Calibration is understood through the perspective of not only adapting to new situations but also with creating the hybrid forms that result from the interactions between interlocutors and their environments. In this regard, calibration is not only connected with linguistic alignment but also with the creation of new linguistic identities, unique in their usage and the selection of linguistic repertoire. Another concept that can be used to discuss linguistic convergence as a response to adaptation is *corporate linguistic allostasis* (Bielenia-Grajewska 2012b). In biology, allostasis is connected with producing hormones that facilitate the process of adaptation; in the case of companies, “corporate hormones” are such elements as effective corporate communication and the selection of understandable linguistic tools that can shape the corporate linguistic allostasis.

Convergence as a way of dealing with crisis can be discussed through the prism of adaptation; in the literature on psychology, one can find the dichotomy of alloplastic and autoplastic adaptation, in the writings of, e.g., Sigmund Freud, Sándor Ferenczi, Heinz Kohut, etc. (e.g., Kohut 2009). The main feature of alloplastic adaptation is the purpose to change a situation, whereas in the case of autoplastic adaptation, an individual tries to change himself or herself.

The mentioned psychological typology of dealing with crisis and the distinction in putting the focus on either the person or the issue in focus have been applied to the investigation of linguistic convergence. *Linguistic autoplastic adaptation* can be defined as the sum of activities performed by an individual that aims at dealing with the situation by altering one's perception, cognition, and understanding of a situation. It is connected with a psychological shift, visible in finding the solution within oneself and one's capabilities. At the language level it is represented in the usage of expressions stressing the active participation of an individual in the process of dealing with crisis. On the other hand, *linguistic alloplastic adaptation* is connected with the attempts to change the environment to one's needs and expectations. On the linguistic level it is represented by the expressions that aim at showing how the environment is to be changed by the application of a given linguistic tool.

Linguistic convergence as a factor of creating and sustaining identity can be analyzed at both individual and social levels. One of the concepts that can be used to discuss linguistic convergence is *hybrid linguistic identity* (Bielenia-Grajewska 2010). This term is used to denote how different elements shape the linguistic identity of a person, giving it a new (third) form that simultaneously results from the combining elements and constitutes a unique phenomenon in the way it has dynamically responded and changed. Another term that can be applied in the discussion on linguistic convergence is *heteroglossic linguistic identity*. Linguistic heteroglossia is represented in the multilingualism of workers and the role of corporate linguistic policies in maintaining the linguistic rights of diversified workforce. In addition, the linguistic dimension of heteroglossia in modern companies is associated with the terminological and syntactical diversification of corporate communication, depending on one's profession and function (Bielenia-Grajewska 2013).

Difference can be studied from the linguistic perspective by taking into account the terms *linguistic homology* and *linguistic analogy*. According to the dichotomy used in evolutionary biology, homology is connected with common ancestry, whereas analogy does not have any common biological background. Applying this distinction to the sphere of linguistics, *linguistic homology* mirrors converging notions taking place between linguistic systems having common ancestry. It encompasses languages belonging to the same language families or professional dialects used by specialists coming from similar domains. On the other hand, *linguistic analogy* encompasses issues and elements that do not share common features (or at least not the dominant ones). Examples may include converging processes taking place between unrelated domains of science or among dialects that do not share common ancestral elements. A similar concept in evolutionary biology is *convergent evolution* that describes the process of distinct organisms adapting to similar environmental conditions. This term can also be used in the discussion on linguistic convergence, and thus a concept of *linguistic convergent evolution* can be coined. *Linguistic convergent evolution* can be understood as the adaptation to new conditions of individuals coming from culturally and linguistically diverse environments.

Theory and Discipline Perspectives

The scientific literature contains many different approaches that stress the converging element within the studied domain or phenomenon, including network, discourse, and communication theories. Since the modern world is a complex entity, system and network theories are used to describe the complexity. The systemic approaches can be divided into closed and open systems. Closed systems are influenced and steered by internal forces, and their interaction with the outer reality does not influence the performance of a system very much. In contrast, open systems do not have strict boundaries, and different flows exist between systems. The converging element is visible in linguistic systems in facilitating the communication between systems. One of the theories that can be studied from the perspective of convergence is *social network analysis* (SNA). This approach highlights the role of relations between individuals in communication, for example, the extent to which a chain of weak social ties can facilitate innovation (Granovetter 1973). The SNA discussion on linguistic convergence may focus on the way social contacts lead to the creation of common linguistic representation. To stress the linguistic convergence between living and nonliving entities, *actor–network theory* (ANT) may be used to discuss how computers or telephones, together with human beings, determine modern communication (Bielenia-Grajewska 2011).

The dichotomy of convergence versus divergence is studied in *communication accommodation theory* (CAT) by Howard Giles. Convergence is understood as a strategy aimed at becoming similar to interlocutors, for the purpose of approval, affiliation, and the reduction of social distance. Divergence, on the other hand, is aimed at stressing differences between interlocutors, in order to highlight one's superiority or distinctiveness (Soliz and Giles 2014). Linguistic convergence is also studied through the prism of translation. For example, Becher et al. (2009) elaborate on how language contacts in the form of translation lead to converging or diverging processes. They discuss that convergence can be observed when bilinguals view a linguistic item as equivalent in form and function. An example is a concessive conjunction in English and German that introduces something that might not have been expected, such as *although* and *obgleich* or *regardless* and *ungeachtet*. Linguistic convergence is also studied by specialists representing such subfields as contact linguistics, applied linguistics, and sociolinguistics. Linguistic convergence can also be studied through the perspective of education. Taking into account the changes going on in modern education, there are almost no geographical limitations that determine the access to knowledge. Nowadays many universities offer online courses, such as MOOCs that are the platforms where people from different places, different cultures, and speaking different languages meet, interact, and learn. This boundary-free education has also led to the appearance of convergent ways of decoding and offering knowledge. Another aspect of convergence studied in teaching is the notion of *intercomprehension* that is defined as the possibility of understanding the speakers using different but similar languages (e.g., EU 2012). The application of this notion is visible in learning foreign languages, business, and broadly understood forms of communication.

Level and Type Perspectives

Linguistic convergence as a complex phenomenon can be studied at different levels, with macro, meso, and micro dimensions. The *macro level* of linguistic convergence is connected with linguistic policies at the national and international level, such as the regulations and laws underlying the coexistence of national languages with minority languages. Convergence at the national level can be studied with the example of Switzerland, having four national languages, in alphabetical order: French, German, Italian, and Romansh. As Grin (2010, 55) discusses, modern Switzerland faces different challenges in the linguistic sphere, such as “the need to develop and continually renew the conditions of a convergence of interests between linguistic communities; the role to be granted to the languages of immigrant groups; and the linguistic effects of globalization, which has endowed English with a certain influence in fields from which this language was previously absent.” To the extent that English has become the lingua franca of the modern world, convergence at the macro level is encouraged. Another pan-national example is specialized communication; languages of special/specific purposes are the examples of professional communication handled between specialists using often different mother tongues on everyday basis.

Macro phenomena also occur at the level of genre. For example, digital storytelling, operating at the crossroads of different visual and verbal elements, is an example of linguistic convergence operating at almost all levels of linguistic representation, taking into account such macro phenomena as linguistic policies and simultaneously taking care about such elements as words. The macro level is also connected with alterations taking place in languages themselves, across different dimensions, such as semantics and syntax. Thus, not only vocabulary but also grammar undergoes alterations, making the language as a system more converged. Macrolinguistic convergence could be observed with the arrival of a new economic system in Poland in 1989, and the consequent change in the way economic communications are handled.

The *meso level* encompasses convergence taking place in the text. An example can be the studies on intertextuality and the relation between different elements and texts, such as concerning literary works. In addition, meso convergence can also be observed from the organizational perspective, elaborating on the role of companies and other entities in making communication more uniform. Convergence is studied in linguistics on the level of dialects. As discussed by Hinskens et al. (2005), dialect changes can be classified into *dialect convergence* and *dialect divergence*. An example of converging processes is *dialect leveling* that leads to the homogenization of individual dialects and the similarity of different dialects. To compare, *koineization* is represented in mixing characteristics of different dialects and resulting in a new dialect, named after Koine Greek that emerged from the conquests of Alexander the Great and served as a lingua franca throughout the Mediterranean for centuries.

The smallest element of linguistic convergence considered here is the *micro level* of words that can be studied by taking into account the dichotomy of literal and nonliteral language. Literal communication encompasses the use of nouns, verbs, and adjectives in their standard meaning. An example of this usage entails the application of parts of speech that facilitate the symbolic language-converging and diverging strategies. Metaphors can function both as the instruments of convergence and divergence. The converging aspect of metaphors is visible at different levels. At the word/term level, disciplinary coexistence has led to the creation of biocorporate metaphors, for example, symbolically transforming machines into living organisms (Leibold et al. 2005).

Metaphors can also have a converging effect on modern communication, since they offer effective communication between interlocutors by relying on domains understood by people regardless of their native tongue and cultural background. For example, a war metaphor is used to discuss the sudden and violent appearance of an illness, whereas the symbolic language relying on domains from natural disasters underlines that a disease is often unpredicted and difficult to control (e.g., Bielenia-Grajewska 2015a). Moreover, since metaphors rely on figurative understanding, they allow for one's own interpretation of a given phenomenon and for one's individual convergence of experience, knowledge, opinions, preferences, etc. It should also be stated that metaphors do not only determine linguistic convergence at the word level but also converge the whole perception of an organization as such.

This type of convergence can be studied by taking into account the *3P's model of company linguistic identity and its metaphorical dimension* (Bielenia-Grajewska 2015b). It consists of interrelated spheres of metaphorical communication that focus around *personnel*, *products*, and *purchasers*. The area of metaphors and personnel encompass such organizational issues as organizational relations and corporate education. As far as metaphors and purchasers are concerned, symbolic language is used to denote the new position of a customer, being an active player on the market, whose needs and expectations are heard and observed. The last sphere, metaphors and products, is focused on showing how the merchandise is used to emphasize group membership and how metaphors carry emotions toward the product. This model shows the converged metaphorical perspective of company identity and the way it is presented in the eyes of the broadly understood stakeholders.

Another example of linguistic convergence is the application of borrowings and loanwords. This phenomenon can be observed in the language of economics (e.g., Bielenia-Grajewska 2009a, b), being represented in the usage of foreign terms in a specialized type of communication. The convergent nature of specialized terms is observed in the amalgamation of different linguistic roots and influences as well as the merger of economic knowledge with linguistic representation. The way the term converges with the new target linguistic and economic reality is represented in the stages of term adaptation. In the very first stage, the term is often used in the original form, being a foreign, usually English word or phrase, accompanied with a descriptive translation or explanation in the target language. Later the mentioned version is often substituted with an equivalent in a target language, often being a calque of the original term. An example can be drawn from the terminology of mergers and acquisitions – *white knight*. In the

1990s the term was often used in Polish in its original form, with a description of what this strategy in Polish is. Nowadays the Polish equivalent *bialy rycerz* is used, being a direct translation of the English term. It should be stated, however, that the linguistic convergence of specialized terminology has many types and depends not only on linguistic policies but also cultural determinants. For example, the mentioned term *white knight* may be difficult to be understood by cultures where white has different connotations.

Typologies of linguistic convergence can be subclassified by taking into account various factors. One of them is the role of passiveness/activeness and the individual/social direct influence or one's position in linguistic convergence. *Passive linguistic convergence* can be defined as convergence taking place without the active participation of individuals. On the other hand, *active linguistic convergence* implies the direct involvement of individuals in the convergence-related activities, in the creation of terms, adopting novel linguistic rules and forming hybrid linguistic communities. The active and passive attitude to convergence is also connected with the notion of voluntariness. *Voluntary linguistic convergence* is related to the acceptance of convergence-related activities and their outcomes, whereas *involuntary linguistic convergence* implies forced convergence, with linguistic rules being imposed on the speakers. The examples of involuntary linguistic convergence include the obligation to use a corporate language at work. Linguistic convergence can also be studied through the prism of an individual/group dimension. *Individual linguistic convergence* is defined as the personal adaptation to the (linguistic) environment and the assimilation of (linguistic) elements into one's own way of speaking and writing. On the other hand, *social linguistic convergence* is related to the assimilation of linguistic elements by a group or a community.

Causes and Effects of Linguistic Convergence

The first determinants of linguistic convergence are relations. They can be studied by examining the types of contact that encompass such notions as frequency, directness, and temporality. *Frequency*, being connected with how often one is in touch with another person, determines the exposure to linguistic forms. In many cases, the more often the language contact takes place, the more intense and fast linguistic convergence is. It should be stated, however, that not always do frequent contacts lead to linguistic convergence, since the outcome may be opposite, leading to rather divergent processes as a result of nonacceptance or the need to strengthen one's linguistic identity. *Directness* describes the nature of contact. Direct contacts involve face-to-face interactions, whereas indirect ones lack this direct component, being conducted without the opportunity of direct response. This may be connected with the asynchronicity of contacts, being the result of the presence of mediators, translators, or other people establishing and conducting communication processes between individuals and groups. The asynchronous character of contacts is also related to the type of technological medium used for interaction. For example, chat tools offer immediate interaction, whereas emails and forums do not require prompt responses. *Temporality*, on the other hand, focuses on the time characteristics and their influence on linguistic contacts.

Another dimension connected with linguistic convergence is the set of determinants underlying the relation between interactors. Factors related to the connections between interlocutors are relations symmetry, dependency (e.g., parent–child, employer–employee), diversity, hierarchy, membership, knowledge, and team characteristics. *Relations symmetry* is studied in literature through the perspective of harmony and balance. *Dependency* is connected with a sort of inequality embedded in a given social relation, connected with the unequal position of interlocutors, associated with their family or professional status. An example of such dependencies may be a parent–child relation or an employee–employer affiliation. They influence linguistic convergence in a number of ways. One of them is the imitation of linguistic behaviors that is characteristic of dependency relations. Imitation and adoption of another person's linguistic behavior are not only characteristic of children learning a mother tongue from their parents. A similar process can be observed in the case of workers in an organization who may imitate the way a boss speaks in order to gain his or her appraisal, stress respect toward his or her professional achievements, or the eagerness to share corporate rules.

Diversity is connected with such features as uniformity in members, their languages, culture, or ideas. Taking into account this determinant, it should be stressed that individuals may have different attitudes toward linguistic difference/novelty, and the process of linguistic convergence may take different forms, depending on such factors as morphological characteristics of one's mother tongue or past absorption of new linguistic elements. Diversity is thus to be observed on both individual and organizational level, since, being a very complex phenomenon, it may lead to both linguistic convergence and divergence. Another important notion connected with both symmetry and dependency is *hierarchy*, also being a determinant of linguistic convergence. In heterarchical organizations the flows connected with linguistic convergence are not one-directional as in the case of organizations characterized by strict hierarchical relations. Thus *membership* is important, as individuals group around clubs, associations, and in the case of business entities, in corporate departments. In such situations, membership as a determinant of linguistic convergence should be studied at both individual and social level. At the individual level, it is connected with one's position in a group he or she belongs to. At the social level, it is represented in a hierarchical position of a given group, association, or department within a larger studied group.

Knowledge constitutes another determinant of linguistic convergence. The type and amount of information one possesses determines one's influence on linguistic interaction. In many cases, the one who is more experienced, possessing more sophisticated and profound knowledge, becomes the key "linguistic donor," making the weaker interlocutor (the one in no possession of deep knowledge or broad experience) converge to the linguistic style of the dominant speaker. It is represented in the usage of new specialized terms denoting the domain the dominant interlocutor is an expert in, the structures favored by the specialists, as well as the "professional idiolect" of an expert. Staying within the social level, team homogeneity and heterogeneity determine the way communication is conducted. Thus, the way a group interacts at the internal level and the way members' relations are shaped influence the way it responds to the linguistic situation. The next group of determinants is composed of factors related to individual characteristics. They include but are not limited to commitment to professional or social activity, confidence in one's skills or experience, attitude to technology, and openness to novelty.

One way to classify the effects of linguistic convergence is analysis of form. Linguistic convergence can lead to amalgamation, with more or less equal importance of elements which constitute the structure. Moreover, linguistic amalgamation may lead to the hybrid form as discussed earlier in hybrid linguistic identity. Also, the processes related to linguistic convergence may result in linguistic divergence, being visible in the proliferation of tools and methods to distance oneself from others. The effects of linguistic convergence can be divided into language-related effects and non-language-related effects. The language-related effects encompass the effects of linguistic convergence that directly influence the way people communicate. For example, linguistic convergence leads to new forms of communication, new specialized languages, and new terms. Thus linguistic convergence results in linguistic divergence, as the appearance of new jargons and forms of specialized communication accompany dynamic developments in the sphere of technology and economy. Taking into account the nonlinguistic dimension, linguistic convergence leads to information convergence, represented by information tailored to diversified audiences and understood by a relatively large group of recipients. Moreover, linguistic convergence leads to social convergence, being reflected in stronger and more cohesive groups.

Linguistic convergence also results in cultural convergence, in adapting norms and approaches from other cultures. It should also be mentioned that linguistic convergence influences other types of convergence as the ones presented in the model. Moreover, language is a powerful instrument, "the role of language being the key that opens different doors to knowledge influences leadership because it offers innovators a palette of different sources from which the most appropriate methods and tools can be chosen" (Bielenia-Grajewska 2012a, 41). Language accompanies different stages of convergence. As Roco et al. (2013) state, the first stage of convergence was connected with converging disciplines, such as, among others, biology, chemistry, condensed matter physics, materials science, electrical engineering, and medicine. The second stage was associated with converging emerging technologies that share such components as atoms, DNA, bits, and synapses. The next stage is linked with joining both societal and technological aspects and disciplines to answer questions and face problems that cannot be dealt separately in an efficient way. This gives a starting point for how linguistic convergence should be studied, taking into consideration different levels of investigation.

The Future of Studies on Linguistic Convergence

One of the possible new trends in studying linguistic convergence is the growing interest in applying neuroscience in humanities and social studies, including the extensive research on linguistics. Neuroscience facilitates the investigation on a deeper level, offering an insight into issues that are difficult to observe by using standard methods. Although the application of specialized neuroscientific equipment is generally more expensive than the standard forms of investigation taking place in humanities and social studies, it provides information that cannot be acquired through questionnaires or interviews. One of the key features of using neuroscientific methods in studying linguistic convergence is their reliability. In standard methods of investigation, there exists the possibility of answers being created by the respondent. Observing the brain or the nervous system provides the researcher with real data, gathered independent of possible fake answers being provided by the respondents.

An example of a neuroscientific tool used in neurolinguistic investigations is functional magnetic resonance imaging (fMRI). In this type of experiment, a subject is placed in a special tube-like machine. In the first stage of a study, an individual has to lie still, and anatomical brain scans are done. The next stage is an active one, with a respondent providing answers or choosing linguistic options. During the execution of these linguistic tasks, the BOLD signal (blood-oxygen-level dependent) is measured. This measurement shows which parts of a brain are active during a linguistic task. Another noninvasive technique is facial electromyography (fEMG). In this technique the activity of face muscles is measured when an individual is exposed to a stimulus. Another technique used in humanities and social studies is electroencephalography (EEG). The electrodes attached to an individual's head measure the electrical activity of a brain. In addition, galvanic skin response (GSR) is applied in experiments measuring one's dermal reaction to a stimulus (Bielenia-Grajewska 2014).

Studies on linguistic convergence should also encompass the needs and expectations of diverse audiences. Attention should be focused on providing education for diversified users, including those with special needs. In that case, convergence is researched through the prism of divergence and how the converged message/information/learning methods are the resultants of diverging expectations, needs, and possibilities, offering at the same time educational options that are convergent and divergent, allowing a group to study together and individuals to benefit from the offered materials.

Additionally, there are also visionary studies on biological language modeling. Klein-Seetharaman and Reddy (2013) elaborate on the notion of converging inherent and external human abilities, visible in interfacing computers with humans, such as speech interfaces that can be more advanced in the future by facilitating the link between the human brain and the machine. Another aspect crucial to the future of linguistic convergence may be the linking of genome sequence information to biological functions of organisms. The convergence between computational linguistics and biological chemistry, realized through such activities as mapping, extraction, and decoding as well as retrieval, summarization, and translation, may lead to more advanced studies on such aspects as the meaning of words, sentences, phrases, and paragraphs.

In the future, linguistic convergence will be even more interconnected with other domains and nonlinguistic determinants. Moreover, the studies on linguistic convergence are a dynamic phenomenon since they not only shape other determinants, but they are also shaped by other factors. The effects of linguistics can also be predicted on the basis of main advantages of convergence, such as the improvement of wellness and human progress, the rise of production and promotion of economic boost, the focus on societal sustainability, and the development of people at individual and social levels, creating a society that is characterized by knowledge, education, innovation, and equity.

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Network of Cooperation Between Science Organizations

Katherine Richardson and Will Steffen

Contents

Abstract

Appreciation of the fact that our planet functions as a system, i.e., the Earth System (ES), defined as "the interacting physical, chemical and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes which provide the conditions necessary for life on this planet" (Oldfield F, Steffen W, The earth system. In: Steffen W, Sanderson A, Tyson PD et al (eds) Global change and the earth system: a planet under pressure. Springer, Berlin/Heidelberg/New York, p 7, 2004) has emerged over the last approximately three decades. By definition, the study of this system – Earth System science – then relies on the convergence of traditional natural science disciplines. Furthermore, however, because a salient feature of the ES is that "human

K. Richardson (✉)
Sustainability Science Centre, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark
e-mail: kari@science.ku.dk

W. Steffen
Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

Fenner School of Environment and Society, The Australian National University, Canberra, ACT, Australia

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beings, their societies and their activities are an integral component of the Earth System, and are not an outside force perturbing an otherwise natural system" (Oldfield F, Steffen W, The earth system. In: Steffen W, Sanderson A, Tyson PD et al (eds) Global change and the earth system: a planet under pressure. Springer, Berlin/Heidelberg/New York, p 7, 2004), Earth System science also relies on the convergence of disciplines from the social sciences and humanities. This convergence of disciplines has led to a current understanding of the function and behavior of our planet – as well as the role of human activities in that function – that would not have been possible using a traditional disciplinary approach. This chapter examines the role of international scientific networks in catalyzing the disciplinary convergence necessary for Earth System science to evolve and concludes that these networks have likely been of pivotal importance for this convergence.

Introduction

The last half of the twentieth century (and including the time up to the present) is often referred to as the "Great Acceleration" (Steffen et al. 2007), where essentially all activities and facets relating to human society have grown astoundingly and with increasing rate. Global population, economic activity, and technological advances are most often used to illustrate this Great Acceleration, but it is also clearly evident in scientific thinking in relation to the human–Earth relationship. It was in 1824 that Joseph Fournier discovered the greenhouse effect, whereby certain gases in the atmosphere act to retain the Sun's heat near the surface of the Earth and, thereby, increase the surface temperature relative to what it would be without these gases. In 1896, the Swedish chemist, Svante Arrhenius, not only predicted that anthropogenic release of CO_2 from the combustion of coal would lead to global warming but also estimated (remarkably accurately!) how much warming could be expected. Nevertheless, scientific and societal focus on this topic did not begin in earnest until the 1980s. Only three decades later, it is not only recognized that human activities are influencing climate but numerous other global processes as well. Indeed, a scientific – and to some extent policy – discourse relating to the need for global management of human activities in relation to global processes they impact is developing (e.g., Steffen et al. 2015).

A prerequisite for the development of such a discourse was a change in the understanding of planetary function with respect to that which flourished at the beginning of the 1980s. Science now recognizes that the Earth is a complex system that operates at the planetary level and that cannot be simply viewed as or described by an aggregation of processes that are observed at lower levels. The individual disciplinary approaches generally employed at the start of the 1980s allowed only descriptions of processes at lower levels. Description of single processes within a system does not, in itself, allow prediction of how change in the process will influence the system as a whole. Thus, in order to arrive at the recognition of the Earth System (ES) and to begin to develop an understanding of how it functions required the convergence of many disciplines. Many factors can catalyze convergence. Using the example of global change research and the emergent understanding of the ES, this chapter examines the role of international scientific networks in promoting the convergence that, ultimately, has led to today's understanding of the ES.

Moving from Climate Science to Earth System Science

Defining the actors. The networks playing a role in the convergence of disciplines that led to an understanding of the Earth as a system and the development of Earth System science are comprised of several different types of actors. A number of government (especially UN) and nongovernment organizations (NGOs) have been important in creating the networks in which convergence was fostered. Generally, these organizations have as part of their mission to employ research to contribute to societal development, but they are usually populated by member states or organizations, i.e., not necessarily, and indeed often not, active research scientists. All of the organizations listed in Table 1 actively contributed to/financially supported the establishment of international programs designed to address one or more environmental challenge that was ultimately recognized as being a vital component of the ES. By far the most important organization, in the sense that it was initiator or co-initiator of the most programs, was ICSU (see Table 2).

Within the programs established by these organizations, foci (projects) for further research were identified and developed. The work plans and priorities of each program were developed through hearings in the relevant scientific communities and ultimately approved by the program leadership (usually comprised of members of the scientific community). In this manner, the programs brought scientists together that otherwise would not necessarily have interacted. For some of the programs, representatives of other programs participated as observers in the discussions and decisions of the scientific committees responsible for executing the programs. Thus, networking was occurring not only within but also between programs, and, by this mechanism, scientists from quite disparate disciplines were brought to the same table. It was this organizational structure that formally brought scientists from disparate disciplines into direct contact. However, simply bringing disciplines together does not, in itself, necessarily lead to convergence. By tracing the evolution of the ES concept within the framework provided by this organizational structure, some of the conditions that may stimulate convergence can be identified.

Climate as a Starting Point

The web of interaction between organizations and the scientific community described above ultimately linked scientists and new scientific results to the international policy discussions occurring, for example, in the UN. As Table 2

Table 1 Principle actors contributing to the creation of a scientific network within global change research

International Council for Science (ICSU)	NGO, established 1931; global membership of national scientific bodies (121 members, representing 141 countries) and International Scientific Unions (32 members). Mission is to strengthen international science for the benefit of society (http://www.icsu.org/)
World Meteorological Organization (WMO)	Specialized agency of the UN; established 1950; 191 Member States and Territories; "the UN system's authoritative voice on the state and behaviour of the Earth's atmosphere, its interaction with the oceans, the climate it produces and the resulting distribution of water resources" (https://www.wmo.int/pages/index_en.html)
Intergovernmental Oceanographic Commission (IOC)	Established by UNESCO in 1960; "promotes international cooperation and coordinates programmes in marine research, services, observation systems, hazard mitigation, and capacity development in order to understand and effectively manage the resources of the ocean and coastal areas" (http://www.ioc-unesco.org/index.php?option=com_content&view=featured&Itemid=100001)
United Nations Environment Program	Established following UN Conference on the Human Environment (1992, Rio) "to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations" (http://www.unep.org/)
Scientific Committee on Problems of the Environment (SCOPE)	NGO; established 1969; to identify and undertake analyses of emerging environmental issues that are caused by or impact on humans and the environment (http://www.scopenvironment.org/)
United Nations Educational, Scientific, and Cultural Organization (UNESCO)	Established 1945; "to build networks among nations" (http://en.unesco.org/about-us/introducing-unesco)
International Union of Microbiological Societies (IUMS)	Established in 1927; one of 31 scientific unions in ICSU; "promote research and the open exchange of scientific information for advancement of the health and welfare of humankind and the environment" (http://www.iums.org/)
International Social Science Council (ISSC)	Established by UNESCO in 1952 for "advancing the social sciences for solving global problems" (http://www.worldsocialscience.org/)
International Union of Biological Sciences (IUBS)	NGO; established 1919; "promoting biological sciences for a better life" (http://www.iubs.org/)

Table 2 Scientific milestones in global change research, the evolution of scientific networks relating to global change research, and relevant policy milestones over the past three decades. Sponsors for the individual global change programs are identified in Table 1 with the exception of two sponsors for Future Earth: UNU United Nations University http://unu.edu/ and Belmont Forum https://igfagcr.org/. Unless otherwise indicated, references for the scientific milestones identified can be found in Richardson et al. (2011)

Research milestones	Network evolution	Political milestones
1970		
Realization of human-caused ozone hole		
1980		
Ice cores provide evidence of rapid climate change and a relationship between CO_2 + temperature over time	1980: WCRP established (WMO, ICSU; + IOC 1993)	
	1986: IGBP established (ICSU)	
		1987: Montreal Protocol agreed; Brundtland Report presented
	1988: IPCC established (WMO, UNEP)	
1990		
1990: 1st IPCC Report		1990: UNFCCC negotiation starts
	1991: Diversitas established (SCOPE, UNESCO, IUBS, ICSU, ISSC)	
		1992: UN "Earth Summit" (Rio); UNFCCC and Convention on Biological Diversity opened for signature
1995: 2nd IPCC Report		
	1996: IHDP established (ICSU, ISSC)	
1999: evidence that CO_2 is higher now than in the last 420,000 years		
2000		
2001: 3rd IPCC Report	2001: Amsterdam Declaration on Global Change; establishment of ESSP	
2007: 4th IPCC Report		
2009: "Planetary Boundaries" concept (Rockström et al. 2009)		
2010		
	2012: Future Earth established (ICSU, ISSC, UNESCO, UNEP, WMO, UNU, Belmont Forum)	2012: "Rio + 20"

demonstrates, the focus of the research programs established by the international organizations coincided to a large extent temporally with discussions on the same topics in the international policy arena. It also appears that the shifting foci in the organizations and within policy can be linked (with some time lag) to the development of seminal scientific concepts or presentation of scientific documentation of ES phenomena. This emphasizes the obvious point that the convergence of disciplines occurring within the network of scientific organizations and ultimately leading to the recognition of the ES and the development of Earth System science did not occur in isolation and was likely catalyzed by events and changing perceptions developing within both scientific and policy communities. The understanding of these interactions is not well developed, but it is worth noting that the often referred to "bridge" between science and policy-making supports two-way traffic which makes identifying cause and effect in terms of policy development and the occurrence of convergence in global change research difficult to identify.

As noted above, the theoretical groundwork leading to the conclusion that human activities could potentially change the climate was laid already in the nineteenth century. Sporadic studies appeared in the academic literature during the first half of the twentieth century suggesting that human-caused global warming was underway, but the scientific interest in this possibility really gained momentum in the 1960s and 1970s after an annual increase in atmospheric CO_2 concentrations was documented (Keeling 1960). It was, presumably, this increasing scientific focus on human-caused climate change that led the WMO together with ICSU to establish the *World Climate Research Programme* (*WCRP)* in 1980. A few years later, WMO together with UNEP also established the *Intergovernmental Panel on Climate Change* (IPCC) which was charged with the mandate not of actually doing research but of assessing the available research evidence of whether human activities were contributing to global climate change.

At roughly the same time, however, it was becoming clear that climate was not the only aspect of the global environment that was potentially impacted by human activities. Several scientific studies that emerged in and around the 1970s linked the emission of CFC gases to the development of a "hole" in the ozone layer. These scientific results led to adoption of the Montreal Protocol in 1987 which limits emissions of CFC gases. It also seems likely that research leading to the understanding of human impacts on the ozone layer was a factor prompting ICSU, in 1986, to establish the *International Geosphere-Biosphere Programme (IGBP)*. A noteworthy initiative in the policy arena in this period was the Brundtland Report (Anon. 1987) which introduced the concept that "sustainability" of human development comprises not only an economic dimension but also environmental and social. In retrospect, one can interpret much of the research coordinated by the international networks in subsequent decades as having been focused on defining and operationalizing these environmental and social dimensions. In the 1990s, two new research programs joined WCRP and IGBP in the family of global environment research programs, Diversitas (focusing on biodiversity loss) in 1991 and the *International Human Dimensions Programme (IHDP)* in 1996. It was, however, within the framework of the IGBP that much of the thinking resulting in the recognition of the ES developed. The evolution of this program is, therefore, considered in some detail here.

Converging Disciplines: The Emergence of the Concept of Earth System

IGBP's implementation phase began in 1990, and six core projects were developed in its initial period. One of these projects (Global Change and Terrestrial Ecosystems (GCTE)) prepared a very successful synthesis of the work it had carried out, and this led to a proposal and decision at the IGBP Scientific Committee (SC-IGBP) meeting in 1998 to create the (first) IGBP Synthesis Project, where the results of the program as a whole could be brought together. Although it was originally envisioned that the project could be completed by 2000, it was first finished in 2003 and published the following year as the book, *Global Change and the Earth System: A Planet Under Pressure* (Steffen et al. 2004).

There were several key milestones in producing this synthesis. One occurred in connection with a 1999 workshop which originally had been envisioned to synthesize existing knowledge on global biogeochemical cycling. A few days before the workshop, however, a now-famous paper was published tracing the close coupling of atmospheric greenhouse gas concentrations and Earth surface temperature over the last 420,000 years (Petit et al. 1999). That paper refocused the workshop toward consideration of how such a tight lockstep in the patterns of carbon cycling and climate variation might be explained. A flurry of interesting ideas and hypotheses were proposed about how important feedback mechanisms worked and how, in more detail, the climate and carbon cycles were coupled. Thus, the underlying theme of the workshop became the remarkable proof this paper provided that the Earth operates as a single system.

The 2000 Scientific Committee (SC-IGBP) meeting also provided a milestone en route to a more general scientific recognition of the ES as it was here the term "Anthropocene" was born. During the routine presentation of the various projects' progress reports, Paul Crutzen, a Vice-Chair of SC-IGBP (and a recipient of the shared 1995 Nobel Prize in Chemistry for his contributions to the understanding of human impacts on the ozone layer) became agitated at the frequent references in the report of the PAGES (Past Global Changes) project to the Holocene, i.e., the official geological nomenclature for describing the current epoch in Earth history. Finally, he blurted out words to the effect of "but we are no longer in the Holocene" and, struggling a moment for words, concluded his intervention with "we are now in the Anthropocene." This intervention was noted in an IGBP newsletter a few months later and the idea further developed in a short Nature paper (Crutzen 2002). Now, of course, the notion that the Earth has entered a unique phase in its history, the Anthropocene, where humanity has become the largest driver of change of the stability and resilience of the planet, has gained widespread attention and acceptance both within and outside of the scientific community.

Progress on the IGBP synthesis project was slowed by the preparation and execution of a large international open scientific conference on global change held in Amsterdam in 2001. The idea of the Amsterdam conference was conceived and most of its initial planning carried out within the IGBP. However, both WCRP and the IHDP were partners from an early stage, and Diversitas joined as a cosponsor of the conference somewhat later. Thus, the conference ended up being a joint product of the four different research programs, and, in his opening address at the conference, the then Chair of the SC-IGBP, Berrien Moore, drew from the research of all four programs and wove it together in a visionary tapestry of how and why the global change scholarship requires the convergence of different disciplines.

The Amsterdam Declaration on Global Change (https://web.archive.org/web/20070721122243/http://www.essp.org/en/integrated-regional-studies/open-science-conferences/the-amsterdam-declaration.html) was produced in connection with the conference by the chairs of the four global change research programs. The key messages that were evolving from the IGBP synthesis project provided critical input to this declaration, and it became a major turning point for Earth System science as it was here that "The Earth System behaves as a single, self-regulating system comprised of physical, chemical, biological and human components. . ." was first publically proclaimed. Formulation of the term/concept, "Earth System science," arose primarily from the IGBP synthesis project, and the term was constructed in this way intentionally, even though it was recognized that it is probably not correct in terms of English grammar and usage. At the turn of the millennium, the concept of Earth as a single, integrated system was not common and was not widely accepted, even in IGBP core projects. Therefore, those involved with the IGBP synthesis, and this included the IGBP secretariat, consciously referred to "the Earth System" in both written and spoken communication. Both words were capitalized, thus making it into a proper noun in English grammar. This was to emphasize that the ES functions as a single entity, not a collection of subsystems that coincidentally occupy the same planet.

Another critical term relevant to the Amsterdam conference and used in the Declaration was "global change" and was used in the IGBP community from its inception. The term "global change" (as opposed, for example, to the often used "global environmental change") recognizes that that humans and human societies are a fully interactive part of the ES and not an "outside force," standing outside of the natural world or the environment and perturbing an otherwise natural system. Thus, "Earth System" and "global change" are internally consistent terms and address trends in a single, complex system that humans are part of.

During the Amsterdam conference, there was a call for greater cooperation between the four global change research programs, and an official alliance of these programs developed as a direct consequence of the conference, the Earth System Science Partnership (ESSP). Cooperation – including joint projects – between the four programs continued until 2012, when a new common program, Future Earth, was launched at the Rio + 20 Conference. The aim of Future Earth is to bring all disciplines relevant for the study of the Earth System under one umbrella.

The joint projects developed within ESSP are noteworthy in that they tended to focus on "systems," i.e., the climate system (Global Carbon Project (GCP)), the water system (Global Water System Project (GWSP)), the health system (Global Environmental Change and Human Health (GECHH)), the food system (Global Environmental Change and Food Systems (GECAFS)), etc. Thus, rather than focusing on description and quantification of specific processes within the ES as most earlier projects in separate global change programs had done, projects within the ESSP were more directly focused on the societal challenges emanating from global change. Interestingly, as Sustainable Development Goals (SDGs) are being negotiated in the UN (in anticipation of ratification in 2015), "systems" also play a prominent role in the narrative. In the words of Guido Schmidt-Traub, Executive Director of the UN Sustainable Development Solutions Network (UNSDN) speaking at a sustainability science congress held at the University of Copenhagen in October 2014 (http://sustainability.ku.dk/sustainability-lectures/previous/iarucongress2014/session-webcasts/), achieving sustainability "requires that there are certain systems we get right."

The systems approach of the ESSP also emphasized the link between researchers and nonscientist field practitioners, thus implementing the idea of "coproduction of knowledge." In many ways, then, the ESSP, at least in its conceptual origins and its intent, was a forerunner of the Future Earth program. This new program is from the outset identified as a 10-year research program open to scientists of "all disciplines, natural and social, engineering, humanities and law"(http://www.futureearth.org/) and categorizes its research into three themes: (1) "Dynamic Planet," (2) "Global Sustainable Development," and (3) "Transformations Towards Sustainability."

Thus it was that the formalized international framework for coordinating science and scientists from different disciplines dealing with global change evolved over three decades from a single program in geophysics focusing on the climate system to a single program encompassing all academic disciplines and focusing on achieving a sustainable development for human societies. The intervening period between these two end points saw first the proliferation of discipline-focused programs followed by a formalized partnership between the different programs and, finally, convergence of all disciplines within a single challenge-based program. Global change research is, then, a "poster child" of disciplinary convergence, but what drove this convergence? Was it forced upon the scientific community? Or did it evolve organically? Again, the IGBP provides a useful case study to search for answers to these questions.

Top-Down Or Bottom-Up Evolution of Convergence in Global Change Research Thinking?

The IGBP "case" provides interesting examples of planned (top-down) convergence – as well as some surprising missed opportunities at convergence in its initial planning – and quite a bit of unplanned (bottom-up) convergence. Planning for the IGBP was launched in 1986 by ICSU (then the International Council for Scientific

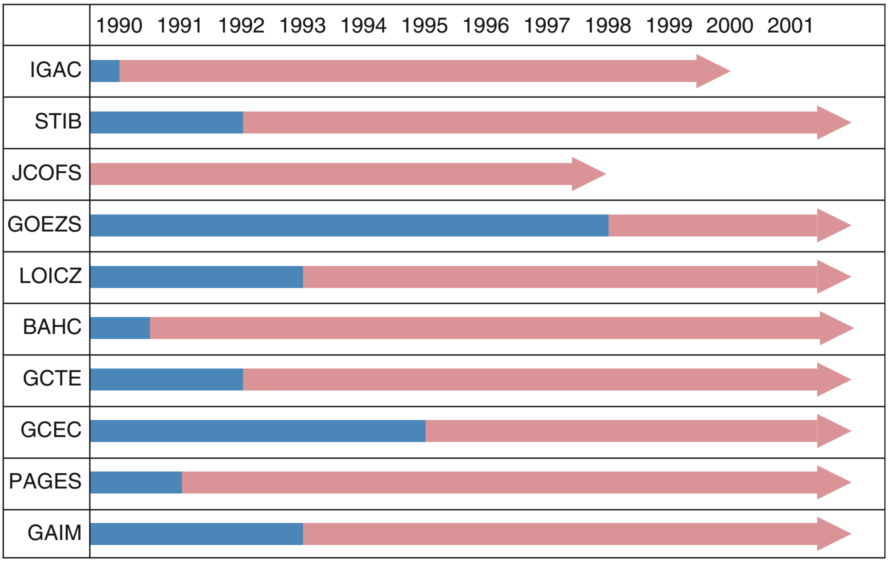

Fig. 1 Scientific project structure as envisioned at the outset of the International Geosphere-Biosphere Project. Acronyms refer to project names and these are explained in the text. *Blue color* indicates planning phase and *red* the expected lifetime of the project (Redrawn from Anon 1990)

Unions, now the International Council for Science). The original objective of the IGBP showed a strong drive toward convergence from a set of individual, discipline-oriented core projects toward one overarching, holistic aim: “To describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities” (Anon. 1990). Note the strong focus on the Earth as single, highly integrated system evidenced by the fact that “Earth System,” not “Earth systems,” is used.

The planning timeline for the first phase of IGBP (Fig. 1) shows a mixture of convergent and more linear (non-convergent) thinking. There are two excellent examples of “planned” convergence which demonstrate the foresight of the IGBP founders: The project GOEZS (Global Ocean Euphotic Zone Study) was explicitly designed to converge the disciplines associated with WOCE (World Ocean Circulation Experiment) and JGOFS (Joint Global Ocean Flux Study). WOCE, a WCRP project, aimed to improve understanding of ocean circulation from a purely physical perspective. The focus of JGOFS, on the other hand, was on the marine carbon cycle and its interaction with the atmosphere, i.e., a strongly biogeochemical perspective. GOEZS was planned from the outset to bring together the new knowledge from these two earlier projects to study integrated physical, biogeochemical, and biological processes in the upper layers of the ocean. GOECZ was to commence implementation when JGOFS was phased out. This project never materialized, however.

Another example of planned convergence was between the IGBP project BAHC (Biospheric Aspects of the Hydrological Cycle) and the WCRP project GEWEX (Global Energy and Water Experiment). Collaboration between the two was planned from early in the development of BAHC, but (as for all these moves toward convergence) the human dimensions were probably more important than scientific plans. After a rather rocky start toward collaboration, some excellent and visionary leadership from both sides in the early to mid-1990s led to a strong degree of convergence between the two projects by the late 1990s.

The GAIM – Global Analysis, Interpretation, and Modelling – was designed to be highly integrative from the outset and explicitly aimed to integrate across the other IGBP core projects. Indeed, to signify this integrative role, GAIM was not called a "core project" like the others but, rather, a "task force," perhaps suggesting the perception that convergence required some sort of special organizational structure. The rationale for GAIM was stated in 1990 as: "A consistent effort is required to ensure that the knowledge gained about the components of the Earth system fits into a globally consistent and internally compatible description that can be used not only to understand the important biogeochemical cycles and processes, but also the feedback and interactions between the various sub-components that regulate the Earth system" (Anon. 1990). The famous "Bretherton" diagram (Anon. 1988) of the Earth System was the visual blue print for GAIM, but it had humans as a single box outside of the system and perturbing it and thus did not incorporate the social sciences. Nevertheless, this blueprint represented a strongly convergent perspective on the wide range of natural science disciplines that are required to understand the biophysical ES.

Despite some of these progressive intentions regarding convergence of disciplines early in IGBP history, there were also some surprising examples of the lack of convergent thinking in a program that had such a holistic, integrative overarching aim. An example here was in the area of terrestrial ecology, where the GCTE (Global Change and Terrestrial Ecosystems) core project was instituted to tackle the land-based processes in the Earth System. In this project, an extremely important feature of terrestrial ecosystems (indeed, of all biological systems on Earth) was omitted, namely, biodiversity and its implications for the functioning of the ES. Biodiversity was certainly recognized as being crucial, but it was left for a future project to be called "Global Change and Ecological Complexity" (GCEC). Intriguingly, the plan was for GCEC to be launched about 5 years after GCTE, but it apparently was meant to run in a parallel track to GCTE, not to be merged with it. The GCEC project never materialized.

Atmospheric chemistry was another area where the opportunity for an early pathway toward convergence was missed. IGAC (International Global Atmospheric Chemistry) was oriented toward near-surface and tropospheric chemistry, while early discussions were dealing with the study of chemistry in the upper atmosphere. The approach proposed in 1990 was to launch a second project – STIB (Stratosphere-Troposphere Interactions and the Biosphere) – to be launched around 1992. However, the timelines for IGAC and STIB ran in parallel for the rest of the decade, with no planned convergence. STIB never came into existence.

The timelines shown in Fig. 1 were, of course, developed in the late 1980s during the planning phase of IGBP. It is perhaps remarkable that they showed the level of planned convergence that they did at that time. As the decade of the 1990s unfolded, the actual evolution of the IGBP core projects was rather different, showing both antecedent pathways that preceded IGBP but also a large degree of convergence as the projects actually developed. Two of the initial IGBP core projects were planned/launched prior to IGBP's inception by organizations that were built around specific disciplines, and so these projects, although becoming part of the IGBP family, had strong disciplinary pathways already defined and that they largely followed when they became a part of IGBP. One of these projects was JGOFS, which was established by SCOR (Scientific Committee on Ocean Research) to study carbon fluxes between ocean and atmosphere. SCOR remained as a cosponsor of JGOFS throughout its lifetime. The other project was IGAC, where the initial planning was undertaken by ICACGP (International Commission of Atmospheric Chemistry and Global Pollution), although the project was launched jointly by the ICACGP and IGBP in 1990.

The terrestrial ecosystem component of IGBP – GCTE – followed a rather different pathway toward convergence than the one (actually non-convergence) shown in Fig. 1. Although the proposed GCEC never eventuated, the Diversitas program was founded in 1991. This was perhaps appropriate as the profoundly important role of life in regulating ES processes became better understood through the 1990s. GCTE did, however, inherit a companion project in the mid-1990s – LUCC (Land Use and Cover Change), which was jointly sponsored by the IGBP and the newly formed International Human Dimensions Programme on Global Environmental Change (IHDP). LUCC was designed to have close interaction with GCTE, as it brought humans and anthropogenic processes into terrestrial ecology in an integrated framework. The move toward convergence between GCTE and LUCC was exemplified by the major conference "Earth's Changing Land," held in Barcelona in 1998 and culminated in the formation of the Global Land Project (GLP) jointly hosted by the IGBP and the IHDP in the early 2000s.

The Past Global Changes (PAGES) project also exhibited an interesting trajectory toward convergence within the project itself. Begun as an almost exclusively biophysical project with a very strong focus on paleoclimate, processes internal to the project moved to include the human element of past global changes as the project developed through the 1990s. "PAGES Focus 4," as it was rather dryly known, proved to be an exciting and revolutionary way of doing paleo-science, bringing in new disciplines such as archaeology, anthropology, and history and generating new insights into the role of human activities in the structure and functioning of the ES in the past. The LOICZ (Land-Ocean Interactions in the Coastal Zone) project followed a somewhat similar pathway as PAGES in that it started as a strongly biophysical project. Not long after its inception, however, LOICZ began incorporating socioeconomic processes into its research and ultimately achieved a very high level of integration between the biophysical and social sciences.

Finally, the formation of GLOBEC later in the 1990s is an excellent example of planned convergence with respect to the marine component of the Earth System. Although this project is not shown on the original IGBP timeline (Fig. 1), it was widely recognized by the mid-1990s that there was a need for a project that focused on human modification of marine ecosystems – a sort of marine equivalent of the LUCC project on land. Global Ocean Ecosystem Dynamics (GLOBEC) was incorporated into the IGBP core structure in 1995 and was designed from the outset to eventually be phased out, along with JGOFS, in favor of the single, more integrated project IMBER (Integrated Marine Biogeochemistry and Ecosystem Research). IMBER is one of the Phase II set of IGBP projects, which were designed in somewhat top-down fashion to build a more complete and integrated Earth System-oriented structure.

The organization of Phase II of IGBP is presented in less detail here. However, the overall guideline for the structuring of the most recent history of IGBP was an increased emphasis on the ES as an integrated whole. There were to be six core projects: three oriented around the major components of the Earth System – land (GLP), ocean (eventually IMBER), and atmosphere (IGAC) – and three oriented around the interfaces that connected these three components, namely, land–atmosphere (iLEAPS), ocean–atmosphere (SOLAS), and land–ocean (LOICZ). It was recognized that the cryosphere was also a critical component of the Earth System but that was handled in the WCRP. Importantly, there were in addition two projects which studied the Earth System as a whole – PAGES and AIMES (Analysis, Integration and Modeling of the Earth System). These provided a continuous timeline of Earth System dynamics from the past (sometimes deep past) through the present and into the future. In keeping with the spirit of the Earth System as a single, integrated system and the advent of the ESSP, several of these projects were jointly sponsored by the different members of ESSP.

Conclusions

This chapter set out to examine the role of scientific networks in catalyzing convergence of academic disciplines to meet the societal challenges of global change. It outlines a convincing transition over the last 30 years from mono-disciplinary descriptions of aspects and consequences of global change to a more systemic approach to the understanding of global change that requires input from essentially all academic disciplines. Thus, there is no doubt that a convergence of disciplines within global change research has taken place. Indeed, the emergence of an understanding of the Earth as a system would not have been possible without this convergence. Given the complexity of interactions and the number of actors involved, identifying the precise role of scientific networks in leading to this convergence is not straightforward. It does, however, seem highly unlikely that this convergence would have occurred over such a relatively short period of time in the absence of some sort of organizational structure outside of the traditional academic (university) structure and transcending national boundaries. It, therefore, seems likely that the combined efforts of several governmental and nongovernmental organizations to coordinate and focus global change research toward societal concerns have played a major role in the convergence that has occurred. In part, this convergence has resulted from "top-down" control of the topics within which research projects have been initiated by the established programs, but interactions within the scientific community, itself, have also contributed to the convergence. In this context, it is interesting to note that the changing landscape of science–society–policy interactions is a part of the ES, as it is now defined. The direction of the trajectory of the ES over the next several decades will depend greatly on the development of the human enterprise, and an important part of any scenario of the human enterprise is how societies will react to the ongoing developments in science and how this knowledge generation process intersects with the policy and governance communities. Therefore, Earth System science must include studies of the changing landscape of science–society–policy interactions in any of its future scenarios. In this sense, the convergence of disciplines that has occurred in global change research over the last three decades may, ultimately, prove to be critical for the future development of human societies.

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Science and Technology Globalization

William Sims Bainbridge

Contents

Abstract

Convergence of science and technology with society entails globalization, but will not necessarily lead to uniformity across nations or institutions of society. In the past, technologies differed from one place to another not only because societies differed in terms of their level of development but also because of contrasting natural conditions, historical accidents, and cultural values. Discoveries and inventions do tend to spread from their points of origin to other locations, and extensive research and theorizing have identified a large number and variety of factors that shape this diffusion. Innovation has tended to be localized, for example, in the familiar "Silicon Valley" phenomenon, in which a relatively small number of scientists and engineers communicated intensively with each other, as they collectively progressed. Thus, we cannot be assured that all parts of the globe will be equally creative in innovating, even as they all are affected by it. Over time, however, cycles of convergence and divergence can ensure dynamism on the global scale.

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Given that the laws of nature seem to be uniform across the observed universe, it would seem that science would also be uniform around the Earth, once all nations were in active communication with each other and had all reached modern levels of technical development. Yet several questions may be raised about the validity of this simple analysis, especially when the topic is science-based technology. Given that many problems have multiple solutions, and many aspects in the design of a machine are somewhat arbitrary, styles of technologies may vary across nations. Some very specific geographic locations are hotbeds of innovation, and rates of diffusion from them may vary in different directions. A fundamental question, not limited to science and technology but encompassing all aspects of human experience, concerns whether the future will see uniformity as globalization advances or a dynamic process of endless convergence and divergence.

Uniformity Versus Diversity

Imagine that two European fighter pilots experience an inconclusive dogfight in the Second World War, and both were able to make it back home safely. The English pilot was flying a Spitfire, and the German was flying a Messerschmitt 109. Both were low-wing, single-engine, propeller-driven monoplanes, of almost the same vintage, and from the perspective of many decades later seem remarkably similar to each other. After returning to their airfields, each pilot gets into a car and begins driving down a road, but the British pilot drives on the left side of the road, and the German, on the right side. And, if we were to compare the political systems of the two nations, we would identify a number of significant differences, at that point in their history, but relatively few differences if we compared Britain with Germany today, except that now as then they use different systems of money and measurement of distance.

That example suggests that complex factors may shape the similarities and differences between the technologies used by different societies. Clearly, when the ancient Romans conquered Britain, and failed to conquer Germany, at best they rode chariots rather than airplanes, so the general history of engineering is a factor. Intense competition between nations may cause their military technology to converge very closely, even as the general level of technology is advancing rapidly, because each side is motivated to adopt innovations quickly from the other side. Automobiles in Sweden originally drove on the left side of the road and then in 1967 switched over to the right side of the road, to conform to the norm in adjacent Norway and Finland, and because many imported automobiles were designed for right-side traffic. In contrast, Britain has been able to maintain its left-side tradition. Thus factors like geographic separation and social interaction patterns are also significant.

Clearly some technology design decisions are arbitrary, while others are adaptations to contingencies in the surrounding environment at particular points in time, but once a standard has been established it may be difficult to change. In science and technology, a common issue concerns how difficult it is to translate from one system to another. Abstractly, the hardware systems for diving on the left versus right side of the road may be identical, merely reversed. But for human drivers and even pedestrians who must learn which way to look as they cross a road, extensive experience in one system may make operating in the other especially difficult.

Many of the often used systems of standards can be translated reliably, although affected by a range of factors. Advanced nations use two competing scales for ordinary distances, the metric and English systems, in which units like feet and meters differ but on stable scales that have the same zero point. The two competing temperature scales, Celsius (Centigrade) and Fahrenheit, have different stable units and also different zero points, neither of which matches the objective zero point in the more scientific Kelvin or absolute temperature scale. Many monetary systems exist – such as US dollars, Canadian dollars, British pounds, and euros, with a shared zero point but unstable units that fluctuate as financial markets change the conversion rates. The existence of multiple competing systems of measurement is more than a mere annoyance, because occasionally the consequences can be catastrophic. Among the most famous examples is the loss of the Mars Climate Orbiter in 1999, which was destroyed in the Martian atmosphere at the cost of hundreds of millions of dollars and lost research opportunities. The official report on the disaster attributed it to a confusion between two familiar systems of measurement (Stephenson 1999, p. 16):

> The MCO MIB has determined that the root cause for the loss of the MCO spacecraft was the failure to use metric units in the coding of a ground software file, "Small Forces," used in trajectory models. Specifically, thruster performance data in English units instead of metric units was used in the software application code titled SM_FORCES (small forces). The output from the SM_FORCES application code as required by a MSOP Project Software Interface Specification (SIS) was to be in metric units of Newton-seconds (N-s). Instead, the data was reported in English units of pound-seconds (lbf-s). The Angular Momentum Desaturation (AMD) file contained the output data from the SM_FORCES software. The SIS, which was not followed, defines both the format and units of the AMD file generated by ground-based computers. Subsequent processing of the data from AMD file by the navigation software algorithm therefore, underestimated the effect on the spacecraft trajectory by a factor of 4.45, which is the required conversion factor from force in pounds to Newtons. An erroneous trajectory was computed using this incorrect data.

A good historical example of complex standards is the proliferation of broadcast television formats. At the risk of oversimplification, it can be said that the history of television is framed by two separate variables. First, the devices producing the picture may be mechanical, analog, or digital. Second, delivery of the information to the user may be via broadcast or cable. The defining decades of the television industry were analog and broadcast. Many early experiments used mechanical devices to scan the image, both in the camera and the receiver, for example, a rotating disk with holes punched in it, perhaps each provided with a lens and at different distances from the center, so that when each passes over a small area, it scans one line of an image. Remarkably, the first color television system approved by the US government at the very beginning of the 1950s was a CBS system that used a huge rotating disk to pass transparent colored filters in front of a fluctuating black and white image to add color (Abrahamson 2003). Already by 1953 a much superior all-electronic analog system was ready from the competing RCA Corporation.

All-electronic black and white (grayscale) television was ready in the 1930s and demonstrated to a large public at the 1939 World's Fair. In the USA, commercial television began on July 1, 1941, but did not become widespread until after the Second World War. It used a standard called NTSC (National Television System Committee) which included several specifications, notably how many horizontal scan lines there would be in the picture, how many frames per second would be displayed, and more complex characteristics such as the fact that it uses *interlacing*, which means that the display goes through each frame of the image in two passes, handling every other line to reduce distracting brightness flicker in the total image. Related features of any broadcast standard concern how much radio bandwidth in which frequency range the broadcast will use.

This last point suggests the most important reason why governments have been involved in setting standards for television: The radio spectrum is a public resource, because a powerful broadcast station monopolizes the band of frequencies it uses, often over a considerable geographic area. A second more controversial justification for government involvement is that setting a standard can facilitate development of an industry, so long as the standard can support future innovations and does not impose stultifying economic monopoly. The NTSC standard was a good one, because in 1953 it was possible to modify it to add color to television, but it did so by adding a *subcarrier* or *sideband* that provided the color information, and preserving the original black and white image so that older TV sets could receive the broadcasts perfectly well. While NTSC was very influential, adopted by many nations, two other technically superior standards, PAL and SECAM, were deployed in other nations slightly later and employed more scan lines for a slightly greater image resolution. Then near the end of the twentieth century, a set of high-definition standards competed (Farrell and Shapiro 1992). Thus, competition between different standards for broadcast technologies typically results in incompatibilities between nations and the ironic result that a nation that pioneers a new technology winds up with a system inferior to that enjoyed by nations that enter the field later.

Ideally, the modern information technologies greatly advance convergence, facilitating translation across systems of measurement and interoperability between different technology design standards. We approach a new era in which the radio spectrum is no longer used for broadcasting mass media like television, but is restricted to short-distance wireless connectivity between mobile devices and special purposes such as radar and radio astronomy. Today, so-called smart TVs already handle multiple standards and even allow the user some control over how images will be displayed, as well as downloading videos of many kinds, including movies and TV dramas, when the user wants to see them rather than at a fixed time. This technological revolution has the potential to reduce or even erase national differences, yet other barriers stand in the way of complete global convergence.

Diffusion of Innovation

Historians and social scientists have studied many cases in which a new technology developed in one location diffused to other locations. Some of the most famous examples are controversial, especially in analysis of their causes and effects, and one of the most interesting was the introduction of the stirrup into Europe. Today many people imagine that the popular movies about the Wild West correctly represent equestrian technology as it must have existed for thousands of years, yet many pieces of horse-related equipment took on their modern forms only after the end of ancient civilizations, and any movie that shows Alexander the Great mounting his horse by putting his foot in a stirrup, grasping the horn of his saddle and leaping up, is wrong. In 1962, Lynn White argued that importation of the stirrup from Asia transformed mounted warfare in Europe, allowing warriors to wear heavy and costly armor, thus concentrating military investment in knights and thus creating the social system known as *feudalism* (White 1962). More recent writers have raised many kinds of doubts about this theory of *technological determinism*, including proposing that Europe adopted stirrups as a consequence of social changes rather than a cause and that more generally social factors shape technology diffusion, even though new technologies have their own distinctive consequences (Stone 2004).

The scientific literature on diffusion is quite extensive, especially if one includes more general research on the communication of information across social networks and cultures. While there is no one dominant theory, a few insightful classification systems have sought to put into a logical framework a number of observations about the factors that are often involved. Perhaps the most prominent example, existing in many variants, is the idea that science and technology relate in distinctive ways to each of the major completing political and economic systems. A political history of the space age by Walter McDougall (1985) argued that a major impetus was the *technocracy* practiced by the Soviet Union, as reflected in Sputnik I and the first orbital flights by astronauts. In contrast, a recent theoretical analysis by Kelly Moore and collaborators argued that the form and direction of innovation were now dominated by a political ideology they call *neoliberalism*, in governments that encourage free markets and are influenced by the interests of technology-based corporations. The result seems to have been transformational (Moore et al. 2011, p. 506):

> Beginning in the 1980s, changes in government, industry, and the university have increasingly pressured academic and industrial scientists to align their research with the goals of national competitiveness, regional economic development, and marketplace opportunities. However, the changes have paradoxically opened new opportunities for scientists and citizens to develop science in the interest of the public and more specific constituencies.

In *technocracy*, experts tell government which policies to adopt, in the case of the Soviet Union from the perspective of a specific ideology, namely, Marxism. In *neoliberalism*, policy will largely be determined by economic expediency, influenced by almost exactly the Capitalist ideology that Marxism opposed. The question may then become what factors influence the diffusion of an ideology. Simmons et al. (2006) have identified four competing theories to explain the rapid diffusion of economic and political liberalism, which might be assembled into a convergent theory in which four factors cooperate:

1. Coercion: Powerful nations compel weaker nations to adopt the policy they prefer.
2. Competition: Policy adoption reflects the interests of investors and merchants in international markets.
3. Learning: Beliefs change as the result of transmission of information, at multiple levels of complexity and abstraction.
4. Emulation: Social meanings are reconstructed on the basis of interpreting and imitating the norms and values of another society that becomes a role model.

A rather comprehensive review of the literature on diffusion of innovation by Barbara Wejnert (2002) identified this rather complex structure of a dozen influential factors:

I. Characteristics of innovations
   1. Public versus private consequences: Social efforts to promote or resist an innovation will take very different forms, depending upon whether the primary consequences affect organized groups and institutions or isolated individuals.
   2. Benefits versus costs: These can be both direct and indirect, affecting the rate and pattern of diffusion in changing ways over time.

II. Characteristics of innovators
   3. Societal entity: Adoption processes differ when the agent is an individual person versus a large group such as a government, an industry, or a social movement.
   4. Familiarity with the innovation: Under normal conditions, the more radical an innovation is, the more resistance there will be to diffusion.
   5. Status characteristics: People and organizations that enjoy high status tend to be early adopters of innovations, so long as they are not highly controversial.
   6. Socioeconomic characteristics: Economic prosperity is a precondition for adoption of costly innovations, but can also inhibit adoption of innovations that contradict economic assumptions.
   7. Position in social networks: The vast social network research reveals complex dynamics, such as the advantage of extensive networks in transmitting information and the concentration of networks in influencing behavioral change.
   8. Personal characteristics: Self-confidence and propensity to take risks are among the personality characteristics of individuals that may favor adoption of innovations.

III. Environmental context
   9. Geographic settings: The physical climate and natural resources of a location may affect adoption of some innovations, while geographic proximity to sites that have already adopted is an advantage for diffusion of many innovations.
   10. Societal culture: Adoption of particular innovations, or of innovations in general, is affected by a society's entrenched belief systems, its degree of traditionalism, its homogeneity versus heterogeneity, and the processes by which children are socialized and educated.
   11. Political conditions: Official ideologies, policy-making institutions, and momentary political conditions may promote some innovations while inhibiting or even prohibiting others.
   12. Global uniformity: The diffusion of some innovations affects the diffusion of others, in at least three ways: (1) the emergence of standardized institutions across societies, (2) the past adoption of economically significant innovations that form the basis for adoption of future innovations, and (3) modern communication systems.

It is one thing for a new product to be adopted in a developing nation, or for new information to be added to the college curriculum in a nation that did not discover it, but quite another for innovation and discovery themselves to diffuse. When all of humanity benefits from science and technology, can all societies contribute equally to their progress? Can all people of the world converge as consumers without also converging as producers?

The Scale of Science

In addition to the natural processes of science and technology diffusion, many conscious efforts have been made to transform research and development into a global endeavor. An especially visible approach has been the organization of special international research efforts for a defined span of time, of which the International Geophysical Year of 1957–1958 may be most famous (Chapman 1959). Reportedly, 67 nations collaborated in this effort to understand the land, sea, and air of the Earth, encouraging scientific exchange between the political blocs of West and East, and marked by a competition between the USA and USSR to launch the first artificial satellite of Earth.

The governments of many nations limit their funding of scientific research to institutions within their own borders, yet engage in outreach to other nations. For example, the US National Science Foundation has overseas offices in Beijing, Paris, and Tokyo. Several pairs of nations engage in extensive scientific cooperation and periodically examine the structure and context of their exchanges, notably the USA with China (Wessner 2011) and Germany (Wessner 2012). This handbook and the book-length report *Convergence of Knowledge, Technology and Society* (Roco et al. 2013) that preceded it were based on a series of conferences in the USA, Brazil, Belgium, Korea, and China.

However, even some of the technically most advanced nations have at times experienced difficulty competing in the international areas of science and technology. One of the most informative studies of this situation was commissioned by the Central Advisory Council for Science and Technology of Great Britain back in 1968 (Layton 1972) which noticed with dismay that British innovations often failed to achieve the economic returns they logically deserved. Many factors were identified, including the fields of specialization that were produced by the educational system or hired by companies and the relatively limited size of the home market for some products.

Japan has also periodically agonized about its competitive situation in science, technology, or the integration of both. Early in the 1980s, the Japanese government launched an initiative to develop "fifth-generation computing," based on a particular artificial intelligence conception of how hardware and programming languages should be constructed, causing consternation in the USA because its rhetoric seemed very persuasive and there then existed general concern that Japan might dominate in many fields of advanced technology (Feigenbaum and McCorduck 1983). Yet the project turned out to have little consequence, as computing technology went in other directions, providing a cautionary tale of how a valiant attempt at innovation by a nation may fail despite plausibility, expertise, and effort.

Given the difficulty that well-educated, scientifically advanced nations like Britain and Japan have faced, one has good reason to doubt that all the peoples of the Earth can be equal partners. But the most powerful factor limiting total science and technology convergence operates on scales both larger and smaller than individual nations, in the social size and structure of professional communities. Keller (2002) has shown that international technology diffusion tends to be geographically localized, while Subramaniam and Venkatraman (2001) have shown that diffusion takes place not merely though transfer of machines and publications but significantly through tacit knowledge, best communicated from one person to another through actually working together.

In the development of modern computer technology, small coherent geographic areas have played decisive roles. Most famous is "Silicon Valley," near San Francisco, where much of the personal computer revolution occurred and many companies like Apple and Google still have their headquarters (Freiberger and Swaine 1984). Less famous but also important in the same way was the "Route 128" area near Boston (Kidder 1997). These areas concentrate on intelligence, technical competence, energy, imagination, and an almost gamelike competitive spirit in a small geographic area with an intensely interacting social network. Like transistors in a computer's central processing unit, the brains of humans in such a rare context can process information faster and better than most of humanity can ever achieve.

This proposition, however, is contradicted by one interpretation of the most influential propositions in the social science of science, the so-called Ortega hypothesis. Its author, Spanish philosopher José Ortega y Gasset, wrote in a somewhat complex and dramatic style open to multiple interpretations, and his hypothesis is usually derived from this passage (Ortega y Gasset 1932, pp. 84–85):

> . . .experimental science has progressed thanks in great part to the work of men astoundingly mediocre, and even less than mediocre. That is to say, modern science, the root and symbol of our actual civilisation, finds a place for the intellectually commonplace man and allows him to work therein with success. The reason of this lies in what is at the same time the great advantage and the gravest peril of the new science, and of the civilisation directed and represented by it, namely, mechanisation. A fair amount of the things that have to be done in physics or in biology is mechanical work of the mind which can be done by anyone, or almost anyone. For the purpose of innumerable investigations it is possible to divide science into small sections, to enclose oneself in one of these, and to leave out of consideration all the rest. The solidity and exactitude of the methods allow of this temporary but quite real disarticulation of knowledge. The work is done under one of these methods as with a machine, and in order to obtain quite abundant results it is not even necessary to have rigorous notions of their meaning and foundations. In this way the majority of scientists help the general advance of science while shut up in the narrow cell of their laboratory, like the bee in the cell of its hive, or the turnspit in its wheel.

The general public has been taught to believe that scientific progress is primarily achieved by a few great geniuses, although most ordinary people cannot name one more recent than Albert Einstein. The author of this paragraph was something of an elitist, and his hypothesis has some qualities of an insult to the dignity of science. Yet if true, it implies that global convergence would allow productive research and development to take place everywhere around the globe, perhaps achieving progress faster because so many people were at work. However, the hypothesis entered serious scientific theory in an article in the journal *Science* by Jonathan and Stephen Cole, which sought to refute the hypothesis with data indicating that only a small minority of scientific publications written by unusually able scientists contribute significantly to progress. Cole and Cole (1972, p. 374) even suggest that "reducing the number of scientists might not slow down the rate of scientific progress."

The Ortega hypothesis, and others listed above, cannot be taken as truths and in the context of convergence must be the subject of intensive, new research. Fragmenting science and engineering into many separate specialties would seem to provide jobs for more professionals, yet inhibit innovation by reducing diffusion of information and ideas from one field to another. Perhaps the correct plan is to combine convergence and divergence, giving prominent roles to small numbers of "genius" scientists at times of scientific revolution (Kuhn 1962), but democratizing science as the hypothesis suggests when vast numbers of empirical studies must be done to confirm ideas or advance already existing technologies.

Sciences as Cultures

Among the most empirically solid yet politically sensitive findings in the social sciences is that most human cultures throughout history have been very poor at scientific discovery. Yes, ancient civilizations, and the indigenous peoples around the globe, possessed great knowledge of their environments, but only very superficial understanding. Why was the periodic table of the chemical elements not discovered by the Ancient Egyptians or the Copernican model of the solar system by the Babylonians? Sociologist Joseph Ben-David (1971, p. 21) has stated the painfully obvious historical facts:

> Rapid accumulation of knowledge, which has characterized the development of science since the seventeenth century, had never occurred before that time. The new kind of scientific activity emerged only in a few countries of Western Europe, and it was restricted to that small area for about two hundred years. Since the nineteenth century scientific knowledge has been assimilated by the rest of the world. This assimilation has not occurred through the incorporation of science into the cultures and institutions of the different societies. Instead, it has occurred through the diffusion of the patterns of scientific activity and scientific roles from Western Europe to the other parts of the world. The social role of the scientist (whether he is a university professor or a research worker in industrial or government laboratories) and the organizational surroundings of his work, in India, Japan, Israel, or the U.S.S.R. are varieties of social forms originating in Western Europe.

Historians of science and technology would find much to debate about this bold statement. What about the scientific progress in ancient Greece? At best it was a brief episode that did not transform the world and in which the science practiced by philosophers had little to do with the technology developed by engineers. What about the science practiced in the early centuries of Islamic societies? In his recent book *How the West Won*, sociologist Rodney Stark (2014) argues that Islamic science was an historical illusion, merely the preservation of innovations achieved by the Greeks. If for sake of argument we consider ancient Athens and Hellenistic Greece to be a near miss, and the Age of Discovery in premodern Europe to be the one bull's eye in human scientific history, then perhaps qualities their societies had in common provide an explanation. Ancient Greece and Renaissance Europe were highly fragmented societies that gave considerable liberty to their most able and best educated citizens, rather than being empires that imposed a rigid ideology such as a monolithic religion.

One well-developed argument in the sociology of science connects the birth of European science to the emergence of Protestantism and free market Capitalism (Merton 1970). Protestantism was monotheistic, with the implication that the entire universe was governed by a single set of laws. But it also placed great responsibility on the individual believer, rather than on any priesthood, with the implication that devout believers could undertake scientific research to learn more about God. In retrospect, it is hard to test such hypotheses, because the religious statements of scientists may have been either incidental to their work or a rhetorical shield for it against criticisms from devout nonscientists. An alternate analysis would suggest that secularism promotes science, indeed that the process a society experiences when it secularizes may be even more favorable than a fully atheistic culture would be, because it energizes as well as permits the search for truth.

It should be immediately obvious that any serious consideration of these issues can quickly become politically sensitive. That may connect back to the fact that really active science was so rare in human history. Thus, it is only at our peril that we ignore the possibility that science and related forms of progress may require certain sociocultural conditions that are themselves rare and therefore controversial. Among the marvels that social science must interpret are the very different social conditions in different areas of the developing world. Why have some parts of Asia innovated technically, if not so obviously in basic science, while Latin America has not taken a leadership role despite its extensive natural and human resources?

At present, and for some years past, world attention has focused on the problematic conditions in many Islamic societies. One cogent but unconfirmed explanation has suggested that the lack of democracy, and thus of science, in many Islamic societies is that many of them are oil-producing states (Ross 2001). Dominance of extractive industries may place political power in distant elites, rather than in the hands of the local people. A variant of that theory blames the misbehavior of colonial powers like Britain, France, or even Turkey, which among other sins drew arbitrary lines on the map to define nations and then set up dynasties that were originally their puppets. Given the significance of the religion variable in traditional sociological theories, it is not surprising that Islam has also been considered the possible factor retarding the liberty that allows science to thrive (Grim and Finke 2011). What commentators often miss when discussing how some cultures may discourage science is that those cultures may encourage other trends that give strength to their societies; in the case of Islam that might be both a high fertility rate producing population growth at a time when Europe is contracting and greater military risk-taking which may at times produce chaos, but at other times, aggressive conquest over more passive peoples (Pew Research Center 2015).

Given the fact that social science has not arrived at a secure consensus on these difficult issues, and even if it had we might lack the power to do anything about the social barriers to science, it is worth looking for a more manageable related topic. That could be the harmony between diverse cultures at the societal level and distinctive subcultures within science. For example, alternative computer software systems, such as the competing operating systems produced by Apple and Microsoft, can be conceptualized as subcultures (Rajlich 2004). Calling programming systems *languages* is more than a metaphor, because they differ in grammar, vocabulary, and the social groups that have adopted them. Given that progress requires a constant dynamic between convergence and divergence, it is entirely possible that the existing cultures of the world will specialize in performing distinctive scientific and technological tasks, for the benefit of all, rather than becoming homogeneous and therefore less dynamic (Sloan and Alper 2014).

Conclusion

Special efforts to globalize science and engineering can be exceedingly valuable, if conducted with awareness of the possible barriers and in conjunction with research on all the human aspects of long-distance collaboration. The insight that convergence should not become a rigid demand, but a partner in the cycle of innovation with divergence, is among the necessary preconditions for success. Diffusion of innovation should continue to be studied, but more effort should be invested on understanding diffusion of *innovating*, in which the ability to discover and invent spreads beyond its currently limited geographic homes. We also need a better understanding of how science functions best on various scales, from small and intensely interacting communities of researchers and theorists to the vast global community, as problems and contexts evolve dynamically. The cultures in and around science and engineering are crucially important as well. The successes of the international converging technologies conferences and publications offer excellent reason for optimism.

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Space Exploration

Roger D. Launius

Contents

Abstract

This essay examines space exploration from its beginnings in the middle of the last century and looks onward to half a century in the future. Beginning by examining the reasons why the 2 twentieth century superpowers believed that space exploration was an important investment, the chronological review of early developments includes discussions on science, commerce, and national security; the evolution of space-related technologies; and progress and advancements in launch vehicles, spacecraft, and spacecraft payloads. With the subjects of robotic solar system exploration and crewed missions to space discussed in some detail, the great advances of the last 60 years establish a foundation for addressing the challenges of future human flight beyond Earth's vicinity – challenges that are technical, political, social, and economic in nature. The author takes a pragmatic view in making forecasts for the future of spaceflight: limiting conjecture, for the most part, to the next 50 years. While it is very

R.D. Launius (✉)
Division of Space History, Smithsonian Institution, National Air and Space Museum, Washington, DC, USA
e-mail: LauniusR@si.edu

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difficult to make realistic predictions for longer periods, the author is confident that space exploration continues to grasp the public's imagination and desire to know more about the universe and that it continues to build on many of the same questions that inspired the space program in the mid-twentieth century. The essay concludes with prospects for the twenty-first century.

Introduction

Space exploration is a preeminent example of many kinds of convergence. It brings together many technical fields – propulsion, life sciences, materials, guidance and control, communication, and a host of others – necessary to sustain the effort. From a scientific perspective, it also demands convergence. Indeed, there is no such thing as "rocket science," despite the popularity of the term. Astronautics necessitates a convergence of physics, chemistry, and other disciplines, as well as every aspect of geology, climatology, oceanography, and a range of material, computer, and medical sciences. Building a space program also required a convergence of societal institutions, such as cooperation between government and industry, and even international cooperation and global convergence. Ultimately, the question is human convergence with the cosmos, in terms of real questions about human space travel and colonization, not just some mystical metaphor. Also, lessons from the history of spaceflight may be applied in other areas of science, technology, and human endeavor into the future.

Beginning the Space Age

The dominant users of space from the beginning of the space age until the 1980s were governments, especially the two superpowers the United States and the Soviet Union. There were several entities in the United States dedicated to space operations. On the civil side the National Aeronautics and Space Administration (NASA) quickly emerged as the preeminent entity, but several parts of the national security apparatus also undertook space research, development, and operations. Later such organizations as the National Oceanic and Atmospheric Administration (NOAA) entered the arena; by 2014 there were 17 separate US government agencies with a role in space activities.

NASA emerged in 1958 out of the "Cold War" rivalries of the United States and the Soviet Union. Engaged in broad contest over the ideologies and allegiances of the nonaligned nations of the world, space exploration was one major area contested. This served as the key that opened the door to aggressive space exploration, not as an end in itself, but as a means to achieving technological superiority in the eyes of the world and geopolitical suzerainty.

The Soviets gained the upper hand in this competition on October 4, 1957, when they launched *Sputnik 1*, the first artificial satellite to orbit the Earth, as part of a larger scientific effort associated with the International Geophysical Year. While US officials congratulated the Soviet Union for this accomplishment, clearly many Americans thought that the Soviet Union had staged a tremendous coup for the communist system at US expense.

After an arms race with its nuclear component and a series of hot and cold crises in the Eisenhower era, coupled with the launching of Sputniks I and II in 1957, the threat of holocaust felt by most Americans and Soviets was now not just a possibility, but a seeming probability. For the first time enemies could reach the United States with a radical new technology. In the contest over the ideologies and allegiances of the world's nonaligned nations, space exploration became contested ground (Launius, Logsdon, and Smith 2000). It was a shock, introducing the illusion of a technological gap and providing the impetus for the 1958 act creating NASA. Sputnik led directly to several US efforts aimed at "catching up" to the Soviet Union's space achievements. Among these are the following:

- A full-scale review of both the civil and military programs of the United States (scientific satellite efforts and ballistic missile development)
- Establishment of a Presidential Science Advisor in the White House who had responsibility for overseeing the activities of the federal government in science and technology
- Creation of the Advanced Research Projects Agency in the Department of Defense and the consolidation of several space activities under centralized management
- Establishment of NASA to manage civil space operations
- Passage of the National Defense Education Act to provide federal funding for education in the scientific and technical disciplines (McDougall 1985; Dickson 2001)

Because of this perception, the Congress passed and President Dwight D. Eisenhower signed the National Aeronautics and Space Act of 1958 establishing the National Aeronautics and Space Administration (NASA) with a broad mandate to explore and use space for "peaceful purposes for the benefit of all mankind." The core of NASA came from the earlier National Advisory Committee for Aeronautics with its 8,000 employees, an annual budget of $100 million, and its research laboratories. It quickly incorporated other organizations into the new agency, notably the space science group of the Naval Research Laboratory in Maryland, the Jet Propulsion Laboratory managed by the California Institute of Technology for the Army, and the Army Ballistic Missile Agency in Huntsville, Alabama (Launius 1994, 29–41).

The Soviet Union, while not creating a separate organization dedicated to space exploration, infused money into its various rocket design bureaus and scientific research institutions. The chief beneficiaries of Soviet spaceflight enthusiasm were the design bureau of Sergei P. Korolev (the chief designer of the first Soviet rockets used for the Sputnik program) and the Soviet Academy of Sciences, which devised experiments and built the instruments that were launched into orbit. With huge investments in spaceflight technology urged by Soviet premier Nikita Khrushchev, the Soviet Union accomplished one public relations coup after another against the United States during the late 1950s and early 1960s (Siddiqi 2003; McDougall 1985; Von Benke 1997).

Within a short time of NASA's formation, it had structured itself to accomplish human spaceflight. During its first 40 years, NASA's human space exploration program consisted of several major components:

- Mercury's single astronaut program (flights during 1961–1963) to ascertain if a human could survive in space.
- Project Gemini (flights during 1965–1966) with two astronauts to practice for space operations.
- Project Apollo (flights during 1968–1972) to explore the Moon.
- An orbital workshop for astronauts, *Skylab* (1973–1984)
- A reusable spacecraft for traveling to and from Earth orbit, the Space Shuttle (1981–2011)
- The building and operation of the International Space Station (1984–present) (Burrows 1998; Jenkins 2001)

The capstone of this effort was the human expedition to the Moon, Project Apollo. A unique confluence of Cold War political necessity, personal commitment and activism, scientific and technological ability, economic prosperity, and public mood made possible the May 25, 1961, announcement by President John F. Kennedy to carry out a lunar landing program before the end of the decade as a means of demonstrating the United States' technological virtuosity.

Project Apollo, backed by sufficient funding, was the tangible result of a perceived threat to the United States by the Soviet Union. The space agency's annual budget rose quickly from $500 million in 1960 to a high point of $5.2 billion in 1965 to complete Apollo. A comparable percentage of the $2.4 trillion federal budget in 2014 would have equaled more than $82 billion for NASA, whereas the agency's actual budget then stood at $16.6 billion. NASA's budget began to decline beginning in 1966 and continued a downward trend until 1975. With the exception of a few years during the Apollo era, the NASA budget has hovered at slightly less than one percent of all money expended by the US treasury. Stability has been the norm for NASA's budgets, but since the end of the Cold War about 1990, it has seen a steady decline (see Fig. 1).

While Apollo was transcendentally significant at a sublime level, the public's support for it was never overwhelming. In answer to the question "Should the government fund human trips to the Moon?" in virtually all cases, a majority opposed doing so, as shown in Fig. 2. Before the landing in July 1969, at only one point, October 1965, did more than half of the public favor the program. From the 1960s to near the present, there is little evidence to support an expansive lunar exploration and colonization program. One must conclude from hard evidence that the United States undertook and carried out Apollo not because the public

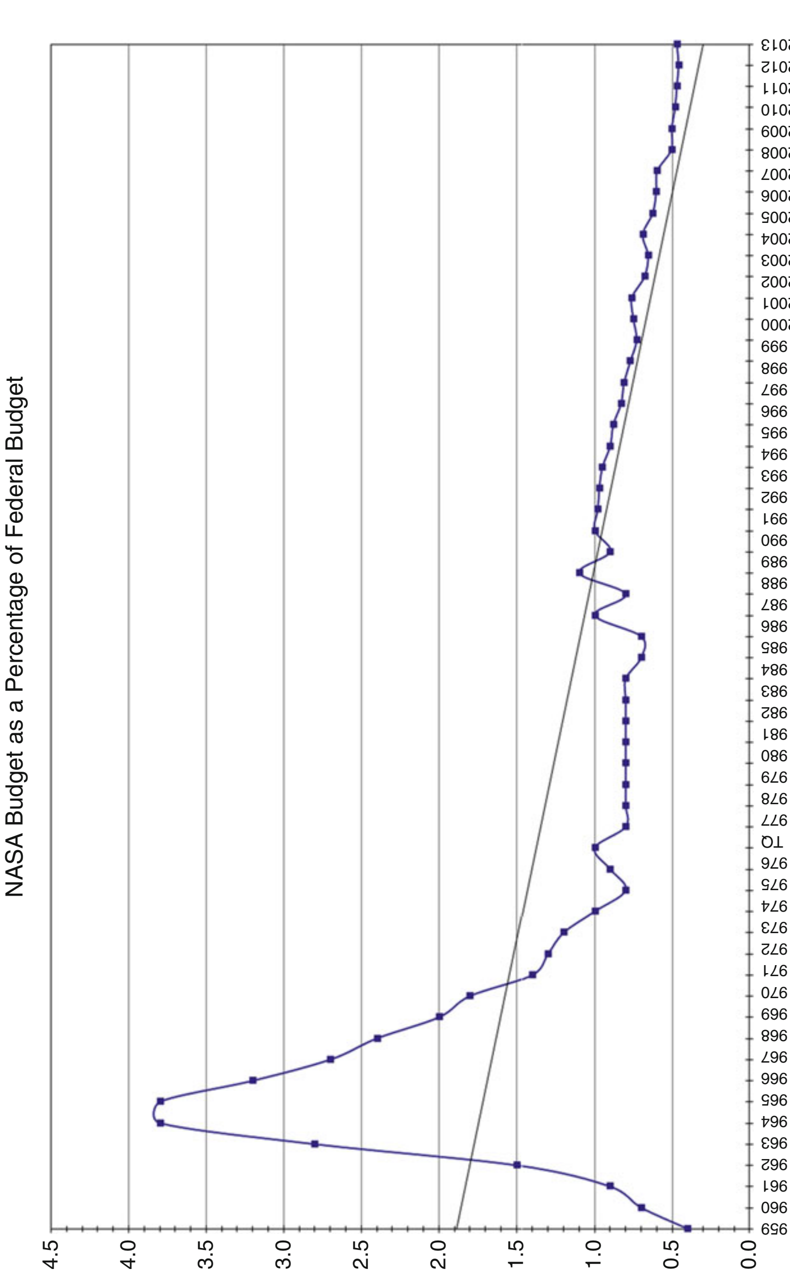

Fig. 1 NASA budget as percentage of federal budget

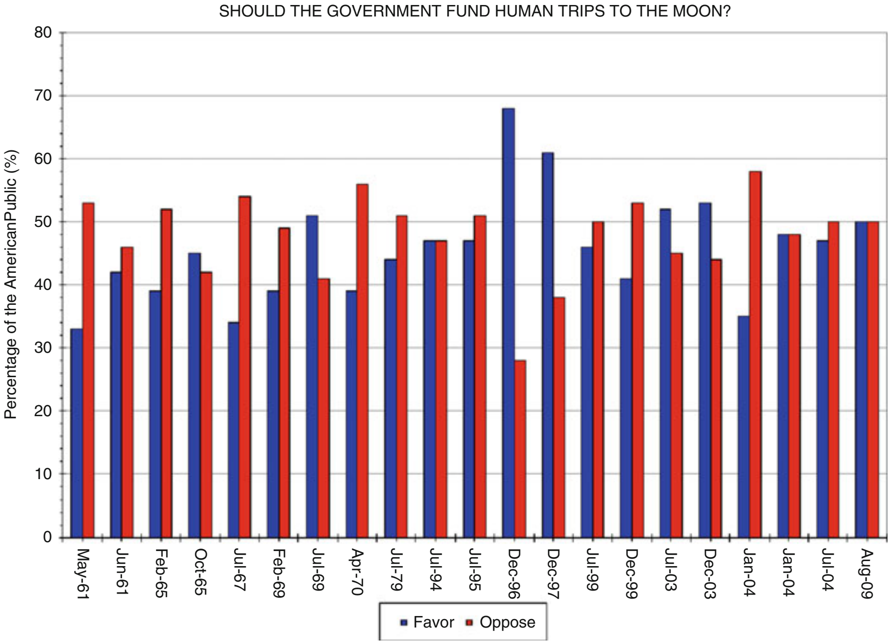

Fig. 2 Should the government fund human trips to the Moon?

clamored for it during the 1960s, but because it served geopolitical purposes. Furthermore, the polling data suggests that should the United States mount another human mission to the Moon in the future, it will also be because the mission serves a larger political, economic, or national defense agenda (Launius 2003).

In all there were three Earth-orbital missions, Apollos 7 and 9 and Apollo-Soyuz; two circumlunar missions during this program, Apollo 8 and Apollo 13 (the result of an accident); and six landing missions, Apollo 11 and 12, 14–17, conducted at approximately 6 month intervals between July 1969 and December 1972. While geopolitics drove the effort, the scientific experiments placed on the Moon and the lunar samples returned have provided grist for scientists' investigations ever since (Zimmerman 1998; Burrows 1998).

Post-Apollo NASA

After Apollo – and the interlude of Skylab – the space program went into a holding pattern as nearly a decade passed. The Space Shuttle was intended to make spaceflight routine, safe, and relatively inexpensive. Although NASA considered a variety of configurations, some of them quite exotic, it settled on a stage-and-one-half partially reusable vehicle with an approved development price tag of $5.15 billion. On January 5, 1972, President Nixon announced the decision to build a Space Shuttle. He did so for both political reasons and national prestige purposes. Politically, it would help a lagging aerospace industry in key states he wanted to carry in the next election, especially California, Texas, and Florida. Supporters – especially Caspar W. Weinberger, who later became Reagan's defense secretary – argued that building the shuttle would reaffirm America's superpower status and help restore confidence, at home and abroad, in America's technological genius and will to succeed. This was purely an issue of national prestige (Logsdon 1986).

Indeed, US leaders supported the shuttle not on its merits, but because of very specific political objectives. In so doing, the Space Shuttle that emerged in the early 1970s was essentially a creature of compromise that consisted of three primary elements: a delta-winged orbiter spacecraft with a large crew compartment, a cargo bay 15 by 60 f. in size, and three main engines; two solid rocket boosters (SRBs); and an external fuel tank housing the liquid hydrogen and oxidizer burned in the main engines. The orbiter and the two solid rocket boosters were reusable.

After a decade of development, on April 12, 1981, *Columbia* took off for the first orbital test mission. It was successful, and after only the fourth flight in 1982, President Ronald Reagan declared the system "operational." It would henceforth carry all US government payloads; military, scientific, and even commercial satellites could all be deployed from its payload bay.

The shuttle soon proved disappointing. By January 1986 there had been only 24 shuttle flights, although in the 1970s NASA had projected more flights than that for every year. Critical analyses agreed that the shuttle had proven to be neither cheap nor reliable, both primary selling points. Many agreed that the effort had been both a triumph and a tragedy. The program had been engagingly ambitious and had resulted in an exceptionally sophisticated vehicle, one that no other nation on Earth could have built at the time. At the same time, the shuttle was essentially a continuation of space spectaculars, *à la* Apollo, and its much-touted capabilities had not been realized. It made far fewer flights and conducted far fewer scientific experiments than NASA had publicly predicted.

All of these criticisms reached crescendo proportions following the loss of *Challenger* during launch on January 28, 1986. Although it was not the entire reason, the pressure to get the shuttle schedule more in line with earlier projections throughout 1985 prompted NASA workers to accept operational procedures that fostered shortcuts and increased the opportunity for disaster. The accident, traumatic even under the best of situations, was made that much worse because *Challenger's* crew members represented a cross section of the American population in terms of race, gender, geography, background, and religion. The accident became one of the most significant events of the 1980s, as billions around the world watched on television and empathized with any one or more of the crew members killed (Vaughan 1996).

With the *Challenger* accident, the shuttle program went into a 2-year hiatus while NASA redesigned the system. The Space Shuttle returned to flight on September 29, 1988. Each undertook scientific and technological experiments ranging from the deployment of important space probes like the *Magellan* Venus

Radar Mapper in 1989 and the Hubble Space Telescope in 1990, through the flights of “Spacelab,” to a dramatic three-person EVA in 1992 to retrieve a satellite and bring it back to Earth for repair, to the exciting missions visiting the Russian space station *Mir*, to the orbital construction of an International Space Station.

In 1984, as part of its interest in reinvigorating the space program, the Reagan administration called for the development of a permanently occupied space station. At first projected to cost $8 billion, within five years the projected costs had more than tripled and the station had become too expensive. NASA pared away at the station budget, and in the end the project was satisfactory to almost no one. In 1993 the international situation allowed NASA to negotiate a landmark decision to include Russia in the building of an International Space Station (ISS). By 1998 the first elements had been launched and in 2000 the first crew went aboard. At the beginning of the twenty-first century, the effort involving 16 nations was a shadow of what had been intended. It had been caught in the backwash of another loss of another shuttle and the inability to complete construction and resupply. Consistently, ISS has proven a difficult issue as policymakers wrestled with competing political agendas without consensus.

After several more missions, tragedy struck the Space Shuttle program again with the loss of *Columbia* during reentry on February 1, 2003 (Launius 2004). After another stand-down to resolve the technical problems that had caused the accident, the shuttle program again returned to flight and completed the construction of ISS. At that point the Space Shuttle program ended in 2011 after 135 missions. Thereafter, the United States had no intrinsically national capability to reach orbit; it contracted for astronaut rides to ISS aboard Russian Soyuz capsules.

In the aftermath of the *Columbia* accident on January 14, 2004, President George W. Bush announced a vision of space exploration that called for humans to reach for the Moon and Mars during the next 30 years. As stated at the time, the fundamental goal of this vision was to advance US scientific, security, and economic interests through a robust space exploration program. In so doing the president called for completion of the ISS and retirement of the Space Shuttle fleet by 2010.

In the end a combination of technological and scientific advancement, political competition with the Soviet Union, and changes in popular opinion about spaceflight converged in the 1950s to affect public policy in favor of government support for human space exploration. This found tangible expression in efforts of the 1960s to move forward with an expansive space program. After that initial rise of effort, however, human space exploration reached an equilibrium in the 1970s that it has sustained to the present. The American public is committed to a measured program that includes a modest level of human missions, as well as other efforts. A longstanding fascination with discovery and investigation has nourished much of the interest by the peoples of the United States in spaceflight. By the end of the first decade of the twenty-first century, however, support for human space exploration had declined to the extent that public support for its continuation was quite soft and there was certainly no groundswell of support for a human return to the Moon or to go to Mars.

The Rise of Private Human Space Exploration

While human spaceflight has been dominated by national actors, there has long been a belief that private activities should open the space frontier to all. This dream received sustenance from early commercial activities such as telecommunications, remote sensing, and other commercial applications in orbit. It also gained traction from the success of Apollo and the desire to settle near space as well as the Moon and Mars. By the 1980s a significant industry had emerged to oversee these commercial activities but nothing in terms of private human spaceflight had taken place.

A new age of space entrepreneurship in the United States really began with a set of decisions in that same era aimed at advancing private space activities. While economic growth and development, as well as international competitiveness, had long been goals of national space policy during the 1960s (with the emphasis on the space race), little had been accomplished to open space to broader activities. This was reflected in a set of relatively narrow legislative and executive branch initiatives outlined in various laws and policy directives. Direct federal investment in space R&D and technology served as the principal means of stimulating the private space community during that era (Reed 1998).

Beginning in the mid-1990s, several start-up companies were organized to develop new launch vehicles in response to the development of an anticipated expansive market. Indeed, 1996 marked something of a milestone in the history of space access. In that year worldwide commercial revenues in space for the first time surpassed all governmental space spending, totaling some $77 billion. This growth continued in 1997, with 75 private payloads lofted into orbit, and with approximately 75 more military and scientific satellites launched. This represented a threefold increase over the number the year before. Market surveys for the period thereafter suggested that private launches would multiply for the next several years at least: one estimate holding that 1,200 telecommunications satellites would be launched between 1998 and 2007. In that context many space launch advocates believed that the market had matured sufficiently that government investment in launch vehicle development was no longer necessary. Instead, they asked that the federal government simply “get out of the way” and allow the private sector to pursue development free from bureaucratic controls (Butrica 2000).

Beyond this, the dream of space settlement sparked a rising chorus of support from the so-called new space community. Many had tied their dreams of space colonies to NASA’s “Spaceflight Participant Program” in the 1980s which had led to the flight of Christa McAuliffe as a teacher in space during the ill-fated *Challenger* mission in January 1986. With that program’s cancellation after that accident, however, they lost hope that NASA would expend private space activities. They supported the efforts of billionaire Dennis Tito, who bucked NASA and pioneered the way for orbital space tourism by spending a week in April 2001 on the International Space Station (ISS). In so doing, advocates of space tourism believed that he had challenged and overturned the dominant paradigm of human spaceflight: national control of who flies in space is overseen with a heavy hand by

NASA and the Russian Space Agency. In making his way over the objections of NASA, Tito supporters believed he had paved the way for others to follow. South African Mark Shuttleworth also flew aboard ISS in the fall of 2001, without the rancor of the Tito mission. Several others have made excursions since that time and more will come, either paying their own ways or obtaining corporate sponsorships (Launius and Jenkins 2006).

Tourism, and this may be the highest form of adventure tourism, seems to be the method of choice for those who want to explore and settle places beyond Earth. Once less expensive access to space is attained, an opening of the space frontier may well take place in much the same way as the American continental frontier emerged in the nineteenth century, through a linkage of courage and curiosity with capitalism. New space advocates also took encouragement from the success of SpaceShipOne in 2004, which received the Ansari X-Prize of $10 million for being the first private space vehicle to fly twice into space within a 10-day period. As this capability advances, supporters emphasized, the role of the government should become less dominant in near space. The development of space tourism capabilities for both suborbital and orbital missions is currently under way. Additionally, there are efforts to undertake a one-way mission to Mars and to form compacts for settlements elsewhere.

The five challenges enumerated here might also apply to many other areas of development. Using the history of spaceflight and futurology as a model, we might apply the same mixture of political, social, technical, scientific, economic, and cultural issues illuminated through this discussion to an exploration and perhaps deeper understanding of other cases. These five challenges contain ideas of general applicability.

What Might the Future Hold?

Who knows what the future might hold? Only time will tell. Space exploration provides a window on the universe from which fantastic new discoveries may be made. Humans may well discover extraterrestrial life. They may set their eyes on the image of an Earthlike planet around a nearby star. They may discover some fantastic material that can only be made in a gravity-free realm. Perhaps they may discover some heretofore unknown principle of physics. Maybe they will capture an image of the creation of the universe. That is the true excitement of the endeavor.

The twenty-first century promises to be an exciting experience for many reasons, but spaceflight offers a uniquely challenging set of possibilities. While other analysts might differ with my list, I would suggest that there are five core challenges for those engaged in spaceflight in the twenty-first century. Each of these may be traced far back in the history of the space age and have served as perennial issues affecting all outcomes involving an expansive future beyond this planet.

The first of these challenges involves the political will to continue an aggressive spaceflight program. At a fundamental level, it is the most critical challenge facing those who wish to venture into space in this century. It is even more significant than the technological issues that also present serious challenges. Because most space activities have been sponsored by governments, governmental decision makers have to agree that the expenditure of funds for exploration is in the best interest of the state. Without that political will, discovery and exploration cannot take place.

At the same time, an expansive program of space exploration has not often been consistent with many of the elements of political reality in the United States since the 1960s. Numerous questions abound concerning the need for aggressive exploration of the solar system and the desirability of colonization on other worlds. A vision of aggressive space exploration, wrote political scientist Dwayne A. Day,

> implies that a long range human space plan is necessary for the nation without justifying that belief. Political decision-makers have rarely agreed with the view that a long range plan for the human exploration of space is as necessary as—say—a long range plan for attacking poverty or developing a strategic deterrent. Space is not viewed by many politicians as a "problem" but as at best an opportunity and at worst a luxury. (Day 1994)

Most importantly, the high cost of conducting space exploration comes quickly into any discussion of the endeavor.

Of course, there are visions of spaceflight less ambitious than some that have been offered that might be more easily justified within the democratic process of the United States. Aimed at incremental advances, these include robotic planetary exploration and even limited human space activities. Most of what is presently under way under the umbrella of NASA in the United States and the other space agencies of the world fall into this category. Increasing NASA's share of the federal budget, currently less than one penny of every dollar spent by the government, would go far toward expanding opportunities for spaceflight, but doing so will require the closer linkage of spaceflight activities to broader national priorities.

The second challenge is the task of developing multifaceted, inexpensive, safe, reliable, and flexible access to space. Pioneers of spaceflight believed that humans could make space travel safe and inexpensive. Despite years of effort, however, the dream of cheap and easy space access has not been attained. Costs remain particularly high. We might continue to use rocket propulsion and, with new materials and clever engineering, make a launcher that is not only recoverable but also robust. We might also develop air-breathing launchers and thus employ the potentially large mass fractions that air breathing theoretically promises to build a more capable vehicle to reach space.

Then there are other options still. Most launch vehicle efforts throughout the history of the space age, unfortunately, have committed a fair measure of self-deception and wishful thinking. A large ambitious program is created and hyped and then fails as a result of unrealistic management, especially with regard to technical risk. These typically have blurred the line, which should be bright, between revolutionary, high-risk, high-payoff R&D efforts and low-risk, marginal payoff evolutionary efforts to improve operational systems. Efforts to break the bonds of this deception may well lead in remarkable new directions in future launcher development efforts. Only once that happens will humanity be able to engage in extensive human activities in space (Lambright 2002).

The third challenge revolves around the development of smart robots in the twenty-first century to explore the solar system. Humans may well travel throughout the solar system in ways unimagined by the first pioneers: that is, by not physically going at all. Using the power of remote sensing, humans could establish a virtual presence on all the planets and their moons through which those of us on Earth could experience exploration without leaving the comfort of our homes. Humans might not progress naturally toward the colonization of Mars in this scenario, but would participate fully in an extensive exploration by robotic machinery. Because of this, the human dimension of spaceflight could take on a less critical aspect than envisioned by most spaceflight advocates.

One of the unique surprises of the space age that opened with Sputnik in 1957 has been the rapid advance in electronics and robotics that made possible large-scale spaceflight technology without humans not only practicable but also desirable. This has led to a central debate in the field over the role of humans in spaceflight. Perhaps more can be accomplished without human presence. Clearly, if scientific understanding or space-based applications or military purposes are driving spaceflight as a whole, then humans flying aboard spacecraft have little appeal. Their presence makes the effort much more expensive because once a person is placed aboard a spacecraft, the primary purpose of that spacecraft is no longer a mission other than bringing the person home safely. But if the goal is human colonization of the solar system, then there are important reasons to foster human spaceflight technology.

This debate has raged for decades without resolution. It is reaching crescendo proportions in the first decade of the twenty-first century as the ISS came online and discussions of future efforts beyond the station emerge in public policy. Scientist Paul Spudis observed, “Judicious use of robots and unmanned spacecraft can reduce the risk and increase the effectiveness of planetary exploration. But robots will never be replacements for people. Some scientists believe that artificial intelligence software may enhance the capabilities of unmanned probes, but so far those capabilities fall far short of what is required for even the most rudimentary forms of field study.” Spudis finds that both will be necessary (Spudis 1999).

The fourth challenge concerns protecting this planet and this species. During the twenty-first century, earthlings will face three great environmental challenges: overpopulation, resource depletion (especially fossil fuels), and environmental degradation. Without space-based resources – especially remote sensing satellites that monitor Earth – humans will not be able to control these trends.

Humans can use space as a place from which to monitor the health of Earth, maximize natural resources, and spot polluters. By joining space with activities on the ground, humans have a fighting chance to protect the environment in which they live. Using space to protect Earth will be as important to twenty-first century history as Moon landings were to the twentieth. At the same time, humans will confront the consequences of environmental degradation *in* space. Orbital debris, derelict spacecraft, and satellites reentering the atmosphere have already created hazards around

Earth. Proposals to strip mine the Moon and asteroids make many people blanch; how dare humanity, having fouled the Earth, destroy the pristine quality of extra-terrestrial bodies? The environmental movement will move into space (Milne 2002).

A final challenge will be the sustained human exploration and development of space. The creation of a permanently occupied space station is presently under way. The United States and the former Soviet Union have joined to make a reality the long-held vision of a space station in Earth orbit. This relationship, along with the critical partnership of other nations, made the ISS a reality in 2000 when the first crew set up residence aboard the craft. With this accomplishment, the space-faring nations of the world intend that no future generation will ever know a time when there is not some human presence in space. Once fully functioning in space, the station should energize the development of other private laboratories. The high-technology tenants of this orbital "research park" would take advantage of the unique features of microgravity. This permits research not possible on Earth in such areas as materials science, fluid physics, combustion science, and biotechnology.

Using the space station as a base camp, humanity may sometime be able to return to the Moon and establish a permanent human presence there. It is no longer hard to get there. All of the technology is available to land and return. Such an endeavor requires only a modest investment, and the results may well be astounding. Why return to the Moon? This is a critical question, especially because humans have already "been there, done that." There are six compelling reasons:

- It is only 3 days travel time from Earth, as opposed to the distance to Mars of nearly a year's travel time, allowing greater safety for those involved.
- It offers an ideal test bed for technologies and systems required for more extensive space exploration.
- It provides an excellent base for astronomy, geology, and other sciences, enabling the creation of critical building blocks in the knowledge necessary to go farther.
- It extends the knowledge gained with the space station in peaceful international cooperation in space and fosters stimulation of high-technology capabilities for all nations involved.
- It furthers development of low-cost energy and other technologies that will have use not only on the Moon but also on Earth.
- It provides a base for planetary defenses that could be used to destroy near-Earth asteroids and other threats to Earth.

From the Moon humans might undertake a mission to Mars, but the task is awesome. There is nothing magical about it, and a national mobilization to do so could be successful. But a human Mars landing would require a decision to accept enormous risk for a bold effort and to expend considerable funds in its accomplishment for a long period. Consistently, only about 40 % of Americans polled have supported human missions to Mars. In that climate there is little political justification to support an effort to go to that planet.

Using Apollo as a model – addressed as it was to a very specific political crisis relating to US/Soviet competition – anyone seeking a decision to mount a human expedition to Mars must ask a critical question. What political, military, social, economic, cultural challenge, scenario, or emergency can they envision to which the best response would be a national commitment on the part of the president and other elected officials to send humans to Mars? In addition, with significantly more failures than successes, and half of the eight probes of the 1990s ending in failure, any mission to Mars is at least an order of magnitude greater in complexity, risk, and cost than returning to the Moon. Absent a major surprise that would change the space policy and political landscapes, I doubt we will land on Mars before the latter twenty-first century.

Conclusion

Since the dawn of the space age, humanity has developed and used effectively the capability to move outward. In the process much has been accomplished, some tragedies have occurred, and several challenges remain. Who knows what transforming discoveries will be made in the first part of the twenty-first century that will alter the course of the future? Only one feature of spaceflight is inevitable. The unexpected will occur. Space is full of achievements, disappointments, and surprises. By going into space, humans learn what they do not know.

Only through a convergence of ideas, goals, opportunities, and challenges might humanity reach beyond its earthbound place and become citizens of the galaxy. That is a destiny encompassing the best humanity has to offer. It is hard to escape the conclusion, stated so well at the beginning the Star Trek television series of the 1960s and since, space really is the final frontier and it really does call all to a higher purpose. If humanity is not up to this challenge, if we cannot travel to the stars, then human history will most assuredly come to an end. The example of spaceflight suggests that humanity really can solve its problems. At the end of the Apollo program, many people began to ask the question, "If we can put a man on the Moon, why can't we. . .?" It served as shorthand for the observation that anything really is possible. That sense of perspective speaks volumes about the difficult challenges to human progress more generally. It signals the possibility of a hopeful future.

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Sustainable Global Food Supply

Norman R. Scott, Hongda Chen, and Robin Schoen

Contents

Abstract

There is no area of human activity more basic to society than a sustainable agricultural, food, and natural resources system. An existing agricultural production system which has provided an abundant, affordable, and safe food supply and many industrial and consumer products face the daunting challenge to meet the needs of a growing world population to approximately 9–10 billion people in 2050 with the need to provide about 60–70 % more food than now

N.R. Scott (✉)
Biological and Environmental Engineering, Cornell University, Ithaca, NY, USA
e-mail: nrs5@cornell.edu

H. Chen
NIFA/USDA, Washington, DC, USA

R. Schoen
Board on Agriculture and Natural Resources, NRC, Washington, DC, USA

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being produced. However, it is more than just agricultural productivity because the system must function within the space of climate change; minimum (zero) negative impacts on the environment; reduced (zero) greenhouse gas emissions (GHG); reduced water usage; concern for availability and cost of energy; increased application of conservation tillage; worldwide adoption of biotechnology; increased organic food production; major adoption of information technologies at all phases of the agricultural, food, and natural resources system; and significant advancements in machine innovations. Specifically, there is a need to transcend the debate between the vocal constituencies rooted in ideological solutions and rather invoke and encourage a broad recognition that many different approaches are needed to coexist to meet this huge challenge. Thus, there is no system more in need of and more likely to benefit from a comprehensive application of convergence technologies embodied in nanotechnology, biotechnology, information sciences, and cognitive sciences.

Introduction

Can the world's population be fed in 2050 and beyond? Can it be done sustainably? Feeding the world is one of society's biggest issues and is considered to be an increasingly major challenge in light of the projection of a world population reaching between 9 and 10 billion persons by 2050 (United Nations 2014). Not only can enough food be produced to meet this need, but can it be done without destroying our planet? Rhodes (2012) in *Earth: A Tenant's Manual* writes, "For all of our freedom, versatility, and creativity, we have only one Earth, and its carrying capacity is finite. And we may be about to test that capacity to support a growing human population at a subsistence level that we would regard as adequate. This will involve a real time experiment and its outcome may not be benign."

Others have issued stark warnings about an adequate food supply, most notably going back to Thomas Malthus over 200 years ago and reinforced by Paul R. Ehrlich in 1968 in *The Population Bomb* and a following pessimistic assertion about scarcity (Ehrlich 1974) in *The End of Affluence*. The Paddock brothers (1967) suggested a dire triage system in their book, *Famine 1975! America's Decision: Who Will Survive?* because they theorized that an exponential population growth, an insufficient agricultural production, and political ineptness would not meet world food needs, and therefore, they suggested that food aid needed to be categorized according to (1) "can't-be-saved nations, (2) those who would stagger through without aid, and (3) those who could be saved with aid". Fortunately, these old forecasts have not come true, at least not yet.

However, Malthus's assertion is not inherently incorrect because food production is bounded by natural resources of soil, water, and crop productivity underpinned by science, and the carrying capacity of the earth is limited. The earth has an approximate land area of 150 million square kilometers (about 16 times the land area of the USA), and this global land area (Rhodes 2012) can be categorized as:

Arable land area	10 %
Permanent crops	1 %
Forest and woodlands	31 %
Pasture	24 %
Unusable	34 %

In addition, almost all of the land area available for sizable and economically feasible food production is in use which creates the challenge of meeting increasing food production, not by adding new land but by increasing food production from the existing area by creating much higher yields. Making the challenge even more difficult is how and specifically what technologies will be acceptable to accomplish the large increases in yields? How can this be done in the face of the huge challenges from advancing global climate change; scarcity of water in many areas; environmental concerns for pollution due to applications of fertilizers, pesticides, and herbicides; increasing cost of energy; and changing diets with an increased worldwide consumption of meat which has tripled since 1961 with an accompanying use of as much as 34 % of grain production?

Another theme frequently raised is that instead of focusing on agricultural productivity, we should address access to food. Gordon Conway (2012) in his book, *One Billion Hungry: Can We Feed the World?* writes, “If we were to add up all of the world’s production of food and then divide it equally among the world’s population, each man, woman and child would receive a daily average of over 2,800 cal – enough for a healthy lifestyle.” On a positive note, the rate of population growth began to decline in the 1980s and may level off at about nine billion according to the United Nations (2014) as a result of increased prosperity and education, particularly for women and girls. Interestingly, Ausubel et al. (2012) write that

> Rather than rampant exploitation, the global use of cropland to supply a growing population in the last half-century shows restraint and innovation and suggests humanity now passes peak use of land in arable and permanent crops. As affluence rises, people do consume more calories and more animal products. Nevertheless their appetites grow more slowly than their affluence and eventually level off. . . ..Leveling population, saturating tastes, and improving efficiencies promise to spare land from cultivation. By 2060 they might allow to revert to Nature nearly 150 million hectares.

Given the expectation of 9–10 billion people, food security is making headlines around the world and is an issue now! Major media coverage in the USA alone suggests that a “tipping point” may have or soon will be reached. Featured stories in Time Magazine (August 2009); *The Real Cost of Cheap Food*, Time (September 2012); *What to Eat Now*, Scientific American (September 2013); A *Special Food Issue*, The National Geographic (May 2014); *The New Food Revolution* and The National Geographic (monthly issues from June to December 2014) have focused on food and the challenge of feeding the global population in the future.

Food security, food safety, and food production are no longer on the back burner. As with water, air, and energy, it is incumbent on us to meet these challenges in a sustainable way. Webber (2015) articulates that our future rides on our ability to integrate this nexus of food, water, and energy.

Thus, can we produce enough food to support healthy people without destroying our biosphere? Smil (2000) articulates three principles to answer this question: (1) an understanding of the complexities of the realities of the food system, (2) a consideration of fundamentals of crops and animal systems to food production, and (3) a need to concentrate on efficiencies of the food chain from production to consumption. Failure to recognize these realities can lead one to despair or for another, a misplaced optimism.

"Toward" a Sustainable Global Food Supply

While agricultural productivity has been a consistent and important emphasis over the past several decades, there has been a significantly increased emphasis on assessment of impacts of agriculture on the environment; reduced greenhouse gas emissions (GHG); reduced water usage; increased application of conservation tillage; worldwide adoption of biotechnology; major adoption of information technologies at all phases of the agricultural production, transportation, and delivery systems; and significant advancements in machine innovations which have led to automation and precision farming.

Many agricultural practices have unintended consequences relative to water quality, greenhouse gas emissions (GHG), degraded soil quality, biodiversity, and animal welfare. Changes in agricultural production systems and usage of natural resources have raised public concerns about the ecological sustainability of agriculture and well-being of rural communities, farm families, farm laborers, and animals. During the past decade, the concept of sustainability of agriculture has been much discussed and was addressed in the NRC report (2010) wherein four goals are used to define sustainable agriculture:

Satisfy human food, feed, and fiber needs and contribute to biofuel needs
Enhance environmental quality and the resource base
Sustain the economic viability of agriculture
Enhance the quality of life for farmers, farm workers, and society as a whole

However, sustainability is best viewed, not as a particular end point, but rather as a process moving agriculture, food, and natural resources toward greater sustainability on these goals. The authors suggest a working description of sustainable development as a "process of change in which the direction of investment, the orientation of technology, the allocation of resources, the development and functioning of institutions and advancement of human and community well-being meets present needs and aspirations without compromising the ability of future generations to meet their own needs and aspirations" (adapted and modified from Roy

Weston 1992). While this description may not satisfy everyone, it suggests an imperative for action by which the goals for development of sustainable agriculture, food, and natural resources can be measured. Moreover, in addition to implications for resources, it embodies the attributes of environmental, economic, and social recognition and responsibility, now and into the future. Clearly not all societies see or will see sustainability the same way, but this description and the goals for a sustainable agriculture, food, and natural resources provide a sound basis for assessing future approaches to advancing sustainability.

Advances in the Agriculture and Food Systems to 2014

Modern agriculture has had an impressive history of increasing productivity that has led to abundant, safe, and affordable food, fiber, and recently biofuels. Farmers today are meeting both expanded domestic and international markets on the same acreage as a century ago as a result of technological innovations, economies of scale, consolidation of food processing and distribution, and advanced retailing.

It is important to recognize that the broad agriculture and food system is huge. For example, the total amount spent for all food consumed in the USA was $1.4 trillion dollars in 2013. The ERS/USDA (Economic Research Service/US Department of Agriculture) indicates that spending on food away from home was 49.6 % of the $1.18 trillion in total food expenditures in 2013 and spending for food at home was 50.4 %. The result is that US residents spent on average about 9.8 % of their annual consumer expenditures on food in 2013 compared to 21 % in 1950, and this is less than any of the other 83 countries which the USDA tracks (USDA 2014). By contrast, in Pakistan the average person spends about half his/her annual income on food.

During the past decade, US agriculture has continued to become increasingly dependent on large-scale, high input farms that specialize in a few crops and concentrated animal production practices; for example, 2 % of US farms are responsible for 59 % of US farm products (NRC 2010). By contrast, small- and medium-sized farms represent more than 90 % of the total farm numbers and manage about half of US farmland.

At this time, hunger and malnutrition are the number one risk to health worldwide, not disease. Thus, to feed the one billion chronically hungry and to get to a food-secure world by 2050, it is necessary to address the issue of poverty. If one looks at this problem as a pyramid (Clay 2010), those wealthy at the “top” (two billion) will be able to afford anything, those at the “bottom” (two billion) the poorest will be greatly challenged to meet daily needs, while for the five billion falling in the “middle,” it is likely to be a matter of where calories come from such as “eating up the food chain,” meaning more animal protein, vegetables, fruits, and processed foods. Bittman (2014) offers a unique perspective suggesting that there are no hungry people with money; there is not a shortage of food nor a distribution problem but rather a need to end poverty.

Thus, it is abundantly clear that the agriculture and food system is exceedingly complex and is a perfect case for the implementation of an integrated application of converging technologies – nanotechnology, biotechnology, information science, and cognitive science. However, first, we offer a brief review of key technologies that have driven the modern success of US agriculture and food system into the twenty-first century.

Biotechnology crops in 2014 (ISAAA 2015) are utilized in 28 countries reaching 181.5 million hectares at an annual growth rate of about 3 %. The global hectares in biotech crops have grown from 1.7 million hectares in 1996 with numerous stated benefits of:

- Contributing to food, feed, and fiber security, sustainability, and climate change. Biotech contributes by creating more affordable food and by increasing productivity and economic benefits sustainably at the farm level. Economic gains at the farm level can be generated through major crop improvements reducing production costs, lesser pesticides, less labor, and increased yield. In 2014, a record number of 18 million farmers grew biotech crops, and over 90 % were risk-averse small, poor farmers in developing countries.
- Conserving biodiversity through land-saving technologies. Higher productivity on the current 1.5 billion hectares of arable land can preclude deforestation and protect biodiversity. For example, as much as 13 million hectares of tropical forests are lost annually in developing countries. It is projected that without impact of biotech crops, 123 million hectares would have had to have been used.
- Contributing to alleviation of poverty and hunger. For example, biotech has made significant contribution to incomes of approximately 16.5 million small, resource-poor farmers in developing countries in 2014, primarily in cotton, maize, and rice.
- Reducing agriculture's environmental footprint by reduction in pesticides, saving on fossil fuels, decreasing CO_2 emissions, and increasing efficiency of water usage.

Despite this rapid adoption of genetically modified crops, there exists a large public controversy surrounding GMOs in terms of risks and benefits as well as the impact on the structure of agriculture and specifically concerns about who benefits (large corporations) or who loses (small and poor farmers). A major meta-analysis study of the impacts of GMO crops by Klümper and Qaim (2014) of 147 original studies reports, "On average, GM technology adoption has reduced chemical pesticide use by 37 %, increased crop yields by 27 %, and increased farmer profits by 68 %. Yield gains and pesticide reduction are larger for insect-resistant crops than for herbicide-tolerant crops. Yields and profit gains are higher in developing countries than in developed countries."

Precision agriculture, or precision farming, is a systems approach for site-specific management of crop and animal production systems. The foundation of precision farming rests on geospatial data techniques for improving the management of inputs and documenting production outputs (Reid 2011). As the size of farm implements and machines increased, farmers are able to manage larger land areas. A key technology enabler for precision farming resulted from the public availability of Global Navigation Satellite System (GNSS), a technology that emerged in the mid-1990s. GNSS provided meter, and later decimeter, accuracy for mapping yields and moisture content. A number of information and communications technology (ICT) approaches were enabled by precision agriculture, but generally, its success is attributable to the design of machinery with the capacity for variable-rate applications. Examples include precision planters, sprayers, fertilizer applicators, and tillage instruments. In general, advances in machine system automation have increased productivity, increased convenience, and reduced skilled labor requirements for complex tasks. Moreover, benefits have been achieved in an economical way and increased overall TFP (total productivity factor) – the output per unit of total resources used in production.

Conservation tillage systems can have both environmental and economic benefits. Conservation tillage leaves a minimum of 30 % of crop residue on the soil surface or at least 1,100 kg/ha of small grain residue on the surface during the critical soil erosion period (NRCS 2012). The most significant advantage is significantly less soil erosion due to wind and water. Conservation tillage systems also benefit farmers by reducing fuel consumption and soil compaction. By reducing the number of times the farmer travels over the field, farmers realize significant savings in fuel and labor. The adoption of less intensive tillage operations, if adopted by many farms, can sequester substantial carbon by allowing the soil to retain more organic matter which will contribute to the reduction and control of greenhouse gas emissions. It is estimated that 35.5 % of US cropland (~35 million hectares planted to the eight major crops had no tillage ["no till"]) operations in 2009 according to an ERS report (Horowitz et al. 2010). These crops – corn, barley, cotton, oats, sorghum, soybeans, and wheat – make up 94 % of the total planted US acreage. No-till practices have increased for corn, cotton, soybeans, and rice at a median rate of roughly 1.5 % per year. However, in some systems there has been an increased reliance on herbicides for weed control. Data on yields are somewhat mixed with many studies showing the same yields, others some reduction and others an increase.

Livestock systems – Positive environmental effects have been realized and opportunities developed for considerable gains in livestock systems during the past decade. In the USA, advances in animal nutrition, management systems, and genetics have resulted in a large increase in annual milk yield of dairy cattle. Capper et al. (2009) report a fourfold increase in milk yield in 2007 compared to that of 1944 with 84.3 billion kg in 2007 compared to 53 billion kg in 1944 with 64 % fewer cows. Carbon emissions and total emissions per unit of milk were reduced by 66 % and 41 %, respectively. Similar results for emissions per unit of product have been seen in the beef cattle industry and in poultry production. The Food and Agriculture Organization (FAO) confirms, on a worldwide level, that as livestock production intensity increases, the carbon footprint decreases substantially on the basis of product output per input.

The livestock sector supports almost one billion of the world's poorest persons, and it is likely to continue for quite some time (FAO 2009). Many people rely on livestock for their sustenance and livelihood. Thus, the livestock sector faces the challenges of balancing opportunities against risks and needs of different smallholders, food security, and nutrition. People relying on livestock for their livelihood are facing increasing pressures from global economic forces of growth and competition that are driving structural changes. Adding to these challenges is the human health concerns due to the potential for pandemic outbreaks of zoonotic diseases. Because livestock agriculture is increasingly recognized as important in rural development and poverty reduction, there is a need to balance policies and innovations technically and socially to meet the multiple demands of society.

Biofuels – At a time when the USA imported 52–60 % of its oil consumption (from 2005 to 2009) and transportation use accounted for about 30 % of carbon dioxide (CO_2) emissions, interest in biofuels reached a high point. The USA, as the world's largest consumer of crude oil, faced two significant problems: concern about energy security and high greenhouse emissions. Thus, the US Congress in 2007 enacted the Energy Independence and Security Act (EISA) because biofuels were seen to improve energy security as a renewable resource and to provide life cycle greenhouse benefits. A Renewable Fuel Standard (RFS) within EISA for 2008–2022 was developed as an annual mandate for biofuel consumption for conventional biofuels and advanced biofuels. In general, conventional biofuel is corn ethanol and advanced biofuels are cellulosic-derived biofuels. Controversy surrounded the use of corn for ethanol because of concerns over effects on food/feed prices, distortion of land use and increased cropland prices, as well as uncertainties about whether there were net environmental benefits. Clearly, corn farmers, primarily in the Midwest USA, were initially beneficiaries of a booming market and increased prices for their corn crop. Against this backdrop, the US Congress requested that the National Research Council (NRC) conduct an independent assessment of the economic and environmental effects in meeting the RFS. The NRC (2011) established two findings: (1) the RFS may be an ineffective policy for reducing global greenhouse gas emissions because the effect of biofuels on greenhouse gas emissions depends on how the biofuels are produced and what land-use or land-cover changes occur in the process and (2) key barriers to achieving the RFS are the high cost of producing cellulosic biofuels compared to petroleum-based fuels and uncertainties in future biofuel markets.

Processes using microorganisms, specifically bacteria, have been utilized to convert organic materials into methane and carbon dioxide. Anaerobic digestion using methanogenic bacteria in the absence of oxygen in airtight structures has been utilized for many years ranging from small home-owned digesters in China to large commercial tanks in Europe and the USA. The biogas, primarily methane (~60–70 %) and carbon dioxide (~30–40 %) with small amounts of other gases, can be used to create energy. In China, over ten million systems have been employed in rural villages for managing both animal and human wastes to provide biogas for cooking at the household level. In Europe and the USA, much larger systems have been developed to handle animal manures and food wastes by co-digestion to produce energy options such as combined heat and power (electricity and heat) and methane, after processing and compressing, for gaseous fuels for transportation vehicles. Germany has been particularly adept at creating bioenergy villages that effectively illustrate the potential for distributed energy generation at a local level from organic materials, including manure and plant-based biomaterials.

Vision to 2050

The challenges or threats of further population growth, increasing hunger, increasing water shortages, energy availability, and climate volatility can only be met by seeking an integrated systems approach where there are environmental, economic, and social benefits – sustainable solutions. Having stated the need for a holistic approach, we deviate for the moment to focus on emerging scientific platforms (Conway 2012) of nanotechnology, biotechnology, information science, and cognitive science (referred to as NBIC technologies by the National Science Foundation [NSF]) to meet the challenges of a sustainable global food supply (Fig. 1).

A series of reports have suggested some possible solutions to address food security and environmental challenges (IAASTD 2009; Royal Society 2009; Godfray et al. 2010; Foley et al. 2011; Conway 2012).

- Stop expanding agriculture – This means primarily stopping the clearing of tropical forests for agriculture. Potential loss of agricultural production perceived to be small can be compensated by reducing losses from productive cropland.
- Closing yield gaps – Foley et al. (2011) suggest that closing yield gaps sustainably will significantly increase global food supplies. For the 16 most important

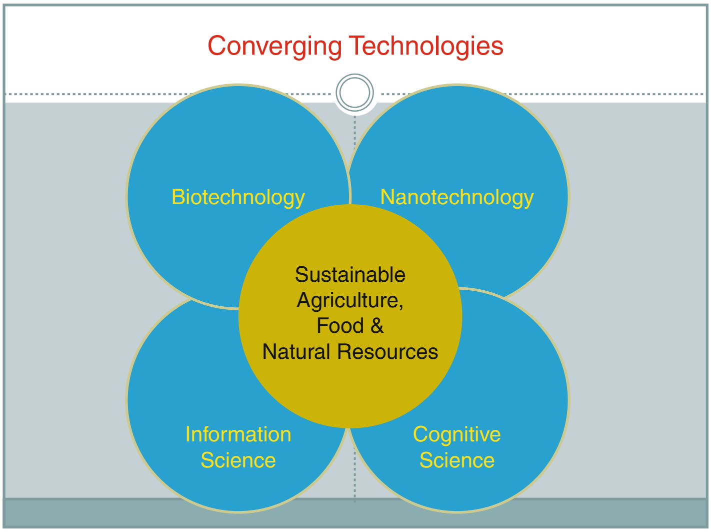

Fig. 1 Converging technologies

crops, if yields were increased to 75 % of genetic potential, global production could be increased by 28 % (by 2.6 × 10^{15} kcal).

- Increase efficiency – More sustainable pathways can be employed for intensification that will increase productivity while, at the same time, reducing water, nutrient, and chemicals.
- Close diet gaps – The current agricultural system has many economic and social benefits and the existing variety of products is not likely to change completely. However, small changes in diet and not using food crops for biofuels can improve food security and reduce environmental effects.
- Reducing food wastes – A surprising amount of food which is produced is not consumed (FAO 2011). This study suggests that as much as one-half of all food grown is lost. In developing countries, as much as 40 % is lost after harvest, and while industrialized countries sustain lower producer losses, it is estimated that losses as high as 40 % occur at the retail and consumer level.

Nanoscale Science and Engineering for Agriculture and Food Systems

Nanoscale science and engineering has the potential to revolutionize the agriculture and food system, comparable to or exceeding the impact of farm mechanization and the green revolution. It can play an important role in creating a safer and more productive agriculture and food system. The food supply chain can and will be affected by the utilization of nanotechnology at each point in the system along the supply chain from production through domestic consumption (Scott and Chen 2012, 2013).

Food Quality and Safety

- Detection of presence of residues, trace chemicals, viruses, antibiotics, pathogens, toxins
- An integrated, rapid DNA sequencing process to identify genetic variation and GMO's
- Tracking process for integrity of food during production, transportation, and storage
- A delivery approach to reduce calories of food while retaining flavor, lowered fat, reduced salt, less sugar, and improved texture
- A system to enhance bioavailability and delivery of nutraceuticals, nutrigenomics, increased vitamins, and nutrient content of foods
- Introduction of "personalized nutrition" to meet very specific individualized health needs
- Major improvements in food manufacturing processes
- Widespread advances in food packaging and food contact materials for quality assessment and enhanced shelf life (eliminate the need for refrigerated storage), including edible packaging

- Processes to substantially reduce crop and postharvest losses from production to consumer

Animal Health Monitoring and Management

- Applications of developmental biology techniques to detect onset of estrus to enhance and advance breeding
- Detection processes to sense presence of residues, antibiotics, pathogens, toxins, etc.
- Processes for early, predisease detection, rapid diagnosis, and prevention of diseases
- An integrated health monitoring process including therapeutic intervention as necessary
- A process for identity tracking of animals from birth to the consumer's plate
- New techniques such as nutrigenomics that will influence or control genetic expression
- Major nutritional platforms which will alter food products (milk and meat) with healthful human benefits
- Approaches to lessen greenhouse gas emissions (GHG) from livestock
- Application to manure management processes to reduce GHG and create renewable energy for distributed generation of electricity and heat

Plant Systems

- Development of "smart field systems" to detect, locate, report, and direct application of water, only as needed and in necessary quantity
- Development of "smart field systems"(possibly electronic "dust" particles) for early detection and monitoring of diseases for intervention strategies
- Applications of precision and controlled release of fertilizers and pesticides
- Utilization of bioselective surfaces for early detection of pests and pathogens
- Applications of a laboratory-on-a-chip proteomics technology for microbial biocontrol agents
- Development of "new" plant varieties with characteristics of drought resistance, salt tolerance, tolerance to excess moisture, enhanced photosynthesis activity, and capture nitrogen from atmosphere
- Plants (nonfood crops) for bioenergy (e.g., photosystems)
- Use of specialized (nonfood) plants, including trees, for nanocellulose and biofuels

Environmental Management

- Utilization of nanophase soil additives (fertilizers, pesticides, and soil conditioners)
- Nanoparticles to transport and deliver bioavailability of nutrients to plants
- Developed understanding of soils as a complex nanocomposite
- Comprehensive management of land, water, and air pollution (detection and remediation processes) – e.g., magnetic nanoparticles to collect pathogens
- An ability to track hydraulic and nutrient flows in the landscape

- Carbon nanotubes as filters to clean water at point of use and at larger scales
- Nanoparticles for desalination systems

Biotechnology

For most agriculture and food operations, the primary way to improve labor productivity is by increasing yields to better approach genetic potential for both crops and animals. Particularly in plant breeding, conventional breeding has had practical limitations of being largely random plant crosses in an attempt to create desirable characteristics, and it is a slow process. However, there are advanced breeding methods that do not involve genetic modified organisms (GMOs) that are being developed that utilize advanced computer analyses and other high-tech techniques. As stated in a preceding section of this chapter, biotechnology has been implemented in 28 countries over a 20-year period with arguably excellent results. Interestingly, the meta-analysis study (Klümper and Qaim 2014) reports higher yield and profits in developing countries than in developed countries. Nevertheless, a significant minority expresses strong concerns about the health effects on the environment (because of claims on increased use of pesticides and herbicides) and possible human health effects as well as demand for the labeling of products that contain GMOs. To date, there has been a lesser effort in inserting genes for yield increases than genetic modification for the control of weeds and pests. Rather, improvement in yields has been accomplished by conventional breeding applied to lines containing GM genes (Conway 2012).

In the USA, persons have been consuming GM foods for more than 15 years without obvious health effects. Lemaux (2009) has reported, based on an extensive review of potential health hazards, that GMO crops and products are "at least as safe in terms of food safety as those produced by conventional methods." Thus, if we are to increase yields and create new crop varieties and improved animal breeds, we need to utilize the science of biotechnology as well as organic practices to advance both large commercial operations and smallholder farmers. The great potential for biotechnology to enhance photosynthesis, nitrogen fixation, nutrient management, and water usage and yield improvement should not be ignored and left underutilized.

Information Science

ICT (information and communications technologies) can be broadly viewed as any communication device or application, encompassing radio, television, cellular phones, computers and network hardware and software, satellite systems as well as the various services and applications associated with them, such as videoconferencing and distance learning. Agriculture and food systems have increasingly embraced ICT at all levels from large farmers to poorest farmers in developing countries through a comprehensive integration of sensors, satellites, and cell phones. Farmers are gaining intelligence and experience to operate within the unprecedented challenges of extreme climate, water limitations, energy availability, price volatility, resource availability, natural disasters, and social issues. As one farmer (a family farm, although large through expansion to over 7,000 ha) said, “I’m hooked on a drug of information and productivity. We’ve got sensors on the combine, GPS data from satellites, cellar modems on self-driving tractors and apps for irrigation on iPhones” (NY Times 2014). Although poor farmers in Asia and Africa are not engaged at this level of ICT, they are increasingly utilizing the cell phone to obtain critical information on expenses of agriculture inputs and prices, connect to markets, and participate in newly developing mobile network operators worldwide through digital financing.

In the USA, from the advances in precision agriculture comes real-time data about moisture, yields, net nitrogen, net yields per hectare, and other information stored on electronic tablets which is sent, by wireless modems, to computer servers (cloud computing) for later analysis. Farmers will use the data from the last season’s information to plan for the next season’s cropping system. Thus, can “big data” be worked to help agriculture meet the numerous challenges? Not only have many farmers invested in this new technology, but numerous businesses from Microsoft to Amazon to Nestle to small software startups are joining an increasingly crowded field to help farmers use data sets in innovative ways for dealing with weather data, scheduling planting and harvests, conserve fertilizer, water efficiency, manage irrigation, nitrogen use efficiency, and global information such as crop production and assessments.

Two technical innovations that are likely to gain rapid and widespread adoption in agriculture, food, and natural resources are robotics and drones (unmanned aerial vehicles). Robotic systems encompassing integration of sensors, imaging, and analytics will play an important role in the future of precision agriculture of animals and plants. Some existing and future applications of robotics are:

- Milking systems (both small and large herds)
- Animal feeding systems based on productivity data
- Plant systems for picking fruits and vegetables
- Application of nitrogen more accurately during growth
- Application of water at specifically water stressed plants
- Vehicle to identify and eliminate weeds
- In food processing plants for sorting, sizing, and packaging

While drones (unmanned aerial vehicles) have been used for years in military missions and intelligence gathering, the use of drones in agriculture (commonly referred to as small unmanned aircraft systems, sUAS) is on the verge of exploding. Some estimates suggest it is likely that there will be ten times more sUAS applications in agriculture than in other civilian area and that 80 % of the economic impacts will be in agriculture. Some farmers/managers have or will use sUAS to:

- Map crops to forecast yields
- Identify water stressed areas
- Identify flooded areas
- Locate weeds to implement management
- Identify hail damage
- Spot onset of plant diseases or pests and deliver intervention schemes
- Implement surveys for agriculture (animals and plants) and forestry
- Deliver fertilizer, possibly water at points of high need
- In absence of bees, supplement pollination process
- Monitor crop emergence
- Monitor animals in inaccessible regions in natural environment
- Deliver contraceptives to manage wild horse and burro population

On the positive side, the cost of small sUAS is relatively small in the range of $1,000–2,000 plus auxiliary sensors, cameras, and actuators. On the negative side, the Federal Aviation Administration (FAA) in the USA has failed to pass an act permitting the use of UAV/sUAS in agriculture, although there is an expectation that an act will be passed relatively soon.

It is clear that the impact of information science is a significant development for agriculture and food systems in both the developed and developing world, the difference being only in scope and size.

Cognitive Science

Convergence in knowledge, technology, and society is suggested as a driver for change, and this chapter has sought to demonstrate that convergence of separate disciplines characterized by nanotechnology (atoms), biotechnology (genes), information technology (bits), and cognitive science (neurons) can change the face of agriculture, food, and natural resource systems. Without question, the element least addressed across the concept of converging technologies in the agriculture and food systems is the cognitive sciences. Cognitive science is defined here "as the interdisciplinary scientific study of the mind and its processes. It includes research on intelligence and behavior, especially focusing on how information is represented, processed, and transformed (in faculties such as perception, language, memory, reasoning, and emotion) within nervous systems (human or other animal) and machines (e.g., computers). Cognitive science consists of multiple research disciplines, including psychology, artificial intelligence, philosophy, neuroscience, linguistics, anthropology, sociology, and education."

Critical to the vision for the agriculture, food, and natural resources system is public acceptance of the converging technologies if they are to be adopted for the benefit of human wellness, happiness, and development. However, by and large, the technical transformations created by nanotechnology, biotechnology, and information science have not included empowerment of persons and groups by expansion of human knowledge and cognition. Rather, ethical and social issues have been largely ignored, leading to a uniformed public at best and an anti-technology mindset at the worst. A true convergence requires that the agriculture, food, and natural resource system begin to include cognitive science as an integral element. Persons outside these technologies often have a quite different belief and value system. While both groups share a concern about effects of these technologies on the environment, health, biodiversity, and food safety and quality, they often diverge in their concerns about:

- The need to label foods if they contain GMOs or nanoparticles
- Questions of ownership and control issues
- Who benefits? Are the poor more vulnerable?
- Consolidation of corporate power and marginalization of farmers' rights
- Lack of regulations? Standards?
- Lack of public engagement or if there is an effort it is seen as a "reactive engagement" rather than an inclusive and participatory one

Thus, if convergence is to embrace a societal component and lead to solutions of a growing world population, increased agricultural productivity, reduced greenhouse gas emissions, and reduced water usage and availability of energy, all in the face of climate change and the complexities of a hugely complex global agriculture and food system, it is crucial that the cognitive sciences be included more actively in moving forward.

Some Guesses for 2050 and Going Forward

In concluding this chapter, the authors are compelled to reflect on emerging areas that may well play an important role in the agriculture, food, and natural resources sector during the twenty-first century going forward:

- *Edible insects for animal feed as well as human food* – The potential role of insects for food and feed is reviewed in a comprehensive report by the FAO (2013).
- *Aquaculture* – Given the diminishing source of seafood from the oceans, it is anticipated that aquaculture, both farm raised (cages in a natural environment and recirculating indoor systems), will grow to meet increasing demand.
- *Synthetic foods* – Although in its infancy, synthetic foods (lab-grown meat) are making headlines, if not yet commercially viable as a replacement for meat.
- *3-D printing* – A futuristic R&D effort is underway on 3-D printing of organic products such as food.
- *Food waste reduction* – The recognition that as much 30–50 % of the food produced is wasted between production and the consumer's plate has awakened scientists and engineers to solving a doable problem.

- *Vertical farming* – Although energy consumption for an indoor, vertical farm is a serious limitation, the idea of vertical farming may be a rational option in megacities of the future for fresh and locally available food.
- *Investing in women and girls* – Increasingly, there is recognition that investing in women is the most efficient and effective way to increase food production in the developing world because about 43 % of all farmers are women.
- *Agricultural investment in the developing world* – As foreign aid decreases, a changing model is developing where private sector partnerships with governments are taking shape. A mix of businesses can offer business skills training, financing, and mentoring. Ideally, the partnership provides greater resources for small farmers to carry out a successful farming enterprise and thereby achieve greater profits. However, the potential for displacement of small-scale food producers and exploitation by businesses is a real concern.
- *Autonomous farming systems* – Interesting developments are being researched to create futuristic farming technologies. Some examples are driverless tractors, machine-to-machine communications, self-propelled sprayer, electric-driven tractors, and electric-powered equipment. At first reflection, this high technology may be perceived as only affordable and applicable in "industrialized" agriculture. However, the possibility of developing electric-driven tractors and equipment is conceivable for the developing world because smaller machines can be well adapted to small land holdings. Advancement in battery technology is key together with the adaptation of solar energy.

Concluding Remarks

Returning to the basic questions, can the food system be adapted to feed the world and can it be done sustainably? There are no silver bullets to meet the many challenges to be faced in feeding the 9–10 billion persons by 2050. Specifically, there is a need to transcend the debate between the vocal constituencies rooted in ideological solutions and rather invoke and encourage a broad recognition that many different approaches are needed to coexist to meet this huge challenge. Thus, there is no system, more in need of and more likely to benefit from a comprehensive application of convergence technologies embodied in nanotechnology, biotechnology, information sciences, and cognitive sciences. Holistic thinking must be employed using a lens of sustainability to insure environmental, economic, and social benefits.

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Socio-Ecological Systems

Claudio Cioffi-Revilla

Contents

Abstract

This chapter provides a unified framework for understanding the ecological triad of coupled human, artificial, and natural systems and processes, based on convergence among the social, engineering, and natural sciences and enabled by computing technology. The framework explains the rise and future of the Anthropocene epoch and a convergence-based approach to civilization, among other phenomena, with roots in earlier paradigms, such as complex adaptive systems and coupled socio-ecological systems, which in turn extend and advance prior knowledge on general systems and cybernetics. The vision is that of a unified science of humans, artifacts, and nature, with a system-of-systems architecture and supported by universal formalisms, systems principles, and object-based computational models calibrated with real-world data.

C. Cioffi-Revilla (✉)
Computational Social Science Program, Center for Social Complexity, Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA, USA
e-mail: ccioffi@gmu.edu

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Introduction

Convergence of science and technology (S&T) synergistically integrates vast areas of human knowledge – including disciplines in the social, engineering, and natural sciences – enabling deeper understanding of complex real-world systems and countering knowledge fragmentation caused by increased specialization. Convergence is occurring in ways that are more rigorous and scientifically exciting than in any previous time in history. This is because fundamental systems and processes across empirical domains – human, artificial, and natural – are now seen as coupled within a common and coherent system-of-systems ecology. By contrast, less than a century ago, the same research communities were viewed as hopelessly belonging to "two cultures" that could not even communicate, let alone converge. Recent advances enable nucleation and expansion of convergence of S&T across the social, engineering, and natural sciences that investigate human, artificial, and natural systems, respectively, primarily through theoretical progress, empirical observation and testing, formalization, modeling, and simulation.

This chapter proposes a unified framework for understanding seamless or integrative multidisciplinary convergence among social, engineering, and natural sciences or disciplines that investigate the ecological triad of coupled human, artificial, and natural systems and processes, respectively – i.e., a way to fundamentally understand connections among all systems and S&T domains of the triad. This framework has roots in earlier interdisciplinary paradigms, such as complex adaptive systems and coupled socio-ecological systems, which in turn extend and advance prior knowledge on general systems and cybernetics (Francois 2004).

The vision is that of a unified science of humans, artifacts, and nature – corresponding to a federation of social, engineering, and natural sciences, respectively – within a system-of-systems architecture and founded on formal concepts, theoretical principles, and testable empirics, consistent with classical scientific precepts and leveraging the unprecedented power of converging fields of S&T. The focus on merging fields for understanding coupled human-artificial-natural systems draws from the intersection of the following fields:

- Complexity science
- Computational social science
- Multi-agent systems modeling and simulation technology
- Network science
- Ecosystems and Earth systems science
- Geography and geospatial information S&T
- Infrastructure systems science and engineering

These fields are current S&T convergence on coupled human-artificial-natural systems as the fields of nanotechnology, biotechnology, information technology, and cognitive science were to the NBIC (nano-bio-info-cognitive) convergence identified in the original convergence report (Roco and Bainbridge 2002). Another analogy is between agent-based models as technology platforms for S&T

convergence on coupled human-artificial-natural systems and smartphones as convergent technology platforms for human communication, social interactions, virtual networks, and knowledge management (Roco and Bainbridge 2013, p. 10).

This chapter highlights the current state and potential of five theoretical and methodological elements that undergird S&T convergence for understanding coupled human-artificial-natural systems and improving human prospects in light of multi-scale challenges such as climate change and disasters. The next section lays out a unified framework for S&T convergence on the complex ecology of coupled human-artificial-natural systems, followed by formalisms and key ideas on complexity, modeling ontology, and simulation. The last section provides a brief summary and prospectus.

Unified Framework

The real world is a triad of human, artificial, and natural systems coupled in inextricable ways, such that it is fundamentally multi-, inter-, or transdisciplinary, not fragmented into disciplines – i.e., it exists "already converged," so to speak. Science and technology necessarily consists of specialized disciplines, because that is the way in which the STEM (science, technology, engineering, and mathematics) disciplines have traditionally organized knowledge across domains. Universities consist of colleges and departments that are most often disciplinary in orientation, specialization, and faculty composition. By contrast, research centers and advanced study institutes (Connor 2003) are often multidisciplinary (e.g., focusing on health, climate change, study of civilizations, sustainability science), which is more aligned with real-world systems, empirical processes, and public policy issues.

Convergence in ecological domains such as coupled human, artificial, and natural systems requires both disciplinary and interdisciplinary expertise. The former is needed for providing deep domain-related expertise on areas such as anthropology, sociology, politics, economics, psychology, geography, infrastructure systems, computation, energy, climate, and other physical and biological phenomena in the domain of interest. The latter is needed to integrate across domains with horizontal links provided by integrative fields, such as computational social science, biophysics, systems engineering, and Earth systems science, among others used to "connect the dots."

Herbert A. Simon made a landmark contribution to convergence in ecological systems S&T with his classic book, *The Sciences of the Artificial* (1996). Founded on the categorical distinction between natural and artificial systems, Simon's paradigm views all artifacts as generated by human adaptation strategies as we attempt to cope with challenging environments, as illustrated by examples in Table 1. The entire universe of artifacts generated in global human history during the Anthropocene epoch – from the first Paleolithic tools and village dwellings to the latest spacecraft headed for the outer limits of our solar system – is explained by a common, universal set of concepts and principles: humans create artifacts as adaptations for meeting the challenges of difficult environments or goals.

Table 1 Examples of artifacts and their function as (sometimes complex) adaptive systems for managing human challenges and opportunities, based on Simon's (1996) paradigm

Artifact	Challenge being addressed	Enabling function
Automobiles	Humans can only walk at relatively slow speed for short distances	Provide transportation at superhuman speed and increased range
Computers	Humans have bounded rationality with poor memory and limited analytics	Quantum gains in memory and computational capability for problem-solving
Institutions	Collective action for solving recurring public issues is costly and ineffective	Ability to produce public collective goods with efficiency, effectiveness, and legitimacy

Every artifact or artificial system (in the case of complex artifacts) enables humans to accomplish goals in environments where our natural abilities alone are insufficient for success. The complexity of an artifact, which comes with a cost, is a function of the difficulty of the task *or complexity of the environment* (Simon's law of artifactual complexity). The high complexity of life-sustaining space artifacts, such as spacesuits, the International Space Station, and their instrumentation and support systems (including Earth-based systems), is caused by the formidable challenges of space – a totally lethal environment for humans. Human presence in space is enabled by an ecology of highly complex and sophisticated artificial systems functioning as buffer between humans and nature (space). The same is true in reference to Table 1: automobiles, computers, and institutions are common examples of artifacts that enable human activities beyond those we can naturally accomplish, each artifact being the product of enabling technologies and underlying sciences. Technology-enabling civilization originated with the Anthropocene (National Geographic 2009) and evolves from prior inventions and discoveries.

The classification of world entities according to a nominal scale of either human, artificial, or natural systems is universal and constitutes a true taxonomy in the formal sense of systematics. Simon's triad is not a mere classification, because the three categories (nominal values) are exhaustive and mutually exclusive. This strong taxonomic property adds conceptual, theoretical, and empirical power to Simon's paradigm.

Simon's paradigm is fundamental for convergence but had two deficiencies. First, it paid insufficient attention to nonutilitarian artifacts that humans build for improving quality of life, such as paintings, music, or wine, among many other cultural creations. Second, it was never formalized to create a mathematically and computationally viable and testable theory.

A profound aspect of Simon's paradigm is to have enabled the theoretically robust and empirically valid understanding of coupled human, artificial, and natural worlds – what each component of the triad consists of and how they operate and jointly interact (Cioffi 2014a, pp. 7–12, 210–220). The *human world* consists of people living on this planet (for now), perceiving experiences, thinking with their minds, making decisions under conditions of bounded rationality, and behaving and interacting with others as well as with their artifacts and natural systems.

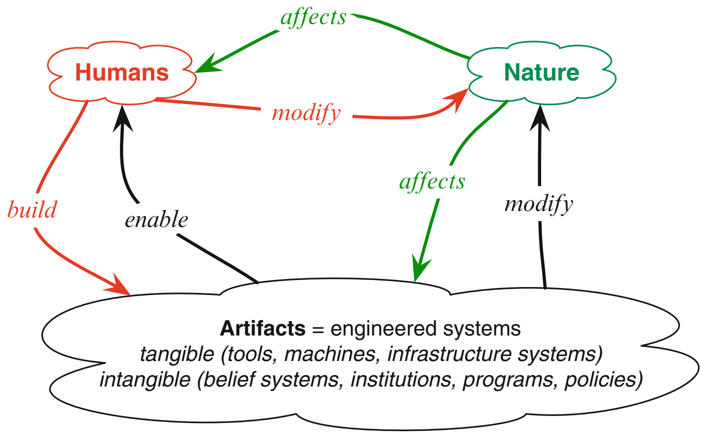

Fig. 1 Coupled human-artificial-natural system with six directional dependencies among pairs of the triad. Formally, such a system constitutes a 3-node directed multiplex graph and a system of systems

The *artificial world* consists of tangible (i.e., physical, engineered) and intangible (organizational, social) systems envisioned, designed, built, operated, maintained, rebuilt, and destroyed by humans and artifacts. The *natural world* consists of purely biophysical entities and processes.

Note that the human-artificial-natural triad for convergence is superior as a classifying ontology and theoretical explanation than the social-engineering-natural triad of traditional disciplines, because the former captures and highlights the artificial nature of institutions, whereas the latter confounds purely human phenomena (e.g., decision-making) with artificial social phenomena (norms and institutions). Some parts of a social system are human (instincts, decision-making capacity), while others are artifactual (belief systems, norms, institutions, procedures, culture, and civilizations, among others). The latter are built over the lifespan of individual persons and human collectivities as a result of interaction with other humans, artifacts, and nature (i.e., within the triad).

Contemporary terminology on convergence at the human-, societal-, and Earth-scale platforms uses the term "coupled human-artificial-natural systems" to refer to the triad illustrated in Fig. 1 (Liu et al. 2015; Ostrom 2009). Humans, artifacts, and nature interact dynamically through six fundamental directional dependencies among all pairs of Simon's triad within a unified framework encompassing three fundamental and coupled worlds.

This unified triadic framework provides a universal paradigm for theoretical analysis and a specifiable model for scientific understanding and analyzing ordinary and extreme phenomena. Climate change is a good example of a phenomenon with multiple effects on coupled human-artificial-natural systems (e.g., IPCC 2012), as summarized in Table 2. Coupled dynamics of climate change and effects on human, artificial, and natural systems are illustrated by the more specific model in Fig. 2,

Table 2 Multiple effects of climate change on natural, artificial, and human social systems

System	Effects of climate change (illustrative examples; not exhaustive)
Natural	Change in inert and biomic composition of life on all scales (molecular, organismic, population) and location, change in life cycle statistics or dynamics, evolutionary changes induced by Darwinian adaptation
Artificial	Stress on the built environment, drift or catastrophic failures, maintenance rescheduling and reengineering, reconstruction
Human	Individual, societal, economic, and political stress; potential failure of institutions; reform, reorganization or updating values and norms

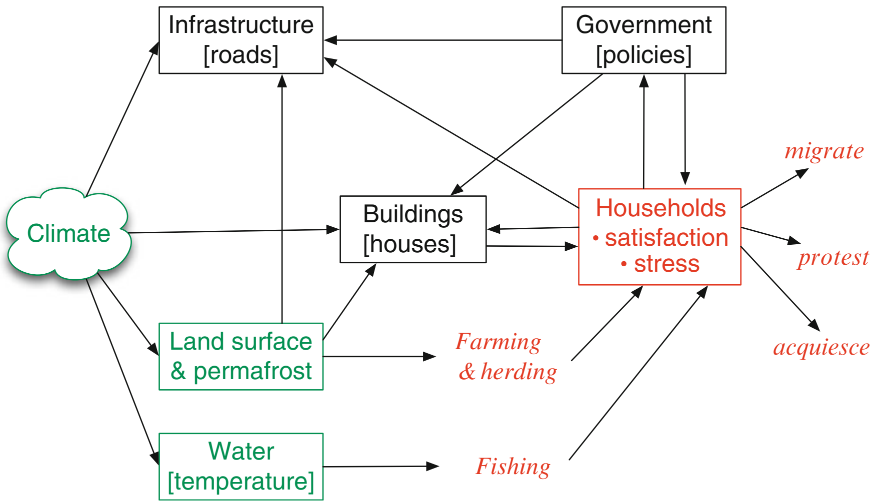

Fig. 2 Coupled human-artificial-natural system disaggregated with detail on dependencies and emergent dynamics

based on the coupled triad in Fig. 1. Figure 2 explains how human (red), artificial (black), and natural (green) systems and processes are coupled in a regional ecology – in this case a northern hemisphere region such as Canada, Scandinavia, or Siberia. As climate changes, land surface temperatures fluctuate, permafrost may thaw, and temperatures rise. These biophysical events in the natural system affect physical infrastructure, which is destabilized by decreasing load-bearing capacity, causing government agencies and institutions to produce policies. Humans are affected and households decide whether to emigrate from affected regions or seek other alternatives. Migration, protest, and acquiescence are emergent compound events – individual and collective outcomes resulting from or generated by a complex process consisting of numerous contingencies, deterministic and probabilistic mechanisms, and linear and nonlinear dependencies.

The unified framework of convergence among social, engineering, and natural sciences and technologies explains the current Anthropocene epoch, defined as the most recent geological period of the Holocene during which human activities have produced a permanent and irreversible layer of vestigial debris from degraded artifacts such as roads, buildings, weapons fallout, and engineered infrastructure. The Anthropocene is a necessary and therefore predictable consequence of coupled dynamics in the triad, because human-environmental interactions always involve the production of artifacts. Therefore, convergent social, engineering, and natural sciences and technologies will necessarily play a leading role in explaining and understanding the Anthropocene.

Formalisms: Foundations and Calculi

Convergence across the social, engineering, and natural sciences is supported by more formalisms than can be covered here, including discrete, continuous, and hybrid mathematical structures for modeling and understanding diverse aspects of coupled human, engineered, and natural systems (e.g., Moore and Siegel 2013; Cioffi 2014a, pp. 147–152, 175–183; Wolfram 2015).

Among the most fundamental and universally applicable formalisms and calculi across social, engineering, and natural sciences are *laws of compound events*, *dominance principles*, and *gradient fields of multivariate functions* in ecologies of coupled human-artificial-natural systems. These formalisms and each associated calculi provide universal and fundamental analytical support for convergence across the social, engineering, and natural sciences.

Laws of compound events specify causal mechanisms (both deterministic and probabilistic) for modeling, explaining, understanding, and shaping the occurrence and probability of events in human, artificial, and natural systems, using concepts and principles of clausal logic and elementary probability. Importantly, these precepts apply throughout the triad, in spite of a widespread misconception that they apply only to natural phenomena, not humans. A compound event $\mathbb{E}$ is an occurrence produced by the conjunction of two or more elementary causal events. If $\mathbb{E}$ denotes a compound event with cardinality Θ (number of causal events required for $\mathbb{E}$ to occur) and E denotes its probability, then the fundamental theorem for the probability of a compound event states that

$$E = p_1 \times p_2 \times p_3 \times \ldots \times p_n \quad (1)$$

$$= P^{\Theta} \quad (2)$$

where p_i is the probability associated with the i-th causal event, P is the probability of causal events when they are equiprobable, and Θ is the set cardinality of $\mathbb{E}$. Equations 1 and 2 are laws that govern the occurrence of numerous and highly significant compound events in the ecological triad of coupled human, artificial, and natural systems, such as climate change (change in one or more of the statistics of climate) and its many consequences, including disasters (loss of human life, property, and habitat caused by hazards) and other significant phenomena.

While the laws of logic and probability provide foundations for modeling compound events in coupled human, artificial, and natural ecologies in the real world, many events of interest are generated by more complex combinations of conjunctive and disjunctive causes, based on causal analysis, generated by necessary and sufficient conditions, respectively. Disasters and other extreme events in coupled ecologies occur in alternative modes, based on disjunctive causal processes or onset mechanisms (Perry and Quarantelli 2005; Helsloot et al. 2012; Jones and Murphy 2009; Rundle et al. 1996). For instance, inundation or flooding, with or without severe human consequences, is a disjunctive compound event that can occur through extreme precipitation, permafrost thawing, or rising sea levels, among others, as in a redundant or parallel system.

Laws of compound events are used for modeling and analyzing coupled human, artificial, and natural phenomena with any degree of specifiable complexity, based on combinations of conjunctions and disjunctions and multiple orders of causation, from immediate to remote or root causes (Pearl 2000). Computational solutions are available through simulation, when closed form mathematical solutions are not feasible. Modeling compound events, mathematically or computationally, is fundamental to understanding dynamics and complex aspects of coupled human, artificial, and natural ecologies such as risk, vulnerability, resiliency, and long-term sustainability.

Climate change is a highly consequential case of a compound event that affects every major component system within the ecological triad of global human, artificial, and natural systems (cf. Table 2; an event tree model of this table, with branching processes, is illustrated in Cioffi 2014a, p. 219). The complex process that generates climate change consequences (ranging from minor effects to catastrophic disasters) begins at a ground state (event $\mathbb{G}$) where society is naturally exposed to a variety of hazards, including climate change. The first contingency to consider is whether preparedness occurs (event $\mathbb{P}$) or not ($\sim \mathbb{P}$). If not, then several outcomes ranging from nothing to disaster may occur, depending on subsequent hazards and response-related events. If preparedness does occur ($\mathbb{P}$), then another subspace of outcomes is obtained, depending on subsequent contingencies. When climate change occurs ($\mathbb{H}$), the range of disaster outcomes depends on further contingencies, such as whether or not preparedness works ($\mathbb{W}$), whether response is undertaken ($\mathbb{R}$), and whether response is successful ($\mathbb{S}$).

Note that all events along each path ($\mathbb{P}, \mathbb{H}, \mathbb{W}, \mathbb{R}, \mathbb{S}$), and their complementary failure modes) are compound events dependent on other causal events with various values of cardinality (akin to causal complexity). For example, in the case of preparedness $\mathbb{P}$, it requires recognition of the need for preparedness (causal event $\mathbb{N}_P$), effective decision-making ($\mathbb{D}_P$), and the implementation of preparations ($\mathbb{A}_P$). In turn, each of these causal events for $\mathbb{P}$ has its own second-order causal events, up to a level of specification required by the research or policy questions being asked of the model.

These basic laws of compound events, combined with the use of sequential and conditional trees (Cioffi 2014a, p. 219), make it possible to model the occurrence and probability of events with theoretically unlimited complexity. For example, consider the case of climate change hazard, a compound event with computable probability. It can be shown that the worst disaster outcome has specifiable occurrence and computable probability given by a set of theoretical and empirically valid equations. As climate change is already occurring, it can be shown that the probability of disaster D is already quite high. By contrast, “ideal” success outcomes have occurrence and probability given by a different set of equations.

These formalisms highlight a generally unknown or underappreciated property of complex compound events in human, artificial, and natural ecologies, such as climate change and potential disasters.

Theorem 1 (Dependence Principle for Compound Events) The probability of outcomes as compound events (ranging from benign to catastrophic) is linearly dependent on the probabilities p of prior causal events, but exponentially dependent on cardinalities (number of necessary conditions Θ and alternate modes Γ).

This is a nonintuitive result that provides specific actionable information for preparedness and response to disasters (anthropogenic, engineering, or natural): organizations (e.g., supply chains) and technologies (i.e., all artifacts) employed in support of preparedness and response should minimize serialized conjunction to maximize results, due to the exponential effect of cardinality on mitigating disaster.

Beyond the laws of compound events, a second class of formalisms for convergent analysis of coupled human-artificial-natural ecologies consists of *dominance principles* (Cioffi 2014a, pp. 179–184). These are formally demonstrable and empirically testable results derived from the multivariate structure of compound events in coupled human-artificial-natural ecologies. Specifically, dominance principles provide insightful and often actionable inferences by identifying those independent variables X_i that matter most in affecting or producing change in a given dependent variable Y, such as dependent variables in laws of compound events.

Theorem 2 (Dominance Principle for Compound Events by Conjunction) The probability of a compound conjunctive event $\mathbb{E}_\wedge$ is more sensitive to the probability P of its necessary causal events than to its cardinality Θ.

Note that the sensitivity of continuous variable P is calculated using partial derivatives, whereas finite differences are used to calculate sensitivity with respect to discrete variables such as Θ.

Theorem 3 (Dominance Principle for Compound Events by Disjunction) The probability of a compound disjunctive event $\mathbb{E}_\vee$ is more sensitive to the probability Q of its sufficient causal events than to its cardinality Γ.

Both dominance principles show that probability (i.e., the chance of a causal event occurring) matters more than cardinality (multiplicity of causes), and such a fundamental property of the real world is independent of causal mode (conjunction or disjunction). From a normative or policy perspective, this is good news, because probability is more susceptible to human control than causal cardinality. These results are also counterintuitive, since the exponential effect of cardinality relative to probability (theorem 1) would appear to state the opposite.

The following are some implications of theorems 2 and 3:

State of a coupled human-artificial-natural ecology. A coupled human-artificial-natural ecology is more sensitive to probabilities than to cardinalities of those events that determine its state. Accordingly, change in the state of a coupled human-artificial-natural ecology is more sensitive to change in individual conditions than to the number of such conditions.

Adaptation. Successful adaptation in the context of complex challenges and opportunities (Simon's paradigm, section "Unified Framework") should rely on ensuring more reliable actions rather than attempting to reduce required steps in achieving success.

Sustainability. Strategies to attain sustainability should aim at minimizing processes that impede endurance, such as serially dependent programs, and maximizing coordinated parallel efforts.

Collective action. Human collective action necessary to manage and develop coupled human-artificial-natural systems in sustainable ways should prioritize effective individual strategies rather than attempt to increase their number through redundancy – which should be used as a tactic to buttress individual collective action strategies.

Climate change effects. Preparedness and response strategies for mitigating effects of climate change should prioritize maximizing probabilities, minimizing conjunctive cardinalities, and maximizing disjunctive cardinalities, in that order.

Dominance principles such as theorems 2 and 3 can be derived for compound events with far greater complexity than simple conjunction and disjunction.

Beyond dominance principles, a third class of formalisms for convergent analysis of coupled human-artificial-natural ecologies consist of *gradient fields* and their associated calculus. A gradient field is a distribution of intensity or flows over a space of variables, such as a "heat map" topography of dynamic forces that affect the state and behavior of a system. Classical gradient fields for functions of continuous variables in coupled human-artificial-natural ecologies include the gradient ∇f, the Laplacian $\nabla^2 f$, and others (Wolfram 2015). The gradient ∇f is a vector that always points in the direction of greatest change, whereas the Laplacian $\nabla^2 f$ is a scalar quantity used to detect if the function f exhibits fluctuating ("harmonic") behavior.

Gradient operators are widely utilized in natural and engineering sciences where multivariate functions consist of continuous variables, such as in mechanics, electrodynamics, and biological processes. However, discrete variables are common in many human systems, such as cardinalities in compound events (variables Θ and Γ for causal connection and disjunction, respectively). Accordingly, the discrete gradient operator is used for functions of discrete variables, such as cardinalities Θ and Γ.

Hybrid functions of continuous *and* discrete independent variables are common in coupled human-artificial-natural systems. For example, the fundamental laws of compound events (Eqs. 1 and 2) are hybrid functions, where p and q are continuous (probabilities) and Θ and Γ are discrete (cardinalities). The "nablaDot" operator $\nabla\!\!\!\cdot$ is defined for a hybrid function $z(x_i, y_j)$ of continuous (x_i) and discrete (y_j) variables using combinations of first-order derivatives and first-order differences with respect to x_i continuous variables and y_j discrete variables, respectively (Cioffi 2014b).

Complexity: Nonequilibrium Systems and Processes

Another major class of ideas that enable convergence of social, engineering, and natural sciences for better understanding the ecological triad of coupled human-artificial-natural systems consists of concepts, principles, theories, models, and methods from complexity science, primarily in the form of laws and theories of nonequilibrium phenomena (Mitchell 2009; Miller and Page 2007; Cioffi 2014a, pp. 152–170). Not by coincidence, Simon added a new chapter on complexity in the third and final edition (1996) of *The Sciences of the Artificial*.

A coupled human-artificial-natural system is a quintessential example of a complex system, which comprises a set of characteristic features, such as nonequilibrium distributions, power laws, scaling, metastability, and long-range correlations, among others.

While some phenomena in human, artificial, and natural systems follow Gaussian or "normal" (i.e., bell-shaped) distributions, others follow irregular or asymmetric patterns that deviate from normality. The log-normal distribution in biological systems and the Weibull distribution in social and technological systems are examples. A Gaussian distribution is known as an equilibrium distribution because values cluster at the center and deviations from the central mean or average are rare; in fact, values become increasingly and rapidly rarer as they deviate from the mean. By contrast, nonequilibrium distributions found in many human, artificial, and natural systems are skewed (asymmetric, not centered), and more *importantly*, extreme values can occur with significantly higher probability than in a Gaussian distribution.

A particularly interesting case of a nonequilibrium distribution is a power law:

$$p(x) = \frac{k}{x^{\alpha}}, \tag{3}$$

where $p(x)$ denotes the probability density function of variable x, and k and α are scale and shape parameters, respectively. Human conflicts, wealth distributions, organizational and country sizes, ecological food chains, social and technological networks, and the size of many natural hazards, among numerous other human, artificial, and natural systems, are known to obey power laws (references to works by pioneers such as V. Pareto, A. Lotka, G. Zipf, L. F Richardson, H. A. Simon, and M. Batty are provided in Cioffi 2014, Chap. 6). A power law is diagnostic of complexity because systems that exhibit such patterns typically generate extreme events with much greater frequency than those governed by Gaussian processes.

Human settlements linked by transportation networks and other infrastructure systems are a major component of coupled human-artificial-natural systems. Zipf's law states that the size S of a city is inversely proportional to its rank R in the settlement hierarchy. Formally,

$$S = \frac{k}{R^{\alpha}}. \tag{4}$$

Zipf's law is a special case of a power law (Eq. 3) and becomes a harmonic distribution (i.e., $1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots, \frac{1}{N}$) when $k = \alpha = 1$.

The average or mean value of a power-law distribution has the unusual theoretical property of vanishing as $\alpha \to 2$. In practice, the mean of any set of city sizes can be arithmetically computed, but the theoretical distribution (Eq. 3) has no average size.

Phenomena that follow a power law are said to be "scale free" or "scale invariant" because small values and large values fall under the same law. Scaling is common in many human, artificial, and natural systems, but it is not a universal property. For example, time durations are more often exponentially or Weibull distributed (Cioffi 2014a, p. 267), whereas power-law scaling is more common in size distributions.

Significant events in coupled human-artificial-natural systems – such as climate change, technological innovation, or social movements – never "come out of the blue," because they must develop potential before they can occur. The state of a coupled human-artificial-natural system is said to be "Lyapunov stable" if it can be maintained under a range of perturbations. For instance, an ecosystem is stable in this sense if it is able to endure in spite of stresses such as seasonal weather fluctuations or human land-use patterns. By contrast, an ecosystem is unstable it if it fails when stressed, such as when prolonged drought induced by climate change causes large-scale human displacement and migration. Many complex system theories use this notion of Lyapunov stability.

Metastability develops in the state space of a complex system when there are one or more potential states or alternative operating regimes to which the system can transition, sometimes abruptly (Helbing 2012). For example, climate change can induce metastability in an ecosystem when temperature increases cause permafrost thawing, which in turn destabilizes buildings and infrastructure systems in the built environment (see earlier Fig. 2; IPCC 2012). Power laws are diagnostic of metastability because they model situations where a broad range of states – not just the extant equilibrium or observed status quo – have significant potential of being realized.

Ontology: From Variables to Objects

A defining feature of real-world ecosystems is the network of dynamic interdependencies existing or hypothesized to operate among human, artificial, and natural entities. The paradigmatic movement from variables to computational objects as

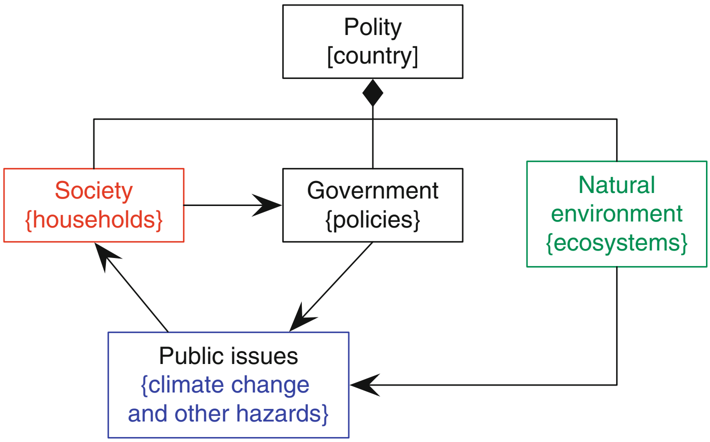

Fig. 3 UML class diagram of a polity as consisting of a society of households situated in a natural environment and governed by institutions that produce policies for managing emerging public issues, such as climate change and other hazards. *Red*, *black*, and *green* denote human, artificial, and natural entities, respectively, and consistent with earlier notation in Figs. 1 and 2, (Adapted from Cioffi (2009, 2014, Chap. 2))

units of analysis supports convergence of social, engineering, and natural sciences by providing a powerful modeling framework (Cioffi 2014a, Chap. 2).

Figure 3 shows the coupled human, artificial, and natural system of a polity, which is composed of entities such as a society, a system of government, and the natural environment where it is situated. Public issues (e.g., climate change) are generated by the environment, causing stress on society. In turn, society places pressure on government to issue public policies that may mitigate or eliminate stress. This diagram is formal, based on the Unified Modeling Language (UML) created to represent structures of various objects (rectangles in the figure) and algorithms (Cioffi 2014a, pp. 39–60). Arrows represent various forms of specific dependencies and associations. For example, the black diamond head denotes the concept that a polity is composed of a society, a government, and an environment, which uses the composition association. Other arrows represent associations such as causing stress (from public issues to society), pressuring policymakers (from society to government), implementing policies (from government to public issues), and climate change (from natural environment to public issues).

By contrast, a generation ago, a similar idea would have been represented by block diagrams linking various variables in a system, rather than connecting entities. Obviously variables remain key to representing dependencies in coupled human-artificial-natural systems, as already seen in the previous section on formal calculi and complex systems, but in an object-based model, variables appear within each entity (called "encapsulation") rather than in isolation. Actors and entities are the units of analysis in object-oriented and agent-based modeling, as examined in

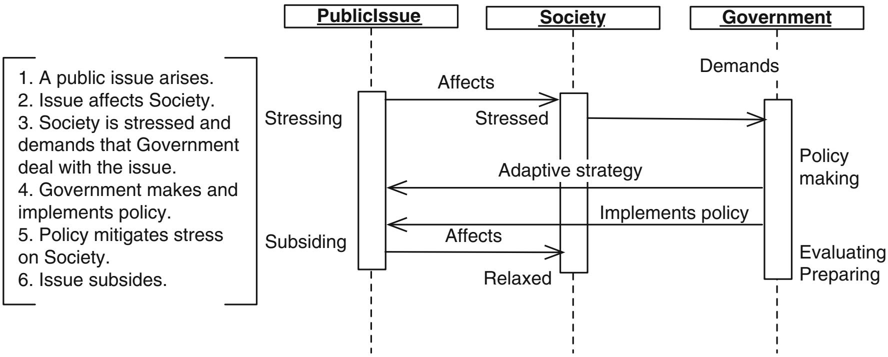

Fig. 4 UML sequence diagram describing a polity's processes for managing a public issue, such as climate change, through dynamic interactions between society and government

the next section. This is an important point and illustrates the difference between systems as used in the 1970s and complex systems ideas today.

Object-oriented modeling (or OOM, as it is known in computer science and software engineering) in general, and UML notation for representing coupled systems in particular, provides a powerful strategy for describing, understanding, and analyzing coupled human-artificial-natural systems. Figure 3 is known as a "class diagram," because it represents the main entities of a system and the associations that exist among entities. A class diagram provides mostly a static representation, whereas other UML diagrams are used for representing behavioral dynamics.

Figure 4 shows a UML "sequence diagram" for representing the dynamic process taking place in the coupled system. The main entities in this case (public issues, society, and government, for simple illustrative purposes) are represented across the top of the diagram, below which are parallel lanes where various events take place. As detailed by the chronology of events on the left, the dynamic sequence begins with an issue arising (e.g., climate change in the Earth's atmosphere) and ends when the issue subsides. During the process, the state of each entity changes, as well as the state of the overall polity.

UML diagrams such as these and others (state machine diagrams, activity diagrams, interaction diagrams, and use case diagrams, among others) enable and support convergence by:

- Providing a domain-neutral modeling framework or paradigm, accompanied by rigorous notation
- Highlighting the main entities and their interactions down to any level of precision
- Placing variables in their respective entity (called "encapsulation")
- Clarifying the hierarchy of entities (such as a polity comprising a society, as opposed to the opposite)

- Distinguishing among various kinds of relationships (e.g., society polity vs. environment issues)
- Providing a catalog of technical blueprints (class diagrams, sequence diagrams, and others) for a detailed and comprehensive description of a human, artificial, and natural system of systems
- Identifying parts of the system of systems that require further study

Most of these features have been unavailable to the various social, engineering, and natural disciplines where convergence is now occurring. Moreover, the UML system itself is being constantly developed and improved, including systems-oriented extensions (Friedenthal et al. 2014).

Computation: Agent-Based Models

In 2013 the NSF study on convergence of knowledge and technology for the benefit of society (CKTS Report) highlighted smartphones and gene sequencing as examples of convergence among previously separate fields. Today convergence within the social, engineering, and natural sciences is taking place with agent-based models, which are enabling a new way of understanding coupled human-artificial-natural systems (Cioffi 2002, 2014a, pp. 287–303). Agent-based models, known as multi-agent systems in computer science and individual-based models in ecology, are object-oriented computational simulation systems consisting of autonomous, interacting, goal-oriented, bounded-rational actors that use a set of rules and are situated in a given environment. Each agent-based model is motivated by and designed to answer one or more research questions, as illustrated in Table 3.

Figure 5 shows the map portion in the graphical user interface (GUI) of one of the most recent large-scale spatial agent-based models, a model called NorthLands, created to explore and better understand effects of climate change on coupled human-artificial-natural systems in the northern boreal and Arctic regions. Besides being able to display geographic and spatial features of regions, models like this can also show a variety of other information displays, such as run-time time series, dynamic histograms, and insightful statistical and qualitative data.

Spatial agent-based models (cf. Crooks 2012 and Rogers et al 2014; Heppenstall et al. 2012; Cioffi 2014a, pp. 273–303 for an introductory summary and list of references) are used as convergent platforms for modeling and simulating coupled human-artificial-natural systems for numerous reasons:

- Convergence across social, engineering, and natural science domains is supported within the common integrated computational platform of an agent-based model.
- Substantive theories from across the social, engineering, and natural sciences can be implemented in code, thereby increasing the realism of dynamics in the model.

Table 3 Examples of agent-based models listed by empirical calibration. Source: Cioffi (2014a, p. 289, including references for each model). See also https://www.openabm.org, a collaborative computational modeling depository sponsored by the US National Science Foundation

Model name	Referent system and research questions	Empirical calibration	Source code
RiftLand	East African coupled socio-techno-natural system; hazards and disaster scenarios	High	MASON
Anasazi	Long House Valley, Arizona; population dynamics and carrying capacity	High	Ascape, NetLogo
Sugarscape	Theoretical system of agents; social consequences of agent rules	Medium	Ascape, NetLogo, MASON
RebeLand	Political stability in a country; insurgency and state-failure dynamics	Medium	MASON
GeoSim	Balance of power system; territorial change	Medium	Repast
FEARLUS	Land-use and cover change; farming dynamics	Medium	Swarm
SIMPOP	Urban systems; growth dynamics	Medium	C++
Heatbugs	Abstract social system; agent happiness and social proximity	Low	Swarm, MASON
Wetlands	Hunter-gatherers affected by weather; social effects of memory	Low	MASON

- Multiple technologies can be integrated within a common system, such as GIS (geographic information systems), evolutionary computation, and machine learning, among others.
- Powerful and constantly evolving programming languages permit implementation of complex data structures and algorithms.
- Distributed computing can be used for large classes of models to improve speed, while problems in decomposability and modularity continue to pose a challenge.
- Agent-based computational technology is constantly improving with new facilities being introduced by users and developers worldwide.
- Spatial agent-based models enable analysis of simple and complex scenarios for policy analysis, in ways that are not feasible through more traditional mathematical or statistical approaches (e.g., econometric modeling).
- Teaching and training are facilitated by the visualization of complex processes that are otherwise difficult if not impossible to comprehend.

Agent-based models of coupled human-artificial-natural systems are created in native code or using a toolkit such as NetLogo (the choice for beginners and for initial prototyping of more complex models), MASON (Multi-Agent Simulator of Networks and Neighborhoods, a more advanced system; Luke 2014), Repast, and many others (Nikolai and Madey 2009).

From a methodological perspective, agent-based models of coupled human-artificial-natural systems are developed according to a sequential set of procedural phases, iterated through “spirals,” from motivation to analysis (Cioffi 2014a, pp. 223–248, 287–300):

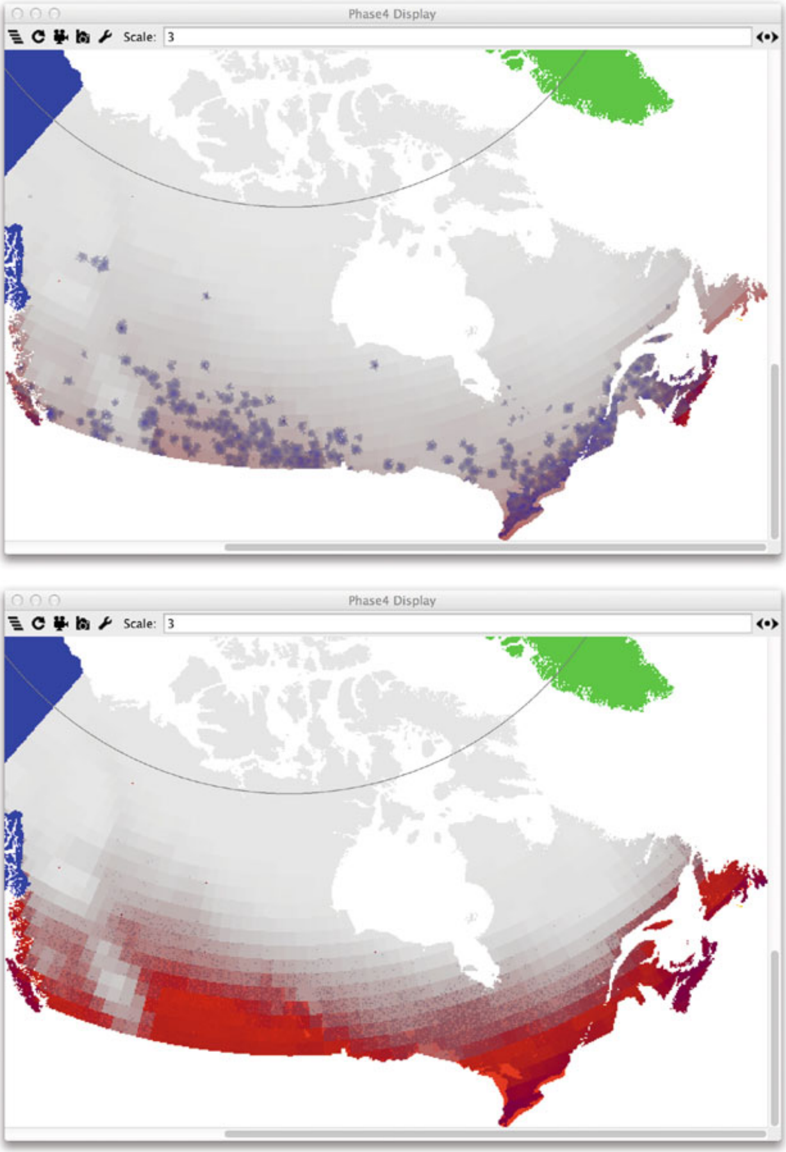

Fig. 5 Map of the Canadian sector in the graphical user interface (*GUI*) of the boreal and Arctic region in the "NorthLands" agent-based model. *Top*: Model initialization with mean temperatures (*red*) and population distribution (*blue*) matching historical data. *Bottom*: After a period of significant warming, population distributions (*blue*) have dispersed and migrated as they adapt to risen temperature (*red*). *Source*: Mason-Smithsonian Joint Project on Climate and Society, funded by the US National Science Foundation. Prepared by J. Bassett

1. Motivation: Every agent-based model is created to answer a set of research questions. For example, in the case of the NorthLands model (Fig. 5), such questions include the following: What is the probability and likely location of human migrations, given a set of changes in climate? Which infrastructure systems and population areas of the northern boreal and Arctic regions will likely be most affected? What if projected changes in climate, such as temperature and precipitation, are off by, say, between 2 % and 5 %? Purpose and research questions drive all subsequent phases.
2. Design: Like all models, agent-based models are abstractions intended to represent selected aspects of reality. In the case of coupled human-artificial-natural systems, an agent-based model will almost always have a spatial representation, often with GIS layers, and entities will include key entities and dynamics from human, artificial, and natural components. UML diagrams are useful tools for a well-specified design.
3. Implementation: Various programming languages and simulation toolkits are available for implementing an agent-based model. For example, MASON and GeoMason are used in the NorthLands model based on special goals and design requirements of the project. Whereas implementation in native code offers great flexibility, it carries the cost of having to build an entire system from scratch. By contrast, using a toolkit enables researchers to use preexisting utilities and facilities that allow more effort to concentrate on unique classes and dynamics.
4. Verification: The quality control process for ensuring that a model works in the way that it is intended is called verification. Debugging, calibration, unit testing, profiling, code walk-through, and parameter sweeps are among the most common verification procedures.
5. Validation: The final quality control procedure prior to analysis consists of ensuring that model output (simulated data) matches empirical reality in the system of interest. Time series, histograms, distribution moments, and other qualitative and quantitative output data are used to compare with the real world.
6. Analysis: Agent-based models enable many forms of analysis, the most common being sensitivity analyses, scenario analyses, and predictive analyses. For example, in the NorthLands model, a primary focus of interest is on analyzing climate change scenarios proposed by the research community (e.g., IPCC and comparable reports) as well as variation thereof.

In practice, these steps are developed in spirals, starting with a simple model at first and later adding more complexity as the model reaches its design goals for answering the original research questions. Spatial agent-based models of coupled human-artificial-natural systems provide virtual worlds with increasing fidelity to the real world and platforms for convergent S&T that will one day generate new fields of knowledge, some of which are already in their infancy. Within a few years, not decades, agent-based computational models will enable us to simulate all past civilizations to better understand universal dynamics of cultural evolution by regions and globally.

Summary

This chapter proposed a unified framework for understanding the global ecology of coupled human, artificial, and natural systems and processes, based on convergence among social, engineering, and natural sciences. The framework explains the rise and future growth of the Anthropocene and can be used for deepening our understanding of significant challenges, such as climate change and its impacts on humans, the built environment, and nature itself, among other phenomena. The framework has roots in earlier paradigms, such as complex adaptive systems and coupled socio-ecological systems, which in turn extended and advanced prior knowledge of general systems and cybernetics. The new vision is that of a unified science of humans, artifacts, and nature, with a system-of-systems architecture and founded on formal concepts, systems principles, and object-based computational models calibrated with real-world data. In combination, these elements undergird convergence of social, engineering, and natural sciences by providing fundamental support.

Besides its intrinsic scientific value, the unified framework potentially offers a set of societal benefits:

- Understanding complexity. Coupled human-artificial-natural systems have a long history extending to the dawn of the Anthropocene, which can help in understanding the nature of uncertainty and hence decrease stress.
- Advancing civilization. A unified science of human, artificial, and natural systems can help in improving evidence-based governance, sustainable economic development, raising living standards, and creating the first civilization based on viable science and technology about all previous and plausible civilizations.
- Improving design. Convergence of the social, engineering, and natural sciences can improve design of all artificial systems, from belief systems to whole civilizations.
- Managing disasters including pandemics. Hazards will always occur, whether caused by nature, humans, or technologies. A unified science of coupled human, artificial, and natural ecology can deepen understanding of global hazards such as climate change and humanitarian crises, by highlighting universal laws of disaster accounted for by viable, verifiable theories.
- Enabling spacefaring civilization. Given our current and growing dependence on space-based telecommunications and information infrastructure, from banking to energy to security to transportation and commerce, we are already a fledging spacefaring civilization. A unified science of coupled human-artificial-natural systems will boost and enable future human exploration, colonization, and civilization beyond our original homeland on Earth.

The scientific road from systems theory to empirically grounded agent-based computational theories and models provides both a destination for convergence among the sciences, pure and applied, and foundation for the next scientific revolution and policy analysis.

Acknowledgments This chapter is dedicated to the memory of Herbert A. Simon and Elinor Ostrom, twentieth-century visionaries of a unified science of coupled human, artificial, and natural systems ("Simon's Triad"). Funding for this study was provided by the US National Science Foundation under grant no. IIS-1125171 and by the Center for Social Complexity at George Mason University. I am grateful to Bill Bainbridge, Dan Rogers, and Rob Axtell for comments on an earlier draft. Jeff Bassett, Ken De Jong, Tim Gulden, Ates Hailegiorgis, Bill Kennedy, Sean Luke, Paul Schopf, and members of the MURI and CDI teams provided earlier discussions.

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Whole-Earth Monitoring

Bruce Tonn, Erin Rose, and Beth Hawkins

Contents

B. Tonn (✉)
Department of Political Science, University of Tennessee, Knoxville, Knoxville, TN, USA
e-mail: btonn@utk.edu

E. Rose • B. Hawkins
Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

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Abstract

This chapter addresses whole earth monitoring, which is defined to include monitoring of geospheric and anthropogenic systems of systems and flows at all spatial levels, including cyberspace and outer space. Drivers for the creation of this system include public policy, knowledge creation, education and the development of the exposome. A plethora of technologies can be envisioned to converge on the whole earth platform; space-based, surface and subsurface, and health sensing technologies. To provide insights into the benefits of whole earth monitoring beyond those related to global environmental issues, an example of the relationships between whole earth monitoring and the theory and praxis of social work is presented. Development of the whole earth system envisioned herein poses numerous difficult policy issues, including personal privacy and system administration.

Introduction

This chapter addresses *whole earth monitoring*, which is defined to include monitoring of geospheric and anthropogenic systems of systems and flows at all spatial levels, including cyberspace and outer space. Beneficiaries of whole earth monitoring include governments, businesses, researchers, health professionals, and educators. Integration of data across whole earth monitoring systems can improve the efficiency of worldwide energy and agricultural systems, actions to mitigate and adapt to climate change, natural disaster planning and response, and the management of megacity infrastructure systems. The data can support real-time, near-term, and long-term decision-making at all levels of society. It is can be argued that whole earth monitoring is a permanent responsibility for all future generations.

To effectively monitor systems of earth systems requires convergence of science and technologies in order to design integrated data collection and analysis systems. Consilience across the natural, social, and policy-related sciences is needed to efficiently govern the administration of whole earth monitoring activities and programs and wisely use the information flowing from the monitoring systems. One can argue that international efforts to comprehensively and intensely monitor systems of earth systems and integrate the data for worldwide access mark a commitment to long-term sustainability and a significant next step in the maturation of human civilization.

The next section "Vision" presents a detailed vision of whole earth monitoring. Section "Drivers" discusses three main drivers in society that are influencing the achievement of this vision: public policy, knowledge creation, and education. It is also discussed how whole earth monitoring is necessary to create the exposome, which will catalogue the exposure of humans to all environmental risks. Section "Implementation" explains the various whole earth monitoring components and the challenge of integrating data in a user-friendly fashion across scales and perspectives. An example is presented in section "Example: Whole Earth Monitoring and the Theory and Praxis of Social Work" of how whole earth monitoring can contribute to research and policy related to poverty, equity, environmental justice,

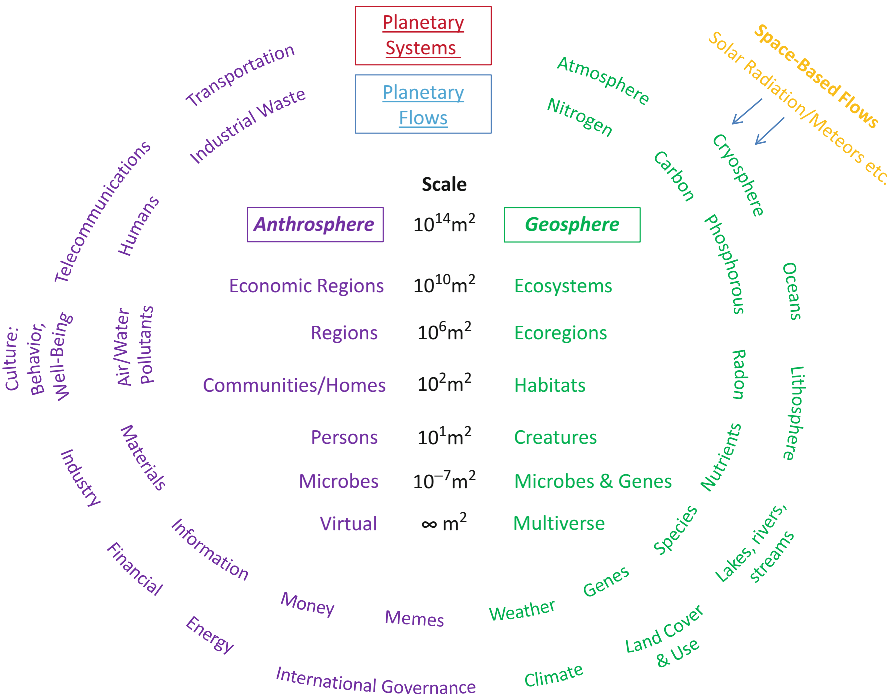

Fig. 1 Monitoring of whole earth system of systems

and climate change. Section "Policy Issues and Recommendations" addresses the numerous policy-related issues and recommendations associated with whole earth monitoring.

Vision

The vision of whole earth monitoring presented herein is systemic, comprehensive, synergistic, and convergent (for a complementary vision, see Group on Earth Observations https://www.earthobservations.org/about_geo.shtml and Fritz et al. (2008)). The spirit of the endeavor is to collect data and information about all major planetary systems and flows within and between these systems. As depicted in Fig. 1, the challenge is to monitor a system of systems. The balance of this section addresses each of the major components of this figure.

Planetary Systems

These systems can be classified as belonging to the geosphere (indicated in green font) or the anthrosphere (indicated in purple font). Among the most important geospheric planetary systems are the atmosphere, oceans, cryosphere (e.g., polar ice caps), lithosphere (i.e., the earth's upper interior), and climate systems (among important essential climate variables to collect data on include air temperature, carbon dioxide and other greenhouse gases, sea surface salinity, and ocean acidity. Global Climate Observing System, http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables). On the anthrospheric side, important systems include transportation, telecommunications, energy, culture, and finance.

Numerous exogenous forces impact both the geosphere and the anthrosphere. Internal to earth, earthquakes and volcanoes emerging from the lithosphere are geological processes that can impact all planetary systems (earthquakes are extensively tracked; see http://earthquake.usgs.gov/earthquakes/map/). On a smaller scale, natural geological flows of substances such as radon into homes and arsenic into drinking water supplies can impact human and nonhuman species alike. External to earth, fluctuations in solar radiation and impacts from meteors can affect numerous planetary systems. Consistent with the broad brush approach to whole earth monitoring adapted in this chapter, both internal geological and external space-based systems should be monitored to complement the monitoring of planetary systems.

Planetary Flows

Flows, activities, changes, and events occurring within and among planetary systems need to be monitored. On the geospheric side, important flows to monitor include carbon (including emissions and sequestration), nitrogen, and phosphorous. It is also important to monitor the flow of species (e.g., those naturally migrating, those shifting habitats due to climate change, and invasives). At an even finer level, it is important for public health, agriculture, and conservation efforts to monitor the flow of genes, for example, from genetically modified organisms to their cousins in the wild, between bacteria, between viruses, and between organisms inoculated with synthetically created genes to the rest of nature.

The flows in the anthrosphere are similarly abundant. These flows include humans, money, materials and goods, and information. The amount of pollutants produced and transported by the anthrosphere, such as air and water pollution and industrial wastes, also needs to be monitored. It is also advisable to monitor the sociological equivalent of genes, "memes," to track how ideas, values, and beliefs emerge, move, merge, and evolve throughout cultural systems.

Geospheric Components

The planetary system of systems is composed of elements that have different geographic scales, spanning over 20 orders of magnitude. Data and information need to be collected at all scales because subsystems within systems of systems all

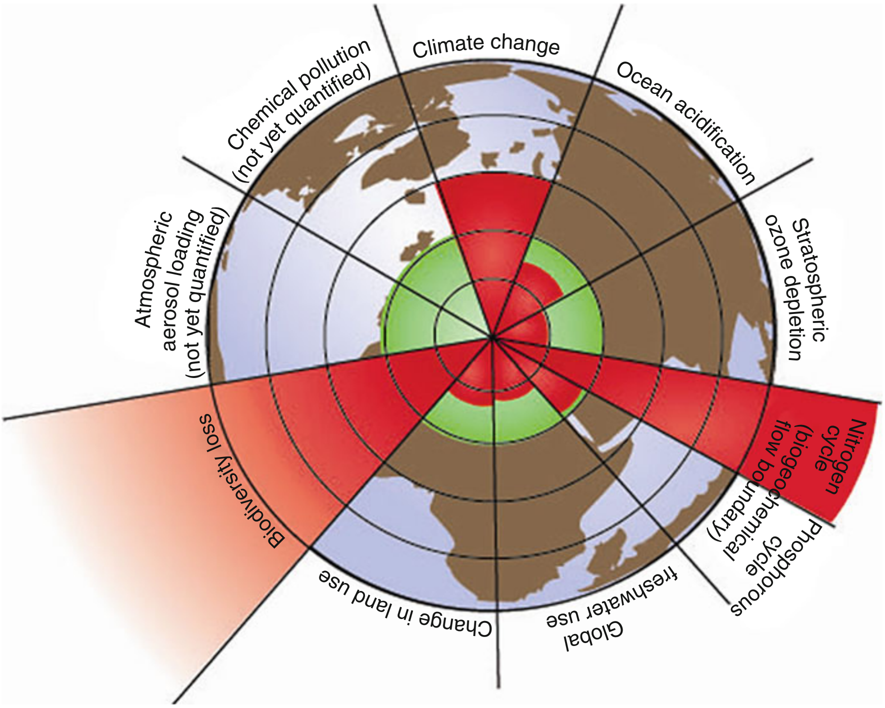

Fig. 2 Planetary boundary indicators (Stockholm Resilience Center)

interact with each other in numerous ways. Thus, within the geosphere is it crucial not only to collect data on planetary flows of nutrients, for example, but it is also necessary to collect data that can be associated with specific ecosystems, ecoregions, and habitats (e.g., wetlands, savannahs). Ideally, a whole earth monitoring system would track enormous numbers of individual creatures, from bears to penguins to tuna to queen bees and even down to the level of microbes found in soils and waters.

The physical analogue of infinite cyberspace can be broadly conceived as the multiverse. Its narrowest definition encompasses the visible universe and entails tracking not only of meteors and asteroids but also monitoring deep space for potentially extinction-causing events such as gamma ray bursts. Its broadest definition includes the reaches of our universe beyond the light-barrier, and other universes, be they parallel to our own, exist in branes according to M-Theory, or exist side-by-side to our own universe as each springs into being from their own birthing big bangs. Since our ability to even detect the existence of the multiverse much less monitor it with respect to potential risks to or opportunities for earth-life is beyond our capabilities, it is included in this discussion solely for completeness of the framework.

Anthrospheric Components

On the left-hand side of the middle portion of Fig. 1 is a list of components of the anthrosphere that are analogous in scale to the components of the geosphere. The anthrosphere spans the same order of magnitude as the geosphere and maybe even an infinite order of magnitude if cyberspace is included. In this case, the largest scale anthrospheric components are economic regions, such as Western Europe or North America. Smaller-scale components are regions (e.g., Great Lakes in North America), communities and homes, individuals, and their personal microbiomes (Fig. 1).

An additional component of the anthrosphere that should be monitored is cyberspace or the virtual sphere. Its scale is indicated as ∞ as there are essentially no limits to cyberspace. What to monitor in cyberspace is an interesting and open research question. Internet commerce, web traffic (e.g., email, videos, web searches), and social media use are already being intensively monitored. It would also be useful to monitor the sizes of the various virtual environments where humans congregate (examples include Second Life (http://www.secondlife.com) and World of Warcraft (http://us.battle.net/wow).). For example, the number of users/avatars, person-hours devoted, and activities conducted in the virtual environments could be monitored. One could argue that cyberspace is an important space to monitor the evolution of memes. Also, from a sustainability perspective, it would be useful to monitor activities and behavior in cyberspace that could be reducing the consumption of energy and materials in the physical world (Bainbridge 2010).

Interactions

Planetary systems, planetary flows, and the geosphere and anthrosphere are all tightly intertwined. Atmospheric processes transport and even create air pollutants (e.g., nitrogen oxide and volatile organic compounds form troposphere ozone in the presence of sunlight.). Fluctuations in solar radiation can impact planetary telecommunications systems, which then can impact numerous components of the anthrosphere, from economic regions to persons. Human behavior as influenced by culture results in energy demands for numerous end uses. Extraction and consumption of fossil fuels, for example, result in changes in carbon flows, which impact climate systems, which then impact components of both the geosphere and anthrosphere. The interactions among these components often produce unexpected and unintended outcomes and consequences.

Drivers

Whole earth monitoring can be justified from several perspectives, namely, public policy, knowledge creation, and education. It can also create novel resources that can simultaneously contribute to all three. An example, the exposome, is presented at the end of this section.

Public Policy

The practical applications of whole earth monitoring are virtually limitless. Governments, businesses, nonprofit organizations, and individuals worldwide need to track energy production and consumption; flows of raw and finished materials and products; refugees uprooted from their homes due to war, famine, or environmental catastrophe; changes in land cover and uses in tropical rainforests and tundra regions; and the state and quality of freshwater supplies for cities and agriculture. Within the anthrosphere, policy makers need to keep track of human health and potential for pandemics, stocks of nonrenewable and rare-earth metals, and air and water pollution. Sustainability issues often involve both spheres. Policy makers need to understand whether environmental resources such as ocean fisheries are being unsustainably exploited, migration of invasive species threaten biodiversity, and conversely, whether creations of synthetic biology also threaten biodiversity. Certainly, much of the information just mentioned is available, but not across all geographic regions and scales, and it is not possible to access any and all combinations of data at any scale for any specified time periods.

Knowledge Creation

The whole earth monitoring system needs to generate the data required to support the development, testing, application, evaluation, and revision of theories that encompass knowledge gained by both the natural and social sciences, whether related to, inter alia, ecology, social psychology, epidemiology, microeconomics, or climatology. In other words, if theory X requires a set of input data to produce predictions related to an important policy issue, then the whole earth monitoring system must be able to provide these data. Additionally, if theory X has some competition, say from theory Y, then the system must provide data to test both theories in hopes of improving our knowledge about the aspect of reality addressed by the theories. Since many theories are expressed through computer-based models, the whole earth monitoring system needs to feed inputs to any number of linear and nonlinear, simulation, global climate change, coupled human-natural systems, economic-emission, and agent-based models.

A robust and user-friendly whole earth monitoring system may engender a Cambrian explosion of theoretical development. This is because data will be available across disciplines, and theorists will not need to circumscribe their efforts based on expectations of only having limited data to test their theories. This is especially important when considering contexts that are interdisciplinary or even transdisciplinary or at the convergence of human knowledge. For example, the creation of the exposome (see section "Exposome") could support theoretical development linking exposures of individuals to various indoor air pollutants to work productivity, exposures to outdoor conditions to automobile

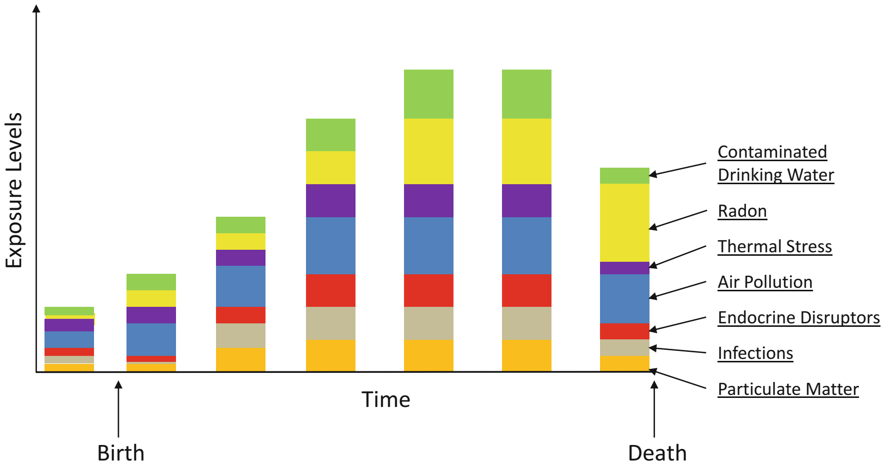

Fig. 3 Whole earth monitoring of the exposome

driver behavior, and more complicated relationships between mood, health, consumer behavior, weather, and levels of outdoor and air pollution in ways not now achievable.

The whole earth monitoring system needs to be able to detect weak signals with respect to trends that may be of concern to policy makers and researchers, such as those signaling impending public health issues, natural disasters, and unintended consequences of the penetration of new technologies into society and the environment (e.g., from the introduction of synthetic life-forms into the environment). Theory can contribute to efforts to focus attention on systems and subsystems where such weak signals are most likely to emerge. However, theory cannot contribute to the identification of weak signals emanating from emergent systems. For example, traffic systems emerged from the invention and adaptation of the automobile, and transportation research was needed to develop theories to understand and control traffic systems. To equip humanity with the capability to detect emergent systems, the whole earth monitoring system needs to continuously monitor new substances introduced into the anthrosphere (e.g., new nutrients for microbes that flow from a waste by-product of a new industrial process), new technologies and technological systems, and new combinations of species, habitats, and the anthrosphere.

An important function of the whole earth monitoring system is to collect data needed to estimate important environmental, sustainability, economic, and societal indicators. For example, the Stockholm Resilience Center has created a planetary boundary framework that includes nine indicators, including climate change, stratospheric ozone depletion, and global freshwater use (see Fig. 3) (http://www.stockholmresilience.org/). The whole earth monitoring system needs to directly feed information into these types of indicator systems.

Education

Specific indicators and the whole earth monitoring system generally can be used for educational purposes at any grade level (for such a resource, see My Community, Our Earth at http://www.aag.org/co/mycoe/digital-library/recommended-resources). For example, grammar school classes might be interested in biodiversity indicators and real-time information about specific species and maybe even specific creatures. High schools could use the data from whole earth monitoring in more sophisticated ways. For example, environmental science classes could use the data to track regional invasive species, estimate local citizen exposure to air pollutants, and explore the environmental and economic consequences of reducing energy use in their communities. The whole earth monitoring system would be a treasure trove for doctoral students studying the interrelationships between geospheric and anthrospheric systems. Lastly, citizen scientists could both contribute to whole earth monitoring (e.g., local water quality or radiation levels (http://spectrum.ieee.org/tech-talk/energy/nuclear/measuring-radiation-in-fukushima-with-pocket-geigers-and-bgeigies)) and use the available data to assess sustainability concerns in their communities.

Exposome

Whole earth monitoring is essential to creating an important new resource called the *exposome* (http://en.wikipedia.org/wiki/Exposome). This is an emerging concept within the epidemiological community that describes the desire among many human health researchers to track the exposure of every human to all potential environmental risks across the lifespan from in utero to end of life. Thus, it is necessary to track individual exposures to indoor and outdoor air pollutants, contaminants in food, thermal stressors, noise, dust and other particulates, the widest range of allergens, pollutants in water, and exposures to natural and man-made radiation. In other words, all planetary flows that pertain to human health need to be monitored not only generally but also with respect to each individual over time. This massive amount of data is needed to allow researchers to better attribute risk to various sources of potential harm to complement human genome research and in an effort to better understand health disparities. Health policy makers will also benefit from the exposome as it will support the prioritization of environmental risks vis-à-vis human health.

Figure 3 presents a schematic of the exposome for one individual over his/her lifetime. The figure only includes seven of potentially thousands of chemicals and other risk elements that this person could be exposed to. This person's exposures were the least, but still potentially significant, while in the womb. Exposures increased and peaked during adulthood. Air pollution was a constant threat. Exposure to indoor radon increased as she stayed indoors more often in retirement. Medical records, patient histories, real-time monitoring of health, subjective accounts of mental and physical health, lifelogs, and ultimately, cause-of-death information need to be synthesized with exposomic data in order to support this research.

The concept of the exposome should also be extended to the geosphere. Instead of only collecting data about humans, it is desirable to collect data about exposures experienced by various species, from polar bears to chimpanzees, from domesticated dogs to wild wolves, from honeybees to frogs, and from endangered condors to endangered Java rhinoceros. It is also necessary to collect information on the exposure of key microbes in agricultural soils to pollutants to track their health, reactions, and potential mutations. These data could be valuable in helping to understand population collapse and potential adaptations to exposomic risk factors.

Implementation

This section addresses the components of a whole earth monitoring system. The first two subsections discuss the space-based and surface-subsurface-based components, whether stationary or mobile. The third and fourth subsections address health sensing of both humans and other species and monitoring cyberspace, respectively. This section concludes with a discussion of the infrastructure needed to aggregate and integrate real-time or near-real-time data flowing from all of these components. Large amounts of data are being collected across most spatial scales with respect to most policy-oriented and science-oriented needs. However, there are gaps and opportunities to improve data collection. It is also the case that the vast majority of data collected are not integrated and available in a user-friendly manner to users worldwide.

Space-Based

Satellites are the quintessential whole earth monitoring devices. The first satellite, Sputnik 1, was launched in 1957 (http://en.wikipedia.org/wiki/Satellite). Since then, over 6,000 satellites have been launched to support telecommunications, defense, locational (i.e., GPS), and environmental applications. A menagerie of geostationary and orbiting satellites collects data about and around the earth (Orcutt 2013) including data to:

- Detect changes in vegetation, land management and crop yields, location of crop diseases, tree counts, illicit deforestation, and rain forests (http://www.planetaryresources.com/technology/leo-space-telescope/)
- Monitor ocean surface temperature, wind fields, and atmospheric ozone
- Track total solar irradiance levels to monitor climate change and variability
- Measure the reflectance of earth, sea surface temperature, sea ice, land heights, and water vapor in the atmosphere
- Measure gases, such as O_3, in the atmosphere by looking at starlight as it travels through earth's atmosphere

- Measure carbon dioxide concentrations and distributions in the atmosphere (Orbiting Carbon Observatory 2, launched July 2014)
- Measure volcanic activity, forest fire detection, ice fields, and drainage basin gradient studies (series of 15 satellites Polar Operational Environmental Satellites (POES) US/EU)
- Support weather forecasting, severe storm tracking, and meteorology research (Geostationary Satellite system (GOES))
- Measure changes in urbanization through nighttime lights (http://www.mdpi.com/2072-4292/5/7/3476/htm)
- Assist with defense intelligence and tactical planning in urban/densely populated areas
- Monitor development of nuclear programs
- Detect previously undiscovered asteroids (http://www.planetaryresources.com/2014/06/asteroid-zoo-live/)
- Conduct maritime vessel reconnaissance and detect contamination (oil spills)
- Collect image data for nine shortwave bands and two long wave thermal bands, visible, near-infrared, shortwave infrared, and thermal infrared spectrums at 400 scenes a day to assist with energy, fire, natural disasters, urban growth, water management, ecosystems, biodiversity, and forest management (Landsat 8, launched February 11, 2013)

The satellites discussed above are traditional in the sense that they are rather large and heavy and are launched into space atop substantial rockets. Recent advancements in numerous technologies have converged on the satellite platform to produce much smaller and lighter satellites, known as miniaturized, nano- or even femto-scale satellites. These satellites are relatively inexpensive and can be launched into space as secondary payloads or atop much smaller and more inexpensive launch vehicles. Because of their lighter weight and lower price, many small satellites can be released at the same time. With respect to earth environmental monitoring, for example, five small satellites may be able to replace one larger earth imagining satellite system and for the same cost reduce the complete global imaging time to 3.5 h from 24 h (see http://en.wikipedia.org/wiki/Miniaturized_satellite). Given the emergence of miniaturized satellites and other novel systems (e.g., a system of independent satellites could share functionalities such as computation and power generation. See Chu et al. (2013)) and the fact that tens of countries now have space programs, one can argue that the capabilities to monitor earth from space will continue to grow over time.

Surface and Subsurface

Envision a dense distribution of stationary and mobile sensors at and just above the surface of the earth and just below the surface. These sensors will measure the air and water for pollutants and the location and movement of humans and nonhumans. Cameras will capture images from both the geosphere and anthrosphere. Stationary sensors could be fixed to and in homes, businesses, skyscrapers, manufacturing plants, hospitals, schools, plants/trees, telephone poles, etc. They can be embedded in caves and deep within the earth and at the bottom of oceans, lakes, and rivers. They also can be embedded in sewer lines, municipal wastewater treatment plants, drinking water mains, roads, and bridges. Indeed, one can imagine an Internet of Things providing whole earth monitoring data (Jara et al. (2013)).

Mobile sensors could swarm through our living environments. Already there are over seven billion mobile devices in the world (http://singularityhub.com/2014/02/18/there-are-7-billion-mobile-devices-on-earth-almost-one-for-each-person/). All such devices could at a minimum track the location of their users. It is a hope of exposomic researchers, for example, that these devices could be outfitted to sense environmental pollutants and be used to test for contaminants in food with sensors or microscopic bioimaging (http://www.kurzweilai.net/low-cost-compact-optics-that-turn-a-smartphone-into-a-powerful-portable-microscope). These mobile devices would be complemented by cars, trucks, planes (planes are routinely used to take images of land uses: http://en.wikipedia.org/wiki/Aerial_photography), trains, boats, bicycles, blimps, balloons, drones, and other flying autonomous objects to collect data on pollutants, crop status, soil moisture, and noise, for instance. It is also worthwhile envisioning attaching GPS and pollutant monitoring sensors to birds, fish, sharks, whales, coyotes, and other mobile mammals, amphibians, and insects.

Health Sensing

Health sensing deserves special attention because of our focus on the exposome component of whole earth systems monitoring. There is a revolution in health sensing technologies, which may lead to collecting vital personal health data in real time through a combination of wearable (e.g., clothes, glasses (Kun 2013)), fixable (e.g., rings, bracelets, headbands (e.g., to measure brainwaves http://singularityhub.com/20124/06/04/headband-opens-the-door-to-brain-to-computer-applications/)), implantable (e.g., chips), and digestible (e.g., nanobots) sensors. These data include heart rate, blood pressure, EEG (http://neuroscapelab.com/), pulse oximetry (http://www.cs.toronto.edu/~mangas/pubs/NO_FFM_Healthgear_BSN.pdf), and even self-images that could be used to detect progression of genetic diseases (http://singularityhub.com/2014/07/09/alogorithm-hunts-rare-genetic-disorders-from-facial-features-in-photos/). In addition to providing their owners with real-time health information, this information would flow into the cloud of the whole earth monitoring system to be combined with anthrospheric and geospheric data to pinpoint emerging health emergencies and conduct sophisticated health-related research. Also in the future, almost every individual would be online (through mobile devices, web-connected glasses, etc.) so that each individual could participate in real-time in global surveys about their health and well-being. The surveys could be extensive (e.g., numerous questions about individual health) or extremely short (e.g., just one question – “How do you feel right now?”).

It is also important to monitor the health status of nonhuman species. Already, biologists and environmental scientists tag individual animals to track their movement (e.g., fish, birds). These tags would be enhanced to collect data on the real-time health status of, say, elephants or gorillas or panda bears. It would be a challenge to collect data for non-mammals like frogs, alligators, or crocodiles or insects like bees, ants, and beetles, given their unique physiologies. For any monitored creature, and especially for the smaller ones, it would also be a challenge to create sensors that do not interfere with their natural behavior and survival. Lastly, selected plants, such as trees in tropical rainforests, should be equipped with real-time health monitors.

Monitoring Cyberspace

Cyberspace in this context refers to everything online and/or in electronic form. This world is broken into two components: (1) big data and (2) virtual environments. Big data encompasses repositories of data held by retailers, medical insurance organizations, government programs (e.g., Medicare/Medicaid), credit card companies and financial institutions, social media companies, web search firms, telecommunications companies, etc. These types of databases and more grow essentially in real time and can be mined individually or concurrently, along with databases containing information depicted in the planetary systems and planetary flow loops depicted in Fig. 1. Big data can also include journal articles, laws, books, and other resources that can be considered archival but may be exceedingly useful in tracking trends and changes in memes, for instance.

Virtual environments are quite different from big data. The most critical difference is that there are flows within the virtual environments, interactions among users, and interactions among users and the systems that may represent new, novel, and emergent behaviors. These flows may contain valuable information that should be tracked by whole earth monitoring systems. One can imagine autonomous avatars and bots roaming through the virtual environments, conversing with user avatars, collecting "images" from the evolving virtual space, and measuring many of the same geospheric and anthrospheric variables captured in Fig. 1.

Integrative Technologies

The ultimate goal is to bring together all data collected as part of the whole earth monitoring system in a way that makes access to and use of the data user-friendly and seamless. Think of a global enterprise system. This will take a tremendous amount of effort with respect to data standardization, geocoding, database documentation, and meta-data guidelines that describe data coverage and quality and data dictionaries (one such effort in the United States was known as the National Biological Information Infrastructure (NBII). It was terminated in 2012: http://en.

wikipedia.org/wiki/National_Biological_Information_Infrastructure. Other efforts include the Global Biodiversity Information Facility, the Global Earth Observation System of System being built by the before mentioned Group on Earth Observations http://en.wikipedia.org/wiki/Global_Biodiversity_Information_Facility, and COOPEUS to harmonize the collection of data about earth's oceans (see Walsmann and Pearlmamn 2013). See Cinnirella et al. (2012)). In fact, the integration process needs to be automated so that variables and data representable in consistent but different units (e.g., different units of energy, weight, length), possibly in different languages, can be transposed into standard units and translated into common languages. An extremely robust technological infrastructure is needed to host these data. This infrastructure requires sufficient computing power to process big, complicated datasets, storage for vast amounts of data, and adequate bandwidth to transmit all of the data, information and results.

Effective human interfaces are also needed. These interfaces take at least four forms. First, an interface is needed to help users structure their problems/queries/analyses in order for the system to communicate what data are available, how different types of data can be synthesized for analysis, and what form the results would take. A second type of interface presents the results of whatever analyses are run. This interface should make use of the most advanced visualization techniques and technologies. Third, a comprehension support system is needed to help users make sense of visualizations and other types of results that describe complex whole earth systems of systems, identify weak signals, and even discover newly emergent whole earth systems.

The fourth interface is needed for those who administer the whole earth system enterprise. This interface will indicate data gaps, data that have major quality problems, and risks to key data collection systems (e.g., from natural disasters to sabotage). One could imagine a spaceship earth control room where the administrators are surrounded by screens, each taking the pulse of some aspect of the earth. During periods of crisis, the administrators have the authority and capability to redirect earth monitoring systems to crisis locations and decision-makers who need more and better real-time data (see Alexander MacDonald's contribution in Sect. 3.8.6 in Roco et al. (2013).

Example: Whole Earth Monitoring and the Theory and Praxis of Social Work

Whole earth monitoring is most often viewed from the lofty perspective of monitoring the global environment. This chapter takes the view that whole earth monitoring needs to include numerous aspects of the anthrosphere as well. In other words, whole earth monitoring not only needs to meet the needs of environmental scientists and climatologists but also the needs of social scientists and those who are working to bridge the two worlds. This example explains how the whole earth monitoring system writ large can benefit social work theory and praxis.

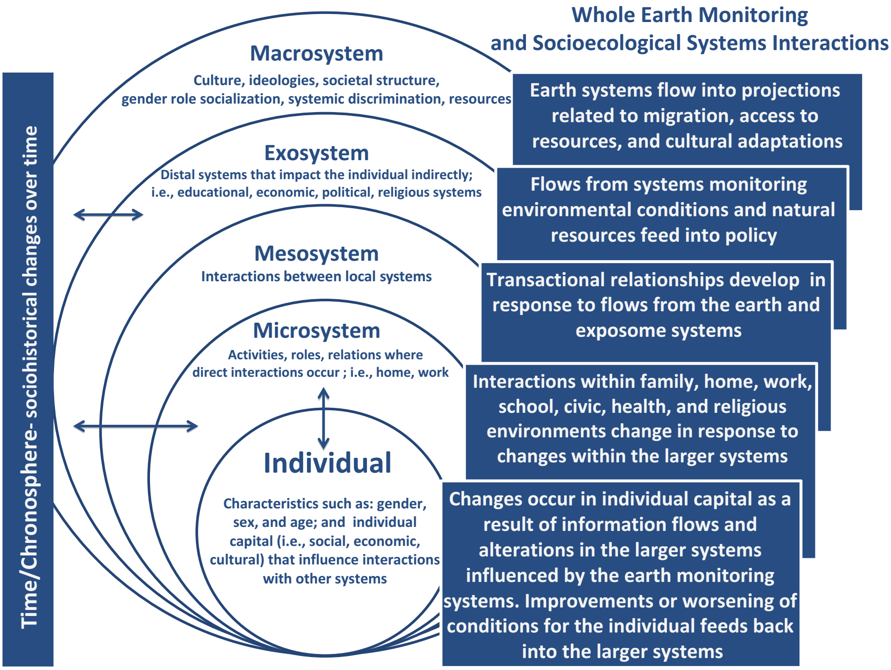

Fig. 4 Ecological systems theory of social work

Social workers seek to improve the daily lives of individuals, their families, and their communities. They intervene in situations where economic, health, and social disparities and other factors are resulting in dysfunctional families and threats to the well-being of children and their parents. Social workers use an ecological systems theory to understand, explain, and predict human behavior. One such theory, developed by Urie Bronfenbrenner, is depicted in Fig. 4. Individuals exist within a set of nested systems, from the microsystem of the family to the macrosystem of culture and society.

Indicated down the right-hand side of Fig. 4 are some of the various ways that a whole earth monitoring system can provide data and information into each system. For social work theorists, data sets could be created that integrate data related to each system to allow them to develop and test theories that incorporate concepts from all of the systems. For example, how quickly might changes in the macrosystem (e.g., cultural mores related to gender roles) work their way down through the various systems to impact individual behavior and capital and how might these influences then combine with others to potentially threaten individual and family health? Also, whole earth monitoring would inject new data into the theorists' world, such as daily exposures to outdoor and indoor pollutants and other data from the exposome and even the interactions between the whole earth monitoring system itself and the health and well-being of individuals and families.

What is also exciting are the benefits that a fully implemented whole earth monitoring system could have for the praxis of social work. For example, if much more data were collected at the individual level, social workers would have much more objective information on the daily lives of their clients (e.g., about environmental stressors, about interactions with family members and coworkers, about behaviors and feelings) that could help them to better understand the situations their clients are facing. That information, in turn, could be used to help educate clients about their situations and the potential benefits of behavioral change.

Using social work as the foundation for this example, whole earth monitoring can support efforts toward interlinking multidisciplinary and funding programs targeting vulnerable populations impacted by global environmental and economic systems. Organized efforts to establish necessary services as part of adaptation, relief efforts, resource management, and urbanization planning can aid in the prevention of risk factors related to overcrowding, hunger, homelessness, poor education, untreated medical and mental health issues, unemployment, poverty, and difficulty with acculturation. Associative factors or outcomes include loss of life, aggressive behaviors and crime, chronic poverty and sanitation issues, poor emotional and mental health (e.g., interference with child developmental milestones, poor attachment patterns with caregivers as a result of child natural disaster trauma and caregiver mental health status, mundane extreme environmental stress (MEES) from emigrating to a region with war, conflict, terrorism, or extreme racism and oppression), and worsened health and health disparity rates.

Poverty, equity, and environmental justice issues are inextricably linked to climate change impact (ODI, 2003; USEPA, 2014). The report put forth by the Globalisation and Poverty Programme provides definitions for key climate change terms; adaptive capacity is “the ability or capacity of countries, communities or households to adjust in order to reduce vulnerability to climate variation, moderate potential damage, cope with, and recover from the consequences”; adaptation is “the process of adjustment that can be anticipatory or planned (disaster preparedness), or spontaneous and reactive (disaster recovery)”; and vulnerability is “the susceptibility of people to the harmful consequences of climate variability and extremes and is largely dependent on their adaptive capacity and the sensitivity of their livelihood systems to climate change.” The poorest are most at risk for climate change impact, and therefore targets for eradicating global poverty, equity, and environmental justice issues as well as sustainable development initiatives will need to be adjusted for climate change impact. Climate change analyses made possible by whole earth monitoring system could support poverty eradication initiatives in efforts to prevent both direct and indirect costs from extreme weather events including loss of life, assets, and infrastructure. Additionally, whole earth monitoring could contribute to the general discussion on poverty indicators and measuring quality-adjusted life years (QALYs) by projecting global, regional, and local poverty trends based on environmental, economic, and development metrics and trends generated from multiple systems.

Whole earth monitoring systems would be able to track the health needs of the migrating homeless persons or refugees in relation to both types of shelter, exposure to contaminants identified for the local area where the homeless or refugees will settle, and access to services or assistance programs. With the flow of demographic information from collected census data, cultural or religious preference could be matched to existing Diasporas of similar demographics to promote positive acculturation outcomes.

Current homelessness tracking systems contain information on local resources used to support this transient population including shelter, food, counseling, and health services. These systems also track intra- and intercity movement of persons. Information related to homeless populations can be used in conjunction with other systems tracking economic, political, or environmental events such as movement of refugees or displaced persons from climate change. Conversely, information from environmental tracking systems can flow into systems tracking homelessness as a means for cities or regions to coordinate around adaptation planning. For example, projections of impending natural disasters computed from environmental monitoring systems can assist with organizing emergency services and relief efforts to prevent and reduce mortality rates and general chaos. They can also feed into planning initiatives related to urbanization, which is projected to increase as a result of climate change impacts in agricultural and coastal regions.

Urbanization tracking (e.g., monitoring of lights from space) can flow into systems tracking human migration and refugees for services tasked with relief efforts focused on persons of vulnerable status. WEMOs would be able to track all this information, analyze patterns, and identify idiosyncrasies alerting organizations or leaders of any critical needs necessitating modification or updating their own systems to better fulfill their mission. Services can also be prepared and accessible for vulnerable persons along migration routes most utilized as observed within one tracking system and ready upon arrival at the final destination. This planned adaptation strategy allows for organized efforts of services previously identified as most needed for displaced adults and children. These services might include:

- Temporary shelter
- Food assistance
- Financial assistance and employment counseling
- Health services
- Mental health services and support groups
- Education services
- Cultural and religious needs

Policy Issues and Recommendations

While the whole earth monitoring system can contribute to innumerable policy discussions, analyses, and decisions, it also poses numerous challenging policy issues. The most basic is whether its evolution should be administered explicitly and, if so, by whom. One could imagine the founding of the Whole Earth

Monitoring Organization (WEMO) whose member organizations would include government agencies, scientific organizations, firms, nongovernmental organizations, and information sharing and analysis centers. The WEMO would work on data standards, interoperability issues, filling data gaps, and meta-data guidelines. It would facilitate decisions by stakeholders to collect and share various data comprising the whole earth monitoring system. It would also help facilitate the establishment of and cooperation among data repository centers (an example of a data repository center at Oak Ridge National Laboratory is the Carbon Dioxide Information Analysis Center (CDIAC). See http://cdiac.ornl.gov/).

Whether or not WEMO is established, challenging privacy issues must be dealt with. Proposed above is the monitoring of the movement, health status, and even mental condition of almost every individual on earth. The exposome requires linking exposures to specific individuals over time. Big data contributions related to health records, consumer purchases, web searches, social media content, and financial transactions add to the amount of data that can be accumulated about a specific individual. Facial recognition systems used on images flowing from mobile devices could virtually end anonymity. Innovative methods and procedures are needed to protect privacy while unlocking the value of the whole earth monitoring system. A challenge to computer scientists would be to design algorithms to prevent the merging of databases and analyzing databases in ways that would reveal the identity of individuals. Balance between human rights and the needs of law enforcement and national security officials to protect us from crime and terrorism also need to be sought.

Another policy question with respect to whole earth monitoring deals with secrecy versus openness. The implicit assumption underlying this chapter is that having more information available to all about every aspect about earth and its inhabitants is better. It is also assumed that the value of one's data can be exponentially increased if it can be combined with the data of others. Thus, it is crucial to gain the participation of stakeholders whom might be more inclined not to share their data (e.g., social media companies, transnational retailers) while finding ways to protect their businesses and competitive advantages.

Another implicit assumption underlying the development of the whole earth monitoring system is efficiency. Data from the whole earth monitoring system will help improve health care, adaption to climate change, and protect endangered species. The data will be useful for improving the efficiency of all anthrospheric systems, from transportation to energy to mega-urban systems. One could pose a question that has both policy-related and ethical aspects: is there ever a case where too much efficiency is a bad thing? Might the drive for efficiency, in part facilitated by the whole earth monitoring system, diminish local, regional, and even national identity? Would individuals and organizations of various types suffer from a loss of agency? Would the drive for efficiency promote homogeneity and conformity of behavior over creativity and the blooming of healthy socio-diversity? These are only some of the challenging research questions associated with whole earth monitoring.

Conclusions and Long-Term View

While not belittling the policy issues just discussed, whole earth monitoring is a next step in the maturation of human civilization. Sustainability of key earth-scale systems of systems is essential for long-term survival not only of *Homo sapiens* but also for all of earth-life. From a long-term view, the sustainability challenge will stretch thousands of years into the future at the very least. If the earth is to be a permanent home for earth-life, at least until the death of the sun makes habitation impossible, then the challenge stretches outward for tens of millions of years. To ensure that the earth is inhabitable into the distant future, much needs to be known about our homes and ourselves. Whole earth monitoring is essential to achieve this task.

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Part V

Societal-Scale Platform

Twenty-First Century Society

William Sims Bainbridge

Contents

Abstract

The legacy of the twentieth century is mixed to say the least, marked by two world wars that increased the human capacity for slaughter, the development of biotechnologies and information technologies that transformed many aspects of life, and the emergence of profound intellectual debates about the possibility of planning a better future. A brief survey of civilization theories, which had fallen out of fashion by the beginning of the present century, reveals that they raise questions that deserve fresh consideration. Beginning in the year 2000, a conference on the societal implication of nanotechnology and four conferences on converging technologies launched a concentrated effort to understand how the components of modern science, technology, and society already interact and could cooperate more beneficially. On that basis, the second decade of the twenty-first century launched a comprehensive exploration effort, communicated through a substantial book-length report titled *Convergence of Knowledge,*

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Technology and Society and this *Handbook of Science and Technology Convergence*. In the context of sophisticated ethical analysis and social science, we may have reached the point at which the governance institutions of society require redesign.

Introduction

Central to the convergence vision is the integration of science, technology, and society. Humans have been described as the tool-making animal, but we might just as well be described as the product of our tools, as our species and our technology coevolved over hundreds of thousands of years. We have reached the point at which all areas of our planet have been explored, most have been exploited, and all are connected by travel and communications technologies. A new era has begun, but that means that an old era is ending, and the end of a stage of evolution brings problems, manifested in the obsolescence of key societal institutions and vast questions for which we as yet lack answers. Thus while we embrace with optimism science and technology convergence with society, we must also be aware of dangers and the possibility of failure if our hopes are not supported by solid understanding.

Refined Pessimism

Everyone has seen gloomy science fiction movies about dystopian or postapocalyptic futures, and the best of them may have the capacity to stimulate thought. However, there also exists a rather substantial if antique social scientific literature that offers serious analyses of the large-scale dynamics of human history, often pessimistic in its long-term predictions. Beginning in the 1890s, Frederick Jackson Turner (1920) analyzed the societal implications of the closing of the Wild West frontier in the United States, offering a theory that became tremendously influential among historians and can be expanded to cover Western Civilization altogether. In 1945, presidential science advisor Vannevar Bush amended this theory, suggesting that science could become the “endless frontier,” sustaining the same social dynamics after the Wild West had been tamed.

The Age of Discovery transformed much of the world, beginning with voyages by explorers like Christopher Columbus and Ferdinand Magellan and followed by colonization and exploitation of the New World by the Old World. The stimulus to science and technology was immensely powerful, but economy and politics were also transformed. As Turner documented, the frontier required colonists to take initiative for themselves and was largely beyond the control of elites who lived back in more settled areas. It also served as a safety value or societal regulator, allowing malcontents to escape tyrannies and influencing traditional societies to become less tyrannical. At the extreme, this theory predicts that democracy cannot survive without a frontier.

A number of European theorists early in the twentieth century brooded about the possibility that their civilization had entered a period of decay, often in reaction to the horrors of the First World War. Oswald Spengler (1926) argued that every great civilization is based upon a distinctive fundamental principle, which for Western Civilization was boundless space. Pitirim Sorokin (1937-1941) proposed a more complex but similar theory, which left open the possibility that after falling a civilization could rise again, potentially going through 1000-year cycles of progress and decline.

There are at least three plausible reasons why civilization theory has been unpopular in recent decades, each of them revealing something about the legacy the twentieth century bestowed upon the twenty-first. By the 1960s, a very different pessimism about the future had become dominant, the realization that civilization could end in a nuclear war, triggered even by a seemingly minor miscalculation by societal leaders rather than preordained by any natural process of societal evolution. To use the title of a 1962 book by Herman Kahn, intellectuals became obsessed with "thinking about the unthinkable." In a grim sense, long-range nuclear missiles were the ultimate convergence technology, feasible only because many fields of science and technology had made all the components of the weapons system feasible, and then great human effort had combined them into doomsday machines. But after a decade of gloom, intellectuals shifted to an optimistic form of convergence, imagining that a prosperous global economy could mute national hostilities, as each person on earth had a vested interest in the success of every other person.

A second reason for the decline of interest in civilization theories was a reaction against the political extremism of the twentieth century. Shortly before the Second World War, the Japanese Ministry of Education (1949 English translation) published a detailed proclamation on how Japan could develop for a bright future, including the idea of drawing the best from the three competing political systems then dominant in the world, what we today would call Capitalism, Communism, and Fascism. A somewhat cynical way to look at Capitalism's apparent triumph in the hot war of 1939-1945, and the Cold War that followed, was simply that the English-speaking nations following this system began the competition with more resources, because they had been central to the Age of Discovery. Indeed, had he lived long enough, Karl Marx would have been surprised to see Russia and China turn to Marxism, because his historical theory assumed that communism was the next stage of social evolution after capitalism and thus would arise first in the most advanced capitalist nations. Civilization theories tended to harmonize with nationalist and elitist sentiments, often associated with right-wing politics, when several of the academic social sciences tended to favor the opposite end of the political system, although varying in political diversity over time. A moderate and well-respected example of civilization theorist was British historian Arnold Toynbee (1947-1957), who conceptualized the rise and fall of a civilization almost entirely in terms of whether its elite was competent and creative enough to respond well to major challenges as they arose.

A third factor may simply have been that civilization theories did not advise individual people what to do with their lives. A global capitalist economy offered many opportunities, not merely in business but in many other walks of life, especially while technology advanced at a rapid pace, opening up new kinds of jobs and providing endless diversions, from flying to distant places as a tourist to playing massively multiplayer online games with team members in other nations.

As several chapters in this handbook document, convergence can be the basis of divergence, and this point was made by one of the founders of sociology, Herbert Spencer (1896). He applied general theories of biological evolution to the development of civilization as a whole, in a very complex argument that included the idea that unification and diversification could go hand in hand. As society advances, it promotes an ever greater division of labor, which has the effect of giving individuals rather narrow points of view. Thus, to see the forest for the trees, we might be well advised to reconsider civilization theories in the light of developments since they were originally formulated.

Spencer's attempts to transfer evolutionary theory from biology to sociology suggests a somewhat different conceptualization based on ideas about evolution that existed in his day but were developed more fully recently, notably the concept of *ecological niche* (Patten and Auble 1981). The original habitat for humanity was East Africa, but the evolution of complex brains interacted with the development of technology, opening the entire Earth to become our habitat. When a major evolutionary development occurs, a common consequence is *adaptive radiation*, in which one species differentiates fully into many offspring species, functioning as separate breeding pools and becoming physically different from each other. Our brains facilitated something comparable but fundamentally different, cultural diversification. We entered the modern age as one, single species, with only very modest physical differentiation adapting to very different climates, but a significant functional variety of cultures.

In the 1960s, a "futurology" rage gripped American intellectuals, many of whom wished to serve as advisors charting the course of the Kennedy-Johnson administration's "New Frontier" or "Great Society" and the continuing competition with the Soviet Union in the "Cold War." The RAND Corporation sponsored studies that sought to combine the views of many experts into unified forecasts concerning a wide range of possible technological and social developments (Helmer et al. 1966). Among the most interesting sequels were two visionary books, *The Year 2000*, by Herman Kahn and Anthony J. Wiener (1967), and *Towards the Year 2000* edited by Daniel Bell (1967). Based on the work of think tanks and university scholars, these books not only attempted to extrapolate trends but also to sketch scenarios describing futures that might result if different decisions were made by societal leaders.

More recently, many serious writers have used the scenario method to explore the human meanings of possible futures. For example, Robert Costanza (2000) sketched four visions of the year 2100, depending upon whether technology will make it possible to overcome limitations in natural resources:

1. *Star Trek*: public policies are optimistic, assuming that technology will overcome limitations, and in fact technology does achieve this, leading to expansion into the solar system.

2. *Mad Max*: public policies are optimistic, assuming that technology will overcome limitations, but technology fails to achieve this, so civilization crashes.
3. *Big Government*: public policies are pessimistic, assuming there are strict limits to economic growth, but in fact technology could have overcome these limits, so progress is unnecessarily suppressed.
4. *Ecotopia*: public policies are pessimistic, assuming there are strict limits to economic growth, and this assumption is correct, so civilization achieves a necessary harmony with the environment.

The Star Trek scenario literally assumed that space is "the final frontier," yet the last flight to the Moon launched in December 1972 and the original *Star Trek* TV series ended the month before the Apollo 11 landing. Serious expansion into the solar system is not even in the planning stages. Yet the "final frontier" could actually be the nanoscale, and nanotechnology could overcome many economic and technical limitations by permitting efficient human design of structures across all size ranges. Or the "final frontier" could be the human mind, pioneered either by cognitive neuroscience or by cultural sciences or by a convergence of both in the realization that mentality proceeds both at the individual and the social levels.

The three other scenarios Costanza sketched seem inferior to Star Trek, with Mad Max clearly the worst and Big Government painfully disappointing. However Ecotopia is optimistic in its own way, predicting that humanity will have the wisdom to adapt to the limitations imposed upon us by the laws of nature. This fourth scenario is reminiscent of a parable titled, "Birds Can't Fly to the Moon" (Bainbridge 2007, pp. 26-28). Had the first birds been very intelligent, they might have imagined that their newly evolving powers of flight would have no limits, and generation after generation they could soar ever higher and farther. But wings require atmosphere, so eventually their progress halted. Similarly, human intelligence gave our remote ancestors tremendous advantages over other species and the ability to exploit a greatly expanded range of environments. But like wings, brains may have natural limitations. Yet maybe we can be smart enough to avoid fulfilling the Mad Max scenario and even the Big Government scenario. Both Star Trek and Ecotopia will require the multiplex wisdom that only science and technology convergence can give us.

The Early Converging Technologies Conferences

The original conception of technological convergence focused on the NBIC quartet of fields, nanotechnology, biotechnology, information technology, and new technologies based on cognitive science. Yet even before NBIC evolved out of the National Nanotechnology Initiative, society and the social sciences were also involved. A workshop on the Societal Implications of Nanoscience and Nanotechnology was held at the National Science Foundation in the year 2000. The book-length published report consisted of a summary of the workshop debates, followed by many contributions by participants. Written at the very beginning of the twenty-first century, the summary included this comment on the unintended and second-order consequences of technological innovation in the context of convergence:

> Perhaps the greatest difficulty in predicting the societal impacts of new technologies has to do with the fact that once the technical and commercial feasibility of an innovation is demonstrated, subsequent developments may be as much in the hands of users as in those of the innovators. The diffusion and impact of technological innovations often depend on the development of complementary technologies and of the user network. As a result, new technologies can affect society in ways that were not intended by those who initiated them. Often these unintended consequences are beneficial, such as spin-offs with valuable applications in fields remote from the original innovation.... Other consequences are not so desirable, such as the risk of closing old industries and environmental pollution, which sometimes becomes a problem, especially for large-scale technologies. (Roco and Bainbridge 2001, p. 13)

Slightly over a year later, the first Converging Technologies conference was held at the National Science Foundation in 2001. Among its five main themes was *enhancing group and societal outcomes*, and other themes also touched on questions about the future of society:

> The third multidisciplinary theme is concerned with NBIC innovations whose benefits would chiefly be beyond the individual level, for groups, the economy, culture, or society as a whole. It naturally builds on the human cognition and physical capabilities themes and provides a background for the national security and scientific unification [in education] panels. In particular, it is focused on a nexus issue that relates logically to most technological applications discussed in this report and that connects to all four NBIC scientific and technological realms - that is, how to enhance group human productivity, communication, and cooperation. (Roco and Bainbridge 2003, p. 245)

Fifteen experts, including several leading social scientists, developed a number of subthemes that constituted a broad research agenda in this area, but one in particular was highlighted: *The Communicator*. This was "envisioned as a multifaceted system relying on the development of convergence technologies to enhance group communication in a wide variety of situations, including formal business or government meetings, informal social interaction, on the battlefield, and in the classroom" (Roco and Bainbridge 2003, p. 276). On one level, The Communicator was a metaphor, expressing the goal of convergence, while technologies to accomplish its goals would initially be developed separately, at different rates, and be combined only over time. But it also provided coherence for a set of scenarios about the future, imagining what could or should be developed on the basis of convergence and in order to accomplish convergence. Here are some of the scenarios imagining Communicator developments that might be achieved in 10–20 years after 2001, some of which clearly have been achieved to a significant degree:

1. Wherever they may be, people would have immediate access to essentially all human knowledge and the ability to add to that store of information efficiently.

2. Education will no longer be confined to classrooms but be experienced at high quality at any location, whether at a site especially relevant to the information or skills being learned or simply convenient for the student.
3. Flexible, multimodal communication among members of a group will be commonplace, involving sights and sounds, statistical data and written text, and any other relevant sensory and informatic dimensions.
4. Flexibly, comfortably, and at low cost, people will be able to interact through virtual environments, represented by avatars, and via other technologies that feel natural but are quite different from what earlier generations experienced.
5. Communication technologies will accurately and swiftly translate between different languages, allowing people who do not share a language to perform effectively on the same team or simply to understand each other and thereby overcome the barriers that separated humanity in the past.
6. If desired by members of a group, the communication system would constantly assess the affective state of each participant, for example, making adjustments automatically to reduce emotional stress and augmenting communication of objective data with communication of subjective feelings.

The second Converging Technologies conference, held in Los Angeles in 2003, had an overarching theme of *coevolution*: "It is expected that converging technologies integrated from the nanoscale would achieve tremendous improvements in human abilities and enhance societal achievements. This is a broad, cross-cutting, emerging, timely opportunity for the benefit of individuals, societies, and all humanity" (Roco and Montemagno 2004, p. vii). At the most general level, participants analyzed the progressive interactions between converging technologies and human capabilities. As they offer us more possibilities, our ability to innovate increases, thus establishing a virtuous circle in which advances on the technological side and on the human side are mutually reinforcing. Consisting chiefly of distinct contributions from participants, the book-length report included chapters on topics conventionally related to biological evolution, notably the human genome project, biomedical technology, neuroethics, and biomimetic information technology. But other chapters applied evolutionary theory to legal, ethical, and semantic systems as well.

New York City was the venue for the third Converging Technologies conference in 2004. The primary focus was management of technological innovation, and the subtitle of the book-length report was "Converging Technologies in Society." A collection of future-oriented essays by participants, the resultant book examined socially relevant topics like progress in developing nations, cultural challenges in developing cyberinfrastructure, coevolution of technology and business, and technopolitics. The concept of progress was examined on many levels, including:

> Technological convergence is progressive in two important senses of the term. First, the NBIC fields are in fact progressively merging, step by step, and apparently at an accelerating rate. Second, the unification of the great realms of technology will promote human progress, if they are applied creatively to problems of great human need. Indeed, unless

> convergence takes place, in both the technical and social realms, it is hard to see how humanity can avoid conflicts, such as those that marred the 20th century, caused by limited resources for available technology and social differences within each country and globally. Only by moving to a higher technological level will it be possible for all of the peoples of the world to achieve prosperity together without depleting essential natural resources to the point at which the future of civilization itself is in doubt. (Bainbridge and Roco 2006a, p. 2)

In 2005, the fourth conference was held in Hawaii, assessing the rate of progress in convergence, and the report was subtitled "Technologies for Human Wellbeing." The chapters of the book were surveys of multidisciplinary fields or reports of related research, with implications for human unity: "Technical dimensions are prominent in the solutions to all the world's social and environmental problems. A unified scientific understanding of nature, of which the human species is an integral part, can be the basis for a universal world culture that supports mutually beneficial trade, understanding, and peace" (Bainbridge and Roco 2006b, p. xi). This meeting concluded the original series of Converging Technologies workshops and conferences, in anticipation that both technical and social developments would most probably require a fresh look within a very few years.

The Second Decade Perspective

A decade after the original Converging Technologies report was published, a series of conferences and workshops was held not only at the National Science Foundation but also in Latin America, Europe, and Asia. Among the outcomes are two extensive publications, a direct report from the meetings, titled *Convergence of Knowledge, Technology and Society* and this *Handbook of Science and Technology Convergence* which builds upon all the conferences and serves as the capstone for this long-term effort. As the title of the first book clearly states, society is an essential component of the convergence process:

> Since the beginning of formal NBIC efforts over a decade ago, there has been an awareness that the social sciences need to be included, probably through their connections to information science and cognitive science. A different conception of how that might happen has arisen very recently, as increasing numbers of research projects enlist nonscientists in what is often called "citizen science." This significant shift has positive educational implications, because the ordinary citizens who contribute their labor learn about the science. But more than that, this shift represents a convergence of science and technology with society and thus may offer an entirely new way in which the societal implications of technology progress can be addressed to achieve progress for society by embedding science and technology more solidly in society. (Roco et al. 2013, p. 54)

It is open to debate how extensive global human convergence should be, and participants in the meetings have a range of opinions about how society should be organized in the future. As a group, however, the scientists and engineers did anticipate that science and technology convergence would cause or permit major changes in the structure of human institutions. Thinking in traditional terms, this implies much work for economists, sociologists, political scientists, and other specialists to identify trends, evaluate alternatives, and predict consequences of likely changes. However, the impacts of the emerging new technologies are likely to be so great that they extend far beyond the capacity of any one discipline to understand. Thus, a new convergent social science must be created, with close connections to cognitive and information sciences, as well as collaborations with scientists and engineers in all the fields that are contributing life-changing innovations.

As the futurologists of 50 years ago advocated, one way to start serious discussions is through use of the scenario technique. For example, in 1946, leading sociologist of technology, William F. Ogburn, considered a range of scenarios concerning the emergence of a unified world government, as a necessary response to the development of nuclear weapons, which he correctly predicted would soon be deliverable by long-range rocket and thus impossible to defend against. The world did not unify politically in the subsequent decades, although something approximating economic unification has occurred. What are the plausible ways in which humanity can be simultaneously united and divided? At present, Western Europe illustrates the complexity of the issue, as different sets of nations belong to the European Union that exercises some admittedly weak governmental functions, the Eurozone that employs a common currency, and NATO that supports a common military defense.

Every statement one might make about the current and changing political systems around the world is open both to partisan debate and scientific research. For example, in the United States many observers perceive a dysfunctional polarization of the two main political parties, which some attribute to "gerrymandering" of political district boundaries and others to the failure of campaign finance reform. Yet, some respected studies appear to demonstrate that the effect of electoral redistricting is quite minor (McCarty et al. 2009). To be sure, vast sums of money are being invested in political campaigns but to support advertising rather than to buy votes. One would think that at this point in the nation's progress most voters would be sophisticated enough to resist being influenced by advertising. A third theory especially relevant to convergence but little discussed in the mass media is the possibility that society has evolved beyond the assumptions on which traditional political parties were based and perhaps even beyond traditional forms of representative democracy.

In 1973, futurologist and sociological theorist Daniel Bell argued that advanced industrial nations had reached a watershed at which they became postindustrial. He defined this new kind of society in terms of five concepts, all of which harmonize with ideas presented throughout this handbook:

1. Economic sector: the change from a goods-producing to a service economy
2. Occupational distribution: the preeminence of the professional and technical class
3. Axial principle: the centrality of theoretical knowledge as the source of innovation and of policy formulation for the society

4. Future orientation: the control of technology and technological assessment
5. Decision-making: the creation of a new "intellectual technology"

The logical implication of this set of observations is that scientists and engineers should play central roles in government decision-making, perhaps even to the exclusion of politicians. It is crucial to understand that such ideas are both radical and traditional, and we consider them here not from the position of advocates but to begin an analysis that will require much future research before it can offer policy recommendations. Ideas in this area may be radical yet plausible, if they can offer alternative ways to gain public input and achieve consent of the governed that can either supplement or supplant party-based elections. Such ideas may be traditional yet creative because they have a long history within social science yet have never really been put into practice, dating at least from the foundation of sociology early in the nineteenth century (Carlisle 1974).

In 1998, the National Science Foundation created a program in Digital Government and continues to fund research in that area, today, but through several programs rather than just one with that distinctive name (Ciment 2003). A decade later, the Executive Office of the President issued a detailed directive for a comprehensive digital government strategy, starting with three principles:

1. Enable the American people and an increasingly mobile workforce to access high-quality digital government information and services anywhere, anytime, on any device. Operationalizing an information-centric model, we can architect our systems for interoperability and openness, modernize our content publication model, and deliver better, device-agnostic digital services at a lower cost.
2. Ensure that as the government adjusts to this new digital world, we seize the opportunity to procure and manage devices, applications, and data in smart, secure, and affordable ways. Learning from the previous transition of moving information and services online, we now have an opportunity to break free from the inefficient, costly, and fragmented practices of the past, build a sound governance structure for digital services, and do mobile "right" from the beginning.
3. Unlock the power of government data to spur innovation across our nation and improve the quality of services for the American people. We must enable the public, entrepreneurs, and our own government programs to better leverage the rich wealth of federal data to pour into applications and services by ensuring that data is open and machine-readable by default (Office of Management and Budget 2012).

This is a classical statement of the digital government concept. It concerns the efficient use of information technology by government agencies and beneficial sharing of government information with the general public. A somewhat broader definition, that has been the framework for much research, concerns Internet-based systems through which organized stakeholders and ordinary citizens can participate to at least a limited extent in government decision-making, for example, through inputs to the rule-making process by which agencies implement new legislation. Two other areas have more recently become the focus of research, the use of information technologies to coordinate activities within local communities that are comparable to but independent from government agencies and their role in political campaigns, elections, and referendums.

Costanza's four scenarios for the year 2100 are determined by the interaction between public policies and technological innovation, with the implicit assumption that policy-making will be centralized. Yet given the dynamic relationship between convergence and divergence, we may well wonder whether decisions will be centralized or distributed and whether the structure of decision-making might vary across areas of human activity. The use of information technology and electronic communications facilitates developing systems of governance that are liberated to some extent from geography, becoming not only polycentric but potentially specialized. That is to say that some decisions like managing energy supplies will apply to specific geographic locations, thus varying from place to place, while others may be divorced from geography, for example, global regulation of patents and copyrights (Tonn and Feldman 1995).

Ethics of the Future

Sometimes antique expressions of fundamental principles can be especially revealing if reconsidered in the modern context of convergence. Consider two of the Ten Commandments in Exodus, as rendered in the King James Version: "Thou shalt not kill." "Thou shalt not steal." Now compare with the Revised Standard Version: "You shall not kill." "You shall not steal." The difference is not just that one is very antique and the other dates from the twentieth century but that because of a change in the English language they actually mean different things. "Thou shalt" is singular, a commandment given to a single individual person. "You shall" is ambiguous as to number, being either singular or plural depending upon the context. This raises a fundamental question: will the ethics of the future be a set of simple principles defining proper behavior of single individuals, or will ethics be meaningful only as applied in great complexity to social systems? It may be that ethical principles will be convergent, taking on meaning only in a complex social context.

To be sure, some professions in society have special responsibilities to be concerned with ethics: priests, philosophers, lawyers, and police most obviously. The division of labor in science and technology determines that key decisions having ethical implication may either be made by some of the participants but not all, or even that no one will be in a position to understand the balance of harms and benefits caused by collective actions, in the absence of a very intense and convergent effort. Often simplifying concepts have been imposed on complex situations, with uncertain results. For example, in the United States, the Common Rule is a set of principles governing ethical treatment of human research subjects, enshrined in

Part 46 of Title 45 of the Code of Federal Regulations (Pool 2013). A key principle is *informed consent*, as expressed in Section 46.116 of the January 15, 2009 version:

> Except as provided elsewhere in this policy, no investigator may involve a human being as a subject in research covered by this policy unless the investigator has obtained the legally effective informed consent of the subject or the subject's legally authorized representative. An investigator shall seek such consent only under circumstances that provide the prospective subject or the representative sufficient opportunity to consider whether or not to participate and that minimize the possibility of coercion or undue influence. The information that is given to the subject or the representative shall be in language understandable to the subject or the representative. No informed consent, whether oral or written, may include any exculpatory language through which the subject or the representative is made to waive or appear to waive any of the subject's legal rights, or releases or appears to release the investigator, the sponsor, the institution or its agents from liability for negligence.

Clearly, a research subject may refuse or may agree to participate in research, without giving up all rights, and refusal would prevent the researcher from observing or experimenting with that individual. This principle is very difficult to apply in some circumstances, for example, social science observation of group activities for which it is impractical to get every person present to sign a release form acknowledging informed consent. There are various clauses of the Common Rule that permit such research, for example, if it is judged harmless by the Institutional Review Board (IRB) that evaluates the ethics of the research plan and is conducted in a public place. Remarkably, Section 46.111 says, "The IRB should not consider possible long-range effects of applying knowledge gained in the research (for example, the possible effects of the research on public policy) as among those research risks that fall within the purview of its responsibility." That is, the Common Rule limits ethical scrutiny of research to the use of individual humans as research subjects, using a kind of rationally accepted contract called "informed consent" as the test of virtue. Wider consequences are specifically excluded from consideration.

Far more recent than Exodus from the bible, but instructive in similar ways, is the book-length proceedings from a 1975 conference, *Ethical and Scientific Issues Posed by Human Uses of Molecular Genetics*. The introduction suggested several abstract ethical principles that are not in full agreement with each other and may be given various priorities by different societies (Callahan 1975):

1. People are ethically responsible primarily for the intended consequences of their actions.
2. People can be held negligent if they failed to consider likely harmful unintended consequences of their actions.
3. When people cannot predict the consequences of their actions, they can be held responsible for harmful effects if they failed to have good reasons for taking the actions.
4. People who are affected by the actions of others have a right for those others to respect their values.

5. Scientists and engineers are governed by the same ethical norms applied to other people.
6. Ethical norms apply not only in engineering and applied sciences, where immediate consequences are to be expected, but also in pure science that may indirectly and over time have consequences.
7. In any debate about the ethics of research, the burden of proof is on those who oppose the research, rather than those who support it.

While these seven principles can spark many debates, the last point in particular can be disputed and seems to contradict some of the other points. Indeed, in recent years, the *precautionary principle* has often been promoted: Research should not be done if it plausibly will lead to more harm than good, even in the absence of certainty (von Schomberg 2012).

Oddly, a key ethical debate that rages in the political realm is almost never considered in the context of decisions about funding scientific research or developing new technologies: the consequences for society's system of social stratification. Rather than cite a thousand or more political speeches and academic essays, one may frame this in terms of two simple but nearly unanswerable questions: Does the current economic system achieve justice, for example, rewarding people appropriately for their contributions to the common welfare? What effect would a given research project have on social justice – positive, negative, or none? In the most recent Converging Technologies conference, the most frequently cited example is the problem of whether the new information technologies may render more jobs obsolete than it creates, giving added advantages to entrepreneurs and computer engineers but leading to a net decline in human welfare as unemployment skyrockets (Brynjolfsson and McAfee 2011).

Some of the most challenging ideas about the ethics of science and technology come from groups of intellectuals who have little if any political influence and are not currently invited to participate in the making of public policy. For example, meeting in Paris at the Transvision 2014 conference, the Technoprogressive Caucus developed a set of ethical principles based on their own communications over the previous decade. One practical outcome was the proposition that government should provide all citizens with a guaranteed income, health care, and lifelong education, given that technology would increase unemployment, possibly to the point that few adults would have full-time jobs. The first clauses of their formal declaration did not use the word "convergence," yet were fully in accord with its principles:

> The world is unacceptably unequal and dangerous. Emerging technologies could make things dramatically better or worse. Unfortunately too few people yet understand the dimensions of both the threats and rewards that humanity faces. It is time for technoprogressives, transhumanists and futurists to step up our political engagement and attempt to influence the course of events.
>
> Our core commitment is that both technological progress and democracy are required for the ongoing emancipation of humanity from its constraints. Partisans of the promises of the Enlightenment, we have many cousins in other movements for freedom and social

> justice. We must build solidarity with these movements, even as we intervene to point to the radical possibilities of technologies that they often ignore. With our fellow futurists and transhumanists we must intervene to insist that technologies are well-regulated and made universally accessible in strong and just societies. Technology could exacerbate inequality and catastrophic risks in the coming decades, or especially if democratized and well-regulated, ensure longer, healthy and more enabled lives for growing numbers of people, and a stronger and more secure civilization.

Conclusion

Rather than dismiss ethical qualms about new technologies as too pessimistic or advocate one uniform code of social ethics on the basis of today's only fragmentary understanding, the logical response would be a substantially expanded effort in the social sciences. But if they are promoted in isolation, social sciences have a tendency to become ideological crusades, so any renaissance of social science will need to be integrated fully into more general science and technology convergence. Yet the current political and economic systems primarily support forms of research that benefit industry and finance, rather than benefiting all societal institutions equally. If the past millennia were marked by coevolution of human biology and technology, the future millennia may require coevolution of society and social science.

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Boundary Organizations

Michael E. Gorman

Contents

Abstract

Achieving the goals of the Convergence of Knowledge, Technology, and Society (CKTS) will require collaboration among scientists, engineers, social scientists, and ethicists. In order to work together, these expertise communities will have to agree on superordinate goals and form trading zones where they can gradually develop creoles. Moral imagination is necessary when incommensurable mental models separate parties who need to trade. This chapter imagines the development of a Convergent Technology Network (CTN) that serves as a boundary organization facilitating trading zones and moral imagination among the diverse CKTS communities, including policy agencies, NGOs, and other stakeholders.

M.E. Gorman (✉)
Science, Technology and Society Program, University of Virginia, Charlottesville, VA, USA
e-mail: meg3c@virginia.edu

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Introduction

The "emerging paradigms of convergence" that are critical to the Convergence of Knowledge, Technology, and Society (CKTS) include goals like ensuring a sustainable quality of life, empowering individuals and groups, and advancing societal progress (Roco et al. 2013). Achieving these goals requires convergence not only across multiple scientific and engineering disciplines but also humanities (especially ethics) and social and behavioral sciences. This convergence cannot be achieved by siloed disciplines, because problems like sustainability cannot be divided into isolated subproblems that correspond to disciplinary expertise.

Therefore, CKTS will require collaboration across multiple expertises. The focus of this chapter is on the capabilities necessary for this kind of collaboration.

Barriers and Goals

Academic scientists, engineers, ethicists, and social scientists acquire deep expertise not only in discipline but usually in a part of discipline. This deep expertise is essential to collaboration: when trying to solve a problem or take advantage of an opportunity that requires combining expertises, it is important to have the best possible experts involved. One barrier to such collaborations is the inability of experts in a community to understand the languages and concepts of another discipline. As we will see below, this problem can be solved, but it involves effort and time.

Most of the incentives for academic promotion, grants, and salary depend on one's individual reputation within an expertise community. Those who collaborate a lot early in their careers can be especially vulnerable when the time comes for tenure. So experts are rarely rewarded by the promotion system for the extra effort involved in collaboration. Notable exceptions include the Centers for Nanotechnology in Society at ASU and UCSB, which fund collaboration among younger as well as more senior scholars.

The social psychologist Muzafer Sherif coined the term superordinate to describe goals that require even hostile communities to work together. His proof of concept was inducing groups of boys to form rival gangs at a camp and then bringing them together by requiring them to solve problems with the camp's water and food supplies. The boys thoroughly enjoyed the camp and went home friends (Sherif et al. 1961).

A goal that affects the survival of groups or nations can make them into allies – and can mobilize experts from multiple communities. Consider the development of the atomic bomb or the global effort to ban CFCs in order to prevent the growth of an ozone hole in the Antarctic. Only the latter is truly a superordinate goal; the former is motivated by the threat of a common enemy, and Sherif observed that temporary alliances against an enemy often dissolve after the enemy is no longer a threat.

A **superordinate goal** requires an opportunity or threat that is obvious to all. Energy is one possibility (Smalley 2005). However, there are nations that have plenty of energy resources and ones who do not; energy is not a superordinate goal for all, unless one takes a long-term perspective. Global warming is a problem that is increasing in urgency, but again, its short-term effects are not obvious to all.

Even if groups can recognize a common superordinate goal, they may not be able to communicate about it. Kuhn called the most extreme form of this barrier the problem of incommensurability: scientists in an old research paradigm literally cannot understand ones in a new paradigm (Kuhn 1962). One of Kuhn's examples was the shift from a Newtonian to a relativistic universe. Kuhn used Gestalt psychology to explain a paradigm shift, but a more appropriate conceptual framework is the idea of a mental model, which is just what it sounds like: a model of the universe or a device or a problem that can be run mentally to predict outcomes.

Convergent technologies promise to develop capabilities that will be vital to addressing superordinate challenges in the future, including opportunities to improve the quality of life. Applications to enhance human performance can involve nanotechnology combined with biotechnology, information technology, and knowledge about human cognition. The convergence of these and other technologies – like robotics – will transform human capabilities. Here the potential for values conflicts looms large. For example, what happens if genetic and robotics enhancements are available only to the wealthy, leaving most of the worlds' population without the ability to keep up (see Gorman et al. (2013) for a discussion of this issue in education)? The affluent could become almost like another species.

These value disputes can occur between scientific paradigms: the accepted methods used by one field may appear totally unscientific to another, blocking any collaboration. The Toolbox Project is one solution to this problem (Eigenbrode et al. 2007). At the beginning of a collaborative project – say an interdisciplinary center – participants are given a questionnaire which probes their assumptions. Then they are shown each others' answers, which often produces surprising differences in assumptions and worldviews about what constitutes science. The participants are encouraged to reflect on and discuss these differences. Two philosophers knowledgeable about science facilitate this discussion. This kind of structure would be a good way to take the first step in moral imagination by getting participants to see each other's assumptions as views.

To deal with incommensurable stereotypes, values, and ideologies, trading zones must be accompanied by **moral imagination** or the ability to walk in another's shoes and see their mental models of how to live. The first step in moral imagination is to recognize that each of us has a view of the world, not an absolute truth. The second step is to compare these views or mental models in order to arrive at something better. The third step is to evaluate different courses of action that stem from the better alternative.

Note that moral imagination is not relativism. All beliefs about the structure of the universe, the future of civilization, and the potential risks of future technologies are subject to modification by debate and evidence.

Moral imagination is not easy. The views or mental models discussed here are the deepest ones, the ones that are regarded as truth, not views. They can be religious, political, or even scientific beliefs that are immune to falsification (Gorman 1992). The key is the first step: recognizing that one's truths are beliefs and can be modified in the light of evidence. The goal of moral imagination is not to get everyone to agree on a set of values; it is to turn unproductive intolerance of other ideas into a creative tension.

Trading Zones

The historian and physicist Peter Galison (in Gorman 2010) used this concept borrowed from anthropology to explain how physicists from different paradigmatic communities could work together on projects like the development of particle detectors and radar. In these cases, not only did theoretical physicists with different mental models have to work together; they had to coordinate with experimental physicists and with the engineers who would design and test the devices. In the case of radar, physicists also had to work with the military and anticipate the needs of pilots using radar in planes.

These different communities certainly began with apparently incommensurable mental models (Galison 1997). To explain how these communities learned to work together effectively, Galison borrowed the idea of a trading zone from anthropology. To trade, groups do not have to understand each other's mental models; they simply have to agree on goods to exchange.

The zone need not be a physical space; instead, it can be defined by the boundary system that the groups are trying to create, which might exist in one place like a superconducting supercollider or many in the case of radar in airplanes.

To create one of these systems, the different communities involved have to learn what each needs and how their part fits into a system that addresses the superordinate goal. In other words, trading zones are necessary when the work is not entirely divisible; some coordination and mutual understanding are involved. Therefore, participants in trading zones have to gradually develop a common language sufficient to conduct starting with a few shared terms or jargon, then a pidgin, and finally a creole which can be taught to others entering the zone. This creole can be the foundation for a new linguistic community; most of the world's languages emerged out of creoles, so did disciplines like biomedical engineering.

The CTKS call for "establishment of higher level languages. . .that can allow construction of shared terminology and concepts that are essential to multiple domains" (Roco et al. 2013, p. 3). These higher-level languages will emerge from the creoles formed in trading zones. The CTKS is recommending making this emergent process a goal, which implies coming up with methods for coordinating the development of creoles across trading zones. What shared terms emerge from one zone that could be used across the convergent landscape? (See the end of this chapter for ideas on how this coordination might work.)

Convergent technologies are a set of potential advances that can be mapped onto a number of superordinate goals. So the end result should be multiple goals and many trading zones. Consider how convergent technologies to enhance performance – like cochlear and retinal implants and even silicone neural interfaces – might transform education (see Gorman et al. 2013; Gorman and Groves 2007). For example, cochlear implants are already in use to restore hearing to the deaf. In the future, they might be used to enhance hearing, allowing those humans who could afford them to access a greater range of frequencies.

Trading zones also involve intercalation, which means that different communities involved in a zone advance at different paces. Galison's example is the way in which theoretical physicists, experimental physicists, and instrument makers (usually engineers) came from different communities, but could coordinate by means of trading zones. Each of these core communities advanced its knowledge and practices at different paces, with innovations inserted into the zone as they emerged. Richard J. Boland, Jr., Kalle Lyytinen, and Youngjin Yoo (2007) described this intercalation process in a study of how Frank Gehry's architecture firm used three-dimensional models to create innovative architectural designs; these models in turn served as a kind of visual creole when Gehry's firm worked with clients in the more traditional architecture, industry, and construction business, stimulating innovation in their design processes that intercalated across the communities. For example, Gehry's firm designed a novel curving roof for the Peter Lewis building in Ohio. The structural engineers received an award for a new way of creating a dramatically curved steel roof; the drywall contractor patented new ways for framing undulating walls, and the fire marshal developed new methods for smoke evacuation that were presented at a national training academy. The point is that each of these intercalated communities developed innovations spurred by the overall design. The ethics community would have to be part of trading zones working on human enhancements, and the debate over these and other CKTS issues would in turn stimulate advances in ethical theory and analysis.

Some CKTS advances will disrupt existing practices, creating an environment that places a high priority on the ability to rapidly adapt to a changing landscape of opportunities. Katherine C. Kellogg, Wanda J. Orlikowski, and JoAnne Yates (2006) use the example of a firm called Adweb whose creative, client services, and technology have to trade rapidly with each other and include the client. This is a highly competitive landscape in which there is no time to develop a stable linguistic creole; instead, coordination is done by means of rapid information sharing using PowerPoint as a common medium.

Galison's counterexample would be radar, where a creole had to be developed in a very fast-paced and constantly changing environment. The key difference is that in the case of radar, there was a critical superordinate goal: saving Great Britain from annihilation by the Luftwaffe. Adweb operated in a competitive environment without a superordinate goal linking the businesses.

The Master Masons who designed medieval cathedrals used molds similar to Gehry's three-dimensional models to illustrate designs; they depended on sketches, tracings on a special floor reserved for that purpose, and oral communications (Gies and Gies 1994). Drawings and three-dimensional models can serve the function of a creole, especially if the conventions for drawing and modeling vary across domains and have to be reconciled into a common format.

Anderson et al. (2010) propose a methodological commons that would serve the function of a trading zone linking humanities and technology. The commons include content most prevalent in the humanities – text, images, sound – and digital tools like hypermedia and ways of storing and analyzing text. This content is created by experts from different disciplines, so in order for them to work together, they will have to trade around a common goal. Anderson et al. cite the example of using multi-agent simulation to understand why a force of Seljuk Turks defeated a larger Byzantine army at the battle of Manzikert in 1071, an event which sparked the crusades. The agent modelers and the historians had to exchange knowledge, time, and resources.

Trading zones are most effective when they include some participants who have T-shaped or **interactional** expertise. A T-shaped professional has a core area of expertise in the vertical bar of the T and the other has the ability to understand and work with experts in the horizontal bar. The technical term for this is interactional expertise or the ability to speak the language of another expert community without being able to do their research (Collins et al. 2007).

Galison thinks the interactional expert masters the "outtalk" of an expertise community, i.e., the language the discipline uses to talk to outsiders (Galison 2010). Collins thinks that all experts have to gain interactional expertise in their own fields as a condition of becoming experts: acquiring expertise involves acquiring the language used in practice. The ability to talk to outsiders is not identical to the ability to talk to insiders as well as outsiders, so at this point, Collins and Galison differ. Collins thinks that interactional expertise is the mastery of the disciplinary language which every contributory expert possesses. Those that master the language of a discipline that is not their own are considered special interactional experts (Collins 2011).

The horizontal bar shows that a T-shaped expert has mastered the special interactional expertise of multiple disciplines. A T-shaped professional therefore can serve as a kind of agent or catalyst in a trading zone.

For example, Gorman (a psychologist) and Groves (a material scientist) did a pilot project to see if they could work with a graduate student to help her produce a Materials Science Master's Thesis that was motivated by solving a global problem – in this case, developing a nano scaffold that could hold blood cells, part of a research program aimed at curing atherosclerosis (Gorman and Groves 2007 (societal dimensions of nanotechnology (SES 0210452)). In order to function on the team, Gorman had to gain interactional expertise in Groves' area of nanotechnology, so that he could make suggestions about the research design and direction. It was Groves' outtalk that was particularly useful to Gorman, supplemented by Gorman's increasingly sophisticated questions.

Ethics

> Ethicists need to go into the lab to understand what's possible. Scientists and engineers need to engage with humanists to start thinking about this aspect of their work. Only thus, working together in dialog, will we make genuine progress on the societal and ethical issues that nanotechnology poses.
> Davis Baird, in testimony before the Senate Committee on Commerce, Science and Transportation, May 1, 2003

Baird's engagement is potentially different from Gorman's integration: Gorman was part of the research team (indeed, he obtained the funding for it), but Baird's ethicist could engage researchers at the point of dialogue without necessarily becoming part of the research team. The advantage to engagement is that the ethicist can keep his or her distance from the project; the advantage of integration is that an ethicist or social scientist's ideas become part of the project. Integration and engagement are best viewed on a continuum; what starts as an engagement can lead to integration.

Can ethicists gain sufficient interactional expertise to engage scientists and engineers doing cutting-edge laboratory research? Erik Fisher's Socio-Technical Integration Research project at ASU embedded PhD students with a Science, Technology, and Society (STS) background into 30 laboratories, at least two-thirds of which were doing nano-related research (Erik Fisher, personal communication, June 24, 2014). Integration implied that the social scientist or humanist become part of the team, and in most cases, this happened. Results from this project are still being analyzed for publication, but results from two cases suggest that the graduate students gained sufficient interactional and procedural expertise to dialogue deeply with one or more laboratory members who in turn gained some interactional expertise in STS and therefore had a new perspective on their laboratory activities and goals (for more details, see Gorman et al. 2014).

A Boundary System for Convergent Technology Engagement

Trading zones can involve organizations, not just individuals. There is even an organizational equivalent of interactional expertise: a boundary organization.

Interactional experts can function in a role similar to trade agents and boundary organizations' trading posts, which create a space (virtual or physical) where multiple cultures and expertises can exchange knowledge and resources facilitated by a trade agent. These trading posts can transform into markets if there are multiple goods and multiple parties. Markets can function across apparently incommensurable cultures if the goods are priced in currencies used by all parties. Trading zones can evolve into markets, or they can evolve into situations where multiple parties co-create a new system.

The National Nanotechnology Coordination Office (NNCO), for example, connects all the federal agencies involved in nanotechnology and also provides a bridge to other stakeholders. I worked on the NNI 2011 strategic plan as a representative from the NSF along with multiple agencies and the Office of Science and Technology Policy at the White House. We formed a trading zone. The main incommensurability was the different agency agendas, obvious to the members of a particular agency but not always to other agencies. No agency could agree to any wording that violated its congressional mandate, so we had to be careful about how goals were worded and, in the course of those discussions, learned a bit about the cultures of each agency. The participants in the meetings were very open to working together, but the management at their agencies would have to be convinced to follow the plan. The NNCO was excellent at facilitating this trading zone, listening, summarizing, provoking, and keeping discussions on task. Indeed, without the NNCO, it would have been impossible to have this kind of trading zone.

All participants agreed on responsible innovation as a superordinate goal, though there were lively debates about the language. Under heading 4.3 we agreed on three points:

1. Fostering a community of expertise on ELSI (ethical, legal, and social implications)
2. Building collaborations among these ELSI stakeholders and expertise communities to provide input on research directions and to enable prompt consideration of the social and ethical implications of research breakthroughs
3. Develop resources for ethical and societal issues related to nanotechnology intellectual property

The first two goals implicitly call for the creation of trading zones. The third would require trading zones among selected lawyers, researchers, entrepreneurs, businesses, government agencies, and other stakeholders in order to determine what resources were necessary and useful. A boundary organization like the NNCO can propose guidelines or standards that emerge from these kinds of trading zones. Guidelines or standards can form a boundary object or standardized package that helps align different agencies and stakeholders, but are also subject to different interpretations (Guston 2001).

The NNCO also served as a boundary organization linking the public to nano scientists, engineers, and policy-makers, as did the two Centers for Nanotechnology in Society, one at ASU and one at UCSB. Both of the CNS conducted research on how different segments of the public viewed nanotechnology and also conducted a variety of public engagement activities like nano cafes, focus group discussions, and surveys. For example, in March 2008, CNS-ASU held a National Citizens' Technology Forum (NCTF) on nanotechnology and human enhancement (Guston 2014), combining face-to-face and online interactions in a deliberative, participatory activity. The major goals were to:

1. Enable democratic participation via a sample of 74 citizens across the United States

2. Promote citizen deliberation on an emerging science and technology frontier before they had formed opinions about it

Bainbridge, in his chapter in this volume, discusses another kind of citizen engagement, in which some of the citizens conduct science themselves, adding useful data to a field and also learning about science themselves. A good example is the important role of sophisticated amateurs in astronomy (Gorman 2006). Citizens can also collect their own scientific data to check industry results on the amount of pollution they experience in their local area (Ottinger 2010).

The CKTS report calls for research designed to make scientists more aware of, and therefore capable of improving, their research processes. One process improvement would be to apply a more open-source model to science, allowing for exchanges of ideas and preliminary results before publication (Nosek 2012; Nosek et al. 2012). The Open Science Framework (OSF) aims to make scientific research more like open-source software development by allowing scientists to share each other's ideas, experiments, and data (see http://centerforopenscience.org/). All of the sharing is done in an online environment that records not only the date and time each idea was created but also when and by whom it was viewed, therefore preserving priority. The scientist has control over how much or little to share and with whom.

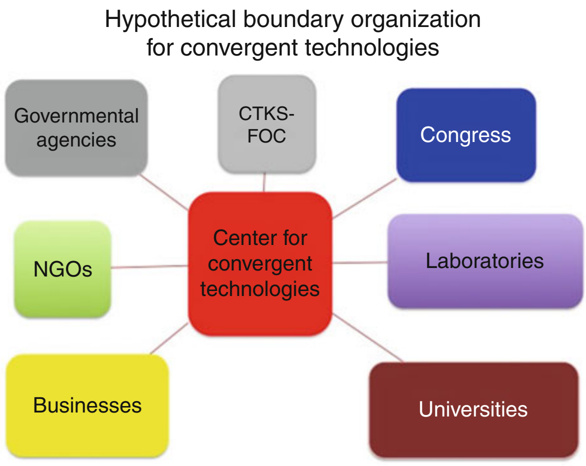
Psychologists of science could access the data on the scientific process, given author permission, and conduct research on what research processes were most effective for different kinds of problems. The OSF does not include tools that encourage metacognition or the awareness of one's own problem-solving processes. An example would be ways of constructing visual representations of the scientific research process (Gorman 1992) in ways that would not only promote metacognition but also facilitate public sharing of processes as well as results.

A Boundary Organization for CKTS

> Competent social scientists should work hand-in-hand with natural scientists, so that problems may be solved as they arise, and so that many of them may not arise in the first instance. (Bronk 1975, p. 413)

There is no equivalent of a boundary organization with the scope of the NNCO and the CNSs for convergent technologies, though the CTKS-Federal Convergence Office (FCO) proposed in Roco et al. (2013) might serve the NNCO function. This section includes ideas for an equivalent of a CNS that would coordinate engagements with multiple policy and scientific arenas. At the center of the diagram in Fig. 1 is the FCO with a Convergent Technology Network (CTN) attached; the CTN represents a boundary organization which would create a trading zone among the domains connected to it by lines. The CTN could be funded like a center that would train and support science technology practitioners – including ethicists – who would be embedded in exemplars of each of the domains

Fig. 1 The Convergent Technology Network could serve as a boundary organization creating a trading zone among the organizations connected to it by lines. The Center for Convergent Technologies could grow out of the Network and serve as a research center which would supply STS scholars that could embed in specific businesses, agencies, NGOs, congressional committees, etc.



that focused on convergent technologies: perhaps the House Science Committee, a group like the NNCO that was itself a boundary organization for agencies, an NGO that was critical of convergent technologies and another that was supportive, a patent foundation at a university trying to obtain intellectual property in the convergent technology space, and the CTKS-Federal Convergence Office, with which this center (or network of centers) would work closely. All of these embedding experiences would be coordinated by the CTN, which would provide feedback and advice to the CTKS-FOC. Eventually, other organizations might ask for embedded STS practitioners; the CTN would help locate, train, and support them. In this manner the network might gradually expand. The CTN would facilitate coordination from the bottom up, by means of embedded STS scholars who would ask the sorts of questions that promote reflection and collaborate on the answers. These embedded STS scholars to use the Open Science Framework to record their questions, the process of obtaining answers and also note signs of the emergence of a linguistic and/or visual creole. Linguists could help analyze these creoles, look for commonalities, and share these with the engaged communities with the goal of creoles that would facilitate connections across CKTS.

The CTN would play an important role in **anticipatory governance**, which is the ability to construct possible future scenarios for convergent technologies, imagining the moral and political consequences (Guston 2014; Barben et al. 2007; Guston and Sarewitz 2002). Consider, for example, the possibility of a rich/poor gap in access to human enhancement technologies, making the wealthy almost a different species from the poor in terms of cognitive and physical capabilities. Scenarios like this can be developed in detail and then subjected to public deliberation, be evaluated by panels of experts from different backgrounds (see Fauss et al. 2011 for an example), and be posed as challenges to regulatory agencies (Wardak et al. 2007). A good example is Oreskes and Conway's (2014).

The Collapse of Western Civilization, which is an imaginary account, supposedly written in about 2020, of why global warming was allowed to disrupt civilization. One of the causes was the lack of collaboration among the natural, social, and behavioral sciences. Global climate is a tightly coupled natural, human, and technological system that cannot be understood by looking at each of these three dimensions separately (Allenby 2012).

Anticipatory governance includes looking for signs that a scenario like Orestes & Conway's is becoming reality and taking steps to avoid it. Imagine applying CKTS to the development of options to reduce the probability of global warming now while the effects are still manageable and perhaps reversible. Collaborative trading zones across disciplines, stakeholders, and institutions are essential in anticipating these kinds of scenarios and also developing metrics or indicators that will signal which (if any) of these possible futures is emerging as the sociotechnical system evolves.

Anticipatory governance can lead to regulations guaranteeing access to some technologies and limiting the use of others, but these regulations should be **adaptively managed** (Allenby 2012), which means their impact on stakeholders and the system should be continuously monitored. Some of these regulations could be introduced experimentally in populations who volunteered to try them. Embedded CTN practitioners could observe, interact, and encourage reflection on these experiments.

A Convergent Technology Network could create the equivalent of a larger-scale trading zone by embedding social scientists and ethicists with appropriate interactional expertise into organizations that need to work together to achieve common goals. But even if an overall boundary organization cannot be created, multiple engagement experiments in different parts of the CKTS landscape can be conducted and results compared at workshops and conferences. Engagement could turn into integration and even collaboration in some of these cases.

Efforts are underway to create the capabilities and tools necessary for embedding STS participant observers into multiple organizations involved in CTKS. Communities of Integration Workshops whose goal is to bring together researchers who either are doing or preparing to do this sort of integration were held at ASU in 2013 and at the University of Waterloo in 2014.

Conclusion

This chapter makes the case that methods designed to ensure responsible development of convergent technologies are also optimal methods for collaborating across scientific and engineering domains. Humans have a long history of trading across deep cultural divides. These trading zones are essential for the development of CKTS. A boundary organization that acts as a catalyst could build understanding and a common language across these trading zones.

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Cognitive Society

Aude Oliva and Santani Teng

Contents

Abstract

The Cognitive Society is one in which ubiquitous, convergent cognitive technologies inform human decisions, actions, and health. In this chapter, we consider the impacts of current and future knowledge in human and machine cognition on a society in which the culture, including popular opinion as well as the educational curriculum, has significantly incorporated the findings and methods of cognitive science. We introduce the cognitive envelope, a framework allowing the mapping of spatiotemporal interactions of technology and cognition and examining the temporal and spatial scales over which we have cognitive access. Beginning with contemporary technology and projecting to the future, we draw the trajectories of three scenarios of speculation, in perceptual, cognitive, and social realms, which have the potential to reshape the cognitive envelope to twenty-first-century needs. As the convergent technology landscape unfolds, a rising science of cognition will provide decision-makers with the tools

A. Oliva (✉) • S. Teng (✉)
Computer Science and Artificial Intelligence Laboratory (CSAIL), Massachusetts Institute of Technology, Cambridge, MA, USA
e-mail: oliva@mit.edu; santani@mit.edu

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to choose the best outcomes for a Cognitive Society that would promote competitiveness, health, and security to individuals and nations.

Introduction

Everything that we formerly electrified we will now cognitize. (Kelly 2014)

By any account, humanity's rate of technological progress has been breathtaking: in 1969, the single, inadvertently prophetic word "login" became the first message ever to travel between two connected computers. Today, 10 billion devices routinely access a vast cloud of near-ubiquitous knowledge and connections; by 2020 the number is projected to reach up to 75 billion (Riggins et al. 2015).

Meanwhile, the field of cognitive science, progressing in intimate parallel with computing technology, has facilitated major advances in our understanding of brains, minds, and their constituent operations. As a result, today we stand at the cusp of producing a *Cognitive Society*, where knowledge-based cognitive processes, natural and artificial, underlie the functions around which human activity is organized.

In many respects, the materials required to forge a society where interconnected objects are integrated into real-time thinking are already in place: the quasi-unlimited knowledge store of the Internet, the burgeoning speed and complexity of available computational power, and the growing scope of online devices are likely to accelerate the rate at which our society changes. These devices will interact with the environment, react to events, and anticipate outcomes faster than human awareness at both individual and global levels.

In fact, we already live in an incipient Cognitive Society. The rise of cognitive science and neuroscience has given study of the brain a cultural, rather than just scientific, significance (Olds 2015). It is commonplace to talk casually about the "pleasure center" or "visual center" of the brain, reflecting a popular acceptance of the neuroscientific principle of modular neurocognitive functions. Cognition as reflected in brain function has gained traction in the form of neurophysiological measurements as evidence in legal cases, albeit controversially so, with neuroimaging scans interpreted as indicating deception or psychopathy (Gazzaniga 2008). At a clinical level, neurodevelopmental disorders with cognitive components, such as schizophrenia and autism spectrum disorder, are now widely accepted as originating in disordered brain function rather than, for instance, psychological trauma alone. Thanks largely to the explosion in available computational power, artificial systems incorporating cognitive principles or functions have also become increasingly prevalent. Far from being an abstraction or far-off prediction, artificial intelligence in various forms has embedded itself into daily life, particularly so for any person equipped with an Internet connection. Deep learning algorithms (LeCun et al. 2015) can now recognize objects and places, read, identify voices, and even predict human memory.

Reflecting this convergence of technological and cognitive progress, our working definition of a Cognitive Society includes a ubiquity of convergent cognitive technologies that are leveraged to enhance human decision-making, well-being, and public health. What does it mean to live in a Cognitive Society? How can we think about the implications of a vast range of human-technology interactions in cognitive terms? What does life in such a society look like, both currently and in the speculative future? In this chapter we will address these questions with illustrative scenarios and the framework of a *cognitive envelope* to conceptualize some of the consequences of human and artificial cognitive interactions.

The Cognitive Envelope

Cognition in the broadest sense is both a straightforward and elusive concept. Intuitively we think of cognition as thinking – "the ultimate brain function" (Robbins 2011). In the context of artificial systems, cognitive computation must be both fast and complex. To speak concretely about the implications of cognitive computation to the Cognitive Society, we propose to sketch a *cognitive envelope* that places the broad concept of cognition within pragmatic dimensions of time and space.

Human thought and action operate on a wide range of time scales: an individual episodic memory, for example, may take fractions of a second to retrieve, seconds to select from among others, minutes to write down, and a lifetime to forget. The concept is not new to cognitive science: in building a case for a universal theory of cognitive architectures, Allen Newell (1990) divided human activity into four "bands" – biological, cognitive, rational, and social – spanning 12 orders of temporal magnitude between 100 μs and several months. For Newell, the range from about 10 ms to 1 s was key for basic cognitive processes and was thus labeled the cognitive band. As Newell himself pointed out, these boundaries were approximate; for our purposes, the bulk of cognitive psychology and neuroscience experiments place critical cognitive processes in this range, up to several seconds.

Cognition has a spatial as well as a temporal scale. This notion is common within the field of embodied cognition, which posits, e.g., that cognition is situated in relevant real-world contexts, optimized for motor action, and sometimes "offloaded" to the environment (Wilson 2002). It also finds traction in the neuropsychology literature, with evidence of distinct cortical networks supporting different behaviorally relevant realms. For example, space within arm's reach has a different behavioral relevance, and thus likely a different cognitive role, than does space at an unreachable distance (e.g., Previc 1998). Notably, the various models reviewed by Previc (1998) and others tend to limit space for interaction to a radial distance of a few tens of meters. For our purposes, the intuition to extract from this body of research is that space matters to cognition and that the interactions for which cognition is most relevant tend to occur on the order of 10^1 m or less.

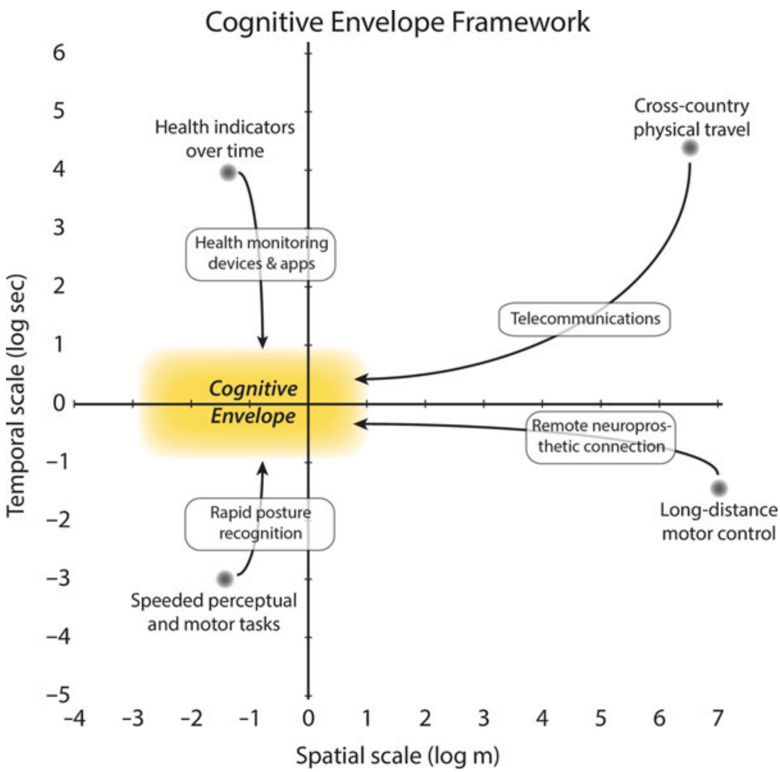

Fig. 1 Illustration of the temporal (in log seconds) and spatial (in log meters) bounds of the cognitive envelope in relation to other processes in the world tied to space and time. The framework facilitates thinking about the kind of technology that would bring specific processes within the cognitive envelope. *Labeled arrows* indicate examples of technology that mediate transfer of these processes into the typical human cognitive envelope. The broad envelope of cognition is centered on the familiar scales of 1 s and 1 m

We can thus concisely circumscribe cognitive processes in a two-dimensional logarithmic space, centered on the familiar scales of 1 s and 1 m, as shown in Fig. 1. This also allows us to examine how technology modifies those constraints and how artificial cognitive systems might compare when doing similar processing.

The cognitive envelope provides a framework to the idea of untapped potentials for systems, natural and artificial, to evolve or enhance human reach. Today, the ubiquity of Web-enabled devices allows people to send a much larger amount of information than even a few years ago. Consider the examples in the four quadrants surrounding the human cognitive envelope in Fig. 1. In various ways, each of them is brought closer to the typical cognitive envelope by convergent technology. The point at the upper right indicates the rough parameters of a cross-country flight in the United States – about 6 h to cover some 4100 km – and represents the minimum practical time to transport physical items or people over this distance. Many of the exchanges that once required travel are mediated by modern communication technologies that bring conversations, images, documents, and so on into a recipient's immediate reach in nearly real time. Illustrated on the upper left, health tracking mobile apps and wearable monitors, for example, can generate and maintain an ongoing record of personal metrics such as steps walked, heart rate, or sleep patterns. The data is not just available to healthcare providers but to users directly. The aggregation of historical data over days, weeks, or months can be more useful than any given instantaneous measurement but presents an impractically tedious sustained attention task to perform manually. Thus, the cognitive load of repeated, regular measurements over long periods of time is transformed into data available at a glance to a device within easy reach.

Many processes, both natural and artificial, operate at short time scales unavailable to conscious perception, i.e., below the cognitive envelope. Represented by the lower left example in Fig. 1, an artificial robot system comprising a three-fingered hand and high-speed camera can achieve a perfect winning record against a human in repeated games of rock-paper-scissors (Katsuki et al. 2015). The implications of this seemingly innocuous example are profound: the robot can perceive the human player's gesture and react accordingly in less time than it takes the human player to complete her own move. Thus, a game premised upon unpredictable decisions, driven essentially by chance, becomes wholly deterministic. In this way, small interactions between humans and artificial systems take on a fundamentally different character from a perspective inside versus outside the cognitive envelope. Finally, at lower right, sub-perceptual speed of processing can span large distances as well. As part of a research program in neural prostheses at Duke University, a monkey in the United States was able to remotely control a walking robot in Japan using implanted neural electrodes (Cheng et al. 2007). The signals traveling from the monkey's brain reportedly reached the robot, over 11,000 km away, 20 ms before arriving at the monkey's own leg. Thus, through this high-speed fiber-optic connection, an artificial motor system on the opposite side of the planet was integrated into the monkey's own cognitive envelope as she controlled the robot using her own motor cortex and visual feedback from a video feed. This demonstration illuminates the possibility that technology can enable cognitive-level operations (in this case, deciding to initiate or stop a motor movement) even across distances otherwise inaccessible to real-time cognitive interaction.

While the cognitive envelope framework is illustrated along two salient dimensions, cognitive operations are necessarily complex and likely to exist in a high-dimensional space. Yet a computer performing a billion floating-point operations in 1 s is not automatically equivalent to a human performing a cognitive act in 1 s. Thus, a third dimension could capture complexity or "cognitive capacity," some measure of not just the time and spatial scales of cognitive processes but of their sophistication.

Operationalizing cognitive capacity, especially into a meaningful single dimension, is difficult at best. However, intuitively, a Cognitive Society should be able to characterize, to some extent, the relationships between artificial systems, biological cognition, and the common principles underlying them. As with the two-dimensional cognitive envelope presented above, a three-dimensional model provides an intuitive representation of the space that cognitive processes inhabit and that human-technology interactions can traverse.

We can speculate on the possible expressions of cognitive capacity. For example, information such as the time of day, the distance to an obstacle, or the number of people in a crowd is difficult to estimate quickly unaided, but does not comprise very different operations from what a human would conduct over a longer time scale. A head-up or other augmented-reality display would therefore present this information into a user's cognitive envelope across time and space, but not capacity. By contrast, humans have many well-documented limits on cognitive capacity: remembering or visually tracking more than a handful of moving items simultaneously will tax a typical person to the point of near-certain errors. Cognitive tasks such as mental rotation or continuous attention, critical to monitoring surveillance, defense, or medical imaging equipment, are also subject to systematic performance limitations. Wearable or prosthetic artificial devices without such limitations could, for example, bring a 20-object tracking capacity, occurring over the same time and space scale as tracking three objects, into a user's cognitive envelope via the capacity axis.

In the next decade, we will likely witness an era where technology will compress or expand time, space, and capacity, to bring remote information into our cognitive envelope. Transformations like these are among the most direct embodiments of the oft-heard sayings that "the world is shrinking" or that "life is speeding up." In a Cognitive Society, the technologies mediating these distortions will become increasingly pervasive, and the consequences of leveraging them, positive and negative, must be taken into account. In introducing the cognitive envelope, we saw the effects of some current technologies, such as Internet ubiquity, biometrics, connected devices, computer vision (and other artificial intelligence) algorithms, and neuroprosthetic interfaces. In the next section, we explore their implications for coming generations of technology merging cognitive and computational principles.

Expanding the Cognitive Envelope

The future is already here—it's just not very evenly distributed. – William Gibson

Smartphones, wearable devices, and other technology continue to provide ever closer and more abundant human-technology interactions in daily life. The act of using an interface itself becomes a bottleneck; hence, efforts to make interfaces more efficient, ergonomic, and "natural" – autocompleting – form fields, search predictions, natural language voice interfaces, gesture recognition, and so on. We might say that a goal of user interfaces is to bring technological operations near to, or deeper within, our cognitive envelope. Recent examples of wearable technology exemplify this trend. Google Glass, Microsoft HoloLens, and similar peripherals project a virtual overlay of data onto the visual world, effectively integrating themselves with the user's perception.

Perceptual Realm: Sensory Prosthetics and Substitution

Beyond integrating with the user's senses, *becoming* that sensory input is the function of sensory prosthetics and substitution devices (SSDs), a class of peripherals whose main goal is to ameliorate the consequences of sensory loss, typically blindness or deafness.

Sensory prostheses attempt to reproduce sensory input lost to injury, disease, or abnormal development. For example, a neuroprosthetic device may capture a visual image and emulate the elicited photoreceptor signals in the case of retinal injury or degenerative disease. The signals would then be transmitted to intact cells using electrodes or optogenetic stimulation (e.g., Nirenberg and Pandarinath 2012). The principle is straightforward, though in practice it is extremely difficult to mimic the complex neural patterns into which sensory information is transduced. Still, currently available sensory prostheses offer crude approximations to the visual functions they replace.

In contrast to sensory prosthetics intended to reproduce the lost sensory input, SSDs operate by converting visual input, such as that from a camera, into a preserved sensory modality (Bach-y-Rita et al. 2005). SSDs for blind persons typically present a visually captured environment in auditory or tactile format. With training, SSDs can be used as aids in navigation and object perception (Maidenbaum et al. 2014). Crossmodal neuroplasticity is amenable to sensory substitution: the brain reorganizes functionally to process nonvisual input in traditionally visual processing regions (e.g., Amedi et al. 2007; Merabet and Pascual-Leone 2010). Importantly, ongoing neuroplasticity in adulthood would also serve the function of *maintaining* sensory and motor functions, known to weaken with aging.

The research community in assistive technology via sensory substitution is recognizing a persistent gap between laboratory-based advances in sensory substitution or maintenance and the widespread usage of such devices in the general population. Put simply, virtually no sensory substitution devices for low-vision and blind persons pass the filter from research labs into real-world usage (Elli et al. 2014). Researchers have begun to identify factors in design and application that could bridge this gap (Maidenbaum et al. 2014), and as with retinal prosthetics, a detailed understanding of not just raw sensory pathways, but *how the brain represents incoming sensory information* is critical to this advance. Understanding the relationship between sensory information and neural representation will be important not just for devices designed to reproduce or substitute for human sensory functions, but eventually for advanced sensory augmentation as well – the technologically mediated expansion of existing, rather than missing, sensory capabilities (Di Pino 2014).

More generally, researchers in fundamental neuroscience have begun to characterize population-scale patterns of information in the brain at a level of abstraction that can be compared across vastly different types of data and species. While this approach has only very recently been applied to the study of sensory loss and brain plasticity, it may prove a critical platform for the convergence of engineering with fundamental cognitive neuroscience research.

Cognitive Realm: A Mnemonic Neuroprosthesis

Within the framework of the cognitive envelope, the logical extension of a sensory substitution interface would be one in which data is accessed or communicated as fast and effortlessly as internal thoughts. Personal electronics and contemporary sensory prostheses are still crude when measured against this standard (a seed of this technology can be seen when our phones and calendars remind us what to do), but an environment in which such interfaces are commonplace would surely constitute one strong convergence technology aspect of an advanced Cognitive Society.

Although we are far from a neuroprosthetic that would encode and retrieve memories as fast as, or faster than, a human brain (but see Berger et al. 2011, for a rat hippocampal prosthesis), such a device could alter the perceived flow of time, as in the rock-paper-scissors robot example (Katsuki et al. 2015). Potentially this could also improve decision-making by allowing more computations to be available in less time than before.

One of the most dramatic differences between natural and artificial cognition may involve the perception of time: subjectively perceived time may exist differently in an artificially modified mind. To put time in perspective, an artificial device producing one cognitive operation per nanosecond could "experience" 30 years' worth of subjective time in one objective second. Because the relationship between the speed of mental operations and time perception is not clear, how and if an artificial device would alter time perception itself is an open question.

Nevertheless, neuropsychology work demonstrates that distortion of perceived time over several orders of magnitude can occur in the human brain, especially as a consequence of injury or disease. For example, in addition to deep amnesia, patients with bilateral damage to their hippocampi, a neural structure important to memory, also experience compressed time, temporal disorientation, and an inability to predict their own futures (Dalla-Barba and La Corte 2013). The most striking example is Henry Molaison, the famous patient H.M., who became amnesic after his hippocampi were surgically removed to save his life. H.M. is best remembered for his memory loss, but psychophysical data suggest that he may have also experienced an extreme form of time compression, in which a year for us may have corresponded to three subjective hours to him (Richards 1973).

While the hippocampus subtends many memory and spatial cognition functions, including the ability to place information into a temporal context, it is also a fountain of cognitive youth: *neurogenesis*, the continuing addition of new neurons in the adult brain, allows the storage of new experiences (Aimone et al. 2006). Importantly, this turnover generated by the dentate gyrus, a subregion of the hippocampus, is barely affected by age, with older adults producing almost as many new neurons as young adults. The impact of neurogenesis on cognitive functions is a subject of active debate, with unanswered questions including the potential costs of adding new units to a fully developed network (Mongiat and Schinder 2014). However, models suggest that increasing the number of codes in a system would increase memory capacity and reduce interference between existing memories. Importantly, changing time perception, for instance, by increasing the number of codes and/or the speed of access to information, is within the brain's plasticity capacity, which suggests that the shape of our cognitive envelope may very well adapt to new technological influences.

Social Realm: Interconnected Devices and People

Beyond individual augmentation, the emerging network of interconnected, Web-enabled devices – the so-called Internet of Things (IoT) – is poised to connect people and artificial systems to an unprecedented degree, influencing everyone, everything, and everywhere. Far-off technology will become commonplace: personalized medicine will be a highlight of the Cognitive Society, possibly in the form of drugs tailored to individual genomes and body-based sensors that monitor vital signs. Beyond the self, one significant net effect of IoT to the economic reality of the Cognitive Society will be a massive reduction of waste: for instance, today, with ride-sharing companies like Uber, car supply and fares are dynamically updated based on demand. Waste and error reduction will impact everything, as it currently impacts lean management, automated inventory, and responsive supply chains. The movement of people, goods, ideas, knowledge, and information will be guided by accurate information, winkling out errors and waste associated with decay, an intrinsic part of "inventory."

At the center of the amplified connectivity realm, through the proliferation of smart sensors and massive data centers, is the "connected individual" who will use IoT as a platform to extend her sensory environment. The result is much more than the sum of its augmented parts: it is an extended self, able to act into a larger scope of the temporal and spatial physical world, changing our perception, and so reality, of what intuitive physics, causal reasoning, and determinism are.

A striking aspect of the Internet of Things is that it will be invisible to the naked eye and dauntingly to people's naked awareness. Most external devices (e.g., phones, wearables, personal computers, monitoring systems, etc.) will be communicating with us and on our behalf, facilitating interactions between physical and virtual worlds at a pace far exceeding the capacity of a human brain. A result of hyper-dynamic regime changing faster than consciously followed is an illusion of continuity to the human brain, which may be countered by devices seeing, hearing, sensing, and informing us outside the standard bounds of the human cognitive envelope.

In this hyper-dynamic world, human mental resources, or attention, will become the scarce and limited resource, probing the human cognitive envelope to reshape in order to deal with information at stretched spatial and temporal scales.

The Cognitive Society: A Society of Knowledge

We envision that a Cognitive Society would take seriously the principles on which individual human cognition is based. This suggests that such a society would value the acquisition of knowledge to create new knowledge and incorporates the principles of cognition, some described here, in its devices and functions.

Understanding cognition on an individual level facilitates communication between natural (i.e., brains) and artificial systems, resulting in improved interfaces, devices, and even neuroprosthetics for healthy as well as injured or disabled people. Neurally inspired algorithms in search engines and computer vision systems already play an important role in present-day efforts to organize information. Ultimately, understanding and applying cognitive principles at a societal level will bring about positive policy changes in education, health-related, and legal systems, which have always tried to account for the drivers of human behavior but have lagged behind the state of the art in understanding those drivers.

Several other outcomes may emerge as the shared knowledge of a Cognitive Society becomes increasingly comprehensive, reflecting a greater diversity of sources. Importantly, such knowledge enables enhanced and more precise predictions. Future events will become predictable at larger spatial and temporal scales, through the collective "cognition" of the devices that connect our independent experiences. This may in turn facilitate increased individual cognitive capacity, as outsourcing tasks to artificial systems frees up cognitive bandwidth. In short, the IoT may have the potential to enable a sort of *cognitive genesis* in which individual minds find themselves enhanced with novel abilities, extending the reach of their cognitive envelope in time, space, and capacity. Finally, greater knowledge will also be beneficial for understanding the goals and beliefs of other individuals and cultures (i.e., theory of mind). As a much greater fraction of the population will share the same living legacy and as convergent technologies allow people to connect over larger bands of spatial and temporal scales, the bonds of common experience and empathy will transcend geographical constraints.

Conclusion

The examples and scenarios discussed here illustrate that the principles and practices of a Cognitive Society are not just speculations on an uncertain future but extrapolations of the present. These signals can be found in individuals and swaths of populations with access to the resources that living in a Cognitive Society demands. Yet they have been slow to distribute vertically to the levels of policy and horizontally to all corners of society. Thus, pockets of such a society exist but in embryonic form.

Additionally, the above examples underscore that we are still far from the synergistic interactions envisioned in a mature Cognitive Society. Some of the technical hurdles are clear: as the number of connected devices explodes, the infrastructure supporting them will be taxed. Neuroscientifically, the computational principles of cognition and perception, crucial to successful interaction with artificial devices, remain incompletely understood. Culturally, there remains a shortfall in education, despite increasing inroads made by cognitive science. This is partly because neuroscientific knowledge has lagged behind enthusiasm in reaching the rest of society, but more fundamentally, because cognitive science and cognitive neuroscience are themselves still maturing fields. One consequence is that research findings may be incorporated into popular opinion and education but in oversimplified, misinterpreted, or simply incorrect ways. For example, popular opinion has largely embraced a "left-brain/right-brain" dichotomy between analytical, logical reasoning and creative, emotive thinking – a vast exaggeration of empirically supported interhemispheric differences (e.g., Kaufman 2013). A more recent and general phenomenon has been what critics call "neurobabble" – the excessive invocation of brain activation to explain phenomena that do not require such an explanation (e.g., McCabe and Castel 2008). In the case of sensory substitution devices for blindness, a telling detail is that despite decades of research and development, none have yet reached widespread use and distribution. They require refined engineering as well as an understanding of cognitive and perceptual principles at a fundamental level. On both counts further research is needed.

The many research fields comprising cognitive science must be able to deliver relevant, ecologically valid, and conclusive research findings to serve as the basis for policy decisions. In this way, a fully realized Cognitive Society will incorporate principles of cognitive science at an advanced level, to all members of society, in a critical and self-correcting fashion. In other words, to paraphrase William Gibson, it will distribute the future evenly.

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Convergence in Ethical Implications and Communication of Emerging Technologies

David M. Berube and Christopher L. Cummings

Contents

Abstract

With unending calls for interdisciplinarity to solve difficult social problems, the drawbacks of interdisciplinarity have received much less attention than it deserves. This chapter examines the proliferation of marginal expertise at decision nexuses. As problems become more entangled in the sensibilities of a global world and multicultural world with incoherent, inconsistent, and sometimes contradictory value systems, the demands for input from the expert sphere will be maintained, if not increased. The public remains dependent on experts for entry points into discussions and debates about a host of scientific and technological problems. When the expert community is challenged by the profusion of marginal experts and expertise, we cannot expect the expert sphere to understand and represent public interests. This chapter begins to examine this phenomenon and offers support for some of the premises underlying the observation that the expert sphere may not be benefitted by the incessant mantra of

D.M. Berube (✉)
Department of Communication, North Carolina State University, Raleigh, NC, USA
e-mail: drdmberube@gmail.com

C.L. Cummings
Nanyang Technological University, Singapore, Singapore

W.S. Bainbridge, M.C. Roco (eds.), *Handbook of Science and Technology Convergence*,
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interdisciplinarity. Finally, this chapter begins a serious discussion of the downside of interdisciplinarity that seems to have been undervalued by most criticisms.

Convergence has multiple definitions. In terms of interdisciplinarity, it seems to involve the association of multiple disciplines to approach a problem. The disciplines converge for a purpose. Sometimes the purpose is economic and entrepreneurial. For example, advances in microscopy, material sciences, chemistry, and so forth came together to move inquiries into nanoscience to the surface as a new field, much like what happened with biochemistry and environmental science. Sometimes convergence refers to a response to disambiguate a problem that may demand different sensibilities from dissimilar disciplines. For example, climate change is more than a function of science and engineering involving issues such as communication, economics, and politics. There has been a tendency to look at some of the solutions to some of world's greatest challenges as intrinsically cross-disciplinary. Convergent cross- or even interdisciplinary activities put increasing pressures on the expert sphere whose members must operate and communicate in subject studies about which they may be less familiar.

The role of experts has been challenged on many levels. For example, recent experience in the human evolution and climate change debates in the USA has politicized the debates such that facts are rebutted as opinions. Intelligent design competes with evolution in explaining the origin of the human species for the minds and hearts of young people. Paleo records are viewed as tests sent by a Supreme Being. Climate change has been frustrated by a noisy hockey stick model of temperature and carbon dioxide rates and some minor e-mails from East Anglia. Deniers find solace is offering scientific uncertainty, the sine qua non of science, as ignorance and misunderstanding.

Scientists want the public to understand science, but the public simply do not nor do they want to learn more about science. The deficit theory of science literacy that argues more science converts disbelievers into believers has marginal utility (Sturgis and Allum 2004; Scheufele 2006). Trying to make the public into scientists is not the way to open entry points for them in debates over applied science and technology. We have learned narratives and anecdotes (Dodge et al. 2005) as well as high-quality visualizations (Burri and Dumit 2008) may increase and improve understanding much better than simply providing the public more information.

The public whether intentional or not have found themselves mostly uninterested in all things scientific unless it relates to a subject close at hand and immediate (Prelli 1989) or is associated with an epiphany (Schneider et al. 1998) brought on by some event in their lives or their near-phobic relationship to death, pain, dread, sadness, or worry. In addition, the public are not homogeneous or even easily segmented, so tailoring communication strategies is problematic.

As technologies converge, we can presume increasing levels of complexity as more and more of the public fail to understand how things work and whether the technologies have significant chronic risk signatures. The public may not understand how their central air conditioning unit works or what is happening when they get an MRI; nonetheless they are happy to be cool in the summer and learn they do not need surgery. The public's relationships with technologies, by and large, work this way. However, as technologies begin to converge, we will experience problems in the expert sphere as well as the public sphere.

The public sphere has been defined over and over again (Habermas 1962). Its roots can be traced to white male landowners who met in public settings to discuss and decide affairs of state. They read pamphlets, if they could read and if they were available, listened to gossip and the opinions of others, and debated. We would like to believe they behaved much like the ruling bodies of ancient Greece. Political theorists and philosophers argued about what they did and whether they mattered since the public sphere surfaced as a hypothetical entity. The public sphere stood in opposition to the clergy and the elites. The elites began as wealthy families, sometimes monarchs, and in time they evolved into industrialists and scientists.

The expert sphere was loosely constructed in the late nineteenth and early twentieth centuries. Advancements in industry (both wartime and peacetime) supported by work in science and technology in both nonprofit (universities) and profit (corporate) venues produced political and bureaucratic leaders who needed technical expertise about which they knew and understood some, little, or none. The expertise became important in building, debating, and resolving technical policy disputes. To fill the need for this level of information and data, a class evolved and they constitute the expert sphere. They have appointments and credentials. They comment and write commentary. They are mostly self-appointed and other times recognized by others as experts. They belong to professional organizations, including nongovernmental organizations, and disciplinary societies and teach in graduate and doctoral university programs all over the planet. They are not the media, by and large, though some are employed by media and solicited by media to comment on their fields of expertise. The expert sphere is a semiprofessional group of thinkers and commenters who provide opinion in subject areas that are scientific and technical in nature usually outside the knowledge sets of the public and political/administrative spheres.

The chapters in this volume suggest that technological convergence not only offers promises and opportunities but also costs and risks. The following examines what roles, if any, the public sphere (if it exists at all) will play in convergence and, more importantly, what we can expect from the expert sphere.

Students in the social science who have studied public engagement generally agree the public, however we choose to define them, are generally underprepared to participate critically in assessing most technological developments and applications. We want to add: the expert community, the expert sphere, is becoming smaller especially where convergence involves many different disciplines such that top experts in one discipline may be marginal experts or not experts at all in another discipline. Of course, this becomes problematic when the converging technologies involve two or more disciplines.

The role of the expert sphere could not be more important. Innovation is affected by how well convergent partnerships between different technologies are managed.

However, when the convergence is driven by forces about which we have little experience, then innovation becomes premised on unknowns and speculations making planning especially difficult and potentially dangerous.

The Public

Scholars in the social sciences have established that the public knows very little about advanced technologies, including nanoscience and nanotechnology, synthetic biology (PEW 2008, 2009), etc. What they know is heavily mediated, and what is known about what they know comes from surveys where they are asked to self-report their understanding or from outreach experiments where they are approached with some small set of information, primed, and then asked to opine. As such, researchers may know something about how they perceive science and technology, but researchers know very little about why they feel the way they do. From such studies we learn that someone's political affiliation or degree of religiosity may be associated with the attitudes they may hold, but we are generally at a loss to explain what it is about the affiliation or religiosity that is cause or effect.

The public, by and large, may have self-selected themselves out of scientific inquiry. This could be associated with educational opportunities, geographical location, or a host of other variables. It is fair to suggest that some of their decisions to remove themselves from the scientifically literate population were the product of forces beyond their control, such as poverty.

Infobesity (Coplin 2014) is a quaint term and refers to the belief that information overload has reached a point of negative returns. There is so much information on everything that it is nearly impossible to stay on top of what is happening in the world around us without a news accumulator. The problem with news accumulators whether they are human or not is that they are programmed by interests which leads us to be exposed to information about which we already tend to be in agreement, the confirmation bias (Kahneman 2011). When it comes to science and technology, it is highly problematic for the public to stay on top of any issue given both the lack of interest and the dearth of media coverage. The space program got public attention due to its context – the Cuban Missile Crisis and the Cold War. No other single scientific event can make the same claim.

In addition, there is the dual problem of the overcomplexification and diminishing quality of science and technology information. On one hand, the public does not need to be prepared to carry out their own laboratory experiments in order to participate in debates over policy. Maybe some effort needs to be expended in producing public educational opportunities that are sufficient rather than overly complex and alienating. On the other hand, infotainment (Demers 2005) refers to the general downgrading of news, and it affects the quality of technical information to which the public is exposed. It is a disservice to under-inform the public since it opens them up for perception management and manipulation activities on the parts of those with less than wholly altruistic interests in the decisions being made.

These are huge challenges in public science and technology literacy. Given these difficulties, it is less surprising that we have turned to the expert sphere. However, it is incorrect to assume that it is only the public who is affected by heuristics and mental biases, like affect (emotional driver) and availability (experiential driver) (Kahneman 2011). Experts have their own set of biases as are explored briefly below.

The Expert Sphere

The expert sphere has not fared well in recent years. There are many examples of products, such as Vioxx (Vesi 2008) and Takata air bags (Pfanner and Rogers 2014), reaching the market with insufficient oversight to protect consumer welfare and well-being. Critics have begun to speculate that this may be a function of too much information and not enough experts, hence the rise of big data analytics.

As interdisciplinarity (Froderman et al. 2012), one of the by-products of convergence becomes more pronounced that we can expect some profound issues to surface in the expert sphere. The expert sphere across disciplines seems to be growing smaller and less responsive. Since convergence involves many different disciplines, we can expect even the top experts in one discipline could become marginal experts or not experts at all in another discipline. While there may be a proliferation of "experts" seen on national news broadcasts, in actuality, truly interdisciplinary experts account for a small number.

We know from the Dunning-Kruger effect (Dunning 2011) that true experts tend to perceive themselves as less competent than they are mostly because they think the world around them is more competent than it is. However, marginal experts are much more problematic because they are less likely to see their own shortcomings. While some may speak without expertise to advance celebrity and fortune without regard to the impact of others' health and welfare, what Dunning discovered is they simply do not know what they do not know. If we see an increase in marginal experts with the onset of convergence, this might become a major issue. Without the expert sphere, there is little if any counterbalance to more self-interested parties when policy is under construction.

While news shows will seldom admit their experts are not omniscient, two guests talking over one another with louder and louder volume do not define expertise. The news media industry has grown so dependent on these talking heads that they have convinced themselves issues must have two sides regardless of the subject (climate change comes to mind).

In addition, experts suffer from their own unconscious biases (a topic destined for another publication). Nevertheless, the expert sphere is not immune to affect, availability, confirmation, etc. For example, one reason the onerous Sarbanes-Oxley Act was passed in 2002 was to attempt to hold the feet of some accountants to the proverbial fire by requiring them to go through step by step approaches in their reports. What has been behind scandals, such as Andersen's audit of Enron, might have been a series of biases rather than deliberate criminality (Bazerman et al. 2002). In the fields of intelligence analysis, books have been written about analytic techniques which are designed to do little more than to reduce the impact heuristics and biases have on expert analysts (Heuer and Pherson 2015). Take, for example, the lesser-known bias called attachment (Chapple et al. 2011) whereby experts favor processes they have used many times before even when the processes may be inappropriate to the task at hand. We know public heuristics and biases are linked to levels of uncertainty (Tversky and Kahneman 1974). Predictably, expert heuristics and biases will take over with higher levels of uncertainty, and given the level of uncertainty associated with convergence, we are confronting an especially challenging problem.

The Experts and the Public

One group of researchers interested in public and expert spheres has studied in the past decade the individuals and groups who claim to speak for the public. For example, it is well known that nongovernmental organizations accept the role as arbiters of the public welfare when one study after another study has indicated that they are much more liberal than the public in general (Niggli and Rothenbüler 2003; Marschall 2002) and are as guilty as the media, in some instances, for framing events hyperbolically to either generate public membership support or to enhance their overall importance in discussions over how decisions may impact different sectors of the public or even the general public. We are not suggesting the public interest is necessarily disserved by nongovernmental organizations, but there have been many examples when the information and activities from them did not represent public sensibilities but rather in some cases the organizational sensibilities of the nongovernmental organization. Interestingly, the role played by NGOs in debates over nanoscience and nanotechnology has eroded significantly. The ETC Group has not self-published recently on nanotechnology. Foresight and their companions at CRN have moved aside. Environmental Defense and Greenpeace (Berube 2006) have left the debates entirely to groups like Friends of the Earth-Australia.

For years, researchers have examined the many mental shortcuts the public takes in making some decisions. These heuristics beget biases and these biases may impact the general sensibilities of the public when it comes to complicated and ambiguous phenomena such as science and technology developments and policy. The literature on heuristics is plentiful. It seems to be driven by the assumption we are cognitive misers (Fiske and Taylor 1991) and assisted by a series of theories on the dualistic nature of cognition (Kahneman 2011).

Presumably, there are two types of cognition; one is very deliberate and analytical, while the other is more intuitive and based on information which may not be integral to the decision at hand. No one seems to suggest cognition exists in these two polar states; rather it is seen as a continuum where some decisions are more analytical than others depending on how salient and exigent the subject of the decision may happen to be. For example, a person (termed *cognator* below) from a family with a history of cancer may be analytical to data suggesting a new way to treat cancer, but less analytical when confronted with data in another context or subject-matter.

Another assumption worth mentioning involves the quality of the decision making. There is a theme in the literature that a decision made intuitively may be less valid than a decision made analytically. While in some cases that may certainly seem to be true, there are instances when the heuristic is a function of a trial of decisions that had functioned more than acceptably for the *cognator*. Indeed, many of the biases are about decisions that the *cognator* has decided may not deserve a deeply analytical analysis at all.

Next, we have a plethora of experimental studies, mostly involving undergraduate psychology students, resulting in a laundry list of heuristics and bias. The most popular seem to be affect, availability, and confirmation though there have been conference and published presentations on nearly one hundred.

From a history of creating analytics for intelligence and defense decisions, it has become obvious more than ever that there is a rationale for bridging the two worlds: psychology of cognition and analytics. Whereby analytics has accepted the premise that even the brightest analysts are impacted by biases which might be problematic, the psychology of cognition has not spent as much time studying expert heuristics and biases as they have on public heuristics and biases. Some transfer very clearly and without too much disagreement.

This may help explain some inconsistencies observed in a series of studies funded as part of a National Science Foundation grant on public unpacking of toxicological data about nanoparticles which began with two research questions:

RQ1 = Will the views of experts and publics in the debates over environmental health and safety of nanoparticles differ?

RQ2 = Will experts demonstrate their own bias when they make predictions about the risks associated with the environmental health and safety of nanoparticles, especially when those predictions involve the public?

From 2008 to 2010, a series of studies examining these research questions concerning the expert-public dichotomy of perception were conducted (PCOST 2015). The mission was to shed light on what had been referred to as “expert perception of public perception” or E-PoPP for short. The researchers were curious to know if nanoscientists could be tapped to reliably and accurately predict public sentiments regarding the risks of the things they study, a task they are commonly asked to do by decision-makers and media. Results showed that representative samples of the public differ greatly in their sentiments toward nanotechnology than the educated guesses provided by expert groups, which may be a symptom of increased convergence and marginal expertise. The findings come from two studies. This data set has not been published before.

Methods and Data

To judge expert sentiments, researchers employed a three-round Delphi study. A Delphi is designed to reduce priming effects and is suited to situations "when accurate information is unavailable or expensive to obtain, or evaluation models require subjective inputs to the point where they become the dominating parameters" (Linstone and Turoff 1975). Designed for small expert populations (N $<$ 20), the Delphi method involves open-ended questions and calls upon experts to offer their own lists and ranks there is less researcher interference. The multiple rounds of rankings as well reduce the investigator interference that arises when lists are pulled together from different inputs. This allows respondents to voice themselves anonymously and change opinions without fear of repercussion. Experts respond individually and avoid direct communication between experts. The Delphi method provides an iterative process that calibrates opinions and builds toward consensus through multiple rounds. For example, anyone in a Delphi survey can argue to return an item to a list or to challenge the incorporation of an item into a ranked category.

For example, in one study 18 experts were asked about the potential risks associated with nanoparticle *applications* as well as the potential risks associated with *nanoproducts in the context of Environmental Health and Safety (EHS). The experts were asked to individually rank order their generated list from most risky to less risky. Table 1 shows the top ten in each category.*

While there are some problems with language in these two questions, they were in substantial agreement among the group and subsequent testing demonstrated overall concordance to be high.

While experts agreed with one another about the risks of applications and nanoproducts, there are some important levels of discrepancy between expert and public concerns. For when asked to rank "What application or products do you assume the public believes is potentially or actually problematic to EHS?" the expert group produced the ranked list in Table 2 below.

This question also demonstrated strong expert agreement, but the expert expectations of the public did not match up to actual sentiments of the public when compared to a national study of public perceptions of 242 US households as detailed in Table 3.

In order to better encapsulate the E-PoPP idea, the public was also asked the following question: "Experts are sometimes asked to give their impressions about products that may concern the public. If experts were asked which potential or actual uses of nanoparticles most concerned the public, how do you think they would rate the public's concern?" From this question, we received the ranked list in Table 4.

What is learned from this exercise is that even when expert communities agree significantly with one another about their expectations of public perceptions, there is a strong likelihood that there perceptions do not match up to the public's sensibilities.

Table 1 Expert rankings of nanoparticle applications and products

Nanoparticle applications	Mean	Std. deviation	Mean rank
Antimicrobial applications	2.22	1.90	1
Nanodrugs and targeted drug delivery	4.72	4.92	2
Fuel additives	5.11	3.89	3
Cosmetics	5.67	4.03	4
Food additives	6.50	4.02	5
Coatings	7.28	3.94	6
Dispersants and fertilizers	8.33	3.40	7
Biomedical	8.44	3.80	8
Sunscreens	9.56	4.08	9
Environmental remediation	11.28	4.25	10
Nanoparticle products	Mean	Std. deviation	Mean rank
Cosmetics	4.06	4.01	1
Fuel additives	4.39	4.65	2
Antimicrobial clothing	5.22	4.17	3
Antimicrobial toys and baby products	7.00	3.36	4
Pesticides and herbicides	7.00	3.53	5
Sunscreens	7.06	6.46	6
Antimicrobial appliances	8.50	5.12	7
Automobile tire additives	9.11	4.73	8
Food packaging	9.72	3.54	9
Building materials	10.06	5.91	10

Table 2 Expert rankings of what the public likely believes is problematic to EHS

Products	Mean	Std. deviation	Mean rank
Cosmetics	3.06	3.24	1
Food additives	3.97	1.64	2
Sunscreens	4.22	3.64	3
All CNTs	4.65	2.59	4
Nanobots	6.09	2.86	5
Antimicrobial toys and baby products	6.56	2.33	6
Antimicrobial clothing	7.00	2.91	7
Food packaging	7.06	2.80	8
Pesticides and herbicides	8.23	3.20	9
Medicine	8.50	2.15	10

Implications and Conclusions

Other than applications associated with food, there is little agreement between public concerns about the EHS footprint of nanoparticles and experts' predictions of nanoparticles about which the public would be concerned. Also of note is that public concerns are unlike expert concerns on many levels as well.

Table 3 Public rankings of nanoproduct risks

Products	Mean	Std. deviation	Mean rank
Food additives	4.52	1.85	1
Pesticides, herbicides, and fertilizers	4.46	1.90	2
Drugs	4.22	1.93	3
Community wastewater treatment	4.16	2.02	4
Food packaging	4.16	1.92	5
Cleaning products	4.10	2.02	6
Explosives	4.05	1.92	7
Toys and baby products	4.04	1.87	8
Water filters	3.90	2.15	9
Paints and inks	3.75	2.04	10

Table 4 Public rankings of nanoproducts that experts likely believe most concern the public

Products	Mean	Std. deviation	Mean rank
Medicine	4.95	1.77	1
Pesticides, herbicides, and fertilizers	4.86	1.76	2
Food additives	4.84	1.65	3
Food packaging	4.60	1.81	4
Antimicrobial treatments on toys and baby products	4.59	1.80	5
Cleaning products	4.35	1.79	6
Sunscreens	3.78	1.76	7
Antimicrobials used in clothing	3.63	1.68	8
Cosmetics	3.61	1.80	9
Small robots or nanobots	2.91	1.60	10

We as a group of scholars and students need to ask ourselves what happens to the expert sphere as convergence moves ahead and the expertise of experts becomes more marginal. We have learned from a multitude of studies that the public seems underprepared to represent their own interests. There has been a trend for public interest groups and nongovernmental organizations to be less interested in nanoscience and nanotechnology over time. This leaves a truncated expert sphere.

The witnessed discordant phenomenon of expert perceptions of public perception (E-PoPP) may hold significant sway over future policy of converging sciences and technologies. E-PoPP has already influenced public policy in the past. Consider the Texas Super Collider cancellation after more than $2 billion dollars had been invested in the project. Tremendous special interest support was victimized by tirades from groups like the Cato Institute (Jeffries 1992), that it was a public boondoggle. Supporters, like former Fermilab director, John Peoples, convinced themselves the project was simply too esoteric to generate public support (Wade and Russell 2009). The poor public relations campaign presumably fueled dissatisfaction on the part of the general public though there is very little evidence the public cares very much at all. Indeed, the support from the Texas community was very strong.

We expect this problem will only increase with the erosion of the expert sphere, and we expect the erosion to continue given the inter- and multidisciplinary nature of convergence. At some point we need to ask ourselves: who will represent the public interest? Are we destined to have regulators and government officials turn to vested interests for support for policy? Or are we destined to turn to marginal experts commenting on converging technology? While they may be offering commentary to the best of their ability as experts, their expertise may not be assuredly sufficient to make wise decisions. History has been pockmarked with incredibly dangerous decisions made on the basis of expert judgments, such as the Titanic and Thalidomide. Can we afford more dangerous decisions when marginal experts serve as the intellectual vanguard? We must invest in the future of both a viable public sphere and a viable expert sphere in science and technology policymaking, especially in a world marked by the converging forces of science and technology.

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Cultural Science

William Sims Bainbridge

Contents

Abstract

Convergence of science with society will require convergence of the social sciences, because despite efforts over the years to unite them, the social sciences remain fragmented today as they were a century ago. The most notable past attempt was "social relations" centered at Harvard University, the combination of sociology, anthropology, and social aspects of psychology, but it failed rather decisively. Today, new research methods employing computer science and information technology offer the potential for a successful unification, building on prior quantitative methodologies such as public opinion research in political science and sociology. Culture may not be the only concept suitable for facilitating the convergence of the social sciences, but it is an especially powerful one in the light of Internet, and could provide the impetus for a more general partnership across the social sciences.

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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Introduction

Unification of the social sciences, and their greater integration into society, might be advanced significantly through the concept of *cultural science*. This is an emerging science of the shared concepts and practices of large social groups, based on convergence across sociology, political science, cultural anthropology, linguistics, and related fields. Cultural science takes its inspiration from cognitive science, but with the ambition to become a coequal partner in understanding and improving human behavior (DiMaggio 1997). As a metaphor, it considers any complex social system to be a "mind" or a "computer" that processes information and takes action, based on shared memory that is called *culture*. As a tool for achieving convergence of the social sciences, it is quite compatible with other unifying concepts, and only vigorous future research can determine its full potential.

Historical Background

Just after the middle of the nineteenth century, organizations dedicated to unified social science were founded, notably the British National Association for the Promotion of Social Science and the American Association for the Promotion of Social Science (Haskell 1977). However, when social science departments were established decades later in the universities, they tended to be more specialized, probably because each served a different constituency outside the walls of academia. Economics served business and finance. Political science functioned as a prelaw degree as well as being connected to the political dynamics inside government and in election campaigns. Historically, an outgrowth of the socialist movement in Europe, sociology partly served to inform government social programs, and partly to critique societal institutions. Cultural anthropology was both an accessory and a corrective to colonialism. To be sure, many individuals in each of these fields had atypical orientations toward these modal constituencies, and many crossed disciplinary lines. Yet separate organizations fractured social science, notably: American Economic Association (founded in 1885), American Political Science Association (1903), and American Sociological Association (1905).

The American Anthropological Association, founded in 1902, represents a significant convergence, including as it does physical anthropology (which might alternatively be a branch of biology), archaeology, linguistics, and cultural anthropology. Another example of convergence in social science is social psychology, which is often conceptualized as a branch of psychology despite the fact that many sociologists consider themselves to be social psychologists (Stephan and Stephan 1990). The Association of American Geographers, founded in 1904, includes a substantial minority of members who are social geographers, often engaged in social science research but classified as geographers because of their focus on spatial patterns. Thus, it would be wrong to claim that convergence was absent in social science, but rather that significant divisions were established over a century ago, and may no longer be scientifically logical, as well as preventing innovations that would be encouraged by convergence.

In the middle of the twentieth century, a valiant attempt at convergence was launched, called *social relations*, centered on a new department at Harvard University, but influential elsewhere, such as at Johns Hopkins University which also established a department with that name (Bainbridge 2012). The leader was sociologist Talcott Parsons, who was the first chairman of "Soc-Rel" when it was established in 1946. He sought to merge his own field with cultural anthropology, social psychology, and also as it was often called *clinical psychology* but might be described less psychiatrically as *personality psychology*. In collaboration with Edward A. Shils, Parsons edited a handbook for the social relations convergence, titled *Toward a General Theory of Action*. It assumed that each society possessed a coherent culture, a system of norms, values, roles, and beliefs that functioned to sustain the society as a functioning unity. Every individual action or subsystem, or even the entire culture, could be described in terms of five dichotomies called the pattern variables (Parsons and Shils 1951, p. 77):

1. Affectivity/Affective Neutrality: how much the decision is based on emotions versus cool assessment
2. Self-orientation/Collectivity-orientation: seeking personal gratification versus following social standards
3. Particularism/Universalism: benefit for one's own family or friendship group versus humanity in general
4. Ascription/Achievement: social status based on birth or other unchosen characteristics versus status based on socially valuable accomplishments
5. Diffuseness/Specificity: applying across wide areas of social life versus limited to specialized circumstances

An example of the first dichotomy is the Judgment of Solomon from 1 Kings 3:16–28 in the Bible. Two women both claim to be the mother of a baby. Solomon pretends to give the logical, affectively neutral resolution to this dispute, saying that the child should be cut in half, so each woman could have a fair share. This was apparently a ploy, intended to reveal which of the women really deserved the child, namely the one who emotionally begs that the child's life be spared, even if that meant the other woman should have him. Her affective response proved she was the mother, so Solomon awarded the unharmed child to her. The Bible contains many examples of particularism, as in Judges 12 when the exact pronunciation of the word *shibboleth* was used by Gileadites to distinguish their own people from fleeing Ephraimites, whom they killed. Particularism illustrates that culture may function to establish social identity, quite apart from the economic benefits of those aspects of culture classified as technology.

In principle, an element of any culture might fit any combination of these five variables, generating 32 categories even before we reconceptualize the dichotomies as continuous dimensions of variation. But Parsons and his collaborators tended to assign the right-hand choice in each pair to modern societies, which they described as rational, dedicated to collective well-being, established on universal norms of justice, valuing individual achievement, and possessing complex roles and institutional structures (Gilman 2003). Parsons explicitly assumed that social scientists could rank societies along a clear dimension from primitive to advanced, but the pattern variables alone might not be sufficient, and later sociologists have debated his fundamental assumption that progress was a well-defined concept (Granovetter 1979). In an influential 1964 essay, “Evolutionary Universals in Society,” Parsons argued that indeed human culture was evolving from a primitive state to an advanced one, progressively adding new characteristics, a few of which were quite major departures.

Four very early innovations characterize all successful human societies: communication through language, social organization through kinship, religion, and technology. Notice that this list included religion, which expresses Parsons’ belief that all societies required a shared culture of transcendence, and that complete secularization was not desirable. More advanced human societies, Parsons said, added six other universal features of cultural evolution: social stratification, cultural legitimation, bureaucratic organization, economic markets, generalized universalistic norms, and democratic association. We could well imagine Parsons adding a seventh, had he survived into the twenty-first century, *pervasive information infrastructure*, based on Internet. The entire social relations approach was optimistic, believing that continued human progress was not only possible but probable, and thus in harmony with science and technology convergence.

Within the walls of Harvard, there existed principled opposition to the social relations concept, including two theoretical perspectives that agreed with the goal of convergence, but rejected Soc-Rel’s means for achieving it. Ironically, each was led by a chairman of the sociology department, first Pitirim Sorokin and then George Homans. Sorokin founded Harvard’s sociology department in 1931, and was far more pessimistic about the human future than Parsons. A refugee from the Russian Revolution, Sorokin had nearly been killed by Marxists, and his own work was motivated by hatred of their doctrines about inexorable social evolution. Between the two world wars, many social theorists were concerned that Western Civilization may be approaching its collapse, which inspired them to postulate laws of large-scale social behavior, some postulating that every civilization that rises must eventually fall. Especially relevant for cultural science was Oswald Spengler (1926), who believed that every civilization was based on a key idea, central to its culture, that would for a few centuries energize and regulate social behavior, until the system collapsed due to old age, if some other civilization had not conquered it first. Spengler said the central idea of western civilization was boundless space.

Sorokin’s own theory was more complex and optimistic than Spengler’s, enunciated in a multivolume set of books, *Social and Cultural Dynamics*, published in 1937–1941. Out of violent and chaotic times, a vigorous social movement will arise, organized not by a single idea but by a complex of ideas about the meaning of life that energize its conquest of all the peoples in its geographic region, and the establishment of a civilization based on this cultural complex. Most specifically, a successful culture must answer four great questions:

1. What is the nature of reality?
2. What human needs and goals must be satisfied?
3. To what extent can each need and goal be satisfied?
4. What are the best methods for maximizing satisfaction within this framework?

Civilizations will differ in their answers, Sorokin believed, but all successful ones will experience the same life cycle. Initially, they will be *ideational*, profoundly dedicated to the particular set of answers. But with success comes decadence, and their commitment will gradually erode. They will become *sensate*, which means not merely dissolute but also focused on empirical reality, rather than on the original ideals, thus comparable to modern secularization. Sorokin was convinced that Western Civilization was falling, admittedly slowly, but was more optimistic than Spengler, because he believed civilizations could be reborn out of a new period of chaos, thus going through rise and fall cycles lasting perhaps a thousand years. Were he alive today, Sorokin probably would say that the most radical Islamist groups were harbingers of the next cycle of Islam, and it would succeed Western Civilization, unless the resurgence of Chinese Civilization defeated them both. While Sorokin is hardly ever mentioned within sociology today, some modern intellectuals do work in this tradition, so a new cultural science would need to take account of it (Morris 2014).

The critique of social relations launched by George Homans (1967) was practically the opposite of Sorokin's, denying the importance of culture rather than emphasizing it, and Homans led the sociology department at Harvard when it broke away from Soc-Rel. He strenuously argued that all the social sciences should merge, notably including both economics and history, but on the basis of research on interactions between individual humans within small groups, rather than large-scale social phenomena. He specifically said that central social relations concepts like values and culture were vacuous platitudes. For a quarter century, Soc-Rel had failed to achieve either convergence or scientific discovery, guided by such notions, which had only served to obscure the very real differences between fields, allowing them to pretend to converge when they really did not. From today's perspective, the approach favored by Homans looks very much like a variant of cognitive science, focused on how individual minds learn successful behavior from interaction with others.

At Harvard, as in many government agencies, convergence of the social sciences in recent years has downplayed the need for overarching conceptualizations that could unify across disciplines intellectually, in favor of narrow practical foci. Harvard's Tobin Project, for example, brings social scientists together to address four policy-related problems: (1) the conditions for successful government regulation of the economy, (2) ensuring the health of the societal institutions required for democracy, (3) how the United States can advance its interests internationally in a changing world, and (4) the consequences of widening income inequality (Gudrais 2014). However valuable such efforts at piecemeal convergence may be, it is not clear they can overcome political divisions in the wider society, and may result in divergence rather than convergence causing fracture lines between practical application areas.

Evolving Debates

The classic way to conceptualize culture in history and the humanities was in terms of distinct entities, some of which were considered to be especially important types or transformative periods. Perhaps the best example is the notion that Europe experienced a revolutionary period dominated by a unique spirit of renewal, called the Renaissance. Supposedly, highly educated Europeans rediscovered the ancient Greco-Roman culture, and were inspired by it to become unusually creative in all of the arts, even as the economy and technology progressed rapidly after the abysmal Dark Ages and sluggish Middle Ages. To be sure, architects began attaching Doric, Ionic, and Corinthian columns to some public buildings, reviving specific ancient Greek styles. But hardly any of the painting and music of the ancient world had survived, and the idea of Renaissance was an extreme oversimplification, if not a total distortion. Today one may argue rather convincingly that the traditional classification of historical periods is almost completely wrong, that technology progressed at least as fast during the Dark Ages as in the Roman Empire, while science and technology were the real drivers of progress, not the arts and literature (White 1959; Stark 2014).

In the history of European music, it used to be said that the Renaissance was followed by the Baroque, and those terms are still used. But the ninth edition of the most influential European music history book primarily organizes its sections in terms of centuries, which are the most arbitrary of classification categories (Burkholder et al. 2014). Linguistics has long understood that languages exist in families, and each major language encompasses multiple dialects, but neither languages nor dialects are fully distinct from each other, except when some central authority like the L'Académie Française asserts the power to define a language. Because it was ruled from one specific city, with one senate and emperor, the Roman Empire could claim to impose a unified culture, yet language and religious beliefs varied greatly across geographic areas. Extensive research in historical linguistics, looking at the period just before London asserted full authority over the vocabulary and grammar of the English language, found huge regional variations, even over short distances (McIntosh and Samuels 1986). Thus, modern cultural science cannot rely upon simplistic category schemes, and most often must therefore employ careful statistical analysis or other quantitative methods such as computer simulation.

Admittedly, the degree of cultural unity versus diversity is itself a variable, that changes over time and space. The debate between Sorokin and Parsons was partly an expression of a distinction made by German sociologist Ferdinand Tönnies in 1887 between *Gemeinschaft und Gesellschaft* – Community and Society (Tönnies 1957; Vaisey 2007). The exact meaning of this categorical distinction is open to debate, but people who belong to a community are tied together by enduring personal relationships, while a society is much more like an economic market in which interaction is based on impersonal exchange. *Gemeinschaft* is comparable to Sorokin's ideational period in the history of a society, marked by cultural unity, while *Gesellschaft* is more sensate and marked by increasing cultural disunity. In the scheme of the social relations movement led by Parsons, *Gemeinschaft* represents premodern societies that emphasize the left-hand sides of the pattern variables, whereas *Gesellschaft* is modern capitalist society emphasizing the right-hand sides. In developing a new cultural science we need not take sides, but should recognize that human culture is the complex interplay of multiple systems, that may from time to time coalesce or disperse, reflecting the convergence–divergence cycle mentioned in several chapters of this Handbook.

Traditional conceptions of culture tended to assume that it endured over time, but Homans argued it was historically contingent, and recently other authors have considered culture to be vitally important yet transient. In a recent popular book, two professors from Yale Law School, Amy Chua and Jed Rubenfeld (2014), drew upon extensive social science research to identify traits that explain why some cultural groups have succeeded rapidly in America, usually but not always immigrant ethnic groups. They identified three factors that combined to increase the chances of success in science and technology as well as business activities: (1) an obsession with being superior to members of other groups, (2) a profound sense of insecurity often reflecting recent historical disadvantages and transmitted to children from their parents, and (3) the willingness and ability to defer gratification, thereby enabling members to work toward socially recognized superiority and security. The irony is that these characteristics are not immutable, and success erodes both the feeling of insecurity and the willingness to defer gratification, ending the period of the group's ascendency. During that glorious period, however, members of the group can play exceptionally important roles in achieving scientific revolutions.

If culture is dynamic, then sophisticated methods will need to be developed to measure its current state and rate of change. A quantitative movement within cultural anthropology emerged immediately after the Second World War, achieved considerable progress, yet never was widely accepted within the discipline. Its main manifestation was the Human Relations Area Files at Yale University (hraf.yale.edu) that catalogued the cultures that had been studied by anthropologists, in terms of a large but standard set of features that some cultures had but others did not (Ember 2012). When sociologists used this evolving quantitative dataset, they naturally were interested in how various elements of culture correlated with each other statistically, perhaps representing societal evolution over a series of stages (Rose and Willoughby 1958). Another very general question was the extent to which cultures were independent units, versus convergent components of a wider system (Ember 1971). Meanwhile, public opinion research developed in sociology and political science, using interviews and questionnaires for decades as perhaps the dominant quantitative research methodology in those disciplines.

Public Opinion Research

Vast quantities of culture-relevant data, collected over the later two-thirds of the twentieth century by public opinion researchers, are currently available at archives like Interuniversity Consortium for Political and Social Research. Table 1 provides a very rough introduction to this method of scientific convergence, based on recent data from a major questionnaire study of the American population, the General

Table 1 Convergence of three social sciences in public opinion research

	Social class: a sociology variable		Political ideology: a political science variable		Church attendance: an anthropology variable	
	Lower (%)	Upper (%)	Conservative (%)	Liberal (%)	Often (%)	Never (%)
On balance, the benefits of scientific research have outweighed the harmful results	60	79	69	77	66	75
The benefits of nanotechnology will outweigh the harmful results	44	71	65	64	49	63
Science makes our way of life change too fast	60	37	51	45	51	41
Human beings, as we know them today, developed from earlier species of animals	44	64	27	70	16	70
Respondent has access to Internet at home	34	81	63	65	65	65

Social Survey (GSS), data which are readily available online to anyone who wishes to analyze them (sda.berkeley.edu). Any serious analysis would need to go much more deeply into the data, using more sophisticated statistical techniques, and this table is intended merely to provide the basis for a very general discussion. It compares the percentages of respondents giving a particular answer to each of five questions about science and technology, across three different but interrelated cultural divides in the society.

Social class is a sociological concept, although also significant in economics. It is very difficult to measure precisely, and often a proxy variable is used, such as annual income, educational attainment, or occupational prestige. The social class question reported here was very simple: “If you were asked to use one of four names for your social class, which would you say you belong in: the lower class, the working class, the middle class, or the upper class?” The table reports just the two extreme classes, which differ greatly on all five science and technology questions, most markedly and understandably the one about their own Internet access.

Political ideology is also complex, but in political science as well as in the news media and popular discourse the concept of a spectrum from liberal to conservative is often applied. The GSS asked respondents to place themselves on this spectrum at one of seven points: (1) extremely liberal, (2) liberal, (3) slightly liberal, (4) moderate, (5) slightly conservative, (6) conservative, and (7) extremely conservative. Table 1 reports just the two extremes. A more detailed analysis of how social class and political ideology correlate found only an exceedingly weak connection between the upper class and conservatism, and some tendency for the working class to contain more moderates, so any serious analysis of social class and politics would need to focus on specific political policy issues about which the interests or cultures of the classes differ.

Anthropologists make hardly any use of the General Social Survey, yet many of its questions do relate to central concerns of that field, such as items related to family structure and ethnic heritage. Probably the largest number of GSS items measuring aspects of culture that were traditionally in the realm of anthropology is the religion questions. Each denomination could be described as a subculture, and each major tradition as a culture. Here, religiosity is measured by frequency of participation in religious services, contrasting the people who absolutely never attend church or other religious activities with those who do so more often than once a week. Never attending is most common in the lower class, 25 % compared with 16 % in the upper class, suggesting that some poor people lack the means to attend or are alienated as much from the culture of the society as from its economy. The numbers are identical for very frequent attendance, at 7 % for both lower and upper class. The interplay between religion and politics changes over time, but today there is a correlation between religiosity and conservatism. Only 14 % of extreme conservatives never attend church, compared with 31 % of extreme liberals. The percentages for attending more often than once a week are 19 and 5.

Conceptualizing Table 1 as a convergence of sociology, political science, and cultural anthropology, we see intriguingly complex patterns. Some of the percentage differences are quite huge, by the standards of questionnaire survey research, while others are quite insignificant. If we looked just at the first row, general confidence in the benefits of science, we might simplistically conclude that science was especially attractive to prosperous, liberal secularists. But the political differences vanish when we look at one particular field, nanotechnology, in the second row of the table. In the third row, we see comparable patterns across the three social sciences, but an especially big difference between the lower and upper classes, possibly reflecting a feeling among poor people that they are being left out of the benefits from technological progress or the realization by rich people that they are disproportionally gaining. The fourth row reminds us that the theory of evolution by natural selection strongly contradicts the biblical religious tradition, and this effect seems to impact the political spectrum and interact with social class as well.

The final row of the table, concerning Internet access, has nothing to do with politics or religion, but reminds us that participation in modern technologies has costs, which poor people may not be able to pay. Recognizing that Internet does not quite encompass the entire world yet, we shall now see how it can become the laboratory for advanced forms of cultural science.

New Century, New Methodology

Internet is not only a network of computers, and of people, but also a network of concepts. Using Google and searching for “related: www.steinway.com” two of the first three hits are the Boesendorfer and Yamaha piano companies that compete with Steinway, and the third site is a seller of used Steinway pianos that compete with new ones. Doing the same for "nasa.gov," the first hit is the European Space Agency which is NASA's equivalent. Using the "related" command on the Wikipedia page for plutonium gives the Nuclear Regulatory Commission and the Wikipedia page for uranium as the first two hits. Those examples illustrate the fact that search engines provide implicit maps of culture and of human social organization.

A very different kind of highly developed online tool for studying culture is a *recommender system*, the commercial method for suggesting a book a customer might buy or a movie a customer might rent. For example, looking up in Amazon.com the Chua and Rubenfeld book at this exact point in writing this chapter, provided three kinds of recommendation. Most prominent were other books by Chua plus books by other authors on modern parenting, the challenge of work in our technological society, and oddly one on how old comic books often taught real lessons. The second recommendation was a categorization system that focused on a subset of the already-recommended books, for example those that were coded as "sociology," thus also describing the book with a set of labels. The third recommendation system listed books with the comment, "Customers Who Bought Items in Your Recent History Also Bought," which happened to be music history books because the previous visit to Amazon.com on the particular computer had been to check the latest edition of the music history book cited above. Online marketers, of which Amazon is the prime example, possess a tremendous amount of information about the behavior of millions of people, and the pattern of book purchases could be used to map the genres of the publishing industry in fine detail, were the data available to social scientists.

Some recommender system data have been widely available, notably movie ratings by about 400,000 people that were part of a contest intended to develop improved clustering algorithms by the Netflix movie rental company. Customers rate the movies they see, and these ratings are used to recommend movies to the individual customer, based on the structure of correlations between ratings of movies by other customers. There are many mathematical methods to make predictions about movie preferences, and all of them could be adapted to create cultural maps of the movie genres, and even to follow cultural evolution over time. Some analytical methods identify one customer's "neighborhood," which is a subset of other customers with similar preference patterns, thus representing a subculture within the population.

To this point, very few social scientists have considered using recommender system data, and almost all the scientific publications concern the predictive power of alternative algorithms, in the context of marketing rather than cultural science, and often narrow in their statistical sophistication (Hand 2009). There has been some research on factors encouraging people to contribute data to recommender systems, notably in connection with MovieLens, an academic counterpart to Netflix (Chen et al. 2010). Some economics research has examined the new online business realities (Ghose and Sundararajan 2006), but usually in the absence of concepts and methods from sociology, political science, and cultural anthropology. In principle, social science using data from book and movie recommender systems could transform the humanities, rendering them more rigorous in terms of theory, as well as quantitative.

A correlational study based on Netflix ratings of two dozen spaceflight movies showed that it was relatively easy to find general concepts that clustered movies into groups or that constituted dimensions of variation within genres (Bainbridge 2014). A standard social science method called factor analysis identified five such concepts. The first factor grouped together recent movies headed by two that concerned travel to the planet Mars, thus reflecting popular assumptions about the future of space exploration. The second factor included movies from the two most influential franchises, *Star Wars* and *Star Trek*, along with three others expressing popular notions of depth psychology and socially engaging action. The third was ironic, connecting comedies and satires, thus implying that spaceflight should not be taken too seriously. The fourth and fifth were far more serious, the fourth collecting stories about the real space program like *Apollo 13* and *The Right Stuff*, while the fifth factor was headed by two mystical movies, *Solaris* and *2001: A Space Odyssey*. Comparable analysis of movies on many other topics could chart the dimensions of popular culture in a great variety of areas.

Future Prospects

The debate among Parsons, Sorokin, and Homans has not been resolved, and each of these now-deceased sociologists represented a school of thought that remains significant today. Parsons was the most optimistic, believing that human society was evolving to ever higher levels of functioning, and suggesting that the next great step forward would be the convergence of all the social sciences to provide key guidance for progress. Sorokin believed that convergence lay in the past, as every great civilization arose in the unification of peoples based on a guiding faith that would erode over the centuries. Homans focused on individuals and small groups, advocating convergence of the social sciences but stating quite explicitly that no laws of large-scale social behavior could be discovered, and indeed it is hard to identify any major sociological discoveries since his death in 1989. Only the passage of time will establish which of these views is correct, whether science-society convergence exists in the future, the past, or nowhere. Yet any level of optimism or pessimism is compatible with the idea that the social sciences should converge, and culture is a theme that could facilitate the unification of social science with society.

The question then becomes: What steps should be taken to explore the value of culture as the theme for convergence of the social sciences? First, an inventory of past theories of culture, especially of theories that have fallen out of fashion, should identify concepts that could be operationalized in new ways and evaluated through modern information technologies. Second, methodological convergence should be promoted between traditional public opinion research and current studies of online communities using techniques such as recommender systems. Third, formal surveys of social scientists and the wider constituencies for their fields should identify other phenomena, such as economic exchange, that could contribute to convergence alongside the idea of cultural science. Fourth, experts in a variety of fields could examine the fundamental metaphor that cultural science is the social twin of cognitive science, viewing both societies and brains as information-processing systems. Several other chapters of this Handbook offer compatible insights about how the social science could be unified, the better to serve society in its convergence with science.

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Digital Government

Jane E. Fountain

Contents

Abstract

Digital government refers to the use of information and communication technologies in governance. The topic is broad encompassing political, governance, and policymaking behavior, structures, processes, outputs, and outcomes at all levels of government from local to global. This chapter summarizes the rise of digital government beginning in the early 1990s through the present. It briefly describes major efforts to increase transparency, openness, citizen engagement and participation, and computational methods underlying "smart" governments. The chapter is divided into three major sections. First, important developments in citizen participation and engagement are examined. Second, convergence within government is described with a focus on coordination and collaboration across boundaries to create "virtual agencies." Third, some of the key challenges facing the future of digital government are discussed. The chapter concludes with the observation that in spite of seemingly intractable challenges to privacy, security, and inequality, digital government continues to hold enormous potential to advance well-being for individuals and governments.

J.E. Fountain (✉)
Political Science and Public Policy, University of Massachusetts, Amherst, MA, USA
e-mail: fountain@polsci.umass.edu

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Introduction

Research on digital government typically focuses on disruptive information and communication technologies (hereafter, ICT) and their adoption by and effects on government. More specifically, digital government refers to the broad topic of governance in the information age including but not limited to service delivery, public management and administration, policymaking, analytical and regulatory behavior and processes, and, not least, the many forms of civic engagement enabled by ICT. Governance, as defined in this chapter, extends from individual civic and political behavior to local, state, and federal jurisdictions as well as practices and processes at regional, transnational, and global scales.

Digital government began in the US federal government in the early 1990s during the Clinton Administration. Leveraging ICT for economic growth and government reform formed a core goal of the Reinventing Government movement spurred by then recent developments of the Internet and World Wide Web (Fountain 2001a). Similar government reform and information society and economy initiatives followed quickly in other advanced industrialized countries as well as in the US state and local governments. First stage digital government projects focused on digitizing public information and development of government websites. Subsequently, governments sought to build greater interactive capacity with security of financial transactions and authentication of digital identities proving among the most challenging problems.

The rapid rise of social media, including the founding of Facebook in 2004 and Twitter in 2006, prompted a "second wave" of developments dubbed Gov 2.0 emphasizing user coproduction to increase citizen participation and engagement in civic affairs, for example, through participatory strategic planning and budgeting (Benkler 2006; Noveck 2009; Mergel 2012). Just as the National Science Foundation employs virtual review panels, other government entities increasingly use virtual panels for several types of evaluation, adjudication, and oversight. Examples include electronic rulemaking for public comment on proposed administrative regulations, peer-to-patent crowdsourcing of patent applications, participatory budgeting processes, participatory strategic planning for community and governments, and disaster and other mapping through platforms such as Ushahidi, a highly effective yet simple-to-employ set of tools developed in Kenya and used throughout the world. Moreover, the increasingly visual culture of pervasive computing and social media forms another dimension of digital government. The growing array of technologies used to produce and distribute visual information affect agenda setting, decision-making, perceptions of risk, and accountability. Examples drawn from some of the more prominent recent developments are summarized in this chapter.

At the beginning of the first Obama Administration in 2009, the president articulated a strategy of "open government," defined as a government maximizing transparency, participation, and collaboration in part through the use of digital tools and platforms. A complementary initiative to make public information available online, called "open data," forms a critical part of open government. Similar efforts have followed globally in national governments as well as in subnational governance and in multilateral organizations including the United Nations and the World Bank, tasked with transnational, regional, and global governance (Open Government Partnership 2014). The Open Government Partnership is an organization that developed a framework of principles and practices for governments seeking to become more open. Central governments become signatories to these principals and work with the Partnership to implement them in a public process.

More recently, governments have begun to explore the potential of “big data,” including data mining and predictive analytics using very large and often dynamic datasets and powerful computational methods to improve government services and policymaking (Lazer et al. 2009). Related to greater use of dynamic data, drawn from sensors, social media, and other user-generated sources is the growth of the concept of “smart cities,” that is, municipal governments that use data and analytics to increase efficiency, improve service delivery, and increase responsiveness to individuals.

In the early stages of the Internet and web, some observers argued that the nation state would wither away, ceding to citizen-led governance arrangements with greater reliance on direct democracy. Indeed, technologies have provided architectures for greater voice, coordination, communication, and distribution to citizens never previously available (Benkler 2006). Yet during the past two decades, evidence has accrued to make obvious that large-scale state and multilateral governance structures play an essential role in the development of knowledge societies and information economies.

Digital government research includes a dual focus encompassing, first, research on technical applications and their uses to governance systems and, second, research in the social and policy sciences that examines, for example, the structure and behavior of the modern state and its relationship to society. Digital government researchers continue to examine enduring puzzles such as how people govern themselves, how communities and societies forge solutions to trenchant problems, and how political and economic systems distribute resources to sustain the common good. As the field of digital government research progresses, its emphasis on grasping and employing new developments in science and technology for government use is converging with a stronger appreciation by researchers of important, enduring questions of social science and philosophy on the nature of democracy, power, and governance. Powerful examples of the importance of these research questions for society are found in revelations of widespread government surveillance, the prevalence of cybersecurity challenges, cyberwar, and related developments in information societies and economies.

Knowledge, technology, and society converge in myriad ways in digital government research. Knowledge of democratic governance and citizenship in the western world stems from philosophy and practices developed in ancient Athens and Rome. From the twentieth century forward, Weberian bureaucracy has formed an enduring organizational arrangement underlying complex governments globally (Weber 1978; Fountain 2001b). Bureaucracy as an organizational form defined in terms of hierarchy, procedural rules and standards, functional specialization, and division of labor has been modified but not eliminated by the use of digital technologies. The US federal government and central governments globally continue to be organized as a collection of large bureaucracies. The convergence of this deeply engrained knowledge base on the purposes, practices, and organizational forms of governance with disruptive new ICTs constitutes the broad terrain of digital government.

The five principles of convergence are demonstrated in digital government research. For example, increasing interdependence, the first principle, is exemplified in recent efforts to address “wicked,” highly complex, and interdependent policy challenges through stronger integration across policy domains and the government agencies that specialize in particular policy areas. Advances in decision analysis are evident in the global move toward greater use of evidence-based policymaking in government as decision-makers draw on stronger, larger datasets to identify and make sense of patterns, trends, and the effects of policy decisions. Evolutionary processes are being used to address a range of dynamic problems from environmental to transportation to epidemiological providing critical information to policymakers. The utility of higher-level cross-domain languages is evident in the growing use of APIs to build applications using open-source computing that may be employed across a range of government settings, for example, across the 50 states of the United States and in other countries. Finally, the value of vision-inspired basic research embodied in grand challenges is profoundly exemplified in “big data” research and related governance questions concerning privacy, liberty, freedom, and security. Such questions are fundamental to political theory and philosophy as well as to systems analysis.

Digital government research during the early 1990s focused on simple, discrete questions such as how many states or government units had websites and descriptions of website attributes. Similarly, researchers focused on user variables drawn from measurements of the adoption of computing in large organizations: user satisfaction, user facility with technology, uptake, and types of use. Early streams of research on ICT in government agencies provide such measures. At the organizational level, fewer studies have examined changes in business or organizational processes (often termed process or business process redesign), roles, and structures. Although this research base exists in organization studies and STS, little research of this type in government settings exists. Yet another area of digital government research converges with administrative law and regulatory studies to examine public participation in rulemaking and regulatory developments as a consequence of new ICTs. Taking the need for interdisciplinarity further, digital government research can draw more forcefully from social science streams of research that examine social inequalities, social movements, political power, social protest, international development, and state structure and behavior, to name but a few opportunities for greater convergence (Hindman 2008; Sunstein 2009; Howard 2010; Morozov 2011). Similarly, digital government researchers include those using some of the most sophisticated interdisciplinary tools of computational research available drawing from mathematics, statistics, linguistics, artificial intelligence, and machine learning (Lazer et al. 2009).

At the transnational and global levels of analysis, decision-makers and researchers focus more intently on Internet governance and related transnational systems and regimes whose purpose is to forge agreement on standards, systems, methodologies, knowledge, and goals. Researchers have found it nearly impossible to separate questions of access and the fundamental architecture and health of the "network of networks" from normative, political questions concerning who should govern the Internet and how state sovereignty intersects with the Internet's global architecture. Global and regional shared information systems have become fundamental to governance in policy areas including sustainability, demography and immigration, disaster preparedness and management, and national security. Convergence of the technical and social coevolves through coordination over time of technical and policy experts and, increasingly, in multilateral organizations organized in the early and mid-twentieth century offering a social platform for global, integrative decision-making.

By contrast to the earth scale, convergence of knowledge and technology for the benefit of society also is intensely individual. Digital government has the potential to empower citizens and communities through platforms and tools that promote civic engagement and coproduction of governance contributing to the "cognitive society." Such empowerment and engagement by citizens is "holographic" in the sense that it manifests at the neighborhood, village, and local levels as well as nationally, transnationally, and globally. For example, the World Wide Views on Biodiversity project, based in Copenhagen, facilitated local deliberations in nodes across the globe. These deliberations were followed by a roll-up and integration of local perspectives to be used in global fora of expert policymakers thereby deepening participatory technology assessment. Increasingly, international development organizations view digital government not simply as information infrastructure but as a broad collection of tools for capacity building by civil society to enhance equitability and innovation or inclusive growth (Gigler and Bailur 2014). Research on the enabling conditions, success rates, and outcomes of such convergence demonstrates important societal and individual progress and increasingly informs development policy in major multilateral organizations. For example, the World Bank recently announced citizen engagement as one of the Bank's priorities in 2015 reflecting an estimate by the Bank that such engagement is central to economic and social development.

Digital government should also remind us that rational individuals do not always act for the common good. Realism in international affairs may lead national governments away from globally optimal capability development to perceived local optima. War, genocide, and conflict continue with horrifying consequences and form an integral part of global interdependence. These ruptures are themselves fueled by advances in digital technologies. Terrorist organizations attract new members across national boundaries through sophisticated use of social media. Yet in these challenging areas, greater transparency through, for example, global tracking systems for counterterrorism and tracing the flow of materials used for nuclear weapons has transformed the landscape of governance. Moreover, the ubiquity of social media vividly displays unjust acts to the world with an immediacy that has changed relationships among nation states and relationships between individuals and their governments (Howard 2010; Morozov 2011).

This chapter is divided into two main sections. The first deals with convergence and its effects on citizen participation and civic engagement and the second with internal government and policymaking processes. It will become evident that similar technologies, systems, platforms, and tools are used within government and by citizens in their coproduction of governance. The chapter concludes with a brief examination of selected major challenges for digital government on the near-term horizon.

Citizen Participation and Engagement

Digital government has deeply influenced the connection between citizen and governments. Advances in technology have catalyzed change in fundamental dimensions of government from the nature of governance itself to the challenges of service delivery to potential for political participation and deepened citizenship (Fountain 2015). Most direct delivery of government services – including policing, housing, education, and health services – are implemented at the municipal, or city, level. Much of this section therefore focuses on developments in the US city government. Convergence is evident in the development of so-called smart cities, that is, city governments that employ an array of sensors, systems, and tools to gather and analyze data, often in near real-time, to manage city services including transportation, parking, security, environmental issues, and health.

Similar examples and trends may be found in many other countries, although examples herein are US based. Increasingly, city governments offer web portals customized for citizens and business and provide online services, including the ability to apply for city jobs; to register property; to pay utility and bills, parking tickets, and taxes; and to apply for building and other permits and licenses. Cities are developing capacity to conduct such transactions over mobile phones and devices. Such services potentially offer convenience and lower costs of operations, maintenance, and security. A third, critical development is increased participation and interaction by the public. Transparency and civic interactivity reduce the opaque nature of policymaking and the ability of politicians and public managers to control the agenda and public conversations. Technologies that increase transparency, communication, and coordination cannot substitute for trust in government – or for strong city leadership and management – but are reshaping its nature and antecedents.

The interactivity, affordability, and transparency of social media platforms and tools have led to reconceptualization of civic engagement and possibly to citizenship itself in the knowledge society. Digital governments have embraced interactive platforms and tools on smart phones and through pervasive media including Facebook and Twitter to improve service delivery, information channels, and civic engagement. Social media can be linked at no cost to city government websites completely bypassing complex procurement processes. Some researchers question the efficacy of social media to engender online participation in governance. But other experts are optimistic about the potential of social media to deepen citizenship and democratic participation. They note greater use of digital government tools with the potential to promote direct democracy and representation online. Transformation of digital government may rely on the extent to which citizens can expect their comments and online interactions to matter in policy outcomes. Thus, the perceived legitimacy and efficacy of citizen engagement is as important as provision of infrastructure for interaction.

"Civic technologies" are meant to improve the quality of civic life and are highly interdependent with social media. Many are open source, meaning that the source code is "open" or available for examination and modification. The WhiteHouse.gov website was the first major open-source federal government site. In addition, some state and local governments have used open-source computing for many years. A number of developing countries embraced open-source computing in digital government as a way to save money, avoid lock-in, and maintain flexibility. Thus, a substantial knowledge and experience base has developed for open-source system use in government.

Among the more typical open-source systems and tools recommended for city governments (Harper 2013) are the following:

- **Open311** – a reporting and tracking system for civic issues
- **SeeClickFix** – a reporting tool that has been expanded to include workflow management, reporting, and other tools for nonemergency service management.
- **FixMyStreet** – an open-source app that allows people to report issues related to the conditions of roads and streets.
- **CitySourced** – a reporting tool to assist people in reporting civic issues including public safety and environmental issues.
- **OpenPlans** – typically used in larger cities; these planning and transportation tools can be adapted to smaller cities.
- **Electorate.Me** – a website for people to exercise voice in political and social affairs.
- **NationBuilder** – a group of open-source tools for communities including maps, surveys, and updates to facilitate interaction between agencies and individuals.
- **OpenPublic** – an affordable content management system for cities to use in outreach to the public.
- **Granicus** – provides cloud storage for media and a suite of tools to broadcast and manage media online.
- **Open City** – volunteers who develop apps at the request of cities.

Civic technologies often connect to 311 systems in city government. Digital hubs using 311 systems form an important platform for digital municipal government. The 311 telephone system is a subset of an N-1-1 special number, for example, the emergency call number 911. These 311 systems link citizens to nonemergency services via a central phone number with coordination through dispatchers often working in call centers. Original 311 telephone-based systems, pre-Internet, operated independently across municipal governments without contemporary interoperability.

The Open311 platform makes it possible to share innovations developed in one city with other municipal governments when standards are interoperable. The Open311 application programming interface (API) for making visible civic data allows civic application developers to construct reusable tools and applications as municipal government platforms, systems, and tools are standardized. Open311 has been implemented in more than 30 cities globally and has catalyzed an array of apps and services.

Open311 digital hubs build on the digital government goal of a one-stop shop for services, no "wrong door" for citizens to access government information, and demand for increased transparency and stronger performance management through enhanced tracking, visualization and other analytics, and stronger use of time-sensitive and geospatial data to develop and implement city services. For example, the New York City 311 site – NYC311 – intensively uses Facebook and Twitter to communicate with citizens through their modal communication channels. The system enables public managers to record demand for services, response times, and other key performance measures. The New York City 311 system also includes public health, events, and other municipal information. Citizens use the system to report problems and to track follow-up. By crowdsourcing problem identification, municipal governments increase responsiveness to citizen concerns while improving infrastructure and resource efficiency.

Open data has been a catalyst for a burgeoning industry formed around data analysis and management for governments. Firms sell technical assistance to cities, as back-office management systems have grown in analytical complexity. Firms in this space are developing civic technologies to delegate to and integrate across agencies and policy areas, across various communication channels (phone, text, email, etc.).

SeeClickFix is a firm that has partnered with several other firms in an ecosystem for "smart city" management including Open311, Microsoft Dynamics, Cityworks, and others. This burgeoning industry offers communications platforms, tracking systems, report management, and automated reply capacity to citizens who post on municipal sites. Systems incorporate visual information through photos uploaded by individuals, geocoding, and time stamps to order data typically uploaded through mobile devices. The systems automatically create workflows, work orders, and workflow management routing information to the appropriate municipal agency.

Although developed for routine problem identification and management, these networks have expanded in their use as citizens employ them. For example, SeeClickFix is a technology partner with 55 municipal governments in the Boston area. After the 2013 Boston Marathon bombings, residents used the platform to share housing with those dislocated or in need of temporary shelter. Within 2 h, 750 people had made their homes available on the site. Boston area residents also have used the site to coordinate snow removal following major snowstorms.

Civic technologies rely on transparent public data to increase accountability. City governments, including those of New York, Chicago, Seattle, and Boston, have launched open data portals. Moreover, several cities have compiled their municipal data on the website cities.data.gov to increase access and comparisons. By sharing municipal data across the United States, the initiative promotes transparency and provides standardized data on which to build applications that work in several municipalities.

Municipal police and local emergency management departments use digital government platforms and systems with implementation increasing rapidly following September 11 and more extreme weather conditions occasioned by climate change. For example, the Seattle Police Department established a social media presence using Twitter as a type of digitized police scanner with tweets alerting citizens of police dispatch calls and reports of neighborhood crimes. Several other municipal police departments use this and similar reporting capabilities.

Developing countries also use easily organized content platforms to gather and visualize user-generated content. Ushahidi, a nonprofit software development organization based in Kenya, is one of the best-known innovators in this space. Ushahidi's systems were first used to record and map voter suppression during an election in Sudan. Citizens used simple text messages to anonymously report infractions, which were then mapped and made public. The same platform and tools have proven enormously useful in post-disaster reporting and management and in environmental reporting. These tools function similarly to other citizen science, citizen reporting, and user-generated forms of information that, when aggregated and visualized, provide important, dynamic information that has transformed citizen participation and engagement.

Convergence Within Governments

Digital government requires substantial, deep-level organizational change in processes, structures, systems, and culture. Disruptive technologies overlaid on traditional bureaucracies do not automatically lead to transformation (Fountain 2001a). Thus, convergence also implies coevolution or technology enactment, over time, of social, political, organizational, institutional, and technological arrangements. Moreover, it is evident that individuals often "enact" new technologies in ways that preserve the status quo, thus subverting opportunities for transformation. A cogent example of such coevolution or technology enactment is the increase in cross-agency collaboration in the US federal government signaling the emergence of a more highly networked capability in policymaking (Fountain 2013a, b).

Public officials have cooperated across boundaries for decades via interagency working groups, internal procedures for managing shared services, and other more or less ad hoc arrangements. But recently, legislation requiring cross-agency collaboration as a strategic imperative for government performance has formalized previous informal modes of cooperation, driven by urgent needs for:

- Solutions to pressing, complex policy problems that cross traditional boundaries
- Cost savings and efficiency
- Reduction of duplication and overlap of programs, systems, and expenditures
- Improved service to citizens and business by building coherence and streamlining
- Leveraging technological capacity for agencies to share platforms, systems, applications, and information

This legislation could not be implemented without substantial and pervasive use of digital government that has developed since the early 1990s including government-wide information systems, cross-agency shared databases, and other boundary-spanning and networked communications, coordination, and analytical capacity. The legislation is a vivid example of coevolution in that these legislative requirements bring federal agency behavior into better conformance (or convergence) with well-established technological change.

Using digital government to foster cross-agency collaboration is not new to the federal government. During the Clinton administration, virtual agencies such as Students.gov, Seniors.gov, and Business.gov integrated information and services for specific target populations in one-stop shops or online portals. The Clinton administration made an explicit decision not to try to reorganize agencies and programs but to use virtual reorganization of information to improve governance. The Bush administration Presidential Management Initiative included 25 cross-agency e-government initiatives in an effort to consolidate information systems and streamline standard business functions such as travel, payroll, and authentication across the government. The projects ranged across policy domains as diverse as disaster management, rulemaking, grants, benefits, and government loans. During the Obama administration, the open government initiative advances cross-agency collaboration alongside legislation that requires closer connections across data, systems, procedures, and tools.

An emphasis on data transparency – through dashboards, other visualizations, and tools – prompts government managers and agencies to systematize and examine data. Efforts to standardize how agencies track what they are trying to achieve build analytical yet interdependent capabilities. Current capacity often remains fragmented, but the trajectory is toward interdependence and integration. Similarly, bureaucratic culture is shifting in some instances from information ownership and control of access to data to open data, implying an obligation to make data publicly accessible.

Contemporary digital government also includes the increasing ability of multiple agencies to engage in joint grant-making and shared budgets. These developments are challenging institutionally because of strict legislation that prohibits commingling of funds and blurring congressionally approved mandates and missions. The Partnership for Sustainable Communities – an ongoing effort to integrate policies for urban development across the US Department of Housing and Urban Affairs, the US Department of Transportation, and the Environmental Protection Agency – developed joint grant-making capacity by HUD and DOT to enable communities to submit one proposal to one request for proposals that was funded by two agencies. The goal is to integrate policymaking for municipal development that includes interdisciplinary analysis of transportation, housing, and environmental planning (Fountain 2013b).

Other efforts at convergence include, by way of example, the Partnership Fund for Program Integrity Innovation, which awarded several million dollars to seven states through Interoperability Innovation Grants meant "to develop and implement improved information technology (IT) systems interoperability and integration in eligibility and enrollment, case management, and other related [human service] systems." The "Interagency Ecological Site Handbook for Rangelands" is the output of a collaboration to harmonize ecological data and methods (Caudle et al. 2013). The Landscape Conservation Cooperative establishes 22 ecosystem regions within which federal agencies coordinate with other government levels, NGOs, universities, and colleges in efforts that increase data coordination, identification of gaps, and shared strategy development for use of scientific information.

Key Challenges

Among the key challenges for digital government in the next 20 years or so are the development of legislation and new conceptualizations of privacy, search, surveillance, and security. A second challenge lies in expanding inclusion of newly developed countries in Internet governance, through ICANN or other multilateral organizations. A third challenge, among many, lies in reducing what is now obviously a trenchant digital divide that mimics and compounds related and growing social and economic inequalities in the digital age.

The release of highly secret government documents by Edward Snowden, a government contractor, and previous huge leaks of confidential information through WikiLeaks and other organizations has made evident the growing challenges of protecting both government and individual privacy in the knowledge society. Moreover, September 11 and the ensuing changes to law and procedures in government, exemplified in the Patriot Act and other legislation, have reshaped the landscape for digital government in the domains of privacy and security (O'Harrow 2005). Increasing convergence produces externalities, as do all science and technology advances, that must be incorporated into legal, political, and social rule systems.

More fundamentally, however, the very meanings of privacy and security seem to be morphing as individuals use social media, interact constantly with a variety of networks, and move through day-to-day life under the constant watch of cameras, sensors, and other devices that form the ecosystem of the knowledge society.

Ironically, citizen empowerment and engagement has not yet filtered upward to more inclusive governance of the Internet globally. The Internet was originally developed and governed primarily by US actors. Over time, as the Internet has become fully embedded globally into economic, social, political, and other systems, its governance will inevitably develop. At present, the future direction is unclear.

Claims for inclusion and representation in governance must be matched with capabilities and commitment to preserve the integrity of the world's most critical infrastructure.

The digital divide persists nationally and globally and has converged with deeper forms of social and economic inequality globally. Technology alone and Moore's law will not ameliorate the digital divide. If anything, disparities between information haves and have-nots are increasingly entrenched. But as populations globally move to cities, their high and increasing population density is well aligned to produce economic and social benefits from broadband access and digital literacy.

In the United States, racial and ethnic disparities in access persist stubbornly and at socially unacceptable levels. In 2010, 65 % of Americans had broadband access at levels sufficient for digital citizenship, that is, the ability to use the Internet to gather information about education, health, employment, and civic affairs. Yet almost 50 % of underrepresented minorities are either poorly connected or completely unconnected to the Internet and associated digital resources. Lower income geographic areas in cities often correlate highly with unaffordable access. Urban Latinos are the most disadvantaged technologically. While broadband access is necessary, it is not alone sufficient for digital citizenship. Individuals require a basic level of digital literacy to exploit digital information to advance their well-being (Mossberger et al. 2012).

Ironically, those who access the Internet exclusively via cell phones tend to possess low levels of digital skill and activity. Such users tend to be from under-represented minorities with low levels of education and income. These developments may portend a digital divide not only in access and literacy but also in Internet use. While mobile access as a replacement for broadband access from home affords powerful potential, mobile-only users tend not to use the Internet in ways that improve their economic, educational, and political prospects (Mossberger et al. 2008).

Conclusion

In spite of serious, seemingly intractable challenges, the promise of digital government remains strong. In only 25 years, digital government has transformed citizenship, bureaucracies, politics, and interdependence among countries and regions globally. Continued, as yet unknown, advances in technology and continued convergence among current capabilities across knowledge, technology, and society hold enormous promise to advance the well-being of individuals, communities, societies, and nations through the ways in which they govern to benefit the public good.

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Ethics of Convergence for Enhancement of Cognition

George Khushf

Contents

Abstract

This chapter considers the ethics of the enhancement of cognition in the Convergence initiative. In mature areas of research and development, ethics can be regarded as a specialized domain of practice with its own distinctive expertise. Debate on use of stimulants for enhancement can be taken as representative. Such ethical reflection usually takes for granted the concepts, norms, and ends that govern the development and uses of pharmaceuticals in medical contexts. Instead of engaging these background interpretive frames, ethical analysis tends to focus on potential harms or negative disruptive effects associated with a specific application and is oriented toward mitigating these and renormalizing the practices. In emerging areas such as those contemplated in Convergence initiatives for enhancing cognition, such analysis is not possible. A more complex ethical discourse is required which will be entangled with scientific and technologically oriented reflection on the nature of the cognitive capacities being advanced. This will be illustrated by considering the ways notions of executive

G. Khushf (✉)
Department of Philosophy and Center for Bioethics, University of South Carolina, Columbia, SC, USA
e-mail: khushf@sc.edu

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function, metacognition, ethical responsibility, and Convergences advancing cognition might be iteratively refined in relation to one another. As a broad effort to understand, foster, and manage emerging practices, Convergence provides a helpful framework for cultivating long needed reforms in the way ethical analysis and policy are approached. At the same time, cultivation of a full ethics of Convergence adds something that is missing from the current Convergence efforts. A richer convergence of Convergence and ethics would thus be mutually beneficial for both forms of second-order reflection.

Introduction

Convergence is a broad policy initiative that seeks to foster science and technology by developing a general knowledge base and tools for cultivating the synergies that are crucial for emerging areas of research. (In this chapter, Convergence will designate the general policy initiative, and specific instances cultivated by this initiative are convergences.) In *Convergence of Knowledge, Technology and Society* (Roco et al. 2013; hereafter cited as CKTS), there is an explicit effort to highlight the importance of ethics and governance. However, what should be included in an ethics of Convergence is far from clear. Usually the ethics of some area that might be advanced by convergences is discussed rather than an ethics of Convergence itself. Since Convergence is advanced as a kind of emergent science of emergent sciences; since it involves its own tools and technologies; and since it constitutes a distinctive set of practices with its own ends and values, Convergence may serve as a fitting target of ethical reflection. At the same time, ethics may be regarded as a fitting target of Convergence. Ethics involves its own specialized, disciplinary modes of reflection that have become problematic when considering emerging technologies. As a general initiative for advancing emerging sciences and technologies, Convergence may provide a framework for thinking about, developing a knowledge base for, and developing tools and methods to advance forms of ethical analysis and engagement that are more appropriate for addressing the challenges associated with the visionary, emergent practices that increasingly represent the cusp of science and technology. An ethics of Convergence may thus arise from and advance its own distinctive convergence: a convergence between two forms of second-order, critical reflection oriented toward advancing the flourishing of science and technology.

This chapter highlights the reciprocal engagement that might be associated with a trading zone between the domains of Convergence and ethics (Collins et al. 2007). A specific "application" of Convergence is considered: enhancement of cognitive capacities. But emphasis will be on the ways this application is representative and thus discloses essential characteristics of the general Convergence effort, specifically the way Convergence involves a holistic, reflective orientation that weaves together science, technology, and society and introduces recursive updates on the conceptual frameworks that serve as the initial points of departure. This general Convergence framework leads to a view of cognitive enhancement that is not easily assimilated to the traditional, act-oriented ethical analysis associated with use of stimulants for enhancement purposes.

Stage 1 Enhancements, Conventional Ethics, and Interpretive Frames

The CKTS report is presented as "a framework for advancing convergence" that can guide efforts to develop a "cognitive society" and "increase human potential" associated with cognitive capacities that are broadly defined to include human-machine interactions, computing and information systems, and brain-to-brain communication, among other things (p. 25). "Frames" are acknowledged as central for communication, ethical deliberation, and decision-making (pp. 20–21). (The literature on interpretive frames is vast and varies with the disciplines that study them. Classic sources include Goffman (1974) and Tversky and Kahneman (1981). Representative psychological work is reviewed by Levin et al. (1998) and sociological work associated with social movements by Benford and Snow (2000). The role of tradition in framing of ethical deliberation is nicely reviewed by MacIntyre (1984, 1988). Explicit use of the frame concept in relation to ethics is worked out most extensively in relation to the "environmental justice frame," e.g., Capek (1993), and in science studies work on risk represented by Wynne (1992). Khushf (2004) considers the relation between frames used for ethical analysis and the interpretive frame used in the first NBIC Convergence report.)

Whenever an ethical issue is presented as a specialized, discrete problem, there is a traditional interpretive frame that orients focal attention and deliberation to that issue. (Khushf 2011 presents this as "type framed ethics.") When some area of science or technology is the target of the ethical analysis, the interpretive frame isolates just those features of the science and technology that are deemed relevant for understanding some ethical problem and addressing it. While these frames are crucial to the way ethical problems and questions are isolated as discrete, manageable units, they are not usually presented as part of the ethical analysis itself. Instead, the ethical task settles out with the interpretation as a modular, specialized problem prior to efforts that address that problem.

In contexts where technology involves relatively modest developments and fits antecedent precedents regarding technological type, the ethical issues can be worked forward in this specialized manner. For example, when a new pharmaceutical is developed, this is usually sufficiently like antecedent pharmaceuticals that it can be managed in similar ways by the same infrastructure (Khushf and Siegel 2012). Established disciplines can be deployed to evaluate health and safety of the drug, design phase 1–3 drug trials, and, if the trials are successful, regulate the prescription and use of the drug. All these will be governed in roughly the same way health and safety, human subjects research, and prescription of other drugs have been governed. There are a set of well-developed standards and regulatory practices that normalize the way a novel technology is evaluated. While the specific chemical composition and function of a drug might be novel, the drug itself is not a novel type of technology and thus does not pose novel ethical or regulatory challenges. Instead, the regulatory frame and contexts of use of the drug can be taken for granted, and any consideration of the novel agent can be restricted to standard questions of health and safety, efficacy, and access.

The ethics of cognitive enhancement is often addressed in relation to such conventional interpretive frames. Even when frames used for the ethical analysis are explicitly considered, as with Racine and Forlin (2008), Outram (2012), and Outram and Racine (2011), the medical frame is used as the basis for defining alternatives (such as might be assumed in public health), and the questions of need, risk, utility, and fairness dominate the ethical discourse. Questions about the enhancement of cognitive capacity are situated in relation to a normalized medical practice, for example, the use of a stimulant to address deficient executive function in a class of patients such as those with ADD/ADHD (Singh 2008; Castellanos et al. 2006; Repantis et al. 2010). The "normal use" is presumed to be the medical one (Wolpe 2002). In this context, the contemplated enhancement would involve a use of technology that is of the same type as that associated with medical treatment. The only difference is that a drug usually deployed as a means of mitigating a measurable deficiency in executive control would now be deployed to enhance some aspect of cognitive function in an agent who would not be diagnosed as having a pathology that warrants prescription of the drug. When the ethical issues are addressed in the enhancement case, the same kinds of questions are asked, for example, about safety, risk, and efficacy, about access and fairness, and about long-term consequences of use (de Jongh et al. 2008).

The use of a stimulant to enhance executive capacity is an example of a stage 1 enhancement (Khushf 2005). Such enhancements take the form of discrete, medical interventions that provide a modest, measurable augmentation of some typical functional ability and have risk profiles that can be evaluated in roughly the same ways other medical interventions can be evaluated. The following characteristics of such stage 1 enhancements are generally taken for granted by the interpretive frames used for ethical analysis of any mature technology:

1. A fully developed, discrete technology is evaluated, for example, a stimulant available in the form of a discrete pill or patch.
2. A discrete decision is contemplated, such as whether or not enhancement uses of the stimulant are permitted. The decisions about allowable use are, in turn, associated with a presumed authority to gate technology; for example, judgments about permissibility are equated with legality, and access is gated by physicians who have authority to authorize use by means of a prescription. (This prescription can be taken as representative for the way ethical permission is viewed: ethical analysis is oriented toward attaining a prescriptive judgment – expressed as a deontic modal claim – of the form "obligatory" (prescribed), "permitted" (allowable), or "impermissible" (prohibited).) The framework for the ethical analysis thus maps back to a broader legal framework, with established policies and protocols for managing technologies of the specified type.

3. The perturbation effects of the technology can be evaluated in relation to the "no-use" scenario, and the net utility of the alternate scenarios can be compared. The ethical analysis is oriented toward working up the relevant benefits and harms and for clarifying the values for weighting them in a common calculus of risk or utility. The ethical analysis is usually associated with the preliminary, qualitative characterization of the factors that enter into evaluations of safety, efficacy, and fairness (the "soft" side of this analysis), while the subsequent experimental and statistical evaluations of the hazard, exposure, and effects on health and welfare (the "hard" side) are regarded as part of a clinical science or, where broader social benefits and harms are considered, part of biological, psychological, and social sciences. Where the background theory and methods of ethical analysis are made explicit, these involve some act-oriented ethical theory, usually utilitarianism with some ad hoc adjustments to prevent instrumentalizing human subjects and address fairness in distribution.
4. There is no reflexive evaluation of the fit between the interpretive frame and the technology being evaluated in the context of that frame. The interpretive frame for the ethical (or legal) analysis is usually not put into play as part of the ethical analysis; for example, few questions are asked about whether medical uses should provide the background for normal use, whether the therapy/enhancement distinction is appropriate, what is meant by executive capacity, and so on. Most significantly, there is rarely an effort to evaluate whether the standard act-oriented, utilitarian analysis (with some adjustments for addressing fairness in distribution and assuring autonomous consent) is fitting for addressing the ethical issues. Why, for example, is a discourse on risk or fairness more fitting than a discourse on virtue and flourishing when we evaluate enhancement of cognitive capacity? Any effort to "open up" these questions would problematize the sharp fact/value and science/ethics contrast that conditions how questions of values and ethics settle out as discrete, specialized problems that can be solved by means of an act-oriented ethical analysis.

These four characteristics are now so deeply ingrained in the interpretive frames we use for ethical analysis of technology that any efforts to address ethical issues in some emerging domain immediately evoke questions about what discrete, novel development poses potential harms to some stakeholders that might be mitigated. These questions often are asked in the form of "what is new about the emerging area?" The novelty asked about is related to some discrete, disruptive development that is insufficiently accounted for by current regulatory infrastructure. Those conducting the ethical, policy, and legal analysis are looking for some specific technology and some contemplated decision associated with its use that can be worked up in the abovementioned manner. If a whole class of novel technologies is contemplated, then questions are raised about whether refinements in our taken-for-granted infrastructure are needed for us to properly evaluate the health and safety of developments. In this way, ethical analysis evokes questions about harms that counterbalance benefits and about values for ranking these benefits and harms in relation to one another. Both the risk-based and precautionary approaches referenced in CKTS (p. 393) make the same assumptions about what ethical analysis entails. They simply allocate the burden of proof differently when taking stock of developments in contexts where data is sparse, the developments are in flux, and the benefits and harms are speculative. When authority to gate the technology is presumed, as with medical uses of stimulants, precaution is the watchword.

Visionary initiatives in science and technology often problematize the piecewise analysis that allows the perturbation effects of some discrete technological development to be evaluated. If the conventional frames used for evaluating science and technology are not reflexively put into play, there will be a tendency to either dismiss the emerging developments as hype or reconstruct and rationalize the developments so they fit the conventional frames. Nordmann (2004, 2007) and many of the essays in Gordijn and Chadwick (2008) provide such criticisms of the enhancements associated with the original NBIC Convergence report (Roco and Bainbridge 2002). However, at best the conditions for such analysis will be satisfied at the tail end of development. They cannot be assumed at the outset, and more work is needed on how stabilization of normative discourse regarding emerging developments might arise. What makes the ethics of emerging technology especially challenging is the way interpretive frames for the ethical analysis must be worked out reflexively with the science and technology that are in formation. Here ethical analysis must involve a second-order, sympathetic but critical reflection on the practices and emerging developments, with a view toward clarifying what is in formation, its promise and potential for disruption, and the degree to which its trajectory is still open to reformation, so opportunities for intervening can be identified that are mutually beneficial to implicated agents (Khushf 2011). The task of the ethicist is itself innovative: to try sketch in a provisional way a frame that might be recognized by those developing the science and technology as resonant with their own, so a genuine dialogue might be initiated regarding the character and flourishing of common life. When ethics is viewed in this way, there are some interesting parallels between ethics and Convergence, especially as it is conceived in the most recent CKTS report.

Stage 2 Enhancements: How Questions of Cognitive Enhancement Are Framed Within the Convergence Initiative

This section provides an overview of some general aspects of Convergence and then moves to a discussion of the way cognitive enhancement is understood and advanced as part of that initiative. Cognition can be viewed as a capacity that emerges from convergences, as can the cognitive science that studies such cognition. In Convergence, there is an effort to align these – the cognition and the science of cognition – in such a way that cognition is extended by means of its science (CKTS, Chap. 6). The extension then feeds back upon the agents who deploy their cognition, their cognitive science, and their cognitive technologies to understand and extend their cognition in ongoing ways. The convergence dynamic of enhancement has a holistic and recursive character that is representative of stage

2 enhancements (Khushf 2005). Such enhancements cannot be evaluated by the ethical interpretive frames used for stage 1 enhancements.

Convergence is a general policy initiative and as such a form of intentional social action. It has its own interpretive frame, which aligns three distinct strands:

First, there is a proposal for a descriptive science of convergence: The sequence of conferences and reports discusses such convergences at multiple scales, ranging from the nanoscale to that of earth systems. Convergence is a broad initiative to work out a general language to describe and understand how diverse specialized activities and processes synergistically interact in ways that lead to emergent capabilities that could not be attained by piecewise consideration of the elements that feed into the synergistic interaction. With this orientation toward convergences that are already underway, the Convergence initiative does not just seek to bring something new into existence. Instead, Convergence (the general policy initiative) takes for granted that there are convergences (the synergizing of disciplinary practices and processes) that are crucial to emerging areas of research. By means of the broader policy initiative, there is an effort to create conditions for a kind of science of emerging science and technology.

Second, Convergence involves an effort to advance technologies for facilitating convergences: The goal of Convergence is not just description and understanding of convergences and the capacities that arise from them. Because the capacities are presumed to depend on facilitating convergences of the right kind, there is an effort to develop methods and tools – more generally, the technology – for efficiently and effectively managing convergences. In this context, stages and phases of convergence have been identified, so initially ad hoc, opportunistic convergences oriented toward narrow goals might be extended into broader, systematic convergences that yield extended capabilities to attain a whole range of goals. (Here there is an interesting parallel with the way classical virtue theory, e.g., as advanced by Aristotle (2011), shifts from actions oriented toward specific and narrow ends to virtues that are pursued for their own sake as general capacities for acting in ways that manifest distinctive human excellence.)

Third, Convergence is itself a policy initiative and thus a form of collective social action that is oriented toward attaining distinct social goods. As such, Convergence does not just advance a science and technologies of convergence for their own sake. These are advanced to address goods associated with health and wellness, sustainable energy, economic productivity, and enhanced cognitive and communicative capacity. To orient any convergence science and technology toward social benefit, specific visionary challenges associated with "application domains" have been identified. Cognition and communication is one of the application domains.

One of the distinctive features of Convergence is the way these three strands – the science, technology, and social governance – are intertwined. Such an appreciation of the interrelation between science, technology, and society is often taken as crucial to the orientation of disciplines that study science, technology, and society

(STS), and some prominent STS researchers have contributed to US Convergence developments, especially to the most recent report (e.g., the contributors to CKTS, Chap. 10; for earlier stages of Convergence, Mike Gorman's innovative development of the trading zone concept was especially conspicuous). CKTS notes that the science, technology, and social governance of Convergence must each be sketched provisionally, with iterative adjustments and updates arising as those partially worked out strands inform one another. In this way, convergence science is to be advanced by Convergence and by convergence technologies; convergence technologies are to be fostered by the general policy initiative and by the developing science of convergence; and the general policy initiative, Convergence, is to be grounded in and advanced by the emerging convergence science and convergence technologies. While the visionary challenges are presented as discrete, independent initiatives, there is a holistic orientation that recognizes that these too will feed back upon one another. Each of them is outlined in a way that exhibits how the science, technology, and governance of Convergence mutually support one another.

The nature of the interdependence of these three converging strands can be seen in the visionary initiatives associated with cognition and communication.

Descriptively, human cognitive capacities can be regarded as emergent features of distinct convergences associated with human evolution and historical development (Ardila 2008). Exactly how best to view the converging strands that lead to emergent cognitive capacity might be taken as an open question at the intersection of the sciences of cognition and convergence. Tentatively, four non-independent strands might be isolated (each of these is referenced in CKTS, Chap. 6):

1. Human cognition is grounded in human neurobiology, including the structure and function of the brain, with a consideration of dynamics at multiple scales ranging from neurons, neural circuits and networks, modular brain regions and their interactions, and upward to the ways the brain modulates bodily systems and interacts with the broader environment through sensory and motor systems. (In CKTS, p. 203, the neurobiology of the brain is said to be "[b]elow the level of human cognition, but subserving it.")
2. Human cognition is grounded in linguistic capacities, which might themselves be regarded as emergent upon convergences that likewise involve an organic dimension. In addition to the neural system, language involves the physiological capacities for modulating sound and generating inscriptions and the conditions for generating and using the differential systems that enable humans to symbolically encode, express, interpret, and utilize stable, recurrent neural patterns associated with mapping and control of internal and external relational dynamics.
3. Human cognition is social and institutional, including both the dynamics of communicative interaction that are oriented toward life-sustaining activities and the social and institutional forms for storing, organizing, refining, and using the informational patterns that provide humans advantages in sustaining their ways of life.
4. Finally, human cognition is technological, associated with distinctive ways humans tinker with the world to generate novelty and then incorporate that

novelty into the ways they live their lives (Clark 2003). Technologies like pen and paper are not just ways of storing and organizing patterns but also for externalizing and extending neural structures, for example, by utilizing arrays of numbers and symbols and then generating cascades across the page that lead to some resultant state, as with performance of long division.

Human cognitive capacities cannot be located in any one of these processes or dimensions. Rather, it involves a distinctive kind of alignment and synergy among them. When the neurophysiological, linguistic, social, and technological dimensions align, there is an explosive extension of capacities that is readily apparent in the distinctive way humans evolve. The authors of CKTS lament:

> yet we do not know how our own 'smart device,' the human mind, works. We are rapidly approaching an era in which the benefits of living in a highly technologized society will be put at risk unless we are able to understand how we, as a single individual or group, process and retain information, make decisions, and perform actions. Getting to that point will require a much deeper understanding of the rule set that subserves decision-making. We term that rule set 'cognome.' (CKTS, p. 208)

The science for understanding cognition, and thus for elucidating the cognome, itself arises from a convergence of several physical and social sciences, for example, neurology, psychology, sociology, linguistics, computer science, and applied mathematics and logic. (Historically and in current cognitive science programs, philosophy also plays a central role, as is acknowledged in CKTS, p. 201, when the Cognitive Science Society's own account of constituent fields is cited. But the humanities, especially philosophy, are conspicuously absent from CKTS summaries of both the history and future directions of cognitive science, where the convergences are of "sciences" (pp. 16, 18–19, 20–21) and of "physical and social sciences" (as on p. 203). The need for a broader framework of Convergence that includes the humanities will be considered in the final section.) On the basis of the developing cognitive science, the Convergence report proposes a host of technologies that further extend cognition. This, in turn, would alter the content of that which is studied by the cognitive sciences.

Convergence (as the large-scale initiative concerned with convergences of all kinds) relates in an interesting, not fully specified way to the specific convergence of sciences called "cognitive science." Convergence science might be regarded as the general science that looks at how capacities arise from convergences. Cognition is just one of the capacities that arises, and may be studied. But any science deploys modes of cognition. As a science, Convergence may thus be subsumed under a cognitive science of science, which maps diverse forms of cognition and also works out ways of extending cognition and aligning diverse sciences that currently do not communicate with one another. (One might also say that cognitive science relates to metacognition and cognition as metacognition relates to cognition. Convergence then iterates this again, relating to cognitive science as the latter relates to metacognition and cognition.) This kind of recursive, synergistic extension and modification of science and cognition is representative of the way the Convergence policy reports present emerging sciences and their ongoing development. Concepts from systems and complexity theory are regularly used to highlight the ways developments associated with one kind of convergence feedback to extend capacities associated with other convergence domains. After this feedback, a shift is required in the interpretive framework that is used for initial analysis. These recursive updates might be viewed as generalized accounts of the action loops that are used to define embodied cognition (Clark 2003).

The recursive, iterative extensions of capacities and the associated interpretive frame shifts may be taken as two of the defining marks of the general Convergence framework. These are also the defining features of stage 2 enhancements. Such enhancements provide qualitatively new abilities that alter the ways humans interact, providing significant advantages to those who deploy them. They lead to accelerating recursive extensions and thereby introduce instabilities in the social and institutional systems that are created by and sustain the agents who interact through them. Convergence can itself be viewed as a frame for advancing such enhancements. We can clarify the intentional structure of Convergence by introducing the specific targets of these updates. For example, in relation to metacognition, the goals of Convergence might be taken as follows: (1) understand how cognitive and communicative capacities arise from lower-order convergences and (2) understand how cognitive science arises from convergence of diverse disciplinary approaches to cognition. These are two distinct levels that each arise from distinct convergences. However, once the cognitive science arises, it provides a basis for extending cognition. When cognitive science feeds back to augment cognition, we get a convergence of these distinct levels of convergence. This, in turn, requires that the next generation of cognitive scientists reflexively alter the contents of the cognition they study, so it includes the extended capacities that arise from the ongoing developments of the cognitive science.

The Challenge Posed by Convergence to the Conventional Interpretive Framework of Ethics

In the Convergence reports, the ongoing recursive enhancement of cognitive capacities is made normative. This is in sharp contrast with the medical frame that was presupposed by the traditional ethical analysis of a nontherapeutic use of stimulants (Wolpe 2002). There is some kind of homeostasis presupposed, and pathology is regarded as a kind of nontypical deficiency in the abilities associated with executive function which can be mitigated by means of the stimulant. The enhancement use of the stimulant was regarded as non-normal and thus potentially disruptive.

CKTS suggests that cognitive science arose from a criticism of exactly that medicalized approach to human capacities. When reviewing how the Cognitive Science Society arose by distancing itself from mental health practitioners who were "unduly oriented toward what their clients or patients accept, rather than toward the results of rigorous research," CKTS directly challenges the ways normality is related to disease:

> Applied mental health fields tend to follow a disease model of the problems they face, except to some extent in dealing with cases of mental retardation and autism where a disability model also comes into play. Conceptualizing a mental problem as a disease asserts that proper treatment could return a person to normal, and thus that a clear definition of normal exists. Critics have called the excessive imposition of the disease model medicalization and have suggested that despite the great benefits medicine often can offer, many kinds of 'cases' could better be conceptualized as a poor fit between the innate mental characteristics of a person and the expectations of the surrounding society. . . . Here, cognitive science may often be in a better position than psychiatry to develop really rigorous modes of diagnosis to identify the kinds of cases where a medical model is inappropriate . . . Principles from cognitive science could better decide when efforts to help a person should concentrate on new assistive technologies, educational programs to give the person new skills that can compensate for an incurable disability, and perhaps even make adjustments in society's expectations. (CKTS, p. 202)

While there might be reasons to question whether this approach involves a straightforward extension of a distinct convergence field of cognitive science, the recommendations reflect insights at the cusp of many research areas, including the traditional mental health fields (Young and Amarasinghe 2010; Karbach and Kray 2009). The arguments could be directly extended to the case discussion we earlier considered. For example, how do we evaluate the contexts that are normally taken for granted when the executive function of children is evaluated by physicians to see if they have ADD/ADHD? The mismatch between environments favoring the evolutionary emergence biologically based aspects of executive capacity and current contexts where little children are required to sit still for 8 hours each day staring at symbolic marks on flat sheets is rarely discussed. Fewer still consider how executive capacity and the understanding of such capacity might both depend on culture, not just our biochemistry (Ardila 2008). The social contexts, the problems, and the options for addressing them are all highly unusual constructs of our current societies, yet these are all traditionally evaluated from the perspective of very narrow medical interpretive frames that are themselves constructs of a specific day and state of knowledge. The normality presumed within those frames is anything but normal, and the drafters of the Convergence report are on target with their criticisms. However, I will not further elaborate on this theme. Instead, I seek to consider in a more general way how the ethical analysis itself breaks down.

When we focus on the recursive extensions of capacities and the interpretive frame shifts associated with stage 2 enhancements, we notice that all four characteristics assumed by traditional ethical analysis are not satisfied: Stage 2 enhancements do not arise as fully developed, discrete technologies. There are no clear decision nodes and no clear jurisdictions where permission is required. Perturbation effects of contemplated options cannot be evaluated against no-use options, and any claims about utility or risk would only involve wild speculation. Even when we can identify some general type of technology, for example, human-machine interfaces or institutions for social networking like *Facebook* that enhance social interactions, these denote clusters of intersecting networks with very fuzzy boundaries.

Any general, nonmedical approach to enhancing executive capacity or metacognition has the same kind of fuzzy boundary. We can take executive capacity as an umbrella term for a general, metacognitive capacity that humans have to monitor automatic, habitual responses and detect when these are not attaining their ends (the "cold" component) or, alternatively, to prioritize among ends (with associated emotional valence of significance), plan actions that attain them, and then hold to selected courses of action until the ends are attained (the "hot" component) (Chan et al. 2008). Viewed in this broad way, executive control and metacognition roughly track the mental processes associated with interpretive frames, ethical analysis, and the reasoning, emotional processing, and planning required for humans to live integrated, meaningful lives (Ardila 2008; Fernandez-Duque et al. 2000). When individuals fail to monitor align the potentially divergent strands that constitute a life, this failure might arise from a host of factors, ranging from unwise acceptance of too many responsibilities, poor habits, instabilities in the ebb and flow of obligations, losses in social support networks, failure to keep up with technological developments that support tracking and planning, or deficient levels of dopamine or some other neurotransmitter. If we view ongoing development and enhancement of executive function as a normal part of the development of every individual, then a multidimensional approach that uses new software, a smartphone, exercise, diet, and stimulants (whether of the commonly available or prescription variety) is just an ordinary frame humans deploy for living their life. If we now additionally add a new science initiative oriented toward understanding how lower-order processes converge to constitute an emergent metacognitive capacity that feeds back and controls the convergences, and if we note how such metacognitive capacity might be extended by the science, we only have an additional scientific overlay on the normal activity. If we can identify significant, qualitative extensions that arise as a result of the way specific scientific initiatives to study cognition are deployed to extend cognition, then we might have something with enough coherence to make a target of ethical analysis. But we cannot regard the agents with enhanced cognition as human subjects of a traditional sort, and we cannot take enhancements as discrete technologies we subject to conventional act-oriented ethical analysis.

In sum, conventional kinds of ethical analysis are simply not helpful when evaluating the kinds of emerging research developments that are prominently featured in the Convergence initiatives to enhance cognition and communication. Efforts to provide ethical analysis of this kind of visionary science and policy from within a traditional ethical interpretive frame either must ignore the ways the visionary sciences challenge background concepts such as executive function and cognition or must speculatively generate discrete technologies and normalized contexts, for example, by introducing futurist scenarios, so conventional survey research might be conducted on values, and so utilities for these imaginary worlds might be generated. Either way, there is a profound mismatch between the ethical analysis and the realities of the emerging science and technology.

Directions for Future Work on the Ethics of Convergence

There is significant overlap between normative ethics, metaethics, and the kinds of practical rational deliberation and theory associated with Convergence. All are forms of second-order, critical reflection that seek to modulate life processes that are underway, so individual and social goods are attained. When emerging science and technology are the targets of the second-order reflection, both ethics and Convergence must involve broad, reflexive interpretive frames. When these frames are deployed in relation to specific efforts to enhance cognitive capacities, there will be an interesting recursive relation between the interpretive frame, the capacities associated with the frame, and the capacities that are the targets of reflection. Further, those who adopt these frames can each reflect upon the concepts, histories, practices, and goods associated with the other. In this way, those advancing Convergence can reflect on ethics, and those who are part of the ethics and policy communities might reflect on that distinctive policy initiative associated with Convergence. This closing section considers some questions that might be addressed through a sustained engagement between those in the ethics and policy communities and those advancing Convergence.

First, what are some of the implications of the breakdown in conventional modes of ethical analysis when evaluating emerging science and technology? There are several places in CKTS where conventional approaches to ethics and governance have been criticized (especially in the overview, e.g., pp. 20–21 and Chap. 10), either because data for analysis of utility or risk is lacking (pp. 360, 369), because the processes associated with ethical governance are slow or conservative and reactionary (p. 366), or because the input that might be provided is unscientific (pp. 20, 370). This chapter has sympathetically develop some of these criticisms by highlighting the misfit between traditional narrow ethical frames used for analyzing need, risk, or utility and the realities of emerging practices. But there are implications of these criticisms that have been insufficiently explored within the Convergence initiative.

Consider, for example, the way CKTS presents potential radical implications of cognitive enhancements for the way humans understand themselves and their goods:

> As the new generation of convergent technologies becomes fully embedded within the science of cognition, it is inevitable that our own view of what it means to be human will change fundamentally (e.g., see Giordano 2012). This change in view will be a central characteristic of The Cognitive Society [which they propose a roadmap for creating]. At an obvious level, the boundary between brain and machine will become increasingly blurred as machines are increasingly made out of materials that mimic those of the brain. At a deeper level, as humans become increasingly more deeply connected to one another, the notion of ‘self’ may evolve in as yet unpredictable ways that could have profound effects on

> society. The ethical, social, and legal implications for such trajectories in human development will be extraordinarily important for serious consideration – by scientists, policymakers, and the larger global polity. (pp. 213–214)

What form might such "serious consideration" of ethical implications take? Put in another way: how do norms, values, and priorities of individuals and societies enter into the ways the recursive enhancements of cognition might arise (a passive framing) or might be advanced (an active framing)? In much of the Convergence report, these emergent capacities are presented as if they arise automatically from efforts to modulated convergence. While there is much on how to accelerate convergences, there is relatively little on how emergent capacities arising from them might fit together in a way that genuinely enhances life. What enhances life, and how does it do so? What diminishes life and why? If individual and social forms of agency can facilitate and orient these convergences, and if the modulations are not simply deterministic and automatic (the passive framing), then some normative account is needed to guide deliberative agents. This might be worked out through critical reflective and political processes, but those who come to these deliberations will be informed by a host of influential traditions that have told us who we are and ought to be. In whatever way we understand these normative accounts, they cannot just be worked out by means of some descriptive, social scientific study of values or through some general decision theory. Any account of decisions must introduce norms of rationality, weightings of the factors that enter into the optimization or satisficing analysis, and values/ends that direct such decisions. While much of human cognition, decision, and action is constrained in a host of ways, taking up a practical rational stance presumes there are features of the world that can be otherwise (Aristotle 2011, Book 3). Normative ethics is concerned with how such contingency ought to be managed.

One of the most important questions considered in ethics relates to which capacities of the self might be transformed, and what normative constraints govern such transformations. If human concepts of self are radically problematized by some technological development, it remains open to say that such a development would diminish life and thus should be modified to avoid such diminishment. In this way, a proactive mitigation of what is perceived as a harm, risk, or disruption could establish conditions for continuity of self-concepts that would otherwise be disrupted. There may even be some forms of technologically extending cognition that so deeply alter the structure of being human that we reject them because the "enhancements" are, in the end, really diminishments of human life. While there are some suggestive places where the CKTS report seems to appreciate this, the questions of choice, freedom, and agency never really enter in such a way that they have a full integrity and might serve as a basis for critically engaging the onward march of evolutionary processes that, at times, sound a lot like older discussions of onward marching dialectical material processes.

At one place in the CKTS report, we are told that "the human propensity to think in terms of conscious goals is insufficiently counteracted" by the training of scientists in non-evolutionary fields, and this propensity may undermine convergence between those scientists and evolutionary biologists (p. 204). We are also told "the goal is to find fundamental principles that can unite previously separate fields in a rigorous manner" (p. 19) and that an evolutionary account of convergence processes provides that rigorous, general framework for unity of the sciences (Chaps. 4 and 10, pp. 359–360). The implication of putting these claims together seems to be that the human propensity to think in terms of conscious goals should be counteracted (note the drift from descriptive to normative claims). But how then do we think about the ways convergences are to be modulated so recognizable social goods are attained? If we push hard the implications of not thinking in terms of conscious goals, we notice places in the report where seeming concessions to governance seem muted. For example, CKTS states that "[g]overnance has a critical role to play in setting goals for fundamental research using societies big challenges, besides the approach of curiosity driven research" (p. 368). Initially this sounds like emphasis is being placed on human agents who govern by setting goals. But if we notice how sustained social conversations about the ethics only constitute the "early stages" of the Cognitive Society (p. 214), and if we move toward "cognitive systems and algorithms [that] recognize context and intent without having to be programmed by experts in arcane software languages, but rather learn in an uncertain and changing environment" (p. 216), then perhaps some advocates of Convergence really do want to "reprogram our biology" (p. 203), so we eliminate the "folk psychology" associated with conscious goals and agency. However, there are other ways to think about the recursive relations between the explanatory frames used for a third-person understanding of evolution and those first-person frames we use to make sense of our own lives and plan our actions (Ardila 2008; Khushf 2009). The problematic character of their relation should be presented as an open question, rather than something resolved by fiat from one side. At issue is the integrity of the first-person perspective itself.

In classical ethics (e.g., Aristotle 2011, Chap. 3), being human is related in a central way to our capacity to think in terms of conscious goals and reflectively regulate our actions, so these goals are attained. Human cognition and metacognition/executive control seem to be definitively related to such forms of thinking, and an evolutionary account might be provided for the development and adaptive function of these capacities (Ardila 2008). The complexity of the chains we can trace in our conscious awareness and the reflexive capacity to adjust these chains are often presented as one of the distinctive ways humans differ from other animals (e.g., the so-called theory theory). Language, social institutions, and the technologies that extend human cognition are a central part of this story. But social machines that maximally generate technological novelty and automate science would not be regarded by most people as "enhancements" if they end up reducing humans to grease in those social, bureaucratic engines. If, as CKTS proposes, the developments are said to enhance rather than diminish individuality and the attainment of personal goals, we need to press for clarity regarding what this might mean. Many would closely tie genuine enhancement of cognition to some kind of extension of the human capacity to consciously specify goals, form plans to attain them, and then regulate actions, so the plans are realized. While this capacity has always required and gone hand in hand with automation of a host of the lower-level machinery, such automation was for the purpose of off-loading the boring parts, so conscious attention could be directed to the most important things (Clark 2007). This would at least be a prime topic for debate in ethical discourse about Convergence for enhancement of cognition. The outcome of such debate might then feed back upon certain research trajectories that are cultivated in cognitive science.

One of the most significant things that might be gained from the reciprocal engagement between those reflecting on ethics and governance and on Convergence might relate to the way a convergent interpretive frame might be worked out that incorporates insights from each. This would involve a real bridging of a long acknowledged and problematic science/humanities divide. Convergence is future oriented and tends to regard science and technology as the primary and even sole drivers of human development and progress. "Decelerating scientific progress" means ending progress and economic stagnation (CKTS, p. 366). Where a broader critical analysis is apparent, this tends to be directed against nonscientific ways of understanding human life. Any "linking together of the humanities and natural and social sciences" is to be situated in the context of Convergence, not symmetrically worked out at the intersection of a Convergence discourse and interpretive frames associated with the humanities (p. 18). What is not scientific tends to be viewed as unscientific, and any accommodations "would risk basing decisions on popular illusions or myths promulgated through the mass media rather than on professional expertise" (p. 20). The humanities are rarely viewed as a resource, especially not a symmetrical convergent stream, that is supposed to inform science and industry. Any language about reflective, conscious awareness integral to philosophical and ethical discourse is replaced with a discourse of cognitive societies and technologically mediated communication and information processing. As already noted above, there is even a critical edge against "the human propensity to think in terms of conscious goals." Such propensity is obviously central to discourse in ethics and the humanities. Despite this critical edge, however, the global, reflexive interpretive frame associated with Convergence is ideal for developing a genuinely productive dialogue between the humanities, ethics, and policy communities, on one side, and the sciences and industry, on the other. The interpretive frame associated with the report reflects influential views about science and society that should be put into play as part of a general discourse on science and technology policy.

The potential value of the Convergence frame can be seen in the way the Convergence initiative for enhancement of cognition might inform and be informed by fuzzy concepts of executive control and metacognition that are currently associated with medical norms for use of stimulants. Executive function may be defined in relation to human reflective capacity for monitoring semiconscious, automatic, or habitual life processes at the edge of failure (Rosenthal 2000). Cognition may be viewed as thought directed toward a life-sustaining goal. Metacognition is a reflective capacity to think about such thinking and keep it aligned with goals (Livingston 1997). Human capacity to think in terms of conscious goals is closely tied to executive function, and it is evoked in contexts where normally convergent streams begin to diverge (Fernandez-Duque et al. 2000). It is at just those moments that the routines of life are brought into conscious awareness, goals are more explicitly fixed, and innovation arises to generate novel patterns of action that better assure goals are attained. Failures of executive capacity arise when the distractions and complexity of the world overwhelm the human capacity to sustain goals and the means for attaining them within an ongoing conscious awareness (Ardila 2008). They are also intertwined with our capacities to understand and coordinate our actions with other agents (theory of mind) (Perner and Lang 1999). Viewed in this way, the recursive enhancement of cognition might be viewed as an extension of conscious awareness, and the broader Convergence initiative might be viewed as an effort to work out these extensions at levels of ever broader social networks and ever higher scales of shared communal action (Canguilhem 1991).

In ethical theory, the word for this kind of recursive regulatory control is "responsibility" (Khushf 2009). One of the biggest challenges associated with the rapidly developing, emergent, disruptive developments in science concerns the ways existing individual and social systems fail to track, monitor, and regulate the causally influential streams that need to be harmonized in current societies. The potential breaks in capacity of human conscious oversight might be regarded as the social analogue of a failure in executive function. The breakdown in the traditional, type framed ethics likewise exhibits such a failure. Older modes of responsibility and governance have assumed strands of life can be tracked individually and evaluated piecewise. Convergence might be viewed as an effort to work out an alternate form of executive control, and with this, sketch a form of science and technology that might bring the complex, overwhelming strands back into a kind of social awareness and control. In this way "[t]he governance of converging technologies and the use of converging technologies to redesign governance will critically influence how we address the grand challenges we face in the 'Anthropocene,' an era defined by human activities and a future made by human decisions" (CKTS, p. 368; see also p. 4). But this science-based, technologically oriented mode of engagement needs to recover the concepts, discourse, and logic of responsibility and responsible governance, so the progressive developments can be woven back into an ongoing, continuous historical discourse of human life. Such continuity is itself a property of responsibility: in and through such continuity, humans exhibit the "mindfulness" and "wisdom" that normatively orients how they might get from where they have been and where they are to where they hope to be. The right kind of dialogue over the ethics of Convergence might lead to an interpretive frame and genuine, productive interactions that enable that special, conscious awareness that looks forward and backward in that distinctive way called "responsible."

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Human Enhancement in Sports

Andy Miah

Contents

Abstract

This chapter examines the range of sciences and technologies that converge around sports and the implications of this for issues of fairness and ethics. First, it outlines some of the recent scientific developments that speak to the convergence of disciplines pertinent to sports enhancements. Second, it considers the consequences of convergence within sport, inquiring into the practical ethical issues it provokes. Finally, it explores examples of technological effect in sport, which, collectively, articulate how far ranging are the many ways in which innovation converges on sports. In so doing, it provides a taxonomy of innovations which reveal the complexity of technological change in sports and the challenge of isolating artifice from nature.

A. Miah (✉)
Chair in Science Communication and Future Media, School of Environment and Life Sciences, University of Salford, Manchester, UK
e-mail: @andymiah.net

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Introduction

In 2008, a Paralympic champion named Oscar Pistorius launched a campaign to claim his place as an athlete in the Beijing 2008 Olympic Games as well as the Paralympic Games. As a performer and activist, he was unrivaled in this aspiration and he quickly became a symbol for a new generation of prosthetically enhanced athletes, whose capacities were beginning to rival those of their biologically enabled competitors. It would seem, very soon, that prosthetics would surpass biology, at least insofar as physical performance was concerned, and this period provided a clear indication of how convergence in scientific and technological innovation around sport would change the practice of performance optimization irrevocably.

However, Pistorius' campaign came to a halt quickly, as his initial request to the International Association of Athletics Federations (IAAF) was turned down, on the basis that his prosthetic "cheetah" legs contravened their rules. In response, he contested this claim and, some weeks before Beijing 2008 Olympics, his appeal to the Court of Arbitration for Sport was upheld, and he was given the chance to qualify and compete at the Olympic Games. In the end, Pistorius did not reach the qualification times necessary for selection in Beijing, but, 4 years later, at the London 2012 Olympic Games, he repeated the process and became the first bionic athlete to compete at the Olympic Games, making history in the process.

His example illustrates how, over the last decade, innovation in prosthetics, drug design, genetics, and simply sports science and medicine have had a dramatic impact on how one makes sense of performance capacity and enhancement in sports. After nearly 100 years of sports doping, the World Anti-Doping Code (2009) now encompasses a wide range of methods that reflect the expansion of doping techniques. These include anabolic agents, hormones, beta-2 agonists, agents with antiestrogenic activity, diuretics and other masking agents, oxygen transfer enhancers, chemical and gene doping, stimulants, narcotics, cannabinoids, glucocorticosteroids, alcohol, and beta-blockers. However, there remain numerous enhancement practices that extend beyond what the code covers, and understanding how these technologies are integrated with elite sports practices is essential to coming to terms with how risk is negotiated by athletes around physical excellence.

These conditions of elite sport reveal how they have become playgrounds for convergent technological innovation, where a range of applications demonstrates how sports are embedded within technological structures. The prospects for even more radical technologies to influence athletic performance grow continually as progress in nanotechnology, stem cells, and genetics gains strength. This growing role of technology within sport raises questions about its future direction, particularly how, as Kelly describes it, biology will relate to the "new biology of machines."

At the heart of these debates are key societal questions over what kinds of people there should be and what kinds of enhancements technology should allow. Moreover, one of the pivotal questions surrounding sports is whether the approach to doping needs radical transformation, as the age of enlightenment gives way to an age of enhancement, and this chapter addresses this proposition by exploring the ways in which science and technology converge to usher in an age of enhancement. To this end, the expansion of human enhancement within society also suggests the need for further convergence in sport ethics and bioethics, as the two become mutually dependent on developing insights into what kinds of lives are worth living and what kind of social systems are possible to justify from the perspective of social justice. If simply taking a pill can enable achievements or modifying genes, then the entire system of merit collapses, calling into question how goods are distributed, how achievement is attributed, and how value is ascribed to the things people do.

This chapter examines the range of sciences and technologies that converge to make sports an exemplar of innovation and progress in convergence. First, it outlines some of the recent scientific developments that speak to the convergence of disciplines pertinent to sports enhancements. Second, it considers the consequences of convergence within sport, inquiring into the practical ethical issues it provokes. Finally, it explores examples of technological effect in sport, which, collectively, articulate how far ranging are the many ways in which innovation converges on sports.

The Converging Sciences of Performance Enhancement

While it is often tempting to consider the most high-tech examples of performance enhancement in sport as a way of addressing future implications, perhaps the most important examples are found within the science of performance itself, or what might be more adequately called sports science, which is often focused on much less technological issues, such as the importance of hydration. Yet the frame of reference is even broader than this and extends to any form of technical underpinning that can influence an athlete's performance. Thus, technical enhancements include those that involve knowledge-based insights, which can lead to improved performance. Such examples encompass modifications arising from scientific insights, such as better understanding about the effect of nutrition. However, they also include the way that knowledge affects our understanding of technique. For example, in the 1960s, the Fosbury flop transformed high jumping in such a way as to alter what we now understand by this athletic endeavor. These insights can sometimes arise from spontaneous discoveries, though the expansion of sports science has led to the careful design of such transformations (Busch 1998).

In some respects then, the history of sports science is a history of scientific convergence, as more and more disciplines come together to generate insights into the technological system that is human performance, where physiology, psychology, nutrition, anatomy, physics, engineering, medicine, and more come together to optimize performance. Of course, improvements derived from new scientific knowledge are rarely controversial, though often this is because their use does not imply any misuse of medical technology, which is a primary concern of the anti-doping authorities. Yet such examples are forms of enhancement, and their development dramatically affects fair competition. In this sense, technological convergence makes sports possible, and the ongoing desire to enhance performance reinforces this dependency.

It is not only in-competition technologies that matter when considering convergence in sport. Some of the most interesting examples of technical enhancements involve training systems aimed at improving performance, one recent example of which is the hypoxic chamber (Levine 2006; Loland and Murray 2007). Hypoxic training is a long-established tradition of athletic competition and involves athletes moving from one altitude to another to optimize performance. However, hypoxic *chambers* are a relatively new technology that simulates this effect, while remaining in one location. The science of hypoxia involves changes in the partial pressure of oxygen within an environment, which increases the body's hematocrit level. These changes reduce the partial pressure of oxygen in the pulmonary capillaries, which leads to an increased need to breathe. In turn, the body senses the changes and increases the production of red blood cells, which are rich in oxygen-carrying protein (hemoglobin). This enhanced production leads to a greater aerobic potential for the individual.

In 2006, the world of sport debated their ethical status where concerns arose about the reliance on "expert systems" to bring about performance advantage, but it is important to note that such expertise is contested. Scientists differ on how best to utilize hypoxic chambers to promote enhancement, and so it remains a strategic choice to use, rather than a sure way of gaining an advantage. The risks posed by such chambers are also unclear, and in 2006, after extensive review, the World Anti-Doping Agency concluded that there was no evidence to suggest they are especially dangerous and they remain a permissible means of enhancement. Yet the more intriguing characteristics of this issue relate to the ethical debate that has ensued.

During 2006, the ethical status of hypoxic chambers was put to the recently formed Ethical Issues Review Panel in WADA, which is chaired by Thomas H. Murray. The panel's report raises a number of specific arguments as critical to the ethical status of hypoxic training, beginning its discussion paper by asking what it is about sport that people find honorable, admirable, and beautiful. Their position concludes that hypoxic training is a violation of the "spirit of sport" (WADA Code) insofar as it does not require the "virtuous perfection of natural talents" matters to sport. In short, their view was that the use of such chambers was "passive" requiring no skill, knowledge, or effort on the part of the athlete. They state: "my responsibility for my performance is diminished by technologies that operate upon me, independent of any effort on my part." As was mentioned earlier, the "spirit of sport" concerns constitute only one element of the process by which a technology might be deemed a doping technology. Yet, in this case, it was the first major case where the ethical perspective was seen as being potentially decisive to the overall outcome, since the health risks surrounding hypoxia were unproven. The final outcome of this inquiry made in September 2006 was that the hypoxic chambers should remain legal, which seems satisfactory to a number of commentators who challenged the proposal to prohibit their use (Levine 2006). However, an exploration of its reasoning elaborates on how categories of effect are articulated in moral language within discussions surrounding performance enhancement in sport. Whether or not the risks are significant, the case illustrates how even rest may be seen as a form of performance enhancement and how sport science must draw on scientific research across a whole range of subjects to fully understand how best to optimize physical performance capacities in competition.

Another less known technology is the "Glove," developed by Heller and Grahn. This innovative cooling device has been utilized by the San Francisco 49ers, and it demonstrates the blurred boundary between therapeutic use and enhancement. The problem addressed by this technology is overheating during exercise, which significantly diminishes performance. The Glove device "is used to apply a 35- to 45-mmHg subatmospheric pressure to an entire hand to draw blood into the hand and increase the filling of the venous plexus underlying the palmar surface. A heat sink applied to that palm extracts heat and cools the venous blood" (p. 972). Research on trained persons – military, sportspersons, and emergency services – demonstrates between 30 % and 60 % enhancement of endurance capacity after use. This means that the subject can work for an additional 30–60 % before exhaustion through overheating when working at maximal load. Presently, such a device is not of immediate concern to the World Anti-Doping Agency – and there are many devices that attempt to address overheating – though it remains to be seen whether similar such devices will soon be part of the anti-doping list. Guthrie (2008) describes one of the tests undertaken by the scientists on a trained athlete:

> His routine included 100 pull-ups. One day, Grahn and Heller started using an early version of the Glove to cool him for 3 minutes between rounds of pull-ups. They saw that with the cooling, his 11th round of pull-ups was as strong as his first. Within 6 weeks of training with the cooling breaks, Cao did 180 pull-ups a session. Six weeks later, he went from 180 to 616.

The "Glove" leads us to forms of enhancement that arise from innovations in equipment design, though even this concept has expanded in remarkable ways recently. While sports have always evolved alongside technological developments, equipment has sometimes been controversial, and this often has to do with its transformative effect. For example, in the 1980s, javelins were redesigned due to the fact that athletes were becoming so capable that their distances posed a risk to spectators in the far side of the stadium. Thus, rather than change the size of the arena, the javelin was adapted. The result was an alteration of the skills needed to be a competent javelin thrower, and this meant a change in the kinds of athletes who were successful. Alternatively, there are *unintended consequences* arising from technological change. For example, the development of the plastic helmet in American football was designed to protect athletes from head injuries but was widely reported to have led to more risky behavior (Gelberg 1995).

Examples like this emphasize how difficult it is to preview how an innovation will affect a performance. As technology improves, equipment finds itself in close proximity to doping discussions. For example, swimming costumes have attracted such alarm in recent times and were, until very recently, a recurrent technological story around major competitions. The evidence base to support their enhancing properties is dubious, though the psychological edge athletes may achieve by such campaigns could be considerable. In any case, during 2009, FINA was under pressure to react to a latest costume design, the use of which a number of high-profile athletes protested. Among the protestors was Michael Phelps, the most successful Olympic swimmer of all time, who threatened withdrawal from the sport unless a ban was enforced. The outcome was a complete ban on swimsuit technology, marking the end of an era of alleged technological enhancement. Again, what interests us here is less the final decision and more the manner in which the innovation draws on a range of scientific disciplines, in this case engineering, materials science, physics, and physiology.

A systems-based understanding of performance becomes even more crucial when considering biochemical enhancements, and in this area, the sport's world has continued to struggle to keep up with the range of ways in which, mostly, pharmaceutical science has led to the creation of substances or methods that athletes might use to boost their performance. Such designer steroids as tetrahydrogestrinone (THG) (Sekera et al. 2005) or selective androgen receptor modulators (SARMs) – which allow more target enhancements – continue to frustrate anti-doping authorities, reminding them of how difficult it is to stay ahead of dopers. Even nutritional supplements have been found to cause problems, especially due to poorly labeled nutritional supplements or food products (Hon and Coumans 2007). Supplements are not prohibited methods of performance enhancement, though their use is discouraged due to the quality control problem. Labeling issues continue to arise in the context of standard sports products, as in the recent cases of *Vitaminwater*, which contains caffeine, a controlled substance in some anti-doping codes, or *6-OXO Extreme*, an antiestrogenic substance used to build muscle mass. These examples also point toward the manner in which sports enhancements engage a wider population and such convergent sciences as *nutrigenomics* are constantly creating new areas for convergent practice in sport. In this sense, the science of performance enhancement in sport is inherently convergent, as incremental improvements to performance derive often from the insights of combined knowledge systems.

A further means by which physical enhancements are achieved is through elective surgical procedures. For instance, leg extensions using reconstructive surgery or reparative surgical procedures that translate into improved performance capabilities are examples that beckon an age of enhancement. One example of this is laser eye surgery, which was famously utilized by world champion golfer Tiger Woods. Alternatively, injured athletes may enter into surgery in order to have a chance of returning to competition. One such treatment is Tommy John's surgery, utilized by baseball pitchers who tear their ulnar collateral ligament. Such athletes face the hard choice of never competing again or undergoing invasive surgery and strenuous rehabilitation. While in its early years, this procedure had a very poor likelihood of success, recent anecdotal evidence suggests the additional complication that post-surgery athletes are returning to the field pitching harder and faster than before they were injured. This raises questions over whether athletes may even elect for such surgery prior to injury, just to reinforce their biological capabilities. A similar proposition arises in the context of the earlier discussion about prosthetic devices. While athletes might not choose to replace a limb with a prosthetic, the strengthening of tendons and other connecting tissue may appeal.

Addressing the Consequences of Enhancement

Since the early part of the twentieth century, various sports organizations have employed an anti-doping policy, though it was 1967 when the International Olympic Committee first organized a medical commission whose primary role was to address the use of doping substances. The main concern of this committee involved the risks to health that doping entailed for athletes, which, expectedly, was also seen to work contrary to the values of Olympism. In particular, the televised death of Tommie Simpson in the Tour de France in 1967 began a cultural turn in how the doped athlete was represented. His image of a doped athlete has become characteristic of the abjection associated with unnatural enhancements, which, I suggest, sustains part of the political will surrounding anti-doping. In 1998, the Tour de France again was monumental in transforming this political landscape. The images of athletes under siege by police provoked the world of sport to rethink its approach to doping, and the World Anti-Doping Agency (WADA) was born soon after.

The current international standard for doping technologies is outlined in the World Anti-Doping Code (2015), which indicates that two of three conditions must be engaged in order for a technology to be *considered* for prohibition from sport. These consist of the following:

1. Is the technology harmful to health?
2. Is it performance enhancing?
3. Is it against the "spirit of sport?"

Determining whether these conditions are engaged is not simple and requires some form of discursive process to resolve. However, it is important to realize that the code is not engaged for all forms of technological enhancement. For instance, when a new design element of a tennis racket is introduced – such as the use of piezoelectric dampening technology – the anti-doping code is not engaged. Rather, the specific sports federation will consult its own guidelines on technical specifications to determine whether the innovation is acceptable. This is important to bear in mind, as it has specific implications for how one theorizes the importance of convergence. For instance, if equipment modifications rely increasingly on technologies that resemble more nature than artifice – as may be said of prosthetics – then the separate spheres within which the ethics of any given enhancement is considered may need a closer proximity.

Since its beginning, one of WADA's key roles has been to harmonize policy across sports federations. Since its inception in 1999, it has succeeded in working with UNESCO to develop a convention on doping, and its relocation to Montreal has been accompanied by renewed efforts from a range of countries whose recent actions suggest greater rather than less controls over athletes' actions. In particular, former US President George W. Bush included references to the "war on drugs" within two State of the Union addresses (2004 and 2005). Also, over this period, a series of congressional hearings took place in relation to doping within baseball, which aimed to address the prevalence of substance use within youth culture. Yet, also during Bush's presidency, critics alluded to a need for more careful consideration on how best to tackle the use of performance-enhancing substances in sport. At a time when the USA was beginning to introduce anti-doping tests within a number of high schools, it is pertinent that the American Academy of Pediatrics (AAP 2005) published a statement questioning the effectiveness of such tests as a deterrent.

Other activities within the USA were also relevant for raising the political profile of sports enhancement issues. For instance, during 2002 the US President's Council on Bioethics received two sessions, which discussed enhancement in sport (2002a, b). Also, the leading bioethics institute, The Hastings Center, undertook continual research in this area since the 1980s (Murray 1983, 1984, 1986a, b; Parens 1998), later receiving funds from the US Anti-Doping Agency to explore the possible misuse of genetics in sport. Projects taking place at The Hastings Center during these years have been pioneering in terms of sport's commitment to funding ethical research. In 2006, Murray was also appointed as chair of the new WADA Ethical Issues Review Panel, which, also in 2006, made its first substantive intervention by concluding that the use of hypoxic environments (also known as altitude chambers) should be deemed an infraction of the WADA Code because they violate the "spirit of sport." These developments speak to the growing convergence between sport ethics and bioethics, as suggested earlier.

Other recent historical moments have been critical in shaping the current political landscape of anti-doping. In 2003, the now infamous Bay Area Laboratory Co-Operative (BALCO) affair reminded anti-doping authorities that designer substances are completely unknown and it will be near impossible developing direct tests for them in advance without substantial collaboration between the anti-doping authorities and drug developers. Indeed, the challenge of proving positive doping cases has been one of the major obstacles for anti-doping authorities. This challenge has also recently given rise to changes in the law, where the emergence of a nonanalytical positive – a doping infraction without the need for a urine or blood test – means that athletes now face possible disqualification (and sometimes prosecution) based on evidence other than unequivocal facts. These circumstances are also accompanied by an emerging willingness to criminalize doping infractions and to discuss doping as underpinned by an international criminal drug mafia (see Donati 2005). These terms reshape what is at stake in the issue of doping, transforming a matter related to fairness and ethics in sport to a moral panic over drug use. An additional facet to this debate is also greater willingness to recognize the broader use of illicit substances, which are typically associated with sports performance. The AAP notes that many users are not elite athletes at all, but young people who are preoccupied with body image.

This final point alludes to the relevance of broader cultural studies of body modifications when considering the use of enhancement technologies in sport. While it is tempting to believe that the rationale for any athlete's use is merely to gain an edge over other competitors, other values are engaged. Yet related studies of the cultural context of performance enhancement are often overlooked in the debate about the ethics of sporting performance (Denham 1999a, b) (in 2006, WADA opened a tender for social science studies of doping). For instance, while there is considerable reference to how the media characterize the doping debate, very rarely is this media presentation taken into account in policy discussions. Thus, one could be skeptical of the claim that society broadly is unhappy about *enhanced* athletes. Rather, one might more adequately claim that the media discourses surrounding the *doped* athlete generate a justification for a culture of anti-doping (Magdalinski 2000).

Evidence of convergence in how sport addresses the problem of enhancement is apparent within the activities of key legislative agencies and advisory committees. The current US President's Council has focused considerably on "enhancement" or, perhaps more accurately, emerging technology issues. Its landmark publication *Beyond Therapy* (U.S. President's Council on Bioethics 2003) engages with some of the issues faced by the world of sport in the context of enhancements. Alternatively, in 2003, the Australian Law Reform Commission (2003) published an extensive document on the use of genetic information within a range of social contexts, one of which includes sport. More recently, the UK Government Select Committee for Science and Technology launched a public inquiry into the use of Human Enhancement Technologies in Sport (Science and Technology Select Committee 2006). To this extent, it is useful to employ our convergent metaphor in the analysis of converging legislation surrounding human enhancement technologies. Nevertheless, of critical value is to understand how a range of technological systems affect the conditions of elite sport and how these conditions are also intimately reliant on multiple knowledge systems.

Safety and Harm

One of the central aims of technological change in sport has been to improve safety and reduce the risk of harm. Many rule changes within sports can be viewed as *technologies of knowledge* that aim to restructure the range of technological interactions – such as the foot against the floor or a shoulder's movement when swinging a racket. Other examples include the redesigning of the javelin in the 1980s, when athletes were throwing dangerously close to the spectators. The only reasonable solution to this impending problem was to change the specifications of the javelin so that the athletes could not throw it as far. This resulted in a change in the kinds of athletes that were successful as javelin throwers, from the strongest to the technically proficient. Other examples include:

- Improved floor surfaces within sports halls to reduce shock to athletes when landing or bounding (Bjerklie 1993)

- Introduction of plastic helmets in American football to reduce head injury (Gelberg 1995), later improved by the introduction of helmet concussion sensors, such as Shockbox (see http://www.theshockbox.com/football-sensors) and xPatch (http://www.x2biosystems.com/)
- More sophisticated shoe design for more support to foot during athletic events
- Increased wicking qualities in clothing to protect climber or mountaineer from the cold and rain
- Springboard surface in diving to prevent slip and increase resiliency of board tips to reduce injury (Bjerklie 1993)
- Sturdier épée and foil in fencing as well as Kevlar jackets for more protection but with no loss to movement (Tenner 1996)
- Navigational equipment in sailing (Inizan 1994; Tenner 1996)
- Carbon composite poles in pole vaulting and enhanced safety pits, allowed more daring contest and higher vaults (Bjerklie 1993)

These examples identify the imperative for sports federations or governing bodies of sport to strive for their practices to be less dangerous for the competitors by introducing new technological measures. However, they also show how insights of this kind rely on a complex set of knowledge systems, which encompass visual data capture, data analysis, materials science, and psychology, for instance. In this respect, convergence in sport is parasitic on other convergent practices but may also give rise to new technological applications that can be utilized in other spheres.

De-skilling and Re-skilling

Technological innovations can also alter the way that sports are played. They can change the conditions of training that are required to be successful at a particular skill and can even make it easier to perform the required skills. Examples of such technologies include:

- Zepp sensors, used in baseball, tennis, or golf – a mounted sensor, which reads and evaluates swing; see https://www.zepp.com/ (2015).
- RideOn Augmented Reality Goggles; see http://www.rideonvision.com/ (2015).
- U-groove golf clubs that allowed greater accuracy on stroke (Gardner 1989).
- Depth finders in fishing to make it easier to locate large schools of fish to enhance prospects of catching (Hummel and Foster 1986).
- Superman cycling position that allowed more streamlined position for greater speed (Fotheringham 1996).
- Breathable clothing material used to regulate body temperature in extreme climates (Miah 2000a).

The PGA's reasons for disallowing the "square" or "U-groove" irons from golf in 1990 reflect how technology can alter the kinds of skill required of an athlete (Gardner 1989). Gardner describes how tour players considered that the clubs gave the golfer an advantage by creating a higher spin rate, which translated into better ball control. Some tour professionals had been opposed to their use because of a concern that they "devalue true golf skill and consolidate their talent" (p. 69). Similarly, Hummel and Foster (1986) recognized that the "spinning reel" in fishing "virtually eliminated backlash in casting and thus the necessity of an 'educated thumb' to act as a drag on line being cast" (p. 46). Thus, the innovation was considered to have democratized the skills of the sport and had devalued or de-skilled the activity. While these devices would seem quite useful for a novice who may require assistance to engage in the activity in a meaningful way, their application to competitive sports is implied – yet it is unclear that such things are beneficial within elite competition.

Additionally, it is not representative to argue that these technologies necessarily de-skill a sport. It may also be argued that technological changes in sports "re-skill" an activity. In explanation of "re-skilling," one may consider the controversial "superman" cycling position introduced by Graeme Obree in 1995. The position entailed the arms of the cyclist being placed in front of the face and the seating post being unusually high, thus making the position more aerodynamic. Thus, while the skill had not been made any easier, it had altered the bicycle such that it did not resemble conventional cycling positions (it had been re-skilled and it made it possible to achieve more without any greater physical capability). Interestingly, the International Cycling Union (ICU) made this very argument when legislating against the use of the position. In concluding their stance on the "superman" position, the ICU argued that the technical developments had "obscured the physical demands made by cycling, and had made it harder for the man on the street to identify with elite cyclists" (Verbruggen cited in Fotheringham 1996, p. 23). Despite such claims, it might be wondered how the ICU justify the acceptance of methods of design and construction of bicycles that are more comparable to the design of an aircraft than an "everyday" bicycle. It would seem possible to argue that, on similar grounds, the use of such materials also makes the bicycle unacceptably different from a preconceived notion of what is a bicycle.

Dehumanizing and Superhumanizing

The cycling example raises a more complicated question about whether an athlete can claim responsibility for any performance achievement and puts into question whether the human athlete or the technology has achieved the performance. However, to answer such a question requires being able to make clear distinctions between them. This category presumes that something clear can be said about humanness that is lessened or removed by the use of some technology. This categorization might be criticized for bringing together two quite different claims about a technology that are not at all oppositional. Indeed, the elite athlete might both be dehumanized and superhumanized by a technology.

Nevertheless, the purpose of this categorization is to demonstrate ideas about the moral implications of technology so as to identify the kinds of argument that are being made about the effects of technology. In this sense, dehumanization is justified in as much as researchers of technology have made such claims. Some examples that have been (and might be) seen as reflective of dehumanizing/superhumanizing technologies are as follows:

- Doping and drug taking (Hoberman 1992; Fraleigh 1984).
- Genetic enhancement (Miah 2000b, 2004; Munthe 2000).
- Springboard in diving allowed divers to gain more height on dive (Bjerklie 1993).
- Fiberglass archery bows, more resilience and more consistency (Bjerklie 1993).
- Plastic/metal composite discus allows longer throw.
- Barbells are now stronger with some flexibility to allow the lifter to use more techniques when lifting and drop bar at the end of lift to save strength (Bjerklie 1993).
- Kevlar and carbon fiber kayaks are lighter, more sturdy, and easier to maneuver.

While various authors discuss how these technologies alter what it means to be human, adding content to such claims is more problematic as identifying the salient characteristics of humanness that are removed or lessened by such technology is not easy. Nevertheless, if one is to place any credit at all in these, at least, intuitions about technology, then it is worth considering the possibility that they are not consistent with the characteristics of humanness. If one is not convinced that these technologies do, in fact, dilute human qualities, then it can be useful to discuss whether any kind of technology could be a threat to humanness. Would, for example, a human that is largely a mechanoid be a challenge to humanness? If not, then is a robotic human, one whose mental capacities are formed by some artificially intelligent computer, a threat to humanity? If such beings can be seen as a challenge to humanness, then there might be some grounds for concern. Where this line is drawn is less important than the possibility that it could be crossed, which, I suggest, is often the basis on which anti-doping policy is justified (i.e., there is an imperative to draw a line somewhere).

Increase Participation and Spectatorship

One of the major interests of a sports governing body is to maximize the breadth of inclusion within the given sport. This ambition often translates into the development of technology that can allow a sport to become more accessible to prospective participants. The example is slightly different from developing technologies to make the sport easier, as the main aim here is the maintenance of standards, with the broadening of participation. Alternatively, equipment is often developed that can even exclude particular kinds of individual from participation. For example, the sophistication of technology demands a level of finance that is beyond many individuals. Examples of such technology include the following:

- The Babolat connected tennis racket, with built-in sensors and a mobile app to provide feedback on performance and a social network for sharing (see http://en.babolatplay.com/)
- Artificial turf for field sports (Tenner 1996)
- U-groove golf clubs (Gardner 1989)
- Carbon composite tennis rackets and mass production of other kinds of equipment (Brody 2000)
- The carving ski (alpine) that makes it easier to learn skiing
- Different sized tennis balls (Miah 2000c)
- Varying speeds of squash ball for different levels of competence

The value of such technology is not difficult to understand from a commercial perspective. The ability to reach a wider audience can seem a worthwhile ambition. However, the consequences of such ambitions are not uncontroversial for some sports. For example, in sports such as climbing or skiing, there exist limited natural resources, the overuse of which could seriously damage the environment and lessen the aesthetic experience of the performance. If mountains were overrun with climbers and skiers, they could lose their tranquil characteristics, which would seem to entirely contradict what is valuable about these activities. Along these lines, it is not at all clear how big would be big enough for sports. While the ambition for widening participation is admirable, its justification tends to be more financial than moral. Yet the exploitation of a sport simply to widen participation and generate more financial resources seems ambiguously beneficial.

These varied examples provide some basis for understanding the complexity and effect of technologies in sport and the range of values that are engaged when considering the ethical implications of any proposed technological innovation. In addition to these effects, one must also recognize that there are further concerns about the unknown consequences of new technologies. Indeed, it is crucial to recognize how anti-doping authorities develop policy on the basis of lacking scientific evidence that can demonstrate safety.

Transhumanist Technology

As a final consideration on scientific convergence in sport, the utilization of genetic technology is valuable to consider, as research around genetics can inform our understanding of performance capacities and predispositions. Currently, research implicated for gene doping includes modifications to growth factors such as IGF-1 (Barton-Davis et al. 1998; Goldspink 2001; Lamsam et al. 1997; Martinek et al. 2000), PGC-1alpha (Lin et al. 2002), recombinant EPO (Svensson et al. 1997), and the so-called ACE gene (Brull et al. 2001; Gayagay et al. 1998; Montgomery et al. 1998, 1999).

The rise of genetic technology marks a new paradigm for anti-doping policy makers because it presents a new landscape of ethical issues, political views on enhancement, and concerns, along with new techniques to detect doping. While many applications of gene doping have yet to materialize, the science of genetics is seen as a vehicle through which discoveries can be made to make anti-doping more robust. Furthermore, genetics has entered the public domain already in sport through the creation of performance gene tests, the first of which was released commercially in 2004. One year later, the WADA (2005) announces in its Stockholm Declaration on gene doping that such tests are to be discouraged. In this sense, genetics is symbolic of a science that progresses faster than society can keep up with it.

Conclusion

In April 2015, the weight loss food company Protein World launched a billboard campaign depicting a toned young woman wearing a bikini with the headline “Are You Beach Body Ready?” The campaign caused considerable controversy and was eventually banned by the Advertising Standards Authority in the UK after receiving 360 complaints claiming that “the ad is offensive, irresponsible and harmful because it promotes an unhealthy body image” (Sweney 2015). The basis of the suspension was the legitimacy of the claims made in the advert, namely, that “Substituting two daily meals of an energy restricted diet with a replacement meal, contributes to weight loss.” Whether or not this claim is substantiated, the example is pertinent here, as it reminds us that – in line with the AAP’s conclusions – the pursuit of an athletic body is not the exclusive interest of athletes. Rather, there is a wider culture of human enhancement that provides buoyancy to the enhancement industries, of which sport is a part. Whether the approach is using protein diets to reduce weight, or using surgery to stable stomachs, the pursuit of human enhancements is complex, contested, and subject to all kinds of ideological impositions.

What unifies the examples of enhancements I have considered is their utility for activities beyond sport. One can imagine numerous forms of labor that would benefit from greater endurance, strength, or ability. Elite sports have always been a test space for enhancements, and their rule-governed nature offers a useful structure through which to address how questions of justice would be played out within an enhancement-led society. Yet it is also apparent that enhancement is not just a functional quality, as many such modifications are utilized to improve appearance as much as performance.

The key challenge for enhancement advocates is to bridge the ethical gap between therapy and enhancement, to reach a point where new medical products can be developed and characterized for use by healthy subjects. While it is apparent that the medicalization of various conditions may be leading to this situation, an explicit shift in how medicine progresses will be necessary before a strong enhancement culture can emerge. Many forms of enhancement rely on the use of therapeutic technologies, which bring about transformations in the concept – such as the use of stem cells to promote tissue repair (Templeton 2006). As these technologies begin to arise, an increasing number of questions will emerge about whether sports can stem the tide of enhancements alone, or whether broad social structures will intervene. Once the convergence between therapy and enhancement is complete, then society may be better placed to address the opportunities and limitations of human enhancements, in sport or outside of it.

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Intellectual Property Rights

William Sims Bainbridge

Contents

Abstract

Patents, copyrights, trademarks, and other forms of intellectual property protection are crucial ways in which society rewards inventors and other creative individuals. Yet convergence across fields of science and technology increases the probability of negative impacts, such as "patent thickets" in which it becomes difficult to combine patents that belong to different holders, in order to create a new product or industry. While some philosophers believed intellectual property was a natural right, it generally is explained in terms of its utility for society in encouraging innovation. Yet monopolies may file blocking patents, with no intention of using them but merely to prevent other companies from competing, and at the opposite extreme, today's information technologies make copying of many forms of communication so easy that they severely undermine copyright protections. Norms of intellectual property harmonize with well-established societal institutions, yet many fields of science and engineering are more like social movements and thus less compatible with rigid rules. To the

W.S. Bainbridge (✉)
Cyber-Human Systems Program, Division of Information and Intelligent Systems, National Science Foundation, Arlington, VA, USA
e-mail: wbainbri@nsf.gov

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extent that science and technology convergence is itself a social movement, it will encourage research and debate about what norms are most appropriate in different areas and during the chaotic periods when they converge.

Introduction

Legal regimes which give innovators the temporary monopoly on exploitation of their innovations, notably patents and copyrights, have become increasingly problematic as scientific and technological changes call their basic principles into question. Ideally, intellectual property rights encourage creativity, but unlike trademarks should not be permanent, so that innovations will eventually enter the public domain and can then be readily combined to generate new innovations. Unfortunately, the costs versus benefits to overall innovation seem to vary by field of endeavor, by nature of the innovation, and by circumstances in the surrounding society, such that there is no single optimal set of laws. The situation becomes especially complex in the context of science and technology convergence, which requires a high degree of integration across social organizations like companies and nations, which are under numerous pressures to compete rather than cooperate.

Historical and Philosophical Background

Cultural conceptions of property ownership have changed throughout history, in part because of evolving implications of technology, but also customs varied across societies even at the same level of technical development. For example, land ownership took on new urgency when agriculture was developed, thousands of years ago, and even just 1000 years ago cultures differed in whether farmland was owned by an individual farmer, a distant aristocrat, or collectively by the entire town it surrounded. An example of how abstract conceptions of human rights interact with practical considerations is land tenure inheritance (Homans 1937). If all children of a farmer inherit equal fractions of his land, each resultant farm may be too small to be self-supporting. Primogeniture, inheritance of land exclusively by the eldest son, ensured that large farms could survive through many generations, but exiled many younger children of farmers to seek livelihoods elsewhere. Even just two centuries ago in many nations, one human could own another, either simply as a slave lacking most rights or in the more complex legal situation called indentured servitude.

The complex implications of intellectual property rights for science and technology convergence will become clear as we consider many aspects, but the most obvious factor affecting them is the Internet revolution (National Research Council 2000). In terms of the technical steps required, we can easily download a published journal article that is covered by copyright and email it to a colleague in a different discipline who does not have a subscription to the particular journal, thereby facilitating convergence of our field with that of the colleague. But in so doing, we probably violated copyright law. Suppose we are programming some new software for use in our research, and we copy in a few sections of a program that was written by somebody else for use in a different field. Did this technological convergence violate a patent, a copyright, or nothing? Does it make a difference if we did not have the source code from the other program, but reverse engineered the code by analyzing how that part of the existing program works? Whatever the rules may be, what is their moral or social justification?

In his book, *Virtual Justice*, Greg Lastowka (2010) explored in depth the specific example of online virtual worlds, including massively multiplayer games, that raise many issues about ownership of virtual property that may be contested between the creators of the computerized environment, the company that hosts the software and database online, and the users who may invest hundreds of hours and dollars in acquiring virtual properties. His main point is that this new technology renders problematic all the old rules, and we have not yet developed appropriate new sets of rules that strike a proper balance of rights among all the stakeholders. To develop appropriate new standards will require not only extensive research to understand the practicalities and cost-benefit ratios but also deep philosophical consideration of abstract moral principles.

Lastowka (2010, pp. 129–130) distinguishes two competing philosophical justifications for intellectual property rights: (1) the *natural rights* argument associated with John Locke (1632–1704) and (2) the *social benefits* argument associated with Jeremy Bentham (1748–1832). The first is simpler and Lastowka feels less compelling. From the natural rights perspective, the creator of something valuable has a right to possess it, even without formal recognition as the owner by any government. Traditionally, the main way that an ethical code could be established without government action was through religion, proverbially by bringing down God's commandments from a mountain top: "Thou shalt not steal." But the people who "own" creative works are often not the creators, but manufacturing companies that acquired patents and publishing companies that acquired copyrights. Furthermore, both patents and copyrights are temporary, each expiring after a specified number of years, which in the case of patents is often long before the inventor's death, but after the death of the creator in the case of copyrights.

The limited terms of both patent and copyrights are justified by the social benefits theory. Rights are awarded to creators in order to encourage creativity, by allowing creators to profit from their work. But the rights are temporary, so that the benefits can spread potentially to all of humanity after the rights expire. Thus two competing social benefits are balanced, the encouragement of creativity and the sharing of innovations. Lastowka argues that the social benefit theory is the one that best explains current practice but that it is problematic because it depends upon often untested empirical claims about what the consequences of a regulation are. Do patents really encourage innovation? Do copyrights encourage creative expression and transmission of information?

In a different publication, Lastowka (2012) debates alternative conceptualizations of trademarks, a very different kind of intellectual property that may not seem as relevant as patents and copyrights, yet still has much to teach us. He argues that the main social benefit of trademarks is that they assure the purchaser of a product that it is authentic and thus has the quality implied by the reputation of the trademark owner. In terms of information theory, a trademark is a measure of the *provenance* of the product, which is to say its origin and perhaps also its scientific context. Thus debates about the proper procedures and justifications for trademarks can be instructive analogies for classification debates in several of the sciences and indeed especially important when different fields converge.

Citing past legal disputes, Lastowka argues that four kinds of error have often been made in arguing for the importance of defending trademarks. (1) Trademarks are a reward for creativity, just as patents and trademarks are. (2) Trademarks are an expression of the "right of publicity," which entails privacy and autonomy of the holder. (3) Trademarks improve the efficiency of the market by reducing the costs of searching for information about products. (4) Trademarks clarify the *fair use doctrine* that allows a symbol or other information to be used by nonowners only under well-defined circumstances. Lastowka calls these four *demons*, because they are the source of confusion in legal debates, and we need not agree with his detailed analysis of each one. Their relevance here is that they illustrate how diverse and complex intellectual property issues can become.

Examples of Convergence Issues

Among the classic problems that provide insights relevant to the future of convergence is *patent thickets*. This term refers to situations in which development of a new product or system requires assembly of many components that are protected by separate patents held by multiple corporations or other entities. This issue was extensively discussed at the 2005 Convergence Conference held in Hawaii and can be a metaphor for other situations, as well as being a real challenge in itself. As Clarkson and DeKorte (2006, p. 180) explained, patent thickets may become a major problem in nanotechnology, and:

> These dense webs of overlapping intellectual property rights owned by different companies can present a significant barrier that must be hacked through in order to commercialize new technology. In other industries characterized by cumulative innovations and multiple blocking patents, the existence of such dense concentrated patent rights can have the perverse effect of stifling innovation rather than encouraging it. Such patent thickets are already problematic in other convergent technology areas such as biotechnology and information technology.

One would think that patent thickets would be an easy problem to solve, but that is incorrect. If a dozen different corporations hold patents on things that must be combined to create a new, commercially valuable product, the negotiations among them to come to an agreement could be extremely difficult. Will one company market the product? Then it must negotiate a price to pay each of the other 11, and one or two may hold out for higher profits than the others. If the companies agree to share their patents, transforming the patent thicket into what is called a *patent pool*, they may be in violation of antitrust laws discouraging the formation of monopolies. The research reported by Clarkson and DeKorte focused on another issue, the fact that modern technologies are so complex that very large numbers of patents might possibly be relevant to a new product, which presents the challenge of assessing which patents are really necessary, among potentially thousands that have seemed so initially. Appropriate information technology can alleviate that problem. An additional problem may often complicate this already obscure picture, and that is the tactical use of *blocking patents*, which are secured by a company already well positioned in an industry, and are held without being used or licensed to any other company, precisely to prevent a competing technology from being commercialized.

Specifically related to patent thickets, Joseph Farrell (2009) has explored the complexities of bargaining between holders of intellectual properties. He calls an agreement among multiple corporations to share patents a "big deal" and considers what might often cause such an alliance to break down. One factor is simply an aggravated form of the usual behavior of a dynamic marketplace, the fact that one party to the interaction may bargain especially strenuously or may calculate the benefits versus costs of agreement differently over time, the *balance of interests/opportunism*. Another may especially arise during technological convergence in a context of rapid innovation, the *open-ended set of participants* that results when new companies enter the field.

Any hobbyist who has soldered together one of the traditional radio receivers will be fully aware of how many different kinds of parts they contained, not to mention all the different kinds of equipment in the studio and broadcast facilities. Each component may have gone through a series of improvements in which the new version was patentable, and the increasing complexity of electrical technology early in the twentieth century meant that many different corporations were able to patent radio innovations, creating one of history's worst patent thickets. In 1919, the US government encouraged formation of a cartel, the Radio Corporation of America (RCA), consisting of General Electric, Westinghouse, and the Bell Telephone Company (AT&T), purchasing the American Marconi Company that exploited the radio inventions of Guglielmo Marconi, and giving RCA control of the industry by 1927 (Maclaurin 1950). The RCA monopoly held all the necessary patents to launch the commercial radio broadcast industry based in the NBC network. The RCA monopoly did not last forever, spinning off the ABC network in response to antitrust suits and eventually fading away. At its peak it created an industry but then played highly dubious roles in two technological revolutions in that industry, the development of FM radio and of television.

Traditional radio broadcasts were based on a carrier wave of a constant frequency, encoding the sounds of a broadcast in its strength or amplitude, thus called AM for *amplitude modulation* in contrast to FM which employed *frequency modulation*. Problems for AM as originally implemented included static noise from local electrical disturbances like thunderstorms, interference from distant broadcast stations, and generally low fidelity. FM radio largely eliminated noise by having the radio receiver constantly compare the frequency of the carrier wave with a set frequency to produce the sounds. In addition, FM employed much higher frequency carrier waves, which improved fidelity and reduced interference from distant stations. When broadcast television launched as a new industry, it combined the developments in both AM and FM radio with new innovations for transmitting images. Even when its monopoly position began to weaken, RCA had tremendous advantages, which were especially obvious in the corporation's conflicts with the chief inventors of FM and television, who worked independently of major corporate power.

Edwin Armstrong invented many of the principles of FM, working largely on his own. Yet he could not devote all his mind and energies to innovation, because he was constantly caught in patent battles. He felt that RCA was suppressing his inventions and even stealing from him. After RCA prevented him from benefiting from the use of FM for television audio, he committed suicide (Lessing 1956). Similarly, Philo Farnsworth was the chief inventor of television technology, and historians debate the extent to which RCA stole innovations from him, but it is certain he could not compete with that corporate giant (Schwartz 2002). Thus the example of the RCA monopoly illustrates not only the consequences of pooling patents as a cure for a patent thicket but also the issue of whether lone inventors have important roles to play in innovation, if convergence is allowed to create monopolies.

Government often intervenes creatively in special situations. For example, around 1920 the founders of the Pitney-Bowes Corporation combined technical ideas to create the first really practical postage meter. While mechanical rather than electronic in its design, it was an important step in the development of modern information technology, and it allowed businesses to handle large volumes of outgoing mail without the necessity for manually attaching adhesive postage stamps (Cahn 1961). Over the following years, Pitney-Bowes walked a fine line between providing a reliable standard and exercising unfair monopoly, through its approval from the US government. In US law, an *essential facilities* doctrine may occasionally be invoked, requiring a company to license patents to its competitors, and the actual consequences of doing so or not can be complex and even unexpected (Gilbert and Shapiro 1996).

Conclusive scientific studies to test theories about the consequences of various patent laws are very difficult to do. Suppose nation A has weak patent protections, and B has strong ones. Does a finding that B produces more innovation prove that strong laws encourage innovation or that innovative corporations demand that their governments enact strong laws? Or do both factors result from something else, such as different economic or military histories? It may be that a medium level of patent protection is most conducive to innovation, with low levels failing to reward innovators and high levels sustaining stagnant monopolies. In one study that drew on extensive prior literature and employed sophisticated statistical methods to compare data on nations, evidence suggested that intellectual property right legislation did encourage innovation, and control for several other variables did not erase this apparently causal effect (Kanwar and Evenson 2003). Yet the data came from the 1980s, and decades later both the nature of innovation and the power of governments to prevent theft of intellectual property may have changed, most obviously through a shift from traditional manufacturing to information technology.

Since globalization is an important mode of convergence, it is worth noting that several researchers have considered the effect that strong international respect for intellectual property rights might have on trade and the progress of developing nations. Nations differ in the stringency of their legal protections, most likely more strict in developed nations that happen to have larger internal markets, but complex dynamics between nations can affect the differential benefit of the protections across nations at different levels of development (Grossman and Lai 2004). Shared respect for patent rights can encourage wealthy nations to allow poorer nations to manufacture products invented in the rich nations, therefore benefiting both through increased trade (Helpman 1993).

An example of the complexity of global convergence is the evolution of international norms concerning intellectual property in AIDS drugs (Chorev 2012). Pharmaceutical companies in rich nations developed them, but their cost was too high for most citizens of poor nations. Corporations, national governments, and international organizations sought to find a solution for this imbalance, in a system that proved to be far from stable. A nation like the Republic of South Africa that was poor, faced with very serious AIDS transmission issues and had the technical capability to produce generic drugs prior to the expiration of the original patents, might well decide that health care was a right of every person that trumped intellectual property rights, and should follow policies at variance with the wishes of pharmaceutical companies, unleashing serious legal and economic conflict as well as philosophical debate. Considering this case from a different perspective, we may note that modern societies have not yet come to a stable consensus about the appropriate convergence between corporations, governments, nonprofit organizations, professional personnel, and patients in the medical and health fields.

Freedom of Information

One of the chief social benefits claimed for patents is that they make public many significant innovations that otherwise might be held as trade secrets. Yet copyrights are the chief topic of discussion with respect to the role of intellectual property rights in the context of communication of information. We naturally think of copyrights as protection for novelists and movie producers, yet they are very significant for scientific publications as well.

Among the most remarkable, but least remarked upon, facts about intellectual property laws is that scientists have no rights whatsoever to their discoveries. One common, superficial explanation is that scientists discover qualities of nature which already exist and thus are not exercising fundamental creativity deserving any special reward. However, the same could be said for ownership of land, and yet centuries ago explorers could claim land in the name of their nations, and real estate is among the most familiar kinds of personal property. A more sophisticated explanation can be based upon the work of sociologist Robert K. Merton (1973), who explored the phenomenon of multiple discoveries in science. Once a science and the associated technological instrumentation have advanced to the point at which a discovery is possible, it can be made many times quite independently, until news of it spreads globally and preempts further discovery.

However, the same could be said for innovation in engineering. Sociologist S. C. Gilfillan (1963) argued that individual inventors were of no real significance, because the advance of technology took place incrementally across the entire society. In addition, he asserted that inventions cannot strictly be distinguished from each other and thus the work of government patent examiners in determining the novelty of a patent application is fatally flawed. That criticism is somewhat tempered by the fact that the duration of patents is rather brief, compared to the long duration of copyrights, thus limiting any harm.

In a frequently cited work titled *Inflexible Logic*, Russell Maloney (1956) debated the claim of authors and artists that their works were unique, through the parable of monkeys pounding at random on typewriters, purely by chance producing exact duplicates of famous works of literature. At one point he imagines a chimpanzee producing an exact copy of *Oliver Twist* by Charles Dickens, which seems improbable. And yet the laws of chance are called into question by the fact that the name of the chimpanzee in Maloney's story is identical to that of the author of this chapter. In the real world, many legal cases struggle with the issues of fair use and independent creation when two works seem very similar.

Traditionally, patents protected intellectual property rights primarily concerning mechanical gadgets, and when modern computer technology emerged, there was a debate over the use of patents to protect rights to software. Logically, patents were traditionally designed to cover hardware, and copyrights might fit software better. However, copyright covers the expression of an idea, not the abstract idea itself. For example, while one may not copyright a scientific discovery, one may copyright a textbook that presents the idea. Is a computer algorithm a scientific discovery, an engineering invention, or a literary expression that happens to be stated in a programming language rather than poetry? The common name of the associated field, "computer science," complicates things. The field could have been called "computer engineering," and one may debate whether there really exists a distinct field deserving either name, rather than recognizing that modern information technology depends upon the convergence of electrical engineering with many other fields. In any case, the computer industry decided to rely heavily upon copyrights for software, which had the advantage of providing many more years of protection than patents (Weil and Snapper 1989).

This line of thought brings us to a troubling hypothesis than cannot now be fully tested, but deserves consideration: Traditional intellectual property laws were developed around the time of the Industrial Revolution and may be irrelevant for postindustrial societies having advanced information technologies. Today, a gadget may be represented by software and data and then translated into physical form through 3D printing. The distinction between a scientific discovery and an engineering invention may reflect matters of degree, such as scientific abstraction versus engineering specificity and conceptual truth versus practical use. In computer science, distinctions between hardware versus software versus data are not strict but are superficial notions to facilitate casual conversation.

Because of their commercial implications and thus the considerable effort invested in them in legal disputes, patents and copyrights raise the most prominent intellectual property right questions. But especially when considering the wide range of phenomena relevant for scientific, technological, and social convergence, other topics also deserve study. For example, among the most valuable forms of information for science and engineering are databases, and yet legal protections for raw data are weak, and many new norms and techniques may need to be developed (Ganz-Brown 1998). Anthropologists and archaeologists have often been involved during recent years in debates about the cultural property rights of indigenous peoples, for example, limiting what they perceive as misuse of their symbols, legends, artworks, artifacts, and the remains of their ancestors (Nicholas and Bannister 2004).

Challenges and Opportunities

An exceedingly pressing issue for convergence is the radical transformation of scientific and technical publishing, notably the proliferation of vast numbers of journals in ever more specialized areas. Part of the problem lies in the explosion of online journals, often but not always of dubious quality. John Bohannon (2013) performed a daring experiment, submitting an intentionally idiotic scientific paper to 304 open-access online journals, receiving acceptances from about half. Yet many new specialized journals are legitimate, often with expensive subscription costs that prevent specialists in one area from reading publications in another.

At the present time, book publishing industries are going through very difficult transitions, caused by social, economic, and cultural developments as well as by information technology. Writing from the perspective of Harvard University, which has one of the most extensive library systems in the world, Craig Lambert (2015) reports that sales of scholarly monographs have dropped substantially to the point that this traditional form of scholarly publication may no longer be viable, largely because college libraries must pay increasingly high subscription costs for scientific journals. Partly in response, book publishers are experimenting with alternative technologies and procedures. Many have started prioritizing electronic publication and producing physical copies only when an individual wishes to buy one, using the new "print on demand" technology. Some publishers no longer take copyright on a book, leaving it with the author. This may sound nice to authors, but in fact it indicates the new reality that many publishers are no longer taking on any responsibility to defend intellectual property rights.

Several of the social sciences have long debated whether they were fundamentally book disciplines or journal disciplines, but all fields of science and engineering have the need for significant numbers of books that have the length required to examine a topic in depth or breadth. At the same time, some disciplines, notably computer science, place a high priority on conference papers, rather than either journal articles or books. Technically, conference proceedings may be disseminated as printed books, online archives, or memory devices such as DVDs or thumb drives.

Notice the variety of ways in which modern academic publishing covers the cost of publishing: Many journals illustrate the paid subscription model. Books traditionally were sold as individual copies. Conference proceedings draw upon the meeting's registration fee. Some journals and book series require the author to pay a fee. Dues paid for membership in a scientific organization may also support some of its publication costs. Now, at very low cost, an author may post a publication on a personal website or shared blogsite.

If information technology erases the cost of printing, there remains the cost of scientific review, which provides value to readers by assuring them the publications are high quality and enhances the status of the author. However, among the possible outcomes of the current disorder is an incoherent set of "publish first, review afterward" models. For example, the value of an unreviewed online scientific publication can be assessed from the roster of citations of the publication or the links and traffic data to the site, even just represented by the position of the publication in the results of a Google search on the topic. Several journals have been experimenting with more refined methods, for example, *Atmospheric Chemistry and Physics*, which employs a two-stage review process and a flexible Creative Commons license to handle intellectual property. It has always been the case that owners of intellectual property could license it under complex terms to other parties, but the almost unmanageable complexity of contributions in creation of computer software has stimulated exploration of many new contract provisions (Walden 2005; Shah 2006), although their enforcement can be a challenge.

By their very nature, scientific discovery and engineering innovation are disruptive, and they change the context in which they themselves operate. Therefore, it is unlikely that any one modality for publication of information and reward for creativity will be appropriate for all fields or historical circumstances. Posner (2005, p. 58) has described the dilemma as a tension between *incentives* and *access*: "The principal alternatives for resolving the tension are a system of financial rewards to creators of intellectual property (such as a public subsidy) and a limited property rights system (like patents and copyrights) that enables the creator of intellectual property to exclude others from access to it without the creator's authorization, but not to exclude as completely as in the case of physical property."

At present, the public subsidy alternative is most obviously represented by government grants that often include 1 or 2 months of extra salary per year for academic researchers. Thus, there may be many alternatives to the traditional patent and copyright protections, serving about the same very general social goals, but in ways better suited to particular situations in the convergence of science and technology or the periods of creative divergence that may follow convergence (Varian 2005).

Social Movements

It is conventional to conceptualize fields of science and engineering in terms of their topic material, for example, distinguishing herpetology (the science of reptiles and amphibians) from ornithology (the science of birds). Such a classification seems simply to reflect the natural divisions in the animal kingdom. Yet, one might have separated the science of amphibians from that of reptiles or even combined the studies of reptiles with birds, because amphibians go through a very different early life development process, while reptiles and birds have more similar egg to adult life histories. However compelling the structural features of nature may be, in good measure scientific fields are distinguished as somewhat separate social groups, even as competing social movements. That implies that many of the most important but often unrecognized property issues concern the rights and powers of subcultures in science and engineering, quite apart from government enforcement of copyrights and patents.

An illustrative example is "rocket science" or the social movement that produced modern spaceflight technology and the values that politically sustain government space programs. While many commercial applications of orbiting satellites have been developed, none of them were compelling enough for private corporations to invest the vast sums needed to create the launch technologies required to reach low Earth orbit. Historians have offered several competing explanations for the development of spaceflight, and the one outlined here is selected primarily because it makes good points about collective action in science and technology. Astronautics is the convergence of elements from many fields, including of course astronomy and physics, but also chemistry in the propellants, materials science and mechanical engineering in the physical structures of rockets, and electronics in the control devices.

Creation of a social movement also requires convergence, but of people as well as of their technical expertise and the resources they are able to invest. The history of the spaceflight social movement can be described very roughly in terms of increasing convergence through four stages, each of which is a standard conception in social science (Bainbridge 1976):

1. Parallel behavior: Individuals performing similar actions with similar motivations but without communication between them
2. Collective behavior: Action taken by a collection of people who influence one another but engage in little planning and do not form an organization
3. Social movement: An organized group dedicated to causing or preventing social change and acting in unusual ways or outside of conventional channels
4. Societal institution: A formal organization, operating in accordance with the governmental legislation of the society and in a high degree of harmony with other institutions

Patents, copyrights, and trademarks are primarily connected to the last of the four stages of increasing organization. The first stage, parallel behavior, does not at all recognize intellectual property; ownership is at best informal in collective behavior and open to significant dispute in, around, and between social movements. Especially in the social movement phase, the chief reward to creators is not money but respect, as leaders gain social status that can become progressively more substantial as the movement grows. Thus intellectual property is sustained prior to the societal institution phase not primarily by formalities like patents and copyrights but informally through social respect.

In the case of the spaceflight social movement, parallel behavior is well illustrated by three individual pioneers who independently developed the conceptual basis for what came afterward: Konstantin Tsiolkovsky (1857–1935), Robert H. Goddard (1882–1945), and Hermann Oberth (1894–1989). On the basis of their publications and the independent work of others, widespread communications generated collective behavior that consolidated in relatively small nation-based social movements, notably Verein für Raumschiffahrt (Germany 1927), American Interplanetary Society (1930), Gruppa Izucheniya Reaktivnogo Dvizheniya (Soviet Union 1931), and British Interplanetary Society (1933). First in Germany and then in other countries, these small private movements evolved into components of standard societal institutions, in government agencies, corporations, and professional societies.

For convergence, there are three primary implications of this analysis. First, the nature of intellectual property is highly variable, depending in great measure on the dynamics of convergence and divergence in the broader field around the scientists or engineers. Second, the balance of power between individuals and larger entities such as corporations will vary similarly, relying upon the creativity of individuals in early stages of the field's evolution, providing opportunities for some individuals to benefit personally near the middle, but placing organizations like business corporations in power in later stages, often rewarding innovators far less than the company management. Third, the progress of development from parallel behavior to societal institution is a major form of science and technology convergence.

Conclusion

To the extent that science and technology convergence is a social movement, it will influence changes in legal norms, including those governing intellectual property rights. At the same time, new technologies create new realities, breaking down barriers between previously separate industries and creating entirely new ones for which traditional rules may be inappropriate. Most obviously, information technologies threaten the very survival of copyright protections, because copying and sharing of creative works have become trivially easy. One result might be switching to a different system of reward for creators, for example, if popular novelists were all literature professors at universities, given academic credit for works they posted online for free download. The example of patent thickets suggests that convergence may increase the negative impacts of patents, although it is difficult to imagine major corporations in technically advanced nations being willing to give up their traditional legal protections. Clearly, intellectual property rights in a rapidly changing socio-technical environment are an important topic for scientific research, as well as for policy debate.

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Institutional Transformation

Robert M. Mason

Contents

Abstract

This chapter critically examines societal institutions and the challenges they face from the convergence of multiple information and communication technologies (ICTs) and the ecosystem of information services made possible by this convergence. The discussion begins with a discussion of for-profit manufacturing corporations and observations about their changing roles in the USA and other economies. The chapter raises questions about how the economic stability that communities expected from these firms may be replaced by other types of organizations. The discussion continues with observations of similar challenges faced by community police and societal law enforcement agencies as they grapple with applications of ICTs. The chapter concludes with brief comments about the challenges to journalism and news organizations and publishing, noting that the convergence is affecting all sectors of the economy.

Information and communication technologies (ICTs) and services based on these technologies increasingly are embedded in our societies and economies. New services based on these technologies appear weekly; some disappear or get much

R.M. Mason (✉)
Social Media Lab, The Information School, University of Washington, Seattle, WA, USA
e-mail: rmmason@uw.edu

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less attention as others grow. Not only are the individual technologies continuing to emerge and develop, entrepreneurs are combining them in ways that provide unprecedented services. Moore's Law, the observation that the number of logic circuits on a computer chip ("computing power") doubles approximately every two years, is a technical foundation for what is happening. Advancements in digital technologies that evidence the "faster, better, cheaper" mantra of Moore's Law enable the production of handheld devices ("telephones") that combine location services, on-demand information access, alerts that provide unprecedented situation awareness, digital cameras, music storage, audio and video streaming and recording, and recreational games for when nothing else is available. Computing power and digital storage are less expensive; wideband communication is becoming less expensive and more available; and the convergence of digital and other technologies provides a widening range of opportunities for new products and services. The result is an explosion of available data and opportunities to combine these data in unprecedented ways, creating both opportunities for new endeavors and challenges to established societal institutions. Although these opportunities and challenges are most apparent in the more developed economies, the challenges are global. For developing economies that have fewer investments in infrastructure, the opportunities may exceed the challenges, enabling them to leapfrog intermediate development stages.

Socio-technical Convergence

Institutions are facing the next wave of the information economy. The successive version of the World Wide Web (WWW) is being labeled as Web 3.0. Absent an unambiguous definition – understandable, given the dynamic uncertainty of technical development – this term expresses the concept of something more advanced than the earlier forms of the WWW. If the first wave was simply "the Internet," and Web 2.0 is the more interactive web (still imprecisely defined, as the term communicates changes in both technology and capabilities), the beginnings of the third wave are appearing, with Web 3.0 and the "Internet of Things" forming parts of this wave. The foundations of this latest wave include the convergence of information technologies with other technologies that enable the transformation of products and services from their stand-alone beginnings to a complex network of converging technologies, services, and organizations. The technology convergence – whether in a phone or in other devices, along with advancements in data storage and near-ubiquitous wideband Internet access – provides a rich landscape in which our assumptions about institutional roles are being challenged. The environment is a dynamic twenty-first century embodiment of what early researchers in socio-technical systems termed a social ecology (Emery and Trist 1972; Emery 1959), this time with the technologies supporting human exchanges and knowledge work in addition to physical labor. This dynamic ecosystem tests the customary institutional pillars of society, which have evolved to serve societal needs in more stable times. Established societal institutions often find that their roles evolve, either deliberately or inadvertently.

This ecosystem extends beyond narrow cases of creative destruction (Schumpeter 1950; Christensen 1997) in which a dominant performer in an economic sector is displaced by a newcomer. The dynamic interactions are taking place not only in the society's economy but in a social caldron that can redefine economic sector boundaries and even challenge the logic underlying these sector definitions. It's a fertile information and organizational ecosystem that enables virtual organizations to emerge and go through a complete life cycle within a few years or even less. Existing, presumably stable, institutions that had been successful in an earlier time, a time in which the information environment was characterized by slower changes, now face challenges to their established routines and roles. The idea of *institutions*, as relatively unchanging structures that have steady relationships with other institutions, is challenged by this new ecosystem in which the convergence of information technologies with other products and services enables ever-changing opportunities. Leaders of organizations find that they are in a situation similar to the software condition of "perpetual beta," with continual changes and adjustments substituting for what previously had been unchanging – or slowly changing – roles, products, and services.

A significant and broad-reaching result of the convergence of ICTs into the Internet and web-based services is the growth of crowd work. Often called *crowdsourcing*, this is an effort that is carried out, sometimes anonymously and often without an overriding structure of a corporation or other organization, by individuals acting as autonomous agents. Viewed by some as a logical extension of outsourcing the production function, the increased opportunities for distributing the effort involved in production and the provision of services have the potential to transform a wide range of institutions that previously have been relatively stable societal fixtures.

The growth of crowd work highlights what may be a more general consequence of the convergence of ICTs. As these technologies and the services built around them establish more connections among participants, understanding the crowd behavior and recognizing the potential value in the resulting networks (Benkler 2006) focus attention on the linkages among participants. The relationships (links) between individual nodes are essential to creating value. As noted in the following discussion, the value of the network – the successful operation of the network – depends on these relationships. Organizations that are succeeding in this dynamic ecosystem are those that have found a way to create and maintain trust among entities that would engage in the network.

The following institutional categorization is admittedly subjective and based on the views of US institutions in 2014. The chapter begins with an emphasis on manufacturers, as the challenges may be most apparent in this sector. The evidence suggests that the same forces are at work in other developed and developing economic communities. Within a few years, shifting boundaries and relationships may make this categorization obsolete and may suggest other perspectives. The convergence of ICTs with other technologies occurs and diffuses at different rates in different communities, societies, and economic sectors. The rates of change can be a factor in the degree of institutional transformation and even in determining if a transformation happens at all.

Corporations and Manufacturing

The roles of for-profit corporations are changing and are likely to continue to change as technological convergence continues. The transformation has been happening over the past several decades in the USA. Davis (2013) makes the case that the societal functions of US corporations are changing. Originally, these roles were primarily *production* and *employment*. Later, Henry Ford not only introduced the technical innovation of the assembly line but also began to encourage *social welfare* practices, even to the point of having social workers visit the assembly line workers in the home. Ford was doing this not because of undue concern about the persons themselves but rather to assure that his factory had reliable employees to ensure continuity of production. Ford also recognized the value of paying wages that would enable his employees to become consumers of the goods they were producing. Later, following the New Deal and the introduction of social security, corporations extended their roles to be a *vehicle for personal savings* and to assure that workers had resources for retirement. These four roles (production of goods and services, employment, social welfare services, and a vehicle for savings) for decades served as part of the social contract of the corporation with society.

As noted by Davis, these roles are no longer the core functions of a firm. Instead, today's corporations have narrowed their core function to pursuing the single objective of increasing shareholder value, an emphasis that has become associated with the neoliberal vision (Harvey 2005). As we observe later, this focus has dysfunctional consequences and may be obsolete.

With globalization enabled by ICT and efficient logistical networks, production can take place anywhere in the world, increasing shareholder value by lowering labor costs. Workplace automation has reduced the labor value added in products, and employment in the USA for manufacturing has dropped. New firms, enabled by the convergence of the information systems and logistics systems, can be located in the USA (a large market) yet can locate design and production functions anywhere in the world. Consequently, firms can form, create a popular product, create wealth for the shareholders, and then disappear within a time period of a few years.

As an example, Davis points to the Flip video camera, a low-cost video recorder that enabled an easy USB connection to a computer and direct uploading to YouTube. It was developed in 2006, introduced in 2007, and by 2009 represented 20 % of the video camera market. Successful in terms of market share and profitability, Flip was acquired by Cisco for $600 million. By 2011, Cisco had closed the Flip business. From conception and introduction to peak valuation and closing, the life cycle extended only five years. Even with the huge product and market success, the firm at its peak employed only 100 personnel.

Today, thanks to the convergence of the ICTs, logistics, and business networks, transaction costs are low, reducing the justification for specialized and co-located specialized functions (Coase 1988). Entrepreneurs can replicate the Flip video recorder experience with other products. Someone with an idea can pass a sketch for the product to designers anywhere in the world, find a manufacturing source through Alibaba ("Alibaba.com" nd) or some other online consolidator (often getting multiple bids within 24 h), market the product through one or several online outlets, have the product drop-shipped to the customer, and accomplish all of these functions with only a handful of employees. Such a corporation can have a large financial impact yet produce a small societal footprint in terms of community presence and employment.

The corporation's role as a contributor to the local community in such cases does not exist. Even for larger and more established manufacturing corporations, the older "social contract" is no longer being fulfilled. The consequence of the shareholder value focus, coupled with the concentration of corporate ownership and shareholder power through a handful of financial institutions, means that decisions are driven by the interests of the institutional investors, lowering the engagement of the corporation with individuals or communities. Associated with these trends are the growing disparity of wealth and income and the phenomenon of the shrinking middle class.

All these trends are enabled by the convergence of ICTs with interconnected logistics and banking networks. Together, they facilitate a global production and financial system that has dystopian consequences in terms of societal equity.

The objective of increasing shareholder value and pervasive neoliberal government strategies together have created a mutually supporting and complementary set of policies and decision criteria that have been successful in realizing this objective. The focus on wealth creation has been adopted by most economies, resulting in a near-universal set of standards (profit, return on capital, profit per employee, etc.) by which corporate performance is measured. The results demonstrate the effectiveness of these goals and strategies. However, as Davis and others have pointed out, this has been accompanied by a growing inequity in wealth and income. The increased value is spread unevenly among stakeholders, with rewards going to those segments of society that began with the greater share.

Some observers have begun to question the sustainability of continuing along this path. Corporations and societies today are facing not only the challenge of the dynamic ICT ecosystem of services but confidence in the foundational principles as these have been implemented by existing institutional structures over the past several decades. The questions are evident in the instances of social unrest and in thoughtful books and articles.

The dysfunctional economic inequities have been at center of multiple incidents of social unrest, perhaps inspired by the Arab Spring. Two of these are the *los indignados* or 15 M movement (most prominently in Spain) and the Occupy movement (beginning in the USA as Occupy Wall Street, but quickly becoming global). These protests directed the public's attention toward economic inequities, the growing disparity between the wealthiest few percent (the 1 %) and those at the lower end of the economic scale, and the apparent collusion between government policy and corporate interests. The unsustainability of these inequities has been acknowledged by economists and academics (Stiglitz 2012; Piketty and Goldhammer 2014). Observers, including members of the highest 1 %, anticipate more social unrest (Hanauer 2014), and the Gartner Group's 2013 report (Thibodeau 2013) forecasts that these protests will continue.

If products and services – and even the organizations that develop and market them – are short-lived in this new dynamic ecosystem (as exemplified by the Flip video camera), are there paths forward that can take advantage of the ICT convergence in ways that alleviate the economic and social inequities? Will a new form of organization provide the stability that larger manufacturers once provided? Or does stability in organizational forms remain desirable? If the traditional production corporation is no longer fulfilling its traditional roles and collapsing (as posited by Davis), might it be replaced by the organizations such as the one that introduced the Flip? The same convergence of ICTs and logistics that enable the devolvement of organizational functions may provide a solution to these challenges. New organizational forms may emerge that can provide the structures that permit societies to sustain citizens' expectations of continued improvements in the quality of life for everyone.

Davis suggests that a combination of the same capabilities that lead to the demise of the corporation can be implemented in ways that replace the concentration of power that has been central to the efficiency and effectiveness of corporations. In his view, these capabilities can lead to more democratic institutions and a dispersion of workers into communities. The workers can perform their specialized duties remotely and contribute to new products and services yet still benefit from participating in a global communications network. Although many may recognize the possibilities of such virtual organizations, it is unclear how the transformation of existing institutions can take place in ways that avoid the dysfunctional consequences of the current concentration of wealth. The current corporate institutions may not be able to transform themselves, and new forms may emerge that provide an extension of outsourced functions and a structured environment for crowd work.

The concept of outsourcing of production is not new. Neither is the more specific concept of crowd work, but the latter has become more popular in the past few decades. Outsourcing production became widespread as corporations recognized the opportunities for lowering costs and focusing their internal operations on design and marketing of the corporate brand.

More recently, crowd work became associated with outsourcing innovation (Quinn 2000) and new product design. Procter & Gamble (P&G) made popular the idea of open innovation, partnering with customers and suppliers to identify opportunities and develop new products (Rao and Sakkab 2006).

On a smaller scale, individual inventors can work with brokering organizations such as Quirky to refine, develop, and market their ideas for products. Quirky has created a structured process by which inventors produce product ideas; and others can help the product succeed and earn money by proposing design features and improvements, helping select names and tag lines, and making other contributions to sales success. Quirky reports on the revenue earned by inventors and contributors for their best-selling items.

Crowd work based on small tasks that require intelligence, thought, and judgment (microtasks) can be arranged through an online marketplace formed by Amazon. The marketplace, called Amazon Mechanical Turk (AMT), provides a low-cost way for workers to earn money from their intellectual efforts without "having a job" in the traditional sense of being employed by a company.

Amazon, founded in 1994 as a bookseller, has become the world's largest online retail operation (Netonomy.NET 2013). In supporting the ordering and logistics management required for the retailing business, Amazon invested heavily in ICT (servers and Internet capacity) to assure good customer experience at peak times. Amazon recognized the opportunity to more fully utilize its computer capabilities off-peak and formed Amazon Web Services (AWS) in 2005, providing a scalable source of storage and computer services for firms and individuals. For those who use AWS, computing power and storage become a utility similar to electrical power, scalable up or down as requirements change, with charges based on usage and a market price.

Amazon formed Amazon Mechanical Turk (AMT) as a service of AWS, creating a marketplace for intellectual work so that human intelligence for tasks that can benefit from the decisions and judgment of crowds. AMT serves as a marketplace that enables intellectual work, in the form of human intelligent (HITs), microtasks that require judgment or writing and can be completed within a few seconds or minutes. An employer uses AMT to announce the availability of these opportunities and the pay rate that is offered. Individuals who have signed up with AMT and who are willing to perform these tasks for this amount accept the task, and AMT serves as the intermediary between the worker and the employer. AMT thus enables human mental work to be available as an online utility, capable of being contracted as needed.

Criticized by some as creating the opportunity for "digital sweat shops" (von Ahn 2010), the Amazon service reprises the older manufacturing idea of workers being paid for "piecework" in a distributed cottage industry. In response to the potential for mistreatment and exploitation of AMT workers, graduate students studying the service formed Turkopticon, a forum for the sharing of information about requesters and getting the most from their association. The name was intended to evoke the Panopticon principle suggested by Jeremy Bentham in the late eighteenth century in which the activities of prisoners (or, in this case, actions of the AMT requesters) are easily visible to observers.

The visibility of behavior is a key affordance of many of the more effective social media and crowd-based services. By incorporating crowd feedback on performance (e.g., through a "recommender" feature), a service can increase the trust level among participants in a crowdsourced service, lowering the risk.

Crowd work extends beyond the functions of product innovation and development and micro intelligence tasks. Crowdsourced financing has become an alternative to bank financing or venture capital funding for individuals or groups with ideas for products or services and even for charitable donations. Organizations such as Kickstarter, Indiegogo, and others work on one of the two business models: (a) donations to the innovator, with gifts promised in return but no assurance of any refunds if the project is not successful, or (b) a kind of loan that is refunded if the project is not completed. A website for the emerging crowdsourcing industry, with goals as varied as financing of new products to on-demand labor and creative work (as in the creation of logos) and engineering tasks, identifies over 2500 sites devoted to crowdsourcing.

AMT, P&G, and Quirky exhibit the range of organizational roles and size of what may be emerging as a new type of organization, one that serves as an intermediary between employees who do knowledge work and corporations or markets. The range of these firms suggests that the use of crowdsourcing may not only be a business strategy but may also be changing the nature of the corporation. AMT provides a marketplace for small tasks that require human intelligence. P&G, as an established firm (founded in 1837), maintains its core strategy of providing consumer products but uses crowdsourcing to identify and develop new products. Quirky proposes a structured way for ideas to become reality, lowering the barriers for many contributors to participate in (and benefit from) bringing a new product to market. And the existence of over 2500 sites devoted to crowdsourcing suggests that technology convergence is enabling a new kind of industrial infrastructure.

The emerging organizational roles of broker and marketplace creator may provide the steadiness for the societal functions previously fulfilled by the larger manufacturers. These intermediaries and a network of specialized vendors may provide a dynamic structural infrastructure that enables entrepreneurs and innovators to have access to the design, production, marketing, sales, and support functions that previously were only available within one organizational structure.

The impact of ICT convergence may be most evident with manufacturing and large corporations. It is apparent that the stock market valuation of firms such as Twitter and Facebook, which provide only communication services that serve as platforms for targeted advertising, and Alibaba, which serves as a broker for small businesses seeking sources, suggests that the potential for these intermediaries exceeds investments in traditional integrated manufacturing firms.

Simultaneously, however, the potential for change exists in other services, not only manufacturing. Some are seeing the rise of a substantial *sharing economy*, in which individuals can use their assets to generate revenue through organizations enabled by ICTs. People with cars who are willing to give rides can use intermediaries such as Uber, Lyft, and Sidecar (each using a smartphone app) to match their assets (e.g., type of auto) with customers who have a need for this asset. Similarly, people who have extra rooms or apartments utilize Airbnb to find renters. This sharing economy, estimated to be in the billions already (Botsman and Rogers 2011), depends not only on the affordances of ICTs through the Internet and mobile devices but also on recommender systems to establish trust and manage expectations. In the sharing economy, reputations become part of the currency.

Police, Security Forces, and Surveillance

Police and security forces recognize the potential for ICT, particularly social media platforms, to complement their official activities. Conversely, citizens recognize the value of social media as instrumental both in complementing the work of police and security forces and in maintaining a record of interactions between institutional representatives and the public. The age of surveillance, noted in the late twentieth century (Donner 1980) but now being more fully realized, is eroding the expectation of privacy for both the individual citizen and the institutions that society has established to serve the citizenry. The resulting tension between the desire for privacy and expectation for transparency in societal institutions government is likely to transform roles and shape behavior of those whose mission is to "serve and protect," as stated by the motto of the Los Angeles Police Department.

A survey by LexisNexis of law enforcement professionals in the USA indicated that over 80 % used social media as part of their work (LexisNexis® Risk Solutions 2012). The survey reported that the primary uses were for investigations and to solve crime, although other agencies also used social media to monitor and anticipate criminal activity. These practices preserve the role of law enforcement professionals as separate from those served, a role in which there is engagement only when there is wrongdoing or criminal activity.

Local agencies have invested in the alternative role of community policing, recognizing it as an alternative and complementary strategy. The intent is to build trust and establish more supportive and less adversarial relationships between law enforcement and members of the community. It is believed to help reduce crime and to provide a way to exchange information, especially during times of crisis or emergencies. These alternative uses of social media, as shown in a 2013 survey by the International Association of Chiefs of Police ("2013 Survey Results" nd), include two primary kinds of activities: *informing* the public and *engaging* the community in conversation. The practice seems to be increasing and appears to be boosted when there is an incident in which the police and the community engaged in a joint effort using social media to share information or to solve a crime. Examples of such incidents include the slaying of four Lakewood, WA police officers in 2009 and the Boston Marathon bombing in 2013.

In 2009, the resulting manhunt in the Seattle-Tacoma area engaged the public's interest, and the Seattle Times used Twitter and other social media (including the now abandoned Google Wave) to keep people informed and to "crowdsource" identifying and tracking leads (San Miguel 2009). The Wave site provided both current information and a way for the public to participate in the evolving story.

The April 15, 2013, bombing near the finish line of the Boston Marathon elicited an outpouring of sympathy on Twitter for the victims and for Boston citizens generally. The Twitter activity also demonstrated the capabilities of social media to inform and engage the public, a dramatic demonstration of community policing in a time of crisis and heightened anxiety. As noted in a retrospective report (Davis et al. 2014), the Boston Police Department (BPD) had established the Twitter account in 2009, and the commander on the scene immediately recognized the role that Twitter and other social media (including the BPD's Facebook page) could perform in disseminating trusted information to the public. As a consequence of the round-the-clock effort to maintain a stream of reliable information, the number of followers of the BPD Twitter account (@bostonpolice) increased from about 40,000 prior to the bombing to more than 300,000 by April 19 and as this is written still has over 275,000 followers.

The capability for sharing information rapidly and widely is agnostic about the veracity of the information being shared. Rumors (unverified information) spread as quickly as official announcements, and this was evident on Twitter following the Boston bombing. The crowd can correct information, but early indications are that the volume of misinformation (as measured by the number of tweets and retweets) is several orders of magnitude greater than the volume of corrections (Starbird et al. 2014).

Not all police department experiences with social media have been as productive as that of the BPD. The New York Police Department, in its effort to appear friendly, asked people to post photos of themselves with its officers using the hashtag #myNYPD. The results might have been expected: people posted photos that mocked the NYPD, showing officers dragging or carrying people, presumably under arrest, or otherwise interacting with officers in less-than-friendly encounters. Not all posts were mocking, and many showed the friendly faces of officers with citizens. To its credit, the NYPD responded in good humor. "The NYPD is creating new ways to communicate effectively with the community. Twitter provides an open forum for an uncensored exchange and this is an open dialogue good for our city," said Deputy Chief Kim Y. Royster (Ford 24 April 2014).

The Seattle Police Department (SPD) took a different approach and hired a crime reporter with a sense of humor to write for the department's website and oversee the Twitter account (Hickey nd; Reynolds 2013). The combination of information and humor has worked, if follower counts are useful indicators. The @SeattlePD account in mid 2015 had over 120,000 followers, more than 3 times the number of followers of @LAPDHQ, which takes a matter-of-fact approach in its use of Twitter and other social media.

Law enforcement agencies at all levels, from campus police forces to national and international organizations, have been forced to confront the increased transparency facilitated by the ubiquity of mobile phones and capabilities they provide for text messaging and sharing photos. With the mobility of recording devices, whistle-blowers have increased capabilities to rapidly and widely disseminate notes and images on what they see as wrongdoing, whether by governments or corporations. The public's reactions to information shared by the WikiLeaks organization and the Snowden revelations of NSA monitoring of communications traffic, just as did the Occupy movement, have demonstrated that trust in public institutions, both government and corporations, has been eroded. The affordances of the ICT convergences have given citizens additional tools to observe these institutions and provide alternative ways to "guard the guardians" of public safety and security. As with the emerging organizations that innovate in the private section, public agencies will be required to acknowledge the power of recommender systems for establishing and maintaining trust with those they serve.

Journalism and Publishing

As with other societal institutions, traditional print and mass media journalism, popular publishers, and scientific publishers are facing challenges and undergoing change. The convergence of technologies empowers individuals and groups to effect change, and some companies perceive changes in structure of publishing itself.

The attention economy means that today's "news" stories often are related to sensational topics and less to issues of global consequence that are perceived as have less immediacy. Moreover, the urgency to make the news available quickly means that stories are not as well vetted as when the news cycle could be measured in days rather than minutes. The situation for traditional journalism has been viewed as a crisis and has resulted in considerable debate (McChesney and Pickard 2011).

"Citizen Journalists," individuals who may not have the skills or value systems attributed to professional journalists, have the technology readily available with their smartphones to capture an image or even a video and, within seconds, post it to a social media site. The resulting post can grab attention, "scooping" a breaking story before the print, and other mass media can react. In response to the demand for immediacy in getting a story to the public, professional journalists have taken to using social media (e.g., Twitter) themselves to do their own reporting, recognizing that they are trading off careful vetting of facts, context, and thoughtful perspective for rapid responses to events. A Tweet, blog post, or video can "go viral," then become part of the reporting by established news organizations (Nahon and Hemsley 2013).

As a consequence, the social agenda is no longer being established only by newspapers and other established news organizations. Instead, different social media increasingly have a voice and can participate (as with the Arab Spring and Occupy) in influencing the agenda for public discourse.

For books, Amazon arguably has transformed how publishing and book buying are viewed. The large publishing houses and authors have had a love-hate relationship with Amazon, recognizing the value of making their works more widely available to the buying public and simultaneously resenting the loss of control of pricing. Amazon has accomplished its position with investments in information and logistics systems. Combined, these systems support an extensive crowdsourced review and recommendation system along with package tracking and prompt delivery. Time is further reduced by making the books available electronically, eliminating the need for physical delivery, although continued investments in delivery technology (as in drones) boost Amazon's position as the largest online retailer.

Aspiring writers can take advantage of Amazon's services to self-publish, gaining the advantages of wide distribution and bypassing established publishers. Amazon is not the only avenue open for self-publishing, as other firms (e.g., Lulu nd) seek to provide varying levels of assistance to aspiring authors. The publishers note that this means the publications do not get the scrutiny of editors, nor do the authors get the benefit of marketing and promotion, which can establish the author's credentials. As a consequence, authors have to weigh the benefits of either dealing with new intermediaries such as Amazon or working with established publishers.

Local booksellers have been less ambivalent about their reactions to Amazon. Amazon's investments and the resulting power it exercises over publishers have made it difficult for the local bookstore to succeed. The costs of having a storefront and the costs of books (bookstores are unable to get the same discount as Amazon because of much smaller volume) mean that local bookstores will continue to struggle for economic survival.

However, for both authors and publishers, Amazon's current role has both benefits and risks. The current negotiations will be enlightening and may shape the future of authoring and publishing. If the trend toward the disintermediation of publishers continues, then the role of publishers in assuring quality may disappear.

The issues for academic publishing are even more complex, as academic (journal) publishers traditionally have organized peer review systems to assure quality and additionally assumed the role of archivists and even information database systems as the knowledge becomes searchable electronically. Academic institutions have complained of the increasing subscription costs of journals, and this has stimulated the growth of open-access journals, organized and managed outside the established journal publishing organizations. Such efforts have the advantage of the lower costs of a digital only, Internet accessible journal.

However, as academic institutions continue to emphasize publishing as an indicator of scholarly productivity, the pressure for additional outlets for papers has increased in the number of journal offerings. New publishers, often set up to take advantage of Internet access to electronic-only publications, have augmented the titles from traditional publishers. For some of these new publishers, the costs are covered by authors' fees, and this business model has been criticized by many as providing an incentive for publishers to be less rigorous in the peer review process. This view was recently supported by a "sting" operation that demonstrated that a number of these fee-based publishers accepted a bogus paper, although supporters of open-access publishing point out that inadequate and shoddy peer reviews are not unique to open-access journals and can be observed in subscription-based journals (Bohannon 2013; Redhead 2013).

Additional models may emerge, and it is unclear if academic institutions will continue to place high value on the indexing and archiving functions that the older, more established, scholarly publishers routinely provide. Peer review remains important, but the incentives for rigorous reviews will need to be built into whatever systems emerge.

Concluding Comments

This chapter has highlighted the challenges and opportunities for societal institutions that have in the past been stable pillars around which citizens build their lives of work and meaning. As a consequence of the convergence of ICTs and a rich and dynamic information ecosystem, these institutions are being transformed. The technologies are not *causing* these transformations; this is not a case of technological determinism. Instead, the convergence is enabling individuals and institutions to perceive alternatives. The resulting transformations can be expected to come about through a recursive, coevolutionary, and complex network process in which multiple stakeholders – established interests, entrepreneurs, innovators, and public responses – each contribute multiple voices. In this process, the links among the stakeholders may be more predictive of the outcome than the current positions and espoused interests of individual stakeholders.

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Medical Approach to Wellness

Christopher Hartshorn and Piotr Grodzinski

Contents

Abstract

Bridging the gaps between medical knowledge and modern technologies to target large-scale societal health and wellness problems is no small challenge. Multiple efforts are currently underway to tackle these grand challenges. The focus is on several of the largest worldwide health issues of cancer and neurological disorders although it also extends to many wellness-related issues. Although, the overarching goal still remains the same – a decrease in mortality and morbidity via unique and personalized technologies so that our day-to-day lives are improved.

Introduction

Imagine a time when our approach to medical care is entirely preemptive and proactive. Medical technologies had advanced to the point where morbidity and the subsequent disease-specific mortality rates in society are reduced to significantly lower levels or, at least, lifestyle diseases are the only ones of any

C. Hartshorn (✉) • P. Grodzinski
Office of Cancer Nanotechnology Research, National Cancer Institute, Bethesda, MD, USA
e-mail: christopher.hartshorn@nih.gov

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significance remaining. Mere science fiction or a potential reality that could take place in our lifetimes? The focused convergence of knowledge and technology is the primary reason for these visions being much more realistic in the near future than ever before.

From a societal perspective, human health and wellness would be at the top of a long list of concerns for the coming future. Whether discussing morbidity, mortality, or the financial cost to society, these are always considered to be important issues to the human condition. As of 2008, noncommunicable diseases accounted for 36 million or 63 % of all premature deaths reported worldwide according to the World Health Organization (2014). Of these noncommunicable diseases, cancers, cardiovascular and chronic respiratory diseases accounted for the bulk of the 36 million. As far as the estimates for chronic debilitating disease and disorders, over 350 million people suffer from depression, 347 million have diabetes, and over 90 million suffer from the primary neurological disorders, to name just a few (WHO 2014). Substantial numbers even with a current global populace of more than seven billion and despite the advances in medical care of the last 50 years have continued to rise and will continue to do so (OECD 2013). Personal well-being or wellness, which has been traditionally defined as "a state of being healthy in body and mind," will require a new paradigm in our approach in order to consider a population of people to be truly well. While an incredibly complex topic, with morbidity and mortality numbers such as those reported above, it is not clear whether society will ever be truly well. Certainly, a collective worldwide effort toward healthy lifestyle choices and a cease and desist order on polluting natural resources could improve societal wellness significantly. Unfortunately, these efforts are not as easily guided forward as others. For example, although the US smoking rate significantly to about 20 % of adults today, they only represent about 5 % of the one billion smokers worldwide, and worldwide obesity has nearly doubled since 1980 to about 10 % of adults today. Cigarette smoking and obesity are the leading two causes of preventable deaths and are major contributors to worldwide morbidity from chronic diseases (WHO 2014). Fortunately, it is clear that with modern medical approaches emerging from the implementation of innovative technologies in medicine, that allow for lifelong health monitoring, early/accurate disease diagnosis, and disease/organ targeted therapeutics and devices, our idea of what it means to be well could be drastically altered and improved. An effort to make these changes and improvements is likely to rely on contributions from several areas of science and researchers of many disciplines. Establishing a common goal for these developments, bringing together the disparate fields contributing to them, and enabling a common language among individuals working on them consequently leading to their convergence is a challenge in itself. The reward – an improvement of wellness and global health – is worthy of the effort.

Convergence, pertaining to medicine, has been a bridging of biology and the physical sciences resulting in a cross-pollination of ideas and novel applications. Examples of this cross-pollination effect are seen in biology, which has given cues to materials science by way of biomimetic materials being developed for non-biological applications and in the opposite direction with novel nanomaterials developed to target a biological problem, cancer (Prasad 2012; Jabbari and

Khademhosseini 2014). In both examples, an initial problem was deciphered by both sides and worked upon in tandem until a final solution was discovered. The bridging of these two arenas of science can seem rather cyclic, mostly, because it is. In essence, the convergence of these very broad fields allows technological developments to be built that rely on previous biological knowledge, while at the same time these technologies give answers to previously unknown biological questions, thus increasing biological knowledge, and the cycle repeats.

The idea of integrative or converged disciplines within the health sciences has been gradually introduced since the 1990s (Sharp and Langer 2013). The biotech industry as a whole has had to rely on a combination of materials scientists, chemists, biologists, engineers, and physicists to develop and commercialize products. Similarly, many academic programs such as bioengineering and biophysics have required an ample amount of biology, chemistry, and physics, and many more graduate research projects require spanning several areas of science and engineering to complete. In other words, the twentieth-century paradigm of the pursuit of a doctorate degree within chemistry, in order to dream up novel chemical reactions all day, has been replaced with the realities of the twenty-first century. This new reality requires an understanding of multiple fields in order to remain competitive in an ever-changing and complex funding environment (Alberts et al. 2014).

Although it was not until early in the twenty-first century, under a convergence framework, that several grand challenges in medicine had been started which, at their core, necessitated focused and concerted multidisciplinary efforts. The efforts, which we will expand upon in the following pages, are large-scale focused activities within the health sciences that have been or currently are funded and continue to have a large body of researchers devoted to their success. The defining element that bridges them is the objective to solve some of societies' largest health-related issues utilizing novel technologies and science or, more succinctly stated, convergent medical approaches to societal wellness.

Nanotechnology for Cancer and Beyond

Of course, disease has been around for as long as we have, but the ability to manipulate matter at the molecular scale and process it in such a way as to control its length scale and physical properties is a very recent development. The concept of using nanoscale materials to target the global health problem of cancer seems like a contradiction in scale. Nanomaterials defined by the US National Nanotechnology Initiative (NNI) range in dimensions between approximately 1 and 100 nm, while typical solid tumors range in dimensions between approximately 1 and 4 cm in diameter. In comparison, one could visualize a man kicking the surface of the moon if only volume ratios between the nanoparticle and tumor were considered. The difference in this case is that nanomaterials exhibit unique material and physical properties at these length scales. In addition, nanomaterials' physical properties are tunable (as a function of size and chemical makeup), they can be easily functionalized with other molecular species, and their surface area ratios are

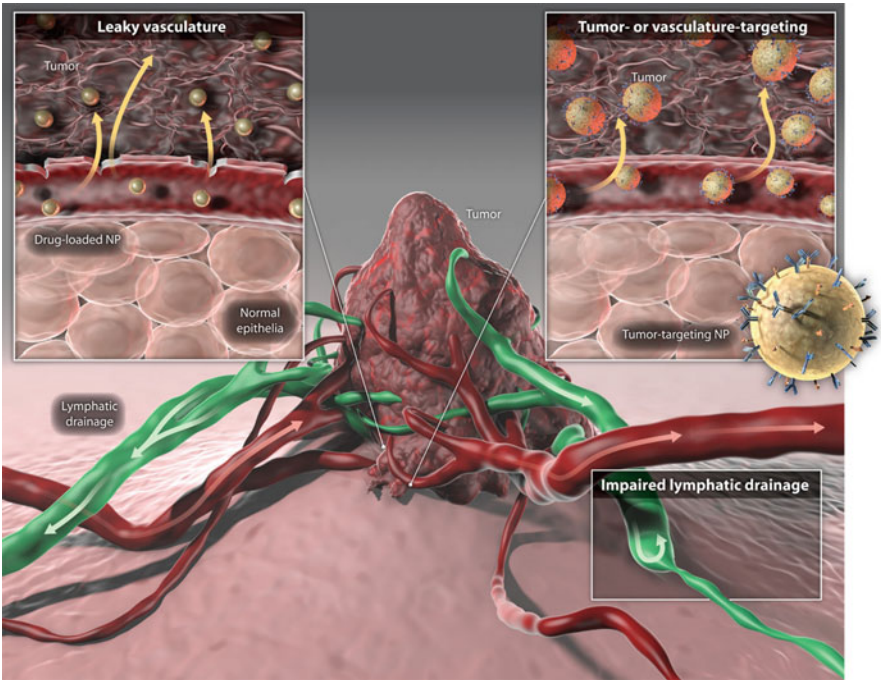

Fig. 1 Pictorial depiction of passive (*top left*) versus active (*top right*) mechanisms of tumor uptake with nanoparticles (Chow and Ho 2013)

much larger than their bulk material counterparts (Prasad 2012). With respect to cancer, these unique fundamental aspects of materials designed at the nanoscale allow targeting (Fig. 1) of specific biological moieties of cancer cells to act as either therapeutic, diagnostic, or both (e.g., theranostic) delivery (Fig. 2) systems (Chow and Ho 2013; Tarn et al. 2013). As a result, the nanoparticle and/or its payload targets biological molecules on or within cancer cells which are more comparable to its size and can have greater effect at disrupting cellular function, acting to report spatial location of cells or both simultaneously. Although the challenge of developing better treatments for cancer is grand, the use of nanotechnologies to enable novel therapies and diagnostics has been quite successful over the last decade.

Nanotechnology had been explored and even utilized in products to target cancer back as far as the mid-1990s. A handful of nanoformulation-based products to deliver the chemotherapy drugs of paclitaxel or doxorubicin were approved by the US Food and Drug Administration (FDA). These albumin-bound nanoparticles (Abraxane, approved in 2005) or liposomal-based nano-delivery systems (Doxil, approved in 1995) delivered their therapeutic loads directly to several tumor tissue types via a passive delivery mechanism known as the enhanced permeability and retention (EPR) effect (Wang et al. 2013). The efficacy of these products is similar to that of the free drug delivery of the respective chemo-agents albeit with greatly decreased toxicity to the patient. Although these were suitable in that they reduced

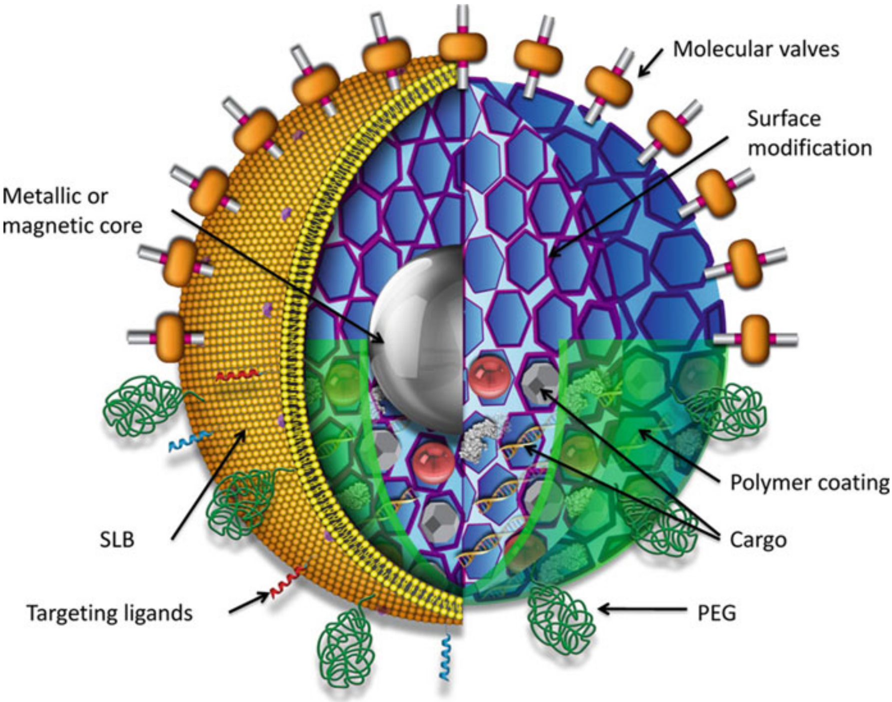

Fig. 2 Pictorial depiction of a multifunctional nanoparticle "protocell" with the ability to passively/actively target, evade immune response, deliver multiple therapeutic types, and act as diagnostic as to its location within the body (Tarn et al. 2013)

the toxicity effects typically attributed to chemotherapies, their efficacies were similar to the free drug, thus giving only an incremental advancement to cancer treatment. In order to develop further generations of nanotechnology-based therapeutics with improved efficacy as well as in vitro and in vivo diagnostics capable of recognizing the disease at earlier stages, the National Cancer Institute (NCI) established the NCI Alliance for Nanotechnology in Cancer in 2004. This initiative relies on a multidisciplinary community of researchers representing diverse disciplines from cancer biology and oncology to materials science, physics, and chemistry with the objective of identifying challenging and difficult to solve, by contemporary approaches, cancer problems and utilizing nanoparticles and nanodevices to tackle them.

The NCI Alliance funds large multidisciplinary cancer nanotechnology centers of excellence, platform partnerships, and training centers across multiple institutions with the core requirement of synergy between all of the components within each individual unit as well as across the Alliance as a whole. Coupled to the academic research units included the formulation of the Nanotechnology Characterization Laboratory (NCL) which consisted of a formal collaboration of the NCI, the National Institute of Standards and Technology (NIST), and the FDA to develop a cohesive set of standardized characterization assays of nanoscale materials that would facilitate successful clinical translation and subsequent commercialization. Although the focus of the program has morphed somewhat with time and necessity, the overarching goal, which is the translation of novel research developed in academic laboratories to clinically approved cancer nanotechnology products developed by industry, has not.

In addition to very prolific scientific output of the initiative, which resulted in close to 2000 peer reviewed publications, over 70 start-up companies were formed to develop further technologies established by academic researchers funded by the NCI Alliance. The program has established a successful model of utilizing government funds for initial stage of research and leveraging other funding from venture capital and philanthropic sources to move these technologies to more mature stage. The Alliance should be viewed as a success story and is often used as an example of effective collaborations of researchers representing different disciplines through science convergence, as well as a model for future initiatives coupling rapid development of novel technologies and their implementation into clinical practice.

Although it is impossible to predict the future, an optimistic assessment of cancer nanotechnology developments over the next 5–15 years is certainly within reason considering the number of nano-inspired therapies and diagnostic devices currently in the development pipeline. Over this short window of time, we should begin to see many novel technologies and tools including, among many others: multifunctional nanoparticles that simultaneously deliver chemotherapy payloads and act as magnetic resonance imaging (MRI) and/or positron emission tomography (PET) image contrast agents, actively targeted nanoparticles that deliver gene or chemo therapeutics, and nano-inspired microfluidic "liquid biopsies" that allow detection and monitoring of disease progression in response to therapeutic selection all from simple *ex vivo* blood draws. It is also expected that newly developed nanoparticles capable of crossing biological barriers will enable more effective treatments of glioblastoma multiforme (blood–brain barrier) or pancreatic cancer (penetration of stroma) and allow for resurrection of formerly failed therapeutics that will now be safely and effectively delivered to the intended target.

Indirectly, these cancer nanotechnology-focused efforts will continue to deliver new insights into cancer biology as well as will be translating into novel nanomaterial approaches to detect and potentially cure other diseases. From nanoparticles that can simultaneously enhance diagnosis and dissolution of vascular plaques or blood clots to nanoparticles that can aid diagnosis and dissolution of renal calculi, the science and technology developed within the cancer space will not require a reinvention of the wheel when translated to other potential targets (Prasad 2012).

Neurotechnology Toward Mental and Neurological Wellness

With aging populations and increasing levels of stress in our daily lives, mental illness and neurological disorders are on the rise. Recent advances in MRI (e.g., functional or diffusion MRI) and PET imaging modalities have certainly given insight into the inner workings of the human mind unlike ever before. Novel small-molecule therapeutics have made the lives of so many who suffer from depression and other neurological disorders much more tolerable. Although, the complexity of the human brain and any subsequent disorder of it are written at a much deeper level than bulk therapies and large-probe volumes (e.g., millimeters cubed) can hope to diagnose or cure. To cure we must understand, and to understand we must couple the unique information processing of the brain's highly interconnected neuronal networks to function and subsequent deviations relative to the disease or disorder. The human brain consists of an interconnected network of over 100 billion neurons, which provide electrical signaling via changes to localized chemical gradients via upwards of 100 trillion individual synaptic connections. As such, not one neuron can be held responsible for function or dysfunction because brain function requires a massively parallel coordination of many. Coupled to the chemical variations that create these electrical patterns are a multitude of biological processes and materials that help to maintain the gradients across the intra- and interneuronal space. The challenge is to map the connections within the brain, and the effort can be likened to the Human Genome Project of the 1990s albeit with more dimensions required. The difficulty here arises from more than just the sheer volume of connections within the brain that need to be mapped in order to develop any useful understanding of function. It is also complicated by the fact that the connections are at the nanometer scale (e.g., the synaptic cleft is ~20 nm), they fire in real time (e.g., 5–50 times per second), they need to be studied in vivo, and they by their very nature are massively parallel. Put simply, this is a grand challenge that indeed requires a targeted multidisciplinary approach to tackle.

Multiple initiatives and programs have begun in the past 3 years to address this grand challenge (Andrews et al. 2014). Often dubbed as the next frontier in science, overcoming the challenges of mapping the brain should provide a quantitative understanding to the complex links between brain function and behavior (Fig. 3), thus, giving rise to novel devices and therapies to alleviate or cure neurological disorders and revolutionize our treatment of mental illness. These funding initiatives cover the spectrum of disciplines needed to develop tools and models to begin mapping the brain (Fig. 4) From nanosensors to robotics and from simulation to informatics, these initiatives utilize highly synergistic approaches to the goal of mapping and assessing brain function. The largest of these are the European Commission's Human Brain Project and the US Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative.

The European Commission's Human Brain Project officially began in 2013 with the primary goal to simulate in silico a complete human brain and secondary goal to use this model to simulate the effects of various therapies. Currently, the project is planned for 10 years with funds close to one billion Euro dedicated to research toward achieving its goals. Alternatively, the US BRAIN Initiative (formerly known as the Brain Activity Map project) officially began in 2014 with the primary goal of mapping the activity of every neuron in the human brain (Insel et al. 2013). The congressional funds set aside for the US BRAIN Initiative will act as an additional funding mechanism and be distributed primarily via four US Federal

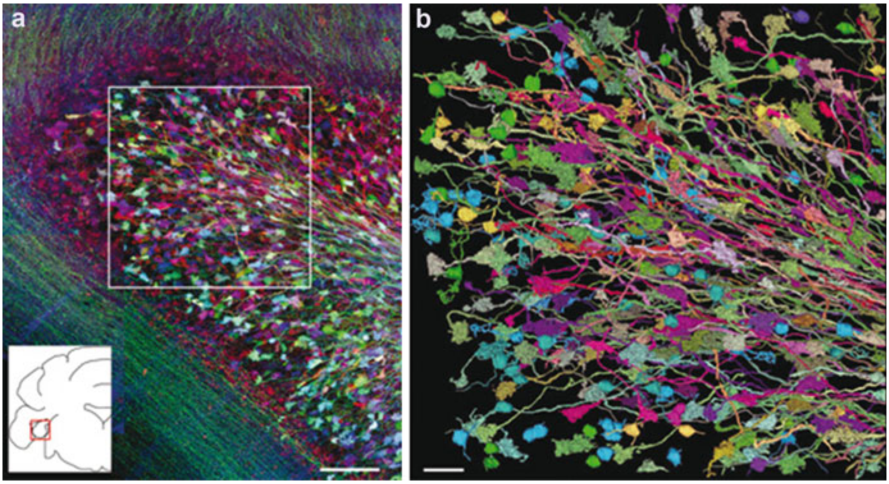

Fig. 3 (**a**) Genetically labeled neurons within the cerebellar flocculus of a mouse brain. *Inset* shows coronal location and (**b**) three-dimensional digital reconstruction of region boxed in (**a**) (Livet et al. 2007)

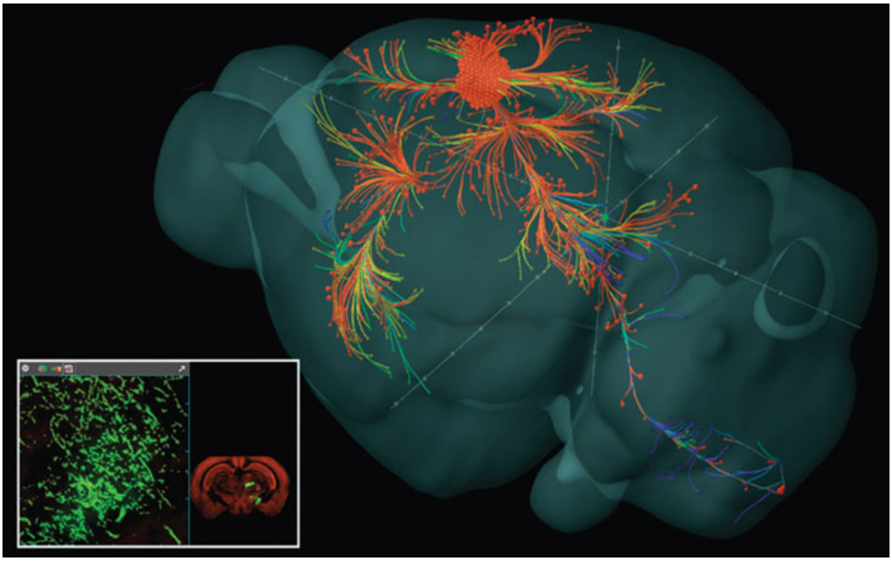

Fig. 4 Reconstructed mouse brain connectivity data from a green fluorescent protein (GFP)-expressing adeno-associated virus injection show the primary motor cortex projectome. *Inset*: magnified view and coronal section of projections in the ventral posteromedial (*VPM*) nucleus of the thalamus (Osten and Margrie 2013)

agencies: the National Institutes of Health (NIH), the National Science Foundation (NSF), the Intelligence Advanced Research Projects Activity (IARPA), and the Defense Advanced Research Projects Agency (DARPA). Several other nonprofit organizations and private sector partners will also contribute to the total expected 4.5 billion USD over 10 years meant to fund the initiative's research goals. Although multidisciplinary programs with similar foci already existed within the USA prior to the US BRAIN Initiative such as the NIH's Human Connectome project, among many others, the purpose of the BRAIN funding is to accelerate the development and application of innovative technologies for its purpose. These technologies will be used to uncover how the brain registers, processes, stores, and recovers enormous quantities of information.

The outlook for these programs in accelerating our knowledge, understanding, and treatment of the least understood problems within the human brain is very promising. The primary components and groundwork had already been completed prior to their initiation, and as such their successful delivery of impactful technologies is very probable. Even more important is that these programs are not just other examples of the convergence of knowledge and technology, but also a novel example of the convergence of multiple programs, mostly due in part to the Human Brain Project and the US BRAIN Initiative having recently agreed to coordinate research across both programs (Reardon 2014).

Personalized Wellness

The preventative and predicative health care that is personalized to our physical and genetic profiles as well as our lifestyles will become more common in the future. In essence, we can view this change as a whole-body or holistic approach to medical care albeit with the use of modern molecular tools and technologies. The convergence of knowledge, technology, and societal needs has been and will continue to be driving innovations into this arena over the years to come. The concept of personalized wellness may seem obvious and something that one would think that has been pursued for years already. It is important to distinguish between personalized wellness and medicine. *Personalized medicine* is focused upon targeted therapeutics and diagnostics toward an individual patient, which in itself can be defined rather broadly (Hamburg 2013). *Personalized wellness* refers to all technologies being developed for a patient-centric medical care model, which includes personalized medicines (e.g., precision medicine).

In this broader scope of *personalized wellness*, it is not only the treatments of the individual, but also environments around him/her contributing to their well-being. Thus, the landscape of technologies which are under consideration includes wearable and home-based health monitoring (e.g., real-time health monitoring), health-centric homes/buildings, patient-specific prosthetics, and artificial organs, in addition to patient-specific therapies/diagnostics. Examples of these can be seen in the market of wearable devices, which one can argue that 2014 was the "Year of the Wearable Consumer Health Monitoring Devices." Also, with respect to real-time health monitoring, the advent of cloud-based computing solutions, secure data access/storage, and ubiquitous network access is enabling many devices to have the ability to upload data to the cloud, allowing for clinical assessment of an individual's health over time (e.g., body temperature, weight, blood pressure, blood glucose, and many more routine measurements). Alas, how this plays out with respect to individual privacy concerns will still involve more debate and strict policy for it to evolve further. Other examples can be seen in the areas of tissue engineering and bioengineering, which have been working toward the ability to regenerate human tissue and organs that alleviate rejection for many years. Most recently, these fields have made large strides in delivering the reality from their initial concepts (Bajaj et al. 2014). Each example is a good model of the convergence of knowledge and technology toward the eventual personalized wellness of society.

Another area of focus toward wellness are personalized diagnostic devices tailored to an individual's own genetic makeup, response to therapeutics, and lifestyle and, eventually, for home-based disease prevention. Novel nanomaterial-based biosensors, microfluidics, and population-level omics/bioinformatics data/analysis will boost this area to a whole new level, and some of them could eventually become wearable devices. Bedside personalized diagnostics and prevention, from instantaneous blood chemical blood cell panels as well as "liquid biopsies," (Fig. 5) obtained from an *ex vivo* analysis of a human blood sample require several key components (Bettegowda et al. 2014). These components include: (1) exceptionally low volume blood draws to reduce patient burden and increase acceptance, (2) "bio-labs on a chip" calibrated to patient type and genetic profile (3) multi-analyte detection schemes, and (4) insignificant form factors and secure wireless connectivity to the clinic. Much of what these key elements entail, from a developmental perspective, is already in place today or could easily be coupled together from current technologies. On the other hand, much of what will be necessary requires significant additional effort to achieve. The potential impact to cancer survival alone, from these efforts, could be significant although the complexity of the problem, specifically the knowledge base required for the diagnosis/prognosis from minimal residual disease detection, is enormous (Hori and Gambhir 2011). Several potential biomarkers (e.g., protein, rare event circulating cells, circulating tumor DNA, μ-RNA, etc.) exist although population-level genetic and proteomic data is critical to the development of general detection strategies that will detect across multiple patient populations and disease types (Haber and Velculescu 2014). Efforts to formulate convergent strategies at tackling this have begun over the last 8 years. It is a combination of developing new technologies, but simultaneously an intense biological discovery effort. The NCI Early Detection Research Network (EDRN), Clinical Proteomic Tumor Analysis Consortium (CPTAC), and the NIH Biomarkers Consortium are good examples of coordinated searches and verification approaches for new biomarkers. Even more recently, US Federal Government intra-agency convergence workshops have been held by the NCI, the Air Force Office of Scientific Research, and the Defense Advanced Research Projects Agency to discuss disease-related stochastic modeling,

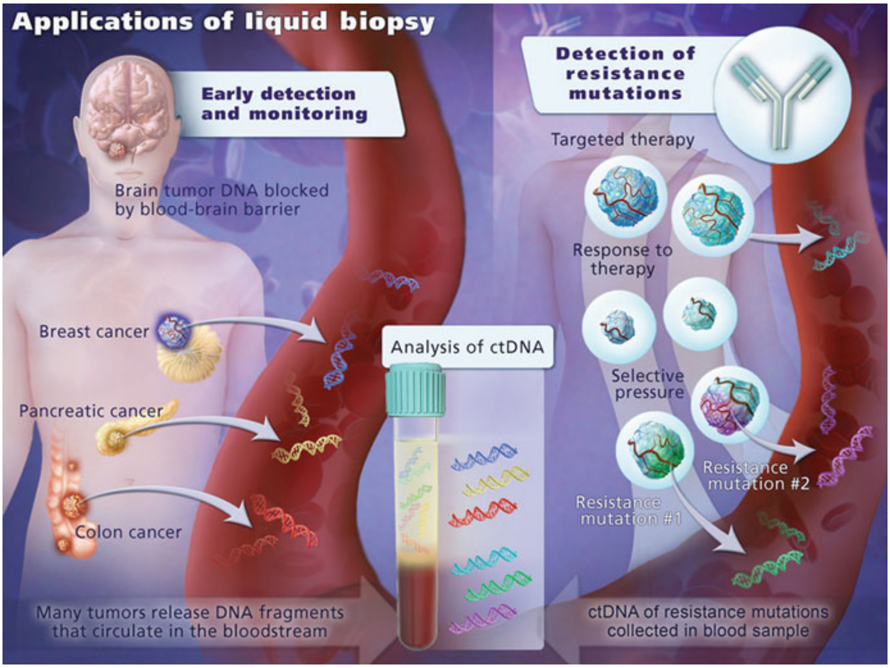

Fig. 5 Applications and conceptual depiction of ex vivo blood analysis of circulating biomarkers released from solid tumor tissue (e.g., "liquid biopsy") as a noninvasive assessment of cancer type, stage, and progression in response to therapy (Bettegowda et al. 2014)

biological phase transitions, and biological network dynamics to build a foundation for modeling of disease-related data at the population level.

Future efforts to improve health and maximize human potential will need to rely not only on convergence and implementation of new technologies into medical care, but also on taking a holistic approach to creating wellness environments in the places where we live and work. There is an effort to improve construction practices to achieve high-performance and sustainable buildings with optimized energy efficiency, conservation of water use, enhanced indoor environmental quality, and reduced environmental impact of used construction materials (see http://www.wbdg.org/references/fhpsb.php). The US Federal Government is aggressively implementing these guidelines in the management of the approximately 450,000 buildings it owns and in the construction of new ones. A correlation between workers' productivity and health with the design of a building with appropriate lighting, ventilation, and control of air contamination has been well documented (e.g., http://www.wbdg.org/design/promote_health.php). An implementation of novel construction methods to improve the in-house environment and conserve energy, in combination with distributed sensor technologies, will lead to the development of "smart homes" capable of sensing the local environment and then, in conjunction with knowledge of inhabitant behaviors, allowing for "smart" adjustment of indoor environmental conditions.

Societal Impact and Implications from Integrated Medical Approaches to Wellness

Large-scale convergent technological approaches to medical care and wellness will be felt by the global community in the near future. Disease will be detected much sooner and once detected, will be eliminated or its effect will be substantially reduced more than any other past generation has experienced. Our sense of physical wellness from day to day will be greatly impacted from almost continual health monitoring, giving the feedback necessary to make more informed and positive lifestyle choices. Our sense of mental wellness will be substantially altered as we begin to understand the underlying causation of mental illness, which undoubtedly will allow for substantially improved and targeted medicinal and psychotherapy treatments.

In general, it is expected that the practice of medicine will move from reactive to proactive. The current care system is rather ineffective in fostering long-term wellness at the level of individuals or larger cohorts. The availability of "adequate information" about health and cost consequences of daily action and inaction is not yet truly available. Developing environments in which, on one hand, continuous data associated with monitoring of the vital signs of the individual is collected, but on the other hand, the data is analyzed, fitted into predictive and behavioral models, should allow for the development of more healthy lifestyles and more friendly environments in which life is carried out. The technological progression enabling these changes will need to move hand in hand with changes in attitudes of how medical care is conducted. Medicine to date has been risk adverse and opposed to dramatic change with the system rewarding consistency, (i.e., standard of care), while the long-term goals, especially those that present risk, liability, or potential sacrifice, were of lower priority. With all of these improvements to our health care and wellness, what will be the impact to society?

All of the potential positive impact of the technological advances and progress arising from converging different fields of science will be somewhat mitigated by challenges associated with this progress. The medical advances that will be gained from these integrated efforts will increase life expectancy. From targeted nanomedicines to extinguish even late-stage tumors and act as arterial "scrubbing" machines to neurotechnology and tissue regeneration that will mitigate the effects of age, disease, and poor lifestyle choices: subsequently, people will live longer. Unfortunately, none of these advances will completely halt or reverse the effects of aging to our bodies. People living longer past the age of retirement, on average, will have the effect of raising the cost to society from long-term care and support of its elderly population. Over the past 40 years, health-care costs have been rising and the cost to society has increased at an accelerated rate. As of 2013, the projection of the average yearly increase in the cost of US health care over the next decade is 5.7 %,

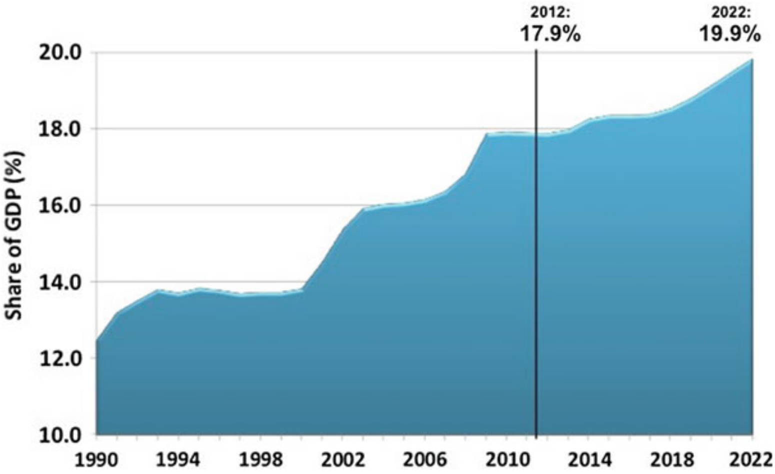

Fig. 6 Graph displaying rising cost of the US national health-care expenditures relative to percent of GDP from the past and projected into future (Cuckler et al. 2013) (Source data obtained from Centers for Medicare and Medicaid Services (CMS 2014))

and as a result national health expenditures will break beyond 20 % of the GDP by 2023 (Fig. 6). The underlying reasons are copious although many stand out. From an increase in average life expectancies and advances in medicine making treatment more costly to an increase in obesity-related morbidity/mortality and cancer related mortality, the cost to society has been taking its toll (Scheiber 2009). Finally, the national health expenditure is currently 34 % for the elderly (aged 65 and higher) – a population group size of only 13 % of the total (CMS 2014).

On the flip side, with advances that keep individuals physically and mentally healthier throughout their lifetimes, society will evolve to working longer before retirement. Hence, we should manage to maintain current societal cost of supporting individuals past retirement while adding an economic boost. If all of these positive projections materialize, more individuals will be more productive, on average, through their lives and remain so on to their respective retirements. Recent reports indicate that global economic loss from cancer and cardiovascular-related morbidity and premature mortality costs society (Fig. 7) over $1.5 trillion (in USD as of 2008) which represents greater than 3 % of global GDP and does not include the cost of the respective health care (O'Callaghan 2011). Accordingly, early diagnosis will reduce societal morbidity and preretirement mortality rates, as it is very well known that early diagnosis in all disease, *especially cancer*, is key to disease-related survival rates and remission (Etzioni et al. 2003). Wellness is additionally a function of mental/neural health and mental happiness determined by a summation of factors that include societal relationships. Thus, advances in the understanding, diagnosis, and therapy of mental and neurological diseases will increase societal productivity and reduce morbidity. Finally, as wellness must be viewed in the broader context of our lifestyles, eating habits, and access to medical

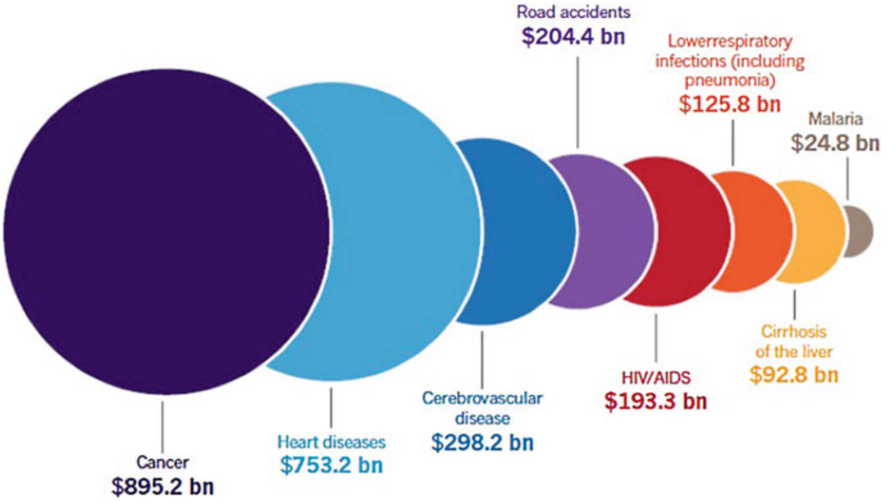

Fig. 7 Bubble diagram displaying the relative costs to worldwide GDP from the top eight causes of economic loss from morbidity and mortality due to disability-affected life years and premature death (O'Callaghan 2011) (Source data obtained from the American Cancer Society)

care, expanding societal education about healthy lifestyles and introducing approaches to screening and vaccination for several diseases should also promote improvements in overall health. Thus, other benefits of introducing several technological improvements in diagnosis are that physicians would now be able to focus more on treatment itself, patients would have a similar benefit of increased time, and, as a side effect of wearable and home-based personal diagnostics, individuals will become more proactive with respect to their health. In total, these advances could and should sum to a decrease in the health-care cost to society and a large economic gain from increased productivity.

Overall, will the ideas presented at the beginning of preemptive/proactive medical care and large reductions in societal disease-related mortality and morbidity due to focused efforts toward medical advancements become reality? Yes. Will the focused convergence of knowledge and technology for a medical approach to wellness deliver a healthier society much sooner than without its precepts? Yes, although stating how much sooner would be merely speculative. Will society be healthier and happier? We think so, but clearly, this still depends on the effort of the individual as innovative technologies can only help to expedite societal wellness and guide in healthy decisions.

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Polycentric Governance

David Feldman

Contents

Abstract

This chapter explores the relevance of polycentric governance – an approach whereby multiple, physically adjacent jurisdictions negotiate rules and policies to solve common problems – for managing converging knowledge, technologies, and society (CKTS). We trace the concept's origins, its advantages and challenges, and how the latter might be surmounted. By offering a means for innovative and improvised collaboration, multiple access points for monitoring problems and reducing risks, and inclusive decision-making approaches, polycentric governance provides a valuable framework for CKTS management. However, traditional divisions of labor among intellectual disciplines – as well as other impediments – will require that adjustments be made to permit shared approaches to intellectual work, enhanced means of communication among protagonists, and achievement of common, collective goals that benefit large groups of collaborators and society as a whole – as opposed to merely satisfying the needs of individual CKTS entrepreneurs or investigators.

D. Feldman (✉)
Department of Planning, Policy, and Design, School of Social Ecology, University of California, Irvine, Irvine, CA, USA
e-mail: feldmand@uci.edu

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Introduction

This chapter examines polycentric governance as an approach to managing the ethical, legal, and social impacts of converging knowledge, technologies, and society (CKTS). Polycentric governance entails multiple, formally independent, spatially proximate jurisdictions ordering their working relationships through a system of negotiated rules in order to solve common problems more efficiently (Araral and Hartley 2013). Its advocates contend that these jurisdictions are in the best position to gauge the most effective means to address these problems in ways befitting their scope and complexity. Solutions may involve working through existing public authorities or establishing new entities with the power to impose fees or levy taxes (McGinnis 2005).

The concept of polycentric governance originated in observations of how locally incorporated communities, typically found in the US metropolitan areas, improvise solutions to cross-jurisdictional problems through contractual agreements. Subsequent studies examined the use of polycentric governance in managing "common-pool" resources such as freshwater, fisheries, and forests and implementing public safety programs in the entire regions (Ostrom 2010; Ostrom et al. 1961).

How is polycentric governance relevant to CKTS? While CKTS comprises products and services derived from intellectual exchange and RD&D, groups engaged in its work aspire to equitably share the benefits and costs of activities affecting each of them while also reducing potential risks that could befall any or all of them – as is true in these other policy domains. We begin with an overview of polycentric governance – its appeal and purported advantages as a governance vehicle for CKTS. We then turn to major challenges facing its application and how they might be overcome. We conclude by discussing future research needs we believe must be satisfied in order to make polycentric governance into an effective approach for CKTS issues. The technologies that comprise our focus include – but are not limited to – nanotechnology, biotechnology, information technology, and other fields based on cognitive science.

The Appeal of Polycentric Governance for CKTS: Advantages

Polycentric governance is an appealing management approach for CKTS for three major reasons. First, the rapid growth of CKTS has raised expectations in many corners that its potential for furthering economic innovation, enhancing environmental sustainability, and fostering improvements in the quality of life (e.g., by creating new jobs, heightening the competitiveness of various enterprises, broadening new energy options, and furthering human longevity and mental and physical health) hinges, most of all, on enabling its protagonists to work more closely together. Through close collaboration, CKTS proponents contend, barriers to innovation can be better identified, and means to efficiently overcome them – without unnecessary duplication of effort – can be developed. One oft-cited vehicle for such cooperation is referred to as a "convergence ecosystem" (Roco et al. 2013).

Convergence ecosystems are networks of actors who collaborate through institutional innovations that permit the free movement and exchange of ideas on a peer-to-peer level in order to generate sustainable innovation while also helping to being new CKTS ideas to viable fruition and practical, commercial application. Entities such as the Semiconductor Research Corporation, Silicon Valley, and various regional science and technology initiatives in the United States and abroad are often cited as examples of convergence ecosystems (Roco et al. 2013).

More to the point, convergence ecosystems display distinct *polycentric governance* characteristics in two explicit respects. First, they are improvised collaborations based on negotiated rules of exchange and governance regarding, for instance, how patents and licenses will be established and comanaged and how costs – as well as earnings – may be shared between partners. Secondly, they entail collaboration among spatially proximate actors committed to hastening innovation through geographically defined partnerships – possibly through developing a conjoint, physical research park or regional coordinating platform comprised of a wide range of academic and entrepreneurial partners (e.g., universities, corporations, investors).

A second reason for the appeal of polycentric governance among CKTS proponents is the wide bandwidth of uncertainties and possible risks associated with CKTS and the perceived need for some type of collaborative mechanism to manage these risks in ways that engender wide public trust and confidence. Using biotechnology as one example, some oft-discussed risks include the unknown environmental impacts of genetically altered or manipulated flora and fauna and the molecular-level effects of new pharmacological products or treatment procedures (e.g., stem cells). One question that has directly emerged out of such concerns is: how to regulate daunting, if unknown, risks of CKTS on one hand while using investment and other strategies to promote its further development in ethically suitable, socially beneficial ways on the other?

Because polycentric governance features multiple, relatively independent centers of power, there is greater opportunity for locally appropriate institutions to tightly monitor developments within a policy area – including emerging risks or hazards – and to introduce locally accessible, trustworthy approaches to their mitigation. Moreover, polycentric governance advocates claim, such local monitoring affords effective early warning, "safe-to-fail" interventions (in other words, policies that – should they not prove immediately effective in reducing risks – can be quickly replaced by newer, more adaptive innovations). In addition, by encouraging open communication and deliberation to build trust and shared understanding among diverse stakeholders, polycentric governance creates opportunities for social learning in places and scales that better match the spatial context of problems (Lebel et al. 2006). While this has been observed to be true in cases of resource governance in various countries, the evidence at least suggests that it also should be true in other policy areas where the desire to bring together subject-matter experts as well as lay audiences concerned with the management of the social and environmental impacts and trade-offs of a policy domain (Lebel et al. 2006).

Finally, with respect to risk management, polycentric governance approaches seek to bring together all the actors, rules, conventions, processes, and mechanisms concerned with how relevant information on risks is collected, analyzed, communicated, and, most importantly, conjointly managed (Renn and Roco 2006). It generally does so, if resource management and related experiences are reliable guides, by providing a platform for public-private partnerships and better incorporation of social science expertise to build public trust and confidence – and not merely wide-scale stakeholder participation for its own sake (Smith and Stirling 2010).

A third and final appeal of polycentric governance for CKTS revolves around a series of unique collaborative challenges that require special effort to overcome. These include the need for knowledge developers to be able to systematically straddle disciplines (cross-disciplinary collaboration is intrinsic to CKTS – less so for innovation within individual scientific domains). It also includes the capacity for technology innovators to go beyond ad hoc or coincidental collaborations that sometimes result in successful innovations, by exploiting the advantages of social networking media with regard to permitting the so-called leaderless movements of partners and associates.

While a number of virtual communities of scholars have emerged to share information about CKTS, thus far governance activities have largely been confined to research on public engagement strategies and their efficacy, as well as conferences that have been convened to discuss ways to better embrace public participation, understand the organizational dynamics of research, and the ethical concerns of CKTS as expressed by some decision-makers (Scholl et al. 2012). In this vein, polycentric governance may afford a platform for broader collaborations and discussions, as well as efforts to codify and standardize certain practices and adopt “best management” approaches for managing risk, fostering innovation, and encouraging effective engagement of all stakeholders. Let us examine these claims in greater detail.

In short, polycentric governance’s major features dovetail closely with CKTS needs. Where CKTS aspires to promote “convergence ecosystems” to permit seamless collaboration in technology innovation, polycentric governance promotes ad hoc institutional arrangements that permit bottom-up, multiple-actor governance through the sharing investment of opportunities and cooperative use of physical as well as virtual intellectual “space.”

Moreover, just as CKTS faces concerns regarding the management of risk through incorporation of participatory mechanisms, social science knowledge about public apprehensions, and social networking to permit rapid dissemination of information regarding both risks and benefits, polycentric governance acknowledges the importance of facilitating the collaborative work of different actors within a locally accessible institutional framework that enjoys a high-level of legitimacy, access to information regarding local conditions, and the capacity to adapt to changing conditions and opportunities expediently (McGinnis 2005; Hammond et al. 1999). As in any innovative governance arrangement, however, the challenges in achieving these objectives are as compelling as the purported advantages.

Challenges to Polycentrism: Fitting Governance to the Problem

A number of issues must be confronted in order to optimally fit polycentric governance to the management of CKTS problems. These include (1) investing in appropriate governance innovations that permit durable decision-making frameworks and information sharing – particularly regarding potential risks, (2) developing social media and telecommunications to connect stakeholders, and (3) facilitating meaningful public participation mechanisms, including facilitating dialogue and permitting direct engagement by the public in governance.

To make polycentric governance workable for CKTS, flexible, bottom-up decision-making is required. These include arrangements for building consensus among a broad range of stakeholders and deliberative interests. This requires a significant investment in the so-called risk governance frameworks – a particular type of polycentric governance innovation that has begun to emerge in biomedical and related fields. Risk governance frameworks seek to encompass the totality of actors, rules, conventions, processes, and mechanisms concerned with relevant risk information and associated data about CKTS consequences and impacts (e.g., Renn and Roco 2006). It is widely believed, in fact, that the successful dissemination of CKTS will depend, to a high degree, on the ability of risk governance methods to become adopted at the advent of new technological projects and involve the public, key stakeholders, and social scientists from the very beginning (Roco et al. 2013).

Recent experimental work on risk governance and public engagement in CKTS (Fleischer et al. 2012a) offers instructive lessons on the challenge of bottom-up decision-making and consensus building in polycentric governance. The European Union is currently focused on how to mitigate the potential risks posed by nanomaterials and their derivative nanoparticles – as found in laboratory – and emerging manufacturing-scale enterprises. There is currently a broad division of opinion regarding how to regulate these potential risks. One position, wedded to a strict interpretation of the so-called precautionary principle, would place nanomaterials under general suspicion "because of their new properties and the limited knowledge about their (potential) environmental, health, and safety implications." Advocates of this view propose broad, strong, and open-ended measures aimed at supervising and controlling nanomaterial development and introduction. A second position, closely linked to evidence from toxicological, ecotoxicological, and biological research and mainly voiced by manufacturers, supports largely voluntary measures for the safe handling of nanomaterials (Fleischer et al. 2012b), and, even in these instances, only those nanomaterials that give rise to palpable concerns should be regulated.

In an effort to experimentally determine how consensus that spans such divergent positions might be formulated through polycentric governance, researchers in the EU employed a series of focus groups comprised of laypersons who took part in a "deliberative test exercise" (Fleischer et al. 2012a, p. 84). Investigators learned that, while the results in and of themselves did not delineate specific governance strategies, they did reveal much about participant perceptions of the appropriate roles of various protagonists in any governance system.

Focus group participants reposed considerable trust in the capacity of both governments and consumer organizations to properly oversee and, if needed, regulate developments in products containing nanoparticles. They were willing to give "a credit of trust, a leap of faith to these institutions," but they also wanted to be fully informed of potential risks of nanoparticles and products containing them in order to make informed choices (Fleischer et al. 2012a, p. 92).

For polycentric governance, three lessons emerge from this experiment relevant for CKTS. First, if one seriously contemplates instituting a risk governance framework for, say, nanotechnologies, it might be useful to have a *national database* of risk governance experiences in comparable – if different – topical areas (e.g., stem cell research, life span-increasing medical approaches) from which guidelines and best management approaches may be drawn. Such an investment provides an infrastructure of experiences that facilitates cooperation across jurisdictions and among groups by offering a common, proven set of methods can be selected – making collaboration easier and allowing protagonists to focus on implementation as opposed to laborious policy identification.

Second, and related to the first, some kind of a portal or repository to collect, disseminate, and most importantly *translate* CKTS information is needed. Such a repository would permit rapid assessment and management of risks and their consequences – particularly by manufacturers and consumers – by ensuring that nonexperts have information in a useful, useable form in order to make reasoned judgments and participate in CKTS governance (Graham 2002). Sometimes referred to as "coproduced" knowledge (i.e., information that synthesizes the scientific basis of CKTS with its societal implications), examples could include unbiased testing and evaluation results and readily available information on possible health and environmental consequences of CKTS. This abovementioned portal or repository would likely have two other responsibilities: (1) providing reliable and judicious means to protect proprietary and national security information related to CKTS and (2) assuring that CKTS information has been thoroughly vetted by several government agencies. According to Araral and Hartley (2013), two students of polycentric governance, such coproduced and translated knowledge is an important element to face the "crucial pathologies" of lack of accountability and information asymmetry, both of which erode public trust and confidence.

Social media and other information technology (IT) are also critical to making polycentric governance workable in the CKTS context. There is considerable debate in the literature regarding the degree to which telecommunication and social media enhance, or deter, inclusive decision-making on CKTS-related issues (e.g., Kamarck and Nye 2002). There is widespread agreement regarding two major infrastructure needs that must be met for telecommunication and social media to effectively support open, inclusive governance. These are access to and proper training in the use of these media and basic support platforms for IT in less-developed societies.

Despite efforts to expand access to the Internet and social networks in developed and developing societies alike, access to these platforms is still limited to the more affluent and, by implication, more technologically savvy elements of the public. In the domain of complex environmental issues, for instance, research suggests that broad electronic platform participation does not generally engage minorities and the poor to the same degree as it does other groups. Generally, more literate, politically energized, and activist groups and segments of the populace are more digitally connected. The latter are also more inclined to embrace the Internet enthusiastically and to extensively use it for organizing around policy issues (Dietz and Stern 2008). Access to technology by lower status groups is often limited – thus, a supportive education and training infrastructure to ensure optimal use is also needed. Experience in educational environments, for example, has shown that once IT is made available in schools where students and their families cannot otherwise afford it, suitable investments must also be made in training teachers – who can then train students – in order to make the best use of IT and social media (Tonn 2005).

Less appreciated is the need for a basic physical infrastructure platform to ensure social media and IT access and use, especially in developing countries. In East Asia, for instance, it has been found that one of the greatest infrastructure barriers to making telecommunication and social media effective governance tools for CT has been the lack of a simple but reliable electricity supply. In such contexts, the most readily effective means of ensuring both the adoption of networking technologies and their use is provision of such "low technology" solutions as, e.g., stationary bicycles hooked into handmade wireless computers – thus permitting the average IT user to "pedal his way to economic self-determinism" (Hurd 2005). Not coincidentally, such integrated power systems also require that participating groups are in close spatial proximity – another feature of polycentric governance – and that the platforms for these systems are simple but durable and ruggedly capable of reliable operations in monsoon or dry seasons.

Establishing and sustaining meaningful and effective public participation mechanisms may be the most formidable challenge facing polycentric governance for CKTS. While public participation and engagement of stakeholders are essential to CKTS governance, polycentric governance analyses are not always clear as to how – precisely – to facilitate such engagement.

The polycentric governance literature speaks to the need for multilevel governance able to deal with "different scales of market and government failures." It also refers to the ability to draw upon the experiences of cross-jurisdictional governance units in other areas of polycentric governance (e.g., economic development zones, tribal districts, school districts, water utility districts, charter cities, trade and monetary zones) – by arguing that specialized units for provision, production, financing, coordination, monitoring, sanctioning, and dispute resolution are needed to address issues of public trust and confidence (Araral and Hartley 2013).

Similarly, other polycentric governance scholars note the importance of encouraging active participation of local users – especially in managing private, locally managed, or even state-governed common-pool resources – through, among other means, matching governance considerations to decidedly local needs (Ostrom 2010; Copeland and Taylor 2009; Grafton 2000). What has all this to do with CKTS? Is it transferrable? For CKTS, public participation requires several infrastructure needs – each of which has polycentric governance implications. These needs include support for both formal and informal science education about CKTS, empowering citizen input in research investments, funding R&D programs through bottom-up investigator- and public-initiated funding opportunities, and facilitating citizen participation in international – as well as US – debates and decisional processes (Roco 2012). Here, we consider three key infrastructure needs: (1) support for stakeholder dialogue, (2) sound design for public engagement processes, and (3) support for a wide range of participatory tools.

To facilitate public participation in polycentric governance arrangements, there is an emerging consensus that stakeholder dialogue requires, at some point, forums that permit face-to-face, structured discussions in which members of the public, government officials, and scientists involved in CKTS can clarify sources of technical and political disagreement and which can guide the decision-making process for which the form of technical solutions has been defined. This form of participatory infrastructure is sometimes called a *science court*, and it can be a vital tool for participatory governance, especially in light of the aforementioned progress made in advanced IT networking and virtual participatory opportunities (e.g., Futrell 2003).

Possible models for such a "science court" for CKTS are afforded by the efforts of the International Risk Governance Council (IRGC), which prescribes an independent participatory framework for identifying, assessing, and mitigating risk in general and of nanotechnology in particular. This prescribed framework consists of two frames – one for the next generation of products (passive nanostructures) and another for future generations (active nanostructures and nanosystems) whose products are more complex and which have broader societal implications; IRCG seeks to bring various stakeholders together to pursue coordinated governance methods (Renn and Roco 2006). Following summary consensus on various risks of CTs, appropriate regulations are then suggested for adoption by government agencies. Other models of public engagement for CTs have also been suggested, including congressional commissions that bring together scientists, consumer groups and other NGOs, and others without a *vested* interest in the outcome of funding decisions, citizen institutional review boards, or other decisional outcomes (e.g., National Citizens Technology Forum 2008).

Regardless of the particular form public engagement processes take, they must be carefully designed and crafted. Support must be provided for collaborative problem formulation and process design. In effect, provision should be made for allowing those who convene these forums – as well as those who participate in them – to jointly design them (Dietz and Stern 2008). Effective polycentric governance forms are based on ad hoc, decentralized, and often improvised means of collaboration, and such provision for localized, participant forum design exemplifies this.

Finally, a range of participatory approaches must be supported – ranging from those that elicit input in the form of opinions (e.g., surveys) to those that elicit judgments and decisions from which actual policy may be derived (e.g., consensus conferences – see Mali 2008). Each of these types of activities, ranging from simple "consultative" bodies to more representative forums (to indirectly represent citizens) and finally deliberative entities such as the aforementioned "science courts," requires a specific support infrastructure to ensure effective governance (see Fig. 1). Among the major factors required are a change in the culture of participating government agencies from what has been characterized as closed, hierarchical decision-making cultures to one of openness and transparency, trained personnel who willingly embrace participation, and possibly changes in regulatory climates which mandate that agencies make, rather than negotiate, rulemaking and other decisions.

Getting to Polycentric Governance: Private-Public Partnership?

CKTS continues to grapple with the question of how to promote workable partnerships that promote innovation by crossing private and public sector boundaries. In turn, as we have noted, polycentric governance tries to avoid simplified division between notions of "public" versus "private" control. Flexible collaborative networks between for-profit enterprises and public sector entities are encouraged and should be guided by needs grounded in circumstance (McGinnis 2005).

There is a need for private-public partnerships that enhance investment opportunities, technological advancement, and public acceptance of CKTS. This has long been recognized as an important element of an overall CKTS governance strategy. Partnerships can help to effectively respond to regulatory uncertainty; promote a broad, democratic review of social impacts; and draw in broad, "evidence-based" assessments of economic, environmental, and other concerns – because they encompass economic development and growth concerns while at the same time embrace public interest concerns for societal oversight and risk management. Some observers contend that such partnerships work most effectively when they can identify funding mechanisms that allow private organizations to share the costs of their operations (e.g., National Citizens Technology Forum 2008).

One possible model for such partnerships is afforded by European regional-level technology assessments. These are designed to provide pragmatic, result-oriented forums for stakeholder interaction regarding the social implications of CTs (Evers and D'Silva 2009). In Belgium, for instance, the Flemish Technology Assessment project (funded between 2006 and 2010 by a private-public partnership formed by the *Flemish Institute for Advancement of Innovation through Science and Technology*) brought together nanoscientists and nanotechnologists in an interactive forum with lay groups to clarify underlying assumptions, visions, expectations, and concerns guiding nanotech research, development, manufacturing, and use. Experts were provided a variety of societal perspectives, needs, and concerns voiced by stakeholders in government, industry, and civil society. They were then required to respond to concerns through a series of "successive participatory rounds" in which experts reported on how they would integrate (or *had* integrated) societal

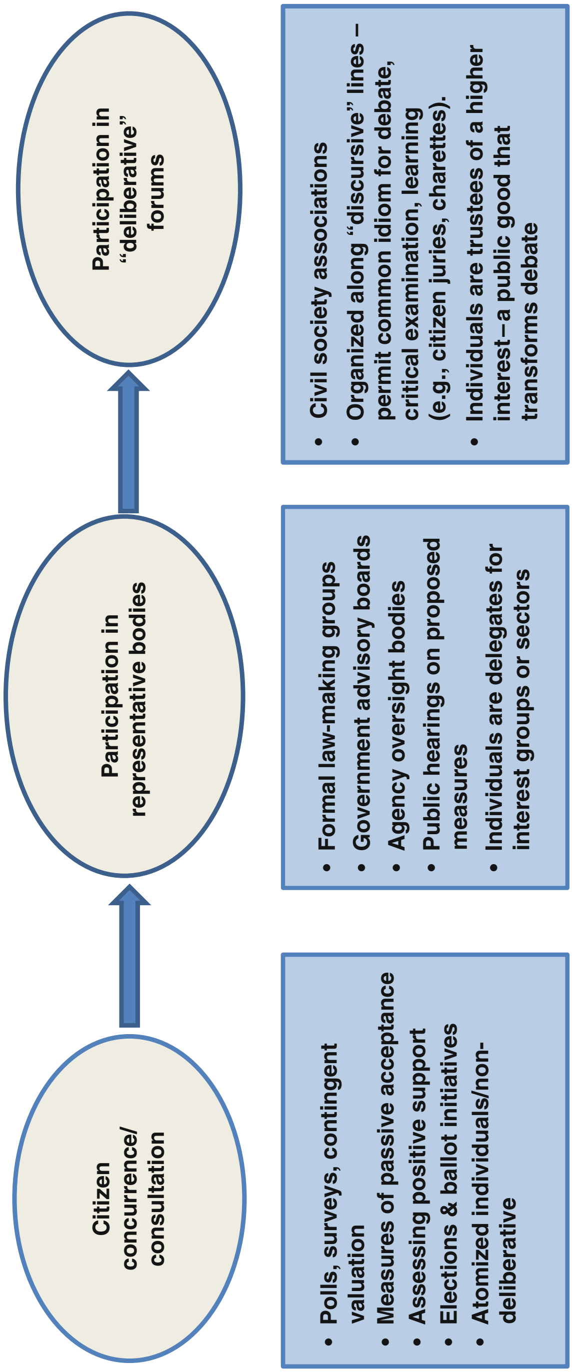

Fig. 1 Range of participatory approaches for polycentric governance

considerations into their research. The end product was a *normative round* of discussion where stakeholders and scientists evaluated the most plausible, short-term impacts of their research and how to manage them. This exercise allows for adjustment and alteration of nanotechnology implementation (Evers and D'Silva 2009).

Research Needs

Thus far, there have been precious few studies of polycentric governance for CKTS specifically. Most research on polycentric governance and its advantages for managing risk, embracing public participation, and enabling flexible, opportunistic management of policy domains has been in fields such as the environment, natural resources, and other global commons issues. An important research need, therefore, is the critical evaluation of polycentric governing institutions in the context of CKTS issues – through case studies, comparative analysis, or both. There are other challenges, among them the following. First, the rapid integration of nanotechnology, biotechnology, information science, and cognitive science in numerous settings since the beginning of the twenty-first century is outpacing the capacity of governance at any level to keep pace. Innovations develop more quickly than reform of governance processes and procedures.

Second, the growing emphasis in society at large in promoting innovation as a means of improving economic opportunities, environmental sustainability, and the overall quality of life is hastening sentiment for rapid introduction of technologies and their products. Third, and somewhat in contradiction of the first two concerns, the advent of ethical concerns over the impacts of CKTS upon the possible transformation of society in adverse ways (particularly synthetic biology and quantum IT systems and nanotechnology), and the challenges these ethical issues pose from the vantage point of uncertainty of regulation, voluntary constraint, or practice, may ironically be impeding CKTS development. In essence, in an uncertain governance environment, technology innovators might in some cases become hesitant to invest large sums of money on the introduction of new innovations only to see those efforts later thwarted by perceived regulatory intrusiveness resulting from public apprehensions.

Fourth, it has already become apparent that some societies have been able to adjust their governance of CKTS faster than others (e.g., smaller countries in Asia in particular) – creating a competitive asymmetry that in the long-term might be costly for other democratic societies grappling with finding effective polycentric governance approaches. Fifth, as we have seen in our discussion of "risk governance," a divergence of regulatory approaches has already begun to emerge – in both western Europe and North America in particular – from extending existing schemes of regulation which emphasize precisely characterizing risk on one hand, as opposed to a "softer" approach that operates with less than complete knowledge of risks on the other (Fleischer et al. 2012).

Table 1 Markets vs polycentricity

	Features	Remediation	CKTS examples
Markets	Easy entry and exit Transaction costs Many buyers and sellers	Institutions supporting free market structures and property rights Information availability	Private investment consortia Proprietary information sources with high "entry" fee – e.g., subscriber services
Polycentricity	Multiple actors of differing types Common-pool resources Disparate individual goals Issue-specific common goal	Institutions enabling equal access Delineation of the bounds of autonomy with regard to specific issues Multi-government solutions	Research parks Silicon Valley Deliberative engagement board and review bodies Risk governance boards for biotechnology

Adopted from Araral and Hartley 2013

In sum, it might be useful to compare polycentric governance as a possible approach to overcome these hazards, with the most likely alternative – reliance solely on market-based solutions. Table 1 (below) is an effort to compare markets and polycentricity along two dimensions – their features and how they rectify.

In effect, in science and technology, actors tend to pursue individual interests while a collective but implicit research agenda develops. The tacit authority structure resembles a market system that accommodates multiple opinions while rewarding activities that complement the collective agenda and research progress are an expression of aggregated individual interests.

Polycentric governance, by contrast, seeks to nurture a holistic approach with shared methodologies, theories, and goals, which is quite different from traditional forms of collaboration in which a division of labor separates disciplines from each other. It also renews the focus on people's capabilities and human outcomes, rather than allowing decisions to be technology-driven, and seeks to transcend existing human conflicts to achieve vastly improved conditions for work, learning, aging, and physical and cognitive wellness and to achieve shared human goals. This notion of governance requires that individuals be willing to expend considerable amounts of time and energy in seeking out a commonly acceptable solution and participating, in some fashion, in its implementation (Araral and Hartley 2013). In so doing, it seeks to chasten people against "free rider" action and in favor of collective well-being.

As Table 1 suggests, polycentric governance approaches compel us to carefully consider the extent to which we, as a society, are committed to CKTS as a common-pool resource, acknowledging the diversity of actors and their values, how disparate the goals of actors might be (e.g., profit as opposed to risk aversion and protection of public interest), and the aspiration to maximize equal access to the benefits – as well as he burdens and risks – of CKTS.

Conclusion

Polycentric governance affords a number of advantages for meeting the needs of CKTS, including ad hoc institutional arrangements that permit bottom-up, multiple-actor governance; cooperative use of physical and virtual knowledge space; and facilitating collaboration within locally accessible institutional frameworks that are flexible enough to adapt to new opportunities and challenges. Among the latter are the need to match polycentric governance principles to CKTS problems through investing in consensus building or risk governance frameworks; developing repositories to collect, disseminate, and translate CKTS information on risks to lay audiences while simultaneously protecting proprietary and national security information; and utilizing telecommunication and social media to support open, inclusive governance. Overcoming these challenges will require public-private partnerships that encourage investments, further technical advances, and hasten public acceptance through facilitating stakeholder forums that bring scientists and nonscientists together in ways that help clarify societal, including ethical and legal, concerns over CKTS. Among the virtues – and vices – of democratic polities is a tendency to “go slow” in unleashing new technologies: harnessing them with regulations designed to abate risk, but which may have the unintended consequence of constraining innovation. The balance between these polar outcomes is difficult to manage. Further investigation of polycentric governance innovations in this regard would be a fruitful avenue of study.

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Systematizing Global and Regional Creativity

Terry Nichols Clark and Scenes Project Collaborators

Contents

Abstract

Creativity is treasured from the natural sciences through the arts. But contexts transform how creativity works. This chapter explores links between creativity and economic development, creative cities, and civic engagement of citizens. It illustrates a framework for analysis which joins two past traditions. Democratic participation ideas come mostly from Alexis de Tocqueville, while innovation/Bohemian ideas driving the economy are largely inspired by Joseph Schumpeter and Jane Jacobs. New developments building on these core ideas are in the first two sections. Reconsideration of each tradition leads to partial integration of the two: participation joins innovation. This is the main theme on the third section; the buzz around arts and culture organizations can be critical to drive the new democratic politics and cutting edge economies. Buzz enters as a new resource, with new rules of the game. It does not dominate; it parallels other activities which continue. The fourth section shows how these patterns vary across distinct

For the Scenes Project and collaborators: http://scenescapes.weebly.com

T.N. Clark (✉)
Department of Sociology, University of Chicago, Chicago, IL, USA
e-mail: tnclark@uchicago.edu

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scenes, specifying 15 dimensions of scenes measured in 1000s of zip codes and other small areas from Korea to the USA to Spain.

Introduction

Many are skeptical of the idea that the arts and culture can transform politics and the economy. But this idea has surfaced in multiple science and technology fields from mathematics to medicine. Think of how video games and rap music can energize young persons. Many were surprised at the significance of the findings, as they contradict much of what we learned. The young are classically most in sync with the latest styles, in clothes, music, and lifestyle. Most of us form lifestyles at about age 20. We continue our main lifestyle patterns as we grow older, and these sometimes clash with new practices. This is common with innovations – from the emergence of factories, computers, feminism, or environmental movements – intellectual understandings overlap and interpenetrate political ideologies and economic interests. Dramatic shifts in paradigms take years to diffuse, and even after innovations enter their homes and shift their personal lifestyles, many observers deny the changes.

Consider two parallel and interrelated processes. First, the dynamics of Tocquevillian citizen participation and second the sources of economic growth. Both these Western-generated theories ostensibly failed when analysts pursued them initially in China, Korea, and Japan (Clark et al. 2014). Two propositions:

1. Citizen participation increases legitimacy in the political system (Alexis de Tocqueville, Robert Putnam, and many more).
2. Innovation is a critical driver of the economy and urban development, and Bohemia is a core component driving innovation (Joseph Schumpeter, Jane Jacobs, Richard Florida, Edward Glaeser, and more economists).

This chapter does not seek to refute but to specify more closely the key components of what makes these dynamics work in some places, not in others, and possibly reverse course or go wildly awry in still other places. But rather than framing the analysis in terms of "assumptions," which may not be met for a theory to hold, as is common, the chapter stresses context and scene. Contexts transform the rules of the game and inform specific motivational patterns (from the Protestant or Confucian ethic to discussions of modernism, postmodernism, post-materialism, to the rise of scenes). The arts and buzz are introduced as scenes elements.

Consider how three terms are commonly defined: scene, Bohemianism, and buzz. In American English, as codified by Cambridge Dictionaries Online, *scene* can mean: "a place where an actual or imagined event happens... an event, actual or imaginary... a particular area of activity or way of life." Wikipedia offers definitions of the two other terms: "Bohemianism is the practice of an unconventional lifestyle, often in the company of like-minded people, with few permanent ties, involving musical, artistic, or literary pursuits. In this context, Bohemians may be wanderers, adventurers, or vagabonds." "Marketing buzz or simply buzz – a term used in viral marketing – is the interaction of consumers and users of a product or service which amplifies or alters the original marketing message." This chapter shows how to add more coherence and power to these terms.

Citizen Participation

Tocqueville made a critical point about democracy in stressing civic participation, but later work, such as that of Robert Putnam, Sidney Verba, and contemporary citizen studies by political scientists, has understandably simplified and focused on measuring participation. Tocqueville (1969) discussed many aspects of context in his *Democracy in America*. But he wrote as a traveler/journalist, a century before most social science, and did not frame his observations or articulate their contexts with abstract terms like expressive or hierarchical.

Robert Putnam's (2000) *Bowling Alone* was a major invitation to explore Tocqueville, but unfortunately it largely omitted values and context. This is ironic as Putnam's (1993) earlier book *Making Democracy Work* was a highly innovative (thus controversial) introduction of context into Italian political analysis. He showed that democratic forms had emerged centuries earlier in city-states like Venice, Trieste, and Florence and were reflected in the present dramatic regional differences in how citizens and local politicians related to one another. The key driver in *Making Democracy Work* was citizen participation, but Putnam articulated how it varied by regional context and how these regional/historical differences continued in specific political cultures.

As one moves internationally to ask how well Tocqueville travels, one confronts paradoxical inconsistencies by ignoring culture and context. One goal in stressing scenes is to sensitize the analyst to the contextual variations sometimes labeled political culture and how these shift local dynamics (cf. Eisenstadt 1996; Moreno 2001; Sudarsky 2002).

The universality of Tocqueville is more deeply challenged by a provocative recent doctoral dissertation by Seokho Kim (2008) who compares these patterns across 38 countries using the International Social Survey Program, national survey data for citizen participation, trust, and related items. He finds the expected patterns for much of Northwest Europe and the USA: the universality model holds, though it reveals some surprising exceptions. The most dramatic results, however, are that in many countries outside Northwest Europe and the USA, civic participation has no impact or reduces trust and support for the political system. This implies, for some citizens at least, even the opposite. That is the more some Koreans participated, the less they trusted leaders and institutions.

This is a dramatic new finding, and important to build on, but extends the rising interest in trust as a foundation for civic and social and economic activities (e.g., Fukuyama 1995). Look at the Seoul beef protest in 2008, the noted recent example with many historical counterparts as Korean students protested against authoritarian politics. There are also analogous protests against authoritarian leaders, in recent years and for centuries past around the world, especially by young male students, talented, independent, thoughtful, critical. Bohemian? Not necessarily. The next logical question: how much is specific to Asia?

As one looks at more precise comparative data from many countries, participation often fails to work as theorized by Tocqueville and documented by Putnam (Inoguchi and Blondel 2002). Still, rather than rejecting the positive idea that citizen participation increases leadership skills and legitimacy among citizens, reframe this to ask where and why this may still happen, or not. Many theorists state such issues as, what are the underlying assumptions of this model that may not hold. Rather than asking this question in abstract and focusing on assumptions, consider instead stressing particular contexts where the actual values and rules of the game differ. Some have analyzed US states or metro areas, but these are large and messy for systematic testing (Clark and Graziul 2008). Often more productive is to contrast individuals within separate nations, thousands of postal codes in the USA and Canada, or communes in France and Spain. This identifies variations of each in these many different contexts. But in comparing the results, scenes project collaborators use key common concepts, permitting specific contrasts of participation patterns, as well as contexts that vary globally. Adding the arts and culture shows how they operate in terms of these interrelated factors. Some of findings below are solid and clear; others are new and tentative.

The effort here is to codify these inconsistencies in results and build a more coherent theory, stressing context. This illustrates and continues work-labeled local or neighborhood effects which have become distinctly important in recent years in several science and technology subfields from health to crime to citizen participation and voting. Sensitivity to such local variations has been made possible by bigger data, but the key is not bigger but how they vary cross-nationally and by digging deeper for more micro data than in past work on one nation or state/regional studies.

Next extend a second line of theorizing stressing not citizen participation but how economic development is increasingly driven by innovations in ideas and how these innovations are often generated by persons and cities where there are more tolerant, nontraditional, and sometimes Bohemian residents. These ideas were stressed in the Schumpeter (1942) and Jane Jacobs (1989) tradition and pursued further by Richard Florida, Edward Glaeser, Richard Lloyd, Elizabeth Currid, and Michael Fritsch among others. The core idea is that a Bohemian neighborhood and lifestyle encourages or at least reflects more tolerance which in turn encourages in-migration by creative persons and more risk-taking innovation. This in turn leads to outcomes such as patents, inventions, and in turn drives economic growth in these locations. Similar ideas inform many science and technology subfields from patent research to neighborhood organization to social psychology of workgroups to organization theory. Many in these and related fields converge around similar ideas stressing innovation for productivity.

Much of this work has focused on geographic proximity (e.g., of biomedical firms and research labs/universities) and stressed tolerance of an antiestablishment lifestyle, epitomized by artists and gays. Yet insofar as decentralization and collegial engagement are key elements of this creativity story, one can develop a convergence with the specifics of the Tocquevillian civic groups. This is part of the rationale for joining here the Tocqueville and Schumpeter traditions, even if few have done so to date.

Related to the Bohemia-drives-development thesis are empirical studies of artists, especially by economists and urbanists. A key point is that most of these recent studies of artists and the arts have not included values explicitly. Many analysts, and artists, assume that artists are hip and Bohemian and broadly oppose the traditional establishment, but they often have no direct evidence as to how much this is or is not the case. For instance, Richard Florida's (2002) Bohemian index is simply the proportion of the labor force that works in arts-related jobs, based on census data, often for an entire metropolitan area (not a city or neighborhood). Ann Markusen has often used census data for arts jobs (Markusen and Gadwa 2010). But the US census does not ask people if they are Bohemians or other lifestyle or value questions that might capture values more directly. Thus Boho in this type of research is imputed from the occupational title. By not articulating a coherent value concept or finding data to measure it, this line of analysis is troubled by the same issue as the Tocqueville/Putnam tradition of citizen participation.

Arts Buzz

A third idea is thus to focus on buzz, arts, and culture and how they can add specifics and thus transform analyses of politics, economics, and social life. Citizens have shifted toward the arts and culture. Citizens (in many countries, not everywhere) report in surveys that they join arts organizations more often, that they spend more time on arts and cultural activities, and that these are linked to happiness and good health. This holds when controlling for education, income, occupation, age, and more.

Related, these citizen values have more impact on many political systems, which have grown more populist/media/citizen focused, especially since 1968 and later after fall of the Berlin Wall in 1989, with the spread of global organizations involved with human rights, gender roles, and the environment, often undermining traditional political parties that were slow to respond to these new citizen concerns.

Like the political systems, the economies of many countries have been transformed with general increases in income (especially in less developed countries, although economic growth is clearly uneven) and more critically, with new ways of responding to narrow niche markets. Labels like the iPhone generation illustrate this point, as smartphones can download a set of music, videos, films, and saved photos unique to each person. Detailed surveys of cultural consumption by the French Ministry of Culture document huge growth among young persons in activities of this general sort (the French conduct particularly detailed arts surveys). Similarly several studies stress that key firms have grown by implementing better design, not just low cost or technical excellence (Samsung, Apple, and others). Many are hiring MFAs (Masters of Fine Arts) alongside MBAs (Masters of

Business Administration) to improve design, aesthetics, and related marketing and advertising. Apple ads feature the cool Apple user versus the square businessman in a suit, who still uses Microsoft Windows. Samsung similarly transformed its brand to stress design as linked to user lifestyles, not product technology. Small firms have grown in numbers as they are more responsive to niche consumer markets.

These major global changes in politics and the economy have led to more focus on citizens. The concerns of average citizens have thus entered political and economic decisions more actively, via focus groups, citizen surveys, new candidates and political parties, and new organized groups, like environmentalists. Political party programs have faded in impact or shifted to incorporate more citizen concerns. One such concern, in some locations, has been a rise of the arts and culture. More specifically artists, arts organizers, and arts-related entrepreneurs have helped expand support for theater, concerts, and attention to and sponsorship of arts activities – in some locations. Private business markets have moved in the same direction, dramatically increasing sales of new media, home theater, and other products.

"Buzz" is a valuable symbolic resource, powerfully generated by arts and cultural activities. It is more emotional, visual, and visceral and, in some issue areas, rises to rival the more classic resources like money and jobs. Buzz is obviously critical among arts and cultural activities and related scenes but even more. It is a resource that can be wielded, in certain situations and issue areas, to influence political and economic decisions in new ways. "Cultural power" is increasingly a potent factor; it is part of the soft power that international relations analysts have used to extend work on military and economic factors. Often buzz is local and highly personal, but to cite one globally important example, Cool Japan comprised a range of policies coordinated by the Ministry of Economy, Trade, and Industry "to promote cultural and creative industries as a strategic sector "under the single long term concept of 'Cool Japan.'" In 2011 it had a budget of 19 billion yen, spurred in part to catch up with the Chinese and Koreans whose public spending on culture comprised 0.79 % and 0.51 %, respectively, of total government spending, compared to Japan's 0.12 % (Wikipedia 2013, "Cool Japan"). This led to discussions in Japan that the Gross National Cool was too low and that more sponsorship for pop culture and anime was needed along with establishing culturally distinctive Cool Japan activities in many foreign countries. How to interpret coolness?

Is buzz a trump card resource? Does adding buzz mean dropping all else? Of course not. We live in a multicausal world where dozens of intertwined factors drive most social, political, and economic processes. Buzz is a new flag rising with the transformations of arts and culture into a fundamental part of the new economy. It is a symbolic resource analogous to trust and confidence in political leaders and money in the economy (most forms of money – checks, bank transfers, etc. – are symbolic; bartered physical goods are not money). One can analogously identify inflation and deflation of these symbolic resources as they grow out of proportion to their underlying foundations (elaborated in Silver and Clark et al. 2014) (Table 1).

Buzz links leaders and citizens, albeit loosely, outside political parties and classic hierarchical institutions like the strong state and national churches. Buzz

Table 1 Contrasting cultural scenes, residential neighborhoods, industrial centers, and political arenas

Organization	Cultural scene	Residential neighborhood	Industrial cluster	Political arena
Goal	Expressing and communicating feelings, experiences, moods	Necessities, basic services, housing, schools, safety, sanitation, community development	Works, products	Collective action
Agent	Consumers	Residents	Producers	Citizens, leaders, officials, activists
Physical units	Amenities	Homes, apartments	Firms	Power centers
Basis of social bond	Lifestyles, sensibilities	Being born and raised nearby, long local residence, heritage	Work and production relations	Ideology, party, issues, citizenship
Symbolic resource	Buzz	Trust	Money	Power

may be more general, or specifically related to arts and culture, as used here for the most part. Buzz is part of political branding. Eleonora Pasotti (2010) analyzed how branding was used in subtle ways in Bogotá, Chicago, and Naples to transform these cities, their citizen politics and their economies. Most cities around them in their respective countries lag behind. But to understand the dynamics of innovation, it helps to focus on key leaders who are inevitably far ahead of the pack, like Bill Clinton playing his sax and Japan's Prime Minister Koizumi singing Elvis songs at Graceland (in Karaoke style), for instance.

Many have sought to build and analyze buzz in domains that reach further than culture and politics. Just to illustrate that these are not only humanistic, consider how leading market economists have focused on symbolic resources related to buzz. George Stigler, Milton Friedman, and Gary Becker all published in professional journals and wrote for the more general public. Friedman and Paul Samuelson were the two best-known economists of their day and wrote columns on alternate weeks in *Businessweek* magazine. Gary Becker continued writing for *Businessweek* and even wrote a paper on the concept of buzz, illustrated by a new restaurant which tries to create a long line of would-be customers outside in the street to attract attention from restaurant reviewers and buzz-sensitive foodies. Buzz underlies the main theory informing financial pricing: the efficient market hypothesis or random-walk approach. It holds that what drives stock markets is not just the fundamentals in a material sense like profits but the information about these specifics in the minds of key market participants. When identical information is widely shared, markets operate efficiently; information in this sense drives markets. A simple version of this idea was phrased by Thomas Friedman (2005) as "following the herd" of investors, based on often manipulated information, in his best seller *The World is Flat*.

How do buzz and the arts link to the stress here on how citizen participation and economic innovation vary by context? First, buzz is a label for the context, especially the symbols and rules of the game involving arts and culture. Second, the arts and culture are distinct resources that can influence other sectors, like the more classic economy and polity. These are concretely illustrated in case studies of Toronto and Chicago (Silver et al. 2011), both leading cities where the arts brought deep political and economic transformations. Both actively used culture to transform their images and economies since the late twentieth century. Toronto illustrates a rather Tocquevillian dynamic, driven by neighborhood arts groups, while Chicago does not.

Analogous to the New Political Culture of Clark and Hoffmann-Martinot (1998), buzz and the arts are leading edge drivers of change, but this does not imply that all citizens or countries move evenly in the same direction. Rather, there are dramatically different contexts within which participants argue openly over priorities. Codifying these is illuminating, stressing specific scenes dynamics (cf. Silver and Clark, in production).

Buzz, as an articulation of the symbols and rules of the game about the arts, clearly is not monolithic. The concept of spontaneous artistic creativity only emerged in the early nineteenth century, when the book market grew large enough to support popular novelists like Dickens and Balzac. Balzac became a major spokesman for the arts. He articulated the ideology of the independent artist as a driver of ideas and innovation. This theme of the genius driving innovation was new, although elements emerged with the Renaissance. The arts for centuries had been primarily seen as a product of patronage, where the prince or bishop would invite an artist to create a church mosaic or music for a new mass. The beauty and glories of Christianity and the Church were classic themes, as interpreted by the specific patron. Only after the French Revolution of 1789 ushered in the ideals of democracy, and major patrons were beheaded by the guillotine, were leading chefs, novelists, musicians, and others forced to follow a broader market logic. They wrote cookbooks, proclaimed manifestos, and made symbolic statements – buzz. Some lived in the same neighborhoods that took on the label of Bohemia, *la boheme*. Walter Benjamin (1999) articulated some of these themes in *The Arcades Project*, pointing to the *flâneur*, the consumer of taste, whose decisions drove the dynamics of production. Even if Benjamin used classic Marxist labels to introduce these ideas, he deeply transformed Marxism by stressing not capital and production but the independent driving forces of the consumer and aesthetics. One of his major sources was Baudelaire who, for instance, held that less affluent young women, who followed fashion buzz more closely, could capture more attention by choosing new stylish outfits that surpassed those of the more affluent but less fashion sensitive. This continual style changing, and its buzz, he termed modernism.

Obviously a large gray area surrounds the arts and buzz-driven dynamics. It explains more, and its resources are more valuable, in certain contexts, than others. But the simplest criticism that buzz only works in affluent areas is clearly false.

Africa remains the least economically developed continent, but any tourist can see the dramatic power and emotional engagement of African music and the arts – illustrated, for instance, by teenagers waiting for a bus, singing and dancing. Or consider how the traditional religions of Islam, Roman Catholicism, and the Church of England have been deeply challenged by the rousing music and active citizen participation in evangelical churches, which spread across Africa and poorer areas of Latin America and Asia near the end of the twentieth century. Analogously young persons in low-income areas in much of the world pay great attention to T-shirts, shoes, hairstyles, and the music they dance to or shun. These are personal identity markers. Certainly world areas fundamentally differ in political cultures (as analyzed in Clark, Silva, Cabaço, last chapter in Clark et al. 2014) from Protestantism and Catholicism to Asian areas. So too do the dynamics of buzz vary. Globalizing forces of television and the Internet encourage local areas to follow global dynamics. Mayors in Chinese villages can be elected using global "buzzwords," even if many voters may not fully grasp their implications (like social networking, electronic cable, wired community). More than half the Chinese population has access to the Internet. And it is rapidly growing. Still, local cultural sensitivities, sharpened by local buzz about arts and culture, can resist globalizing tendencies.

The chapter draws on many extensive quantitative studies, omitting details. Still consider just one illustration of how to measure these competing growth dynamics. Total jobs and arts jobs are interrelated in a chicken and egg growth pattern. To assess their relative strengths, Sakamoto and Clark (2014) explored overtime and regional patterns of impact of arts jobs on total jobs and vice versa in the USA. The total job measure simply summed all jobs in all industries collected by the US Census of Business, for each of some 45,000 US zip codes (termed BIZZIP). They then estimated the impact (economic elasticity) of arts jobs on total jobs from the 1980s to after 2000. In the 1980s and 1990s, arts jobs did not have a significant impact on growth in total jobs in subsequent years. But from 1998 to 2001 the arts job impact was the strongest of all variables in a seven variable regression model. Still impacts varied by region: the arts had the most impact in the Northeast and on the California coast, least in the South and Midwest.

These varied examples illustrate how context clearly matters and transforms local dynamics. These forcefully indicate alternatives to a one cause, deterministic approach. Informed analysts do not propose a simple diffusion approach, that one icon will spread everywhere unchanged. Rather, buzz is part of the New Political Culture (NPC), which defines changes in key components of contexts – the rise of social issues, more active media, the decline of traditional political parties and unions, and the importance of values and specific scenes. These NPC patterns are not universal but are more niche like. Still, to observe that there are major niches in the economy, politics, and social life is not to deny that new patterns spread among them – like social media, informal dress styles, or even the popularity of certain icons like soccer heroes or Lady Gaga. How does buzz work? We are only at the beginning of explaining buzz in terms of social science research. There are bits of theory, such as efforts to interpret how media markets encourage superstars, by the

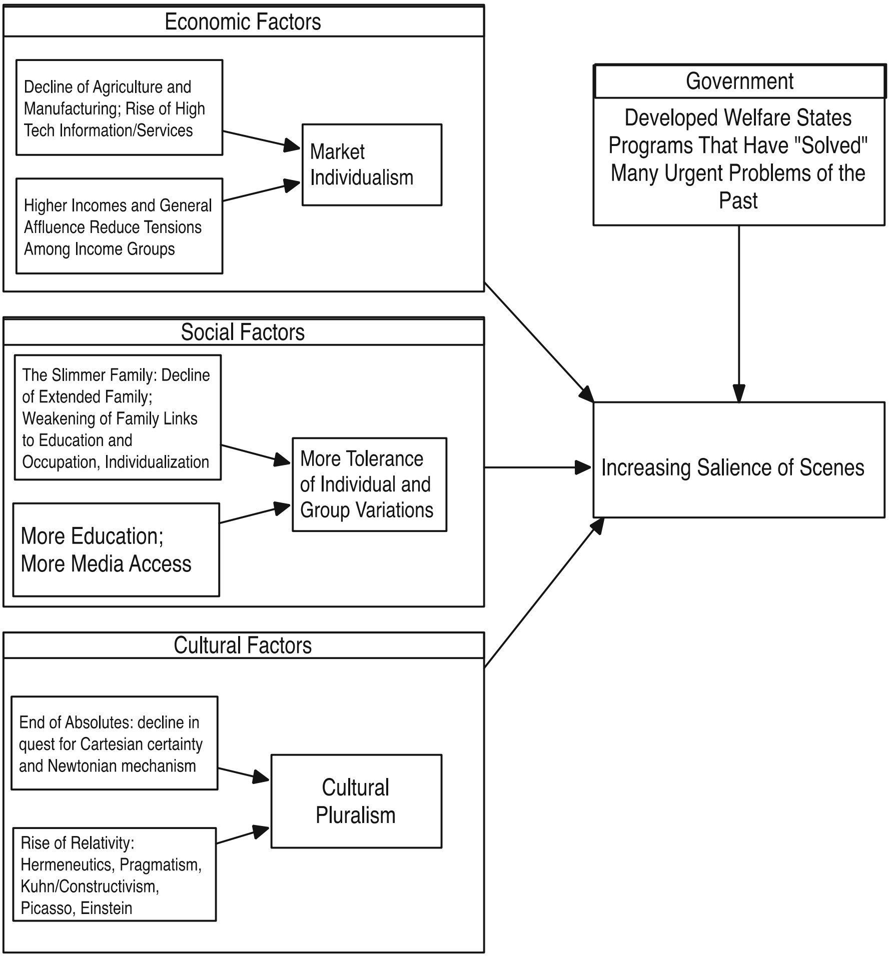

Fig. 1 Factors influencing increasing social importance of scenes

economist Sherwin Rosen (1981) in "The Economics of Superstars," inspiring real estate economist Joseph Gyourko et al. (2006) to identify "Superstar Cities." They and others have started to theorize symbolic media like glamour and buzz in ways that overlap with scenes-related work (Fig. 1).

Several studies show that specific mechanisms by which the arts and culture "work" substantially shift with context, especially the local political culture (e.g., Clark et al. 2014). Tocquevillian theory was energized by the civil rights movement in the 1960s in the USA, where marches and protests joined with song. The example continued in new social movements, and challenging but nonviolent political protests spread globally. Songs like "We Shall Overcome" and "The Battle Hymn of the Republic" stand as powerful classics whose lyrics invoke God and a moral crusade to improve the world. The egalitarian pressures, joined with prayer and sacrifice for progress, are clear and strong. From South Africa to Bangladesh, one finds similar inspiration. By contrast, in more hierarchical and broadly legitimated political cultures, where citizens are not used to such direct personal participation, they may respond more powerfully to time-honored symbols of national pride: military marches, parades of strong political leaders, church music, and paintings of religious icons inspire a duty-based citizenship. More passive arts activities are common, like visiting museums that feature classics. A third Asian trope is the proper 20-year-old daughter in a traditional family. She is politically inspired by ironic and teasing social media, blogs, comics, anime films, and videos of rap songs like Gangnam Style. Her participation may be virtual, via blogs or signing petitions, sent from home.

Young persons the world over are transforming their political and social experiences by creating new artistic experiences – like dancing in a public square, building floats, or recording songs and videos. They participate in and mobilize others in concerts as well as in parades or political demonstrations, with political and economic consequences. Some adults also find new inspiration in distinctive arts and cultural experiences – like a new band, star singer, or inspiring film. Video games, smartphones, and the Internet trumpet themes globally.

These experiences are new for political and economic policy-makers and for analysts. The activities often break with past categories and build new combinations. They create passion, ambition, rage, and revenge. That is the point. The new buzz has deeper and broader impact precisely since it works in new and powerful ways, creating and engaging vast new audiences. Current work is seeking to map major contours of this terrain, which is changing our lives, politics, and economy more deeply and faster than we care to admit. Tocqueville can do karaoke and rap, but he has to practice first.

Contexts, Values, and Scenes

The general propositions about Bohemia and civic participation are transformed both by the arts and by stressing the context, the scene. The family is one obvious context that shifts purely individualistic patterns. But scenes are bigger than families. With the spread of individualism, the "scene" rises in salience, as it is an open physical space where individuals can freely enter or depart, driven more by individual preferences than by externally imposed factors like class, state, church, or family obligations. Think of the teahouse or walk in a garden as a classic Asian activity within a broader scene. Family groups can participate in scenes, around restaurants or churches, for instance. But families go less to the more extreme Bohemian amenities (tattoo parlors, transgressive concerts).

Social scientists and others consider many types of contexts that can join in the scenes approach. But if the components have been used previously, scenes analysts join them together to create a new holistic synthesis. That is a scene which includes the following:

1. *Neighborhoods*, rather than cities, metro regions, states/provinces, or nations.
2. *Physical structures*, such as dance clubs or shopping malls.
3. *Persons*, described according to their race, class, gender, education, occupation, age, and the like.
4. Specific combinations of 1–3, and the *activities* which join them, like young tech workers attending a local punk concert.
5. These four in turn express *symbolic meanings, values* defining what is important about the experiences offered in a place. General meanings include legitimacy, defining a right or wrong way to live; theatricality, an attractive way of seeing and being seen by others; and authenticity, a real or genuine identity.
6. *Publicness* – rather than the uniquely personal and private, scenes are projected by public spaces, available to passersby and deep enthusiasts alike.
7. *Politics and policy*, especially policies and political controversies about how to shape, sustain, alter, or produce a given scene; how certain scenes attract (or repel) residents, firms, and visitors; or how some scenes mesh with political sensibilities, voting patterns, and specific organized groups, such as new social movements. These seven foci are part of a more general effort to retain the sensitivity to local complexity characteristic of ethnographers but disciplined by comparative methods, both quantitative and qualitative.

Scenes are often based on values which are critical in adding deeper meaning to the participants and often more emotion, which can in turn lead to satisfaction or happiness and more powerful voting and economic decisions.

Consider the 15 types of scenes in Table 2 to illustrate the rising "issue specificity" of people's complex and differentiated social lives and value configurations. Scenes analysts have gathered measures of each of these 15 scenes dimensions from data like electronic Yellow Page listings of churches, restaurants, and associations; census data on small industry types (like business organizations and unions as well as web designers); and survey data from citizen respondents. These data have been assembled by cooperating teams in France, Spain, Germany, Poland, Korea, China, Japan, Canada, and the USA. Several county and city reports have been completed for Paris, Seoul, Chinese cities, Spain, Toronto, Chicago, and the USA. The 15 scenes are organized into three main dimensions.

Table 2 A grammar of scenes: three dimensions and 15 subdimensions

Name of dimension	Legitimacy	Theatricality	Authenticity
Meaning	Intentions, reasons for actions	Appearance, mutual self-display	Identity, self-realization
Subdimensions	Traditionalism	Neighborliness	Local
	Self-expression	Transgression	Ethnic
	Charisma	Exhibitionism	State
	Utilitarianism	Glamour	Corporate
	Egalitarianism	Formal	Rational

To build strong theories that can be adapted and extended globally, one must go beyond names of regions like the West or countries. This thus led to formulating concepts at the level of generality illustrated by these 15 scenes, which can be combined and weighted in various ways to generate more specifics for types like Bohemia or Max Weber's ideal types like peasant or bureaucrat. And to analyze how these multiple components variously combine and generate new meanings with new combinations, it is more empirically rich to dig deeper than nations. If one thus drills down to local areas like communes in France or Spain or zip codes in the USA, this provides thousands of cases that vary in more unusual combinations than if one studies nations. The examples above about the limits of Bohemia and Tocqueville illustrate the beginnings of this strategy.

A Grammar of Scenes: 15 Dimensions

First, the dimension of legitimacy is related to people's decisions about a worthwhile way of life. It is a judgment about what is right and wrong, how one ought to live, structuring the legitimacy of social consumption, and shaping the beliefs and intentions of their members. The dimension of legitimacy can be divided into five subdimensions: traditional, utilitarian, egalitarian, self-expressive, and charismatic legitimacy.

While many combinations are logically possible, consider here just one to illustrate how the 15 dimensions can be combined in distinct ways that link to Asian and Western key differences and the core dynamics of the two theories about citizen participation and economic development.

Max Weber (1978) used just three dimensions to capture legitimacy, but scenes analysts add egalitarianism and self-expression. The rise of egalitarian individualism, joined with self-expression and the transgression of bohemia, has spread powerfully from artists to their fans. Fans choose their own scenes. This democratization of cultural participation is a key development informing many changes globally. It contrasts East and West, old and young, traditional and socially liberal. It makes things cool to some and repulsive to others. Whether the analyst personally loves or hates something may not change the world, but analyzing why others embrace different aesthetics is essential to interpret ongoing changes globally. This is all the more the case as the citizens of countries like India and China rise further from poverty and make more complex decisions.

Self-expressive legitimacy. Self-expression grounds the legitimacy of a scene in its capacity to actualize an individual personality. The good person is the person who brings her own unique take, her own personal style, and her own way of seeing, to each and every one of her actions. This is self-expression as an ethical task, a demand to improvise a response to situations in unscripted and surprising ways. Themes of self-expression run through Herder, Emerson, Thoreau, and the American Pragmatists. Here is Emerson (1993, 35) writing on self-reliance in 1841: "Insist on yourself; never imitate. Your own gift you can present every moment with the cumulative force of a whole life's cultivation; but of the adopted talent of another you have only an extemporaneous half possession." These themes remain powerful in popular celebrity culture. "Born this Way" was a popular 2011 song created by Lady Gaga through spontaneous self-expression. In 2012 the Korean musician Psy was the first performer to release a video that achieved one billion views on YouTube, "Gangnam Style" which refers to the lifestyle of the Gangnam neighborhood of Seoul.

The legitimacy of self-expression continues to be affirmed in improve comedy theaters, rap cyphers, and karaoke clubs, in the stress on interior and product "design," or in the demand that each person construct a unique music playlist. Daniel Bell suggested that this sort of outlook has come to dominate the contemporary art world from conductors to poets, extending out from there to the general populace. Robert Bellah's (1996) famous case study in *Habits of the Heart* of a woman named Sheila showed its religious potential – when asked if she believed in God, she replied, yes, I subscribe to Sheilaism.

These brief examples illustrate how forceful legitimation of egalitarianism can lead the citizen to think, for herself, and how some can resonate to diverse scenes (even a mini-scene on her smartphone). These quick examples show how past theories about citizen participation and economic development take on more power when explicitly joined with arts and culture that elaborate and magnify their messages and meanings. Clearly, these self-expressive views shock many older and more traditional Americans, Asians, Southern Europeans, and Arabs to the core. Some 9/11 terrorists claimed that such Western self-indulgence drove them to support the Taliban and Al-Qaeda. Russia banned Lady Gaga. Scenes analysts created indexes for all US local areas of Bobo, Heartland (country/tradition), and Blueblood scenes and found these helped explain party voting, above and beyond the normal factors like race, education, and income (e.g., Silver and Clark, in production). The three-mile downtown area of Chicago, relative to its suburbs, is the fastest growing of any in the entire USA in 25–34 year olds. This area hosts huge concerts and has spawned related entertainment activities that drive Chicago's new economy. Yet other Chicago neighborhoods host staunch conservative scenes, including many immigrants from foreign countries. Neighborhood activists, priests, and bartenders can resist new migrants and their upstart lifestyles. Scenes are more than aesthetic: they can mobilize political conflicts and encourage or rechannel migration and job growth. Scenes analyses can serve as powerful tools of theory and policy.

Conclusion: Elaborating Scenes Globally

Scientists in one lab need others elsewhere to check and extend their findings, either to document their limits or extend their generality. To facilitate this process, we have worked together through two international collaborative projects that feature local contexts (Fiscal Austerity and Urban Innovation (FAUI) and the Scenes project). They explore how cultural patterns vary cross-nationally. There has been continual exchange among the participants, for over a decade for Scenes and over two decades for FAUI, as participants unearthed some surprising and controversial results. One key result was from Seokho Kim's University of Chicago Ph.D. on citizen participation. Contrasting some 30 countries, he found that participation worked in Tocquevillian manner in Northwest Europe and North America. But in some other locations, especially Korea, Portugal, Brazil, the former Soviet area, and Eastern Europe, citizen participation had no effect on legitimacy and trust or was sometimes even negative. This dramatic result of course leads one to ask why. One basic answer, stated in abstract, is that it depends on the local rules of the game and values of key participants. For instance, young people in US cities who participate more in gang activities may grow more alienated from society and distrust people more. Gang participation in this example reinforces a sense that the political leadership in the society around them is not trustworthy and does not inspire confidence. This US gang example is one way that scenes analyses have evolved from exploring comparisons of national averages to identifying subgroups in specific cities as conceptually critical examples, sometimes in case studies. This illustrates how to move back and forth from surveys of citizens across countries to contrasting subgroups by neighborhood. This helps generalize in a more specific manner about the key ways of classifying values, participation, and related concepts like trust and legitimacy and to test these ideas with the best available data. Scenes analysts link where possible with standard measures used by others like voter turnout, citizen participation in organized groups, self-reported trust and confidence, and various economic development indicators such as changes in jobs and population overall, by city or neighborhood and by age and other subgroups.

The distinctiveness of Korea and Portugal from Seokho Kim – that citizens in these countries did not develop trust as in other places – encouraged scenes analysts to dig further into comparing these countries with others to find out more of how they worked. This led to collaboration with Joseph Yi, Wonho Jang, Chad Anderson, Miree Byun, and Jong Youl Lee in Korea and Filipe Carreira da Silva and Susana L. F. Cabaço from Portugal. Yoshiaki Kobayashi (2011) stimulated many with his cross-country comparisons and subtle analyses. Daniel Silver has extended these patterns especially in Canada. Laurent Fleury has elaborated how specific institutions can redefine the ethos of a city and its subsequent politics and economy. Scenes analysts are dynamically pursuing these and related themes in various sub-team collaborations. We started with three common terms – scene, bohemianism, and buzz. We found that they can illuminate many global processes, if we calibrate and analyze them closely.

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Technology and Religion

Robert Geraci

Contents

Abstract

The late twentieth and early twenty-first centuries have seen an acceleration in the historical process whereby technology, once viewed as instrumental in religion (as it was in business, art, and other areas), appears to have become the fulfillment of religious aspirations. That is, technology once served as a signpost for, or necessary precondition of, religious salvation, but in the Western world, technological progress and religious salvation have now converged – they have become one and the same thing.

Introduction

The late twentieth century witnessed a curious phenomenon: there was a company that developed a product that became a religion. But it wasn't just any particular product; it was almost all of the products emergent out of that company's business. Successes with the iMac computer and the iPod music player reached their epitome

R. Geraci (✉)
Department of Religious Studies, Manhattan College, Riverdale, NY, USA
e-mail: robert.geraci@manhattan.edu

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in the iPhone – the mobile phone for which desperate consumers would wait days in line to purchase. While the iPhone's popularity owed much to savvy advertising, a sleek interface, and integration into an informational ecosystem devised by Apple, Inc., it owed as much to the spiritual fulfillment that its owners derived through their participation in a transcendent technological world. Consumers bought more than a mobile phone; they bought salvation.

The well-cited religious affect of Apple products (e.g., see Robinson 2013) is but one aspect of the now ubiquitous convergence of religion and technology in contemporary culture. In the early twenty-first century, a wide array of technologies has been described in religious terms and deployed toward religious ends. This includes artificial intelligence and robotics (Geraci 2010; Noble 1999), biotechnology (Alexander 2003; Noble 1999), spaceflight (Noble 1999), virtual worlds and videogames (Bainbridge 2013; Geraci 2014), and more. Technology, which once appeared as a tool that would help religious practitioners bring about their divinely ordained salvation, has now become a religious end of its own. The religious dreams of salvation have merged with the processes of technological forecasting, development, and consumer use. In the developed world, and to a lesser extent the developing world, people from all walks of life have fastened spiritual visions to their technologies. Scientists, engineers, and policymakers have joined consumers in their expectations that the coming technological revolution will save them from the meaninglessness of the world, the existential threats that face the human species, and even the frailty and mortality of human life.

The Religious Use of Technology

Despite common protests that religion and science (and hence technology) engage in some kind of eternal conflict, historical research indicates that religious practitioners generally take advantage of available technologies and find ways to advance their theological aims through the scientific and technological developments of their contemporaries. A brief survey of Christian approaches to technology in the modern era clearly indicates that technology has served religious interests (in addition to economic, military, and other interests).

The beginnings of a clearly articulated convergence between Christianity and technology can be seen in Francis Bacon's *New Atlantis* in 1627 (see Bacon 1951). Of course, any search for historical precedent must begin somewhere, and often such searches are arbitrary in their interpretation of the connections and conjunctions that lead from one historical moment to the next. Nevertheless, in the exploration, not of the relationship between technology and religion, but of the *convergence* of technology and religion, it seems clear that the publication of Francis Bacon's *New Atlantis* was a watershed moment that simultaneously revealed conditions as they were and anticipated conditions to come. There were Christians in Europe who had previously articulated the religious value of technology, but *New Atlantis* ties these together and portrays a worldly future of technological Christian culture.

Bacon describes a fantastic island of Christians who use technology to fulfill the divine creation. The islands' residents have mastered technologies that promote strength, health, and long lives among human beings, enhance animal husbandry and plant breeding, and even control the elemental forces of nature. For Bacon, technology is instrumental in the historical progress toward the second coming of Jesus and a sign of God's redemptive favor. *New Atlantis* underscores the powerful relationship between technology and religious salvation that emerged in the Scientific Revolution, a relationship that was to persist across the next several centuries.

From the seventeenth through the twentieth centuries, technology remained inextricably intertwined with Christian soteriology in the Western world. Protestants, especially, believed that technology would permit a return to the prelapsarian grace of Adam, and this perception was integrated into the way scientists, engineers, and the public discussed modern technology in the twentieth century, from genetic engineering to artificial intelligence (see Noble 1999). Even destructive technologies were incorporated into Christian visions of salvation, as when the televangelist Billy Graham equated nuclear war with the fires of heaven described in 2 Peter of the New Testament.

Twentieth-century technologies, especially new mass media, were also deployed as paths of salvation for individuals and even religion itself. On the one hand, technologically enhanced ministers reached millions of people through mass media, some creating vast (and profitable) empires designed to spread Christian salvation over the airwaves of radio, TV, and the Internet. Many of the faithful and their leaders believed that they could hasten the return of Jesus and inaugurate a new Christian world through these technologies. On the other hand, there were also religious leaders from across many denominations who felt that religion itself required radical shifts that the new media might enable. Rather than saving individual souls, these new faithful infused their practice – particularly online – with an ecumenical spirit that they hoped would update their religious traditions and promote cross-cultural understanding.

The techno-fueled ecumenism of twenty-first religion gained momentum in the early days of the Internet and was adopted by virtual world residents, such as the users of *Second Life*. For *Second Life* users in particular, online media offer opportunities to find common ground, to share religious perspectives, and to learn from other communities (see Geraci 2014). In these communities, the ecumenical possibilities inherent in online communication and collaboration reinvigorated religious practice and provided an outlet for traditional religious life. Such changes to religious life reflect offline trends in religion as religious practitioners apply their fledgling sense of religious pluralism to their online interactions and leverage the technology toward ecumenical outcomes.

Religious communities have used technology for many purposes, from advanced architecture and engineering that enabled the larger windows and soaring naves of medieval cathedrals to the online worlds where users build virtual churches and welcome practitioners and curious outsiders from around the world. At no time in the modern West were religious leaders and practitioners universally (or even largely) suspicious of technology (even when they refused to embrace specific technologies, as with the Catholic Church rejecting the authenticity of "attending" a Mass by watching it on television). Instead, they adapted to and adopted new technologies as means to their own ends. At the same time, many Christians, in particular, found evidence of divine providence in the newfound powers of humankind, and they swiftly took advantage of new technologies to offer proof of their theological expectations or to develop opportunities for the spread of the gospel. As such, Christians integrated technology into their various theologies, from the millenarian belief that Jesus would soon return to the Earth and inaugurate a new kingdom to the more prosaic expectation that life will continue and modern pluralism demands that religious groups learn to get along.

The Rise of Technological Religion

For many people in the modern world, however, the rise of technology offered an opportunity to throw off the shackles of traditional religion and create new forms of religious practice and belief. The humanistic traditions of the positivist philosopher Auguste Comte were an early move in this direction, which accelerated in the twentieth century. For Comte ([1852] 1973), a new priestly caste of engineers should lead a religion that would be rational and scientifically informed, while retaining many of the basic structures and trappings of his abandoned Catholic faith. For the transhumanists who followed his footsteps, science and technology could lead humanity to a higher evolutionary state. Although these latter frequently deride religion and argued it should be eliminated altogether, their perspectives remain implicitly and deeply religious.

It was not until the twentieth century that science could offer the technological guarantees that might make Comte's dreams compelling. Early in the century, biologists began predicting – as science, not as science fiction – that technology prefigured radical changes in the human condition. J.B.S. Haldane, for example, declared that advances in biology would lead to what we now call in vitro fertilization, external wombs, and neuropharmacology (among other advances). His friend, Julian Huxley, agreed that technology would refashion the world, but diverged with Haldane on the question of religion. While Haldane was an avowed atheist and opponent of religion, Huxley – like Comte – sought to create a new religious community based on scientific principles (Huxley 1957b). Also an atheist, Huxley promoted the foundation of a new religion and ultimately coined the term "transhumanism" for the belief that humanity could use technology to transcend the limitations of mortal life (Huxley 1957a).

Subsequent transhumanists in the late twentieth century tended to follow Haldane in their opposition to traditional religion, but as they did so, they increasingly behaved in ways that put them in company with Huxley. Huxley rightly understood that religion is a meaning-making enterprise, not merely an articulation of gods or ancient mores. The rise of cryogenics, the emergence of cyborg implants (pacemakers, cochlear implants, etc.), and the promise of genetic manipulations eventually did quite a bit more than make old religious systems look old. These technologies became the core of new theories of salvation that paralleled but competed with those articulated by traditional religions.

Cyborgs, Avatars, and the Biotech Sublime

Transhumanist aspirations grew throughout the late twentieth century and culminated in a convergence of religion and technology built upon information technologies and biotechnologies. Based upon the rapid improvement and deployment of computers, scientists such as Hans Moravec and Ray Kurzweil gained fame by describing a world of transcendent machines and a posthuman shift of mind uploading into robot or virtual world bodies. At the same time, enthusiasm for genetic manipulation and for cyborg operations made biotechnology a collaborator in the dream of life extension, human augmentation, and even immortality through technology. The combination of information technologies and biotechnologies, described through the fantastical merger of robotics, artificial intelligence, nanotech, genetic engineering, and pharmacology, took on an unmistakably religious aura, producing a new fantastical vision of technological salvation.

A technological fantasy is not, by its nature, a wish for the impossible, but rather a process where by human beings infuse their deepest longings (whether realizable or not) into their craftsmanship. In the late twentieth and early twentieth centuries, such fantasies revolved around computers and genetic manipulations, but the impetus toward such visions could be served by a wide array of potential technologies. The visionaries themselves shared their dreams through the pop culture landscape, from science fiction to popular science.

Just as Bacon's *New Atlantis* established and revealed the spirit of technological Christianity, science fiction literature of late modernity prompted the dreams of transhumanism and its accompanying sciences. Robert Heinlein's stories of Lazarus Long gave readers hope of long, perhaps even immortal, lives. Roger Zelazny and Frederick Pohl explored the possibility of mind uploading – the transferring of consciousness from a mortal human body to an immortal machine. Perhaps most powerfully of all, Arthur C. Clarke described human evolution as an ongoing process that would – thanks to technology – soon culminate in cosmic powers and unfettered growth. These authors deeply influenced a generation of scientists and children who would become scientists. Their visions replaced the transcendent aspirations of traditional religion, providing direction and hope for the scientifically inclined.

Hans Moravec provided the first truly scientific effort to describe and defend twentieth-century technology as a path to such religious goals as perfect happiness and immortality. Moravec, famous for his work in mobile robotics and former research professor at Carnegie Mellon University's Robotics Institute, acknowledges his own debt to such authors as Clarke, but his work is seminal in its own right. First in an essay in *Omni* magazine, but later – and more influentially – in the books *Mind Children: The Future of Robot and Human Intelligence* (1988) and *Robot: Mere Machine to Transcendent Mind* (1999), Moravec provided a rational (if not necessarily convincing) account of how progress in computer technologies would result in a technologically determined process of evolution. That evolution, Moravec argues, will result in a transition from biological life to machine life. Machines will become godlike in their powers and intellects, and human beings will join them by transferring their minds into computers.

Moravec's ideas found some currency in technological circles, but it was not until the noted inventor Ray Kurzweil published *The Age of Spiritual Machines* (1999) and *The Singularity is Near* (2005) that mind uploading and transcendent computers became widely popular. Early in the twenty-first century, Kurzweil made a new name for himself as the prophet of this new movement focused upon the "Singularity." The technological singularity that Kurzweil describes (as opposed to a mathematical or astrophysical singularity) is the hypothetical moment when technological progress happens so fast that we cannot predict how the world will look after that moment. Such expectations are built upon the belief that technology develops exponentially, a controversial position defended by Moravec and Kurzweil. Kurzweil believes that developments in nanotechnology, artificial intelligence, and general computation lead inexorably toward a future of transcendent machines (with biotechnologies such as genetic engineering providing stopgap opportunities to extend our lives until the day when we can leave biology behind).

Other futurists, however, are less sanguine about the belief that biological life will become obsolete. Roboticist Kevin Warwick (2003), for example, believes that human beings will become cyborgs, but not that we will upload our minds into robots or virtual worlds. And Gregory Stock (2003), a bioethicist at the University of California, Los Angeles, believes that we will never depart our biological bodies, but that we will upgrade them through cyborg enhancements and through the use of artificial chromosomes that will provide genetic enhancement to the species. Whether through cyborg enhancements or genetic manipulations, however, these advocates share the fundamental belief that technology can provide a response to human finitude.

Of course, technology is inherently a response to human limitations. We devise technologies in order to accomplish otherwise unattainable ends. In this sense, futurists like Kurzweil are correct when they claim that as a species, humanity always seeks to transcend its own limits and that we will continue to use our growing scientific expertise to improve our lives through technology. From the mastery of fire to the digital computer, all technologies are efforts at transcendence.

But technology becomes a religious practice when we use it to satisfy traditionally religious desires and when it becomes a practice that produces or participates in a continuum of cosmic meaning. The first of these is easy to define and appreciate. Traditionally, religions have been the only recourse for those who seek desirable goals like immortality or eternal happiness. Many religions promise such goods in the afterlife. When technology becomes the path toward these things, it implicitly acts as religion. In addition, however, technology – in part because it is implicated in the search for what were once the "commodities" of institutional religions – has become the central nexus in the manufacture of human meaning. Historian of religion David Chidester (2005) defines religion as “the negotiation of what it means to be human with respect to the superhuman and the subhuman.” With its direction toward transcendent, posthuman cyborgs, uploaded minds, or genetically modified superhumans, transhumanism has become a religious ideology focused upon contemporary technology.

Certainly it is the case that technology can serve traditionally religious aims, as when early modern Christians sought technological weapons to fight the Antichrist, but in the late twentieth and early twenty-first centuries, technology has become, itself, religious. Both researchers and aficionados of digital technologies and biotechnologies have become futurists, predicting a new age of biological superbeings and godlike machines. The portrayal of human beings as cyborgs in waiting and the suggestion that we will soon reach posthuman states of transcendence mean that information technologies and biotechnologies provide the keys to both our identity in the present and our expectations for the future. In doing so, they have taken up the mantle of religious prophecy, and they have advanced the relationship between technology and religion into new territory. This convergence allows people to experience new kinds of religion, which is especially pertinent when many of the traditional religions can be out of step with daily life.

Convergence and the Challenges of Modernity

Changing demographics could mean that the convergence of religion and technology will continue to accelerate and perhaps come to dominate the cultural landscape. Early in the twenty-first century, census and poll data led to a wide swath of the population being labeled “the generation of ‘none.’” Following the “spiritual seekers” that constituted the Baby Boomer generation, the “nones” were the people who, when asked for their religious affiliation, indicated “none” even when “atheist” or “agnostic” were also options. That is, for these people, none of the options captured their beliefs or practices. Although these respondents did not affiliate with any particular traditions, they still described themselves as “spiritual” or acknowledged belief in gods or higher powers. They were not atheists or even agnostics in the traditional sense. Their own daily religious lives were just not amenable to the kinds of questioning that had occupied previous surveys and censuses. In this environment, the convergence of religion and technology has found fertile ground.

The convergence of religion and technology and the rise of the nones are both features of twentieth- and twenty-first-century secular culture. Although late nineteenth- and early twenty-first-century theorists believed that the rise of secularism would amount to the death of religion, life on the ground has remained religious. Secularism, rather than the end of religion, enables many kinds of religious practices to flourish, from the traditional (which do sometimes wane) to the novel (Bainbridge and Stark 1985). Traditional religions sometimes find themselves retreating from popular culture and in a seeming paradox, they can even use new technologies to do so (see Ornella 2013). In such an environment, as Bainbridge and

Stark note, it is possible – even common – for new kinds of religious experience to emerge.

Modern technology provides, as we have already seen, a host of opportunities for the kind of spiritual fulfillment that secularism enables. The very beginnings of the "digital revolution" were tied up in the US counterculture and benefited from a mystical aura (Turner 2006). Programming and digital computers took a central role in countercultural media, from the Whole Earth Catalog in the 1960s and 1970s to the magazines *Wired* and *Mondo 2000* in the 1990s. These media suffused computers and computing communities with a utopian vision of the future. That vision was, of course, critical to the emergence of transhumanist aspirations that coalesced in the work of Moravec, Kurzweil, and others.

In keeping with the relationship between the counterculture and the rise of computing, digital technologies continue to enable forms of technological transcendence that stop short of posthuman mind uploading or cyborg engineering. In the twenty-first century, many consumers find themselves seeking transcendence and spiritual opportunities from the comfort of their homes. Videogame players, for example, can reflect on ethical behavior (though their in-game practices might leave something to be desired) and can find meaning and purpose in their online lives and communities (Geraci 2014). Indeed, while everyday reality may leave little to admire in its day-to-day outcomes, gamers swiftly find that they transcend the mundane world every time they enter their computer-generated wonderlands – they transform into supernaturally empowered, idealized versions of themselves whose heroic purpose leads them across fantastic landscapes of magic, science fiction, or adventure. These very human, as opposed to posthuman, efforts are but one example of a more "grounded" approach to technological transcendence. Likewise, the community that coalesced around Apple products and made pilgrimage to the minimalist, but beautiful, new Apple stores in New York, Paris, and elsewhere found (or at least sought) an escape from the banality of the old consumer culture but not a posthuman state of being.

Consumerist tendencies – and a mass media devoted to their advocacy – account for much of why commodities such as the iPhone have sold spectacularly, but the religious aura of technology is both part of how advertisers use those media to sell products and part of why consumers relish them. Whether "spiritually seeking" or "none of the above," citizens of developed nations (and often of developing nations also) can locate spiritual opportunities in their everyday technologies. From communion with the Apple faithful to becoming a hero in *World of Warcraft* and *Star Wars: The Old Republic*, many consumers already participate in the beginnings of a technological religion that might one day culminate in a genetically modified or digitally archived posthumanity.

Naturally, not everyone is sanguine about the development of such a techno-religion. Bill Joy, of Sun Microsystems, sent shockwaves through high-tech circles with his widely circulated essay, "Why the Future Doesn't Need Us," which he published in *Wired* magazine (Joy 2000). Similarly, Jaron Lanier, one of the architects of virtual reality technologies, has criticized the capitalist predilection toward technologies that dehumanize their users (Lanier 2010). For Lanier, we may see computers as intelligent only to the extent that we can dumb ourselves down to their level. He believes that the posthuman promises of mind uploading are spectacularly misguided, capable only of destroying the richness and beauty of human experience. Rather than aspire toward a future of transcendent machines, Lanier advises that we use technologies to enhance our own most human dreams of empathy, community, and communication.

The transhumanist faith in a technologically determined future has been derided as "the rapture of the nerds," even by those who generally agree with Singularity theorists and technology advocates. This recognition of the convergence of technology and religion, however, is deeper and richer than snide labels can convey. While it may, indeed, represent the childhood dream of scientifically minded social outcasts, it also infuses the very nature of contemporary technological use. It is not just the Singularity theorists who look for technical solutions to life's problems. That search is fundamentally human, and in the contemporary world, the enormous power of technology leads most, if not all, of its users toward dreams of ever-greater satisfactions. If religious groups offered have traditionally communities, ethics, transcendence, and hope for the future, then today we find that these same commodities are on offer in computer stores, research laboratories, commercial spaceflight, and Internet-enabled smartphones. For some users, these technologies tacitly promise a posthuman transcendence; for others, the more modest promises of a technological wonderland remain anchored to our essential humanity. In both cases, however, users intertwine technological progress and spiritual satisfaction as a path toward new forms of religious self-identification and the construction of modern culture.

Conclusion

The convergence of religion and technology has proceeded apace since the rise of modern science in the seventeenth century. While its roots – which could not be explored here – stretch back centuries earlier even than the publication of *New Atlantis*, this convergence has shifted from a focus upon Christian salvation to varying forms of technological transcendence and technological salvation.

The rise of modern science in Christian Europe made the inclusion of technology into religious visions a near inevitability. Both as a tool to reclaim the prelapsarian grace of Adam and as a weapon against the coming Antichrist, the emergence of modern technology meant the fulfillment of Christian history. This infusion of technology into the Christian story of salvation continued into the twentieth century, where a wide array of technologies, from mass media to rocketry and nuclear power, all became integral to contemporary interpretations of divine providence. In the era of televangelism and virtual temples, it is hard to imagine how religious communities could or would remain technologically out of step.

In recent years, however, persons unaligned with traditional religions saw technology as offering a new kind of salvation. Early advocates such as Haldane and Huxley described the power of science and technology to advance the human species, with the latter making this movement explicitly religious. The development of computers and genetic manipulation made those advocates' promises compelling and led to a shift from science fiction fantasies to pop science advocacy in the works of Moravec, Stock, and many others. Combining the early transhumanists with science fiction and then with the new breed of transhumanists, cyber-utopians, and bio-hackers inspired by it, twenty-first-century commentators have deliberately or implicitly put technological salvation in competition with traditional religions, such as the Abrahamic faiths.

The competition between technological salvation and traditional religions is a consequence of the secularizing processes that have destabilized the cultural authority of individual religious leaders and groups. In a pluralistic, secular society, no one set of practices or beliefs can compel everyone to obedience. Instead, those seeking previously unthinkable forms of religion can do so, though of course not exclusively so, through the technologies that now dominate daily life. The pharmacological search for superior bodies and minds, the power to walk on the moon, the hope for genetic enhancement, and the pervasive reality of digital life – its presence in computers and smartphones, in work, and in entertainment – make technological transcendence the daily experience of modernity. For some users, such transcendence implies posthuman states of being to come, and for such people faith in the Singularity or genetic enhancement satisfies the religious longings of humankind. Perhaps better days, even infinite days, are still to come.

It is in our longing and our dreaming that humanity ultimately retains its purpose. Even as staunch a critic as Lanier sees transcendent opportunities in technology. He aspires to enhance human communication through digital media and believes we can find ways to speak truly of ourselves and to one another. Already, we can communicate across space and time in ways that our ancestors would have found fantastical. Perhaps, as Lanier hopes, we can commit to revealing ourselves to one another and sharing one another's dreams rather than rejecting our biological heritage and placing hope and faith in machines.

On the one hand, the convergence of technology and religion in the twenty-first century might replace humanity with godlike machines or posthumans, but it also responds to the cultural void left by the secular disinterest in traditional religions. The spiritual seekers of the mid-twentieth century and the nones of the early twenty-first find religious value in their technologically mediated communities. It remains to be seen whether the ultimate convergence of technology and religion will be good or bad – whether it will produce terrors to dwarf the Crusades or beatific acts of generosity for all life, human, and otherwise. The transhumanist advocates, from Huxley to Kurzweil, argue that humanity's greatest dreams are yet to be even imagined, and that they will be dreamed and fulfilled thanks to technological progress. Such faithful claim that we are already living in a technological crescendo that could produce a new kind of humanity, a posthuman race whose spiritual fulfillment is simultaneously its technological achievement. Whether toward posthuman divinity or a more human (and hence limited) transcendence, the convergence of religion and technology will continue and will increase its "market share" in the economy of contemporary religion.

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Unifying Ethical Concepts

Barbara Herr Harthorn

Contents

Abstract

This chapter considers nanotechnology innovation, particularly in the National Nanotechnology Initiative (NNI) in the USA, and the emergence in the NNI of fundamental unifying societal and ethical ideas that provide a basis for approaches to other emerging (and convergent) technologies. In it I employ the term "societal science" to reference these ideas and practices that emerge from the nanotechnology case and have the potential to enable the essential goal of converging technologies – that of harmonizing science and society. The chapter begins with my candidate list of the core societal implications that have emerged across the very broad sweep of nanotechnology applications. I then take up in turn each of the five basic principles for convergence cited by Roco, Bainbridge, Tonn, and Whitesides in the CKTS report (Convergence of knowledge, technology and society: beyond convergence of nano-bio-info-cognitive technologies. Springer, Dordrecht/Heidelberg/New York/London, 2013) in relation to what we have learned about societal and ethical implications of nanotechnologies. What follows is a brief assessment of the question of how much nanotechnologies' "societal science" can generalize to other emergent technologies and also scale up in convergence. The larger purpose of this piece

B.H. Harthorn (✉)
NSF Center for Nanotechnology in Society and Department of Anthropology, University of California, Santa Barbara, Santa Barbara, CA, USA
e-mail: barbara.harthorn@ucsb.edu

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thus is to consider how applicable what we have learned from the case of nanotechnology in society will be to fulfilling the fundamental goal of CKTS, defined as "transformative actions to improve societal outcomes."

Introduction

The CKTS report outlines an ambitious set of goals and principles for addressing societal needs through converging technologies for the development of the economy, for addressing major global population goals and needs, and for elevating human activities and systems, including education and health care, to achieve "an innovative and equitable society." Within this model, nanotechnologies figure importantly in both the first and second stages of convergence and hence provide a particularly useful example for thinking through the pathways and impediments to realization of the societal aspects of convergent technologies. The innovation and development of nanotechnologies in the USA have incorporated from the start attention to the societal implications. Indeed, nanotech development "as an emerging megatrend" has arguably created a novel template for integration of science in society, particularly through the investment in two NSF-funded Nanoscale Science and Engineering Centers (CNS-UCSB and CNS-ASU) and a national network devoted entirely to nanotechnologies in society, jointly constituting the largest such investment in the world. While this effort has taken many directions, I identify here what I see as the five most important lasting contributions of the body of nanotechnology in society work in the last 10 years. I note that my views on this reflect the contributions and orientations of the CNS at UCSB which I lead. With that caveat, let me outline these five critical developments:

1. The rhetoric in the CKTS report about technological development "for the benefit of society" clearly carries forward from the NNI the idea of the *imperative for emerging technologies to meet societal needs* and thus moves to reconnect "society" in the technological equation. In doing so, it has created a firm normative (moral/ethical/cultural) basis for the need for "benefit production" – for society to be considered as a part of innovation and commercialization systems and across product life cycles; at the same time, it has also inextricably raised the need for a critical kind of "benefit analysis," as judgments about what constitutes *societal benefit* carry with them essential ideas about equitability, fairness, and justice as well as cultural values. In a large multicultural society like the USA, with diverse megacities, profound regional variance, and many economies, the plurality of views about "benefits" is very broad indeed (this idea is further developed in #3 below), and the complexities of understanding and incorporating such views are significant challenges. Many or even most in the nanotech enterprise can and do agree on this normative principle of "doing good" for society. Who, indeed, is going to advocate openly for innovation for its moral opposite, societal harm, or even morally neutral terrain of neither benefit nor harm? However, the integration of science and

society implied by this principle of societal benefit is in practice far more problematic to achieve. And societal science and ethics experts are needed for this work.

2. The *social sciences and ethics* have been *structured into the nanotechnological innovation system in novel ways* that can form both a template for such organization and a potential workforce for other emerging technologies. Taking its charge to conduct research on key aspects of societal implications seriously, the NNI funded through the NSF a suite of social science and ethics research projects, integrated collaborative efforts (NIRTs), and, most significantly, the two Centers for Nanotechnology in Society at UCSB and ASU. This vibrant new field(s) has produced a new generation of society-minded scientists and science-minded social scientists, a new professional society (Society for the Study of Nanoscience and Emerging Technologies, S.NET), and a large and growing body of relevant research on societal implications of new nanotechnologies from around the globe. Collaboration plays an ever-escalating role in this new field. For example, the US portions of this in the NNI have been lauded by the US President's Council of Advisors on Science and Technology (PCAST) (2010) for their "strong and growing portfolio of research on the societal implications of nanotechnology, nanotechnology education, and public outreach" (http://www.whitehouse.gov/blog/2012/04/27/pcast-releases-assessment-national-nanotechnology-initiative). It is clear that without structured organization, particularly through centers that can produce a leadership role for societal scientists and ethicists in brokering integration of societal science with innovation science, the rhetoric of responsible development will remain a set of prescriptive statements, but not the meaningful framework for the kind of new organizational and substantive advances envisioned in the CKTS.
3. *Decision risk science* has helped map out a critical dimension for assessing valuation of emergent technologies across different sectors and stakeholders. Much of the emergent responsible innovation literature (e.g., Owen et al. 2013; van den Hoven et al. 2014) rejects risk analysis wholesale as too much focused on downstream regulation through quantification of known hazards and too little focused on upstream precaution, anticipation, and foresight (in addition to blanket rejection of its often quantitative methods). Yet work within the risk perception field, including in my group in our Center at UCSB, has been critical in providing evidence-based knowledge about multiple parties' (experts' and publics') multivalent perceptions of nanotechnologies' risks and benefits in the upstream, particularly drawing attention to the social as opposed to physical/technical risks. This framework has also formed the basis for effective development and examination of new forms of public deliberation (Pidgeon et al. 2009; Corner and Pidgeon 2012; Parkhill et al. 2013), which are hailed as an essential component of responsible innovation and development (Stilgoe 2013, xii in Owen et al. 2013) (and see #4 below). And this includes as well innovative work on methods for understanding cultural valuation and its importance in risk controversy mediation (e.g., Gregory et al. 1993; Satterfield et al. 2013) and rigorous empirical bases for risk (and science) communication (Fischhoff 1995).

This work demonstrates the importance of aspects of the risk science toolkit, particularly that regarding psychometric risk (Slovic 2000), in retooling for upstream, anticipatory work and hence its likely import in CKTS. More cross-national and cross-cultural work of this kind will be essential to fulfilling the CKTS vision.

4. The societal science of nanotechnologies has provided important case analyses of possibilities and impediments to *anticipatory governance* of new technologies (Barben et al. 2008), particularly when allied to a *nuanced approach to issues of social inclusion, participation, and equitable development* (Harthorn and Mohr 2012; Parker and Appelbaum 2012) (see #5 below). NNI investment early in nanotechnology development and its funding of *societal science and ethics work* has provoked development and piloting of new methods and approaches for engaging diverse publics to participate in experiments in *visualizing and deliberating the future* (see Corner and Pidgeon 2012; Hays et al. 2013). In the course of these, it has demonstrated convincingly that in the upstream, where anticipation necessarily resides, attention to safety is a necessary but insufficient criterion for considering what constitutes responsibility and that broadening the terms of engagement is essential in *upstream engagement and deliberation* (Pidgeon and Rogers-Hayden 2007). A number of these studies have already gone beyond nanotechnologies to examine neuroscience (Hays et al. 2013) and geoengineering (Parkhill et al. 2013), and synthetic biology is next up.
5. *Participation,* which can reference either multi-stakeholder participation or public participation, is a key element of responsible innovation and development. The emergence of responsible development/responsible innovation as an increasingly unified field follows and parallels the so-called deliberative turn, a global repositioning of the role of “the public” upstream, mandating public opportunities to deliberate on and contribute to policy decisions about technological futures in deliberative democracies. In the USA a pivot point for this turn to the analytic–deliberative model for “understanding risk” is the NRC publication by Stern and Fineberg (1996) which lays out the premise of two-way communication between science and society/innovation system and the public(s). Dietz and Stern (2008) assess the impact of this deep move and document the favorable outcomes achieved through public participation in environmental decision making, *when done ethically and competently*. This shift, in spite of the evidence of efficacy, is still emergent, not clearly institutionalized. It tends to construct society as a recipient rather than key and reciprocal actor, and the nanotechnology case materials cited above reveal many issues between the full realization of public participation and the best practices of nanotechnology deliberation. Corner and Pidgeon’s (2012) excellent overview of nanotechnology deliberations around the globe concluded that upstream deliberation of these often futuristic technologies could indeed be highly effective. Lack of formal institutional connections to policymakers impedes their full realization, and scaling up to conducting national level technological deliberation would require a far more substantial investment in the case of converging technologies than has been possible in the USA in the past 10 years of nanotechnology innovation and

development, in spite of the US global leadership in investment in this area of societal research. However, the development and iterative assessment of basic processes for effective deliberation, across a number of national boundaries, signals a very hopeful future prospect for CKTS to achieve the kind of "transformative outcomes for society" upon which it is premised.

The ambivalence upstream leaders (in science and engineering, industry, and government) unquestionably feel about the potential for disruption posed by direct public involvement in decision making has a tendency to drive the system in the USA instead toward "stakeholder engagement" approaches that de-emphasize what are seen as downstream public interests and participants in favor of selected members of the innovation system and key decision makers, in a process that favors the restriction of full open public participation to open calls for invited comments during time-limited public comment periods. These latter, by nature, are indirect, not interactive, and lack the other attributes of deliberative thinking or analytic–-deliberative process.

A key and understated aspect of science and society harmonization processes and practices is that the emergent frameworks and applications for "societal science" to be effective must engage an intrinsically dynamic system. Thus, their introduction into innovation and subsequent life cycle development systems must be a highly iterative process. For full translation of these unevenly developed and institutionalized processes for knowledge generation and integration across time and global space, there must also occur the kind of meta-learning that will transcend these more local and particular practices. This, indeed, is one of the large challenges of convergence of technical and societal knowledge.

Societal Science for Converging and Emerging Technologies

The rest of this chapter presents analyses of the intersections of the five proposed basic principles of CTKS with the unifying societal and ethical aspects of nanotechnologies discussed above. The purpose here is to consider the key societal aspects essential to anticipating and realizing the transformative effects of convergence as envisioned in CTKS. Where relevant, societal aspects of particular different nanotechnology applications are included as case examples, although this can only be highly selective given the enormous breadth of the nanotechnology enterprise. Applications chosen for discussion include nanotech energy, water filtration, targeted drug delivery, personalized medicine, and nanosensors in the environment – all are applications that offer particular promise for the CTKS mission and all have been the subject of extensive societal science research, dialogue, and engagement.

1. The first basic principle described for CTKS is the interdependence of all components of nature and society. The realization of convergence requires advancing such interdependence across scales, with societal scale arguably

midlevel. Social scientists might alternatively call these micro (human), meso (societal), and macro (earth scale/global) scales.

This type of interdependence is a fundamental aspect of a social/ecological perspective and thus integrates environment with society as a fully interactive system. Global environmental and social sustainability of technologies is thus a critical dimension for nanotechnological innovation and development, and this will ramp up in convergence. How do the unifying principles above for societal implications work on nanotechnologies speak to the social/ecological system across scales? The idea of *equitable development* has been a cornerstone of societal work on the global benefits of nanotechnological development and shows both the enormous potential for benefit and the critical importance of key elements of convergence, particularly the need for change in the intellectual property (IP) system currently integral to global capitalism to one of open source innovation for societal benefit (cf Parker and Appelbaum 2012).

In November 2009 CNS-UCSB hosted a large international conference in Washington, DC, at the Woodrow Wilson International Center for Scholars on "Emerging Technologies/Emerging Economies: (Nano)Technology for Equitable Development" (Nov 4–6, 2009) (For more information, see: http://www.cns.ucsb.edu/events/nanoequity2009 and Parker and Appelbaum (2012)) that particularly asked scientists, scholars, and international NGO leaders from around the world, emphasizing the developing world, how to realize the goal of equitable benefit, across the divides of the Global North and Global South, for nanotechnologies for energy, water, health, and food. These nanotechnologies represent four key areas of universal need and highly promising new technology developments, and all speak to the issues of coupled natural and societal systems. Choosing just one of these, energy applications, conference participants reported numerous examples of NGOs developing and distributing nanotech-enhanced solar-powered lighting systems on both individual and household levels, i.e., small scale and highly distributed, functioning in parts of the developing world lacking other power grid infrastructure. Local level participants reported enhanced educational impacts with light for nighttime study as well as ability to pursue cottage industry economic activities. At the same time, this development is proceeding without the environmental detriments of oil and gas industry-based development.

It is useful to think about scale carefully in configuring new systems. As Perrow (1999) has compellingly argued for nuclear industry, new high-risk technologies with high degrees of complexity that are tightly coupled and depend on expert systems of warnings and safeguards are particularly vulnerable to failure, with devastating consequences. The vision for convergence, like these small-scale, local level nanotech energy applications, that focuses on decentered, multi-local, and hence loosely coupled systems may also provide for a world that will not be typified by "normal accidents."

2. The second principle of convergence is based on advancing decision analysis for research and development, such that decision making will be based on deductive system-based knowledge. This principle is entirely consistent with our work in

the CNS-UCSB where the study of multiple party benefit and risk perception is designed to provide evidence about attitudes, values, beliefs, and practices, rather than the current intuition-based system. Thus, in the 10 years of CNS-UCSB research to date, our researchers have developed a systematic set of knowledge about the attitudes about specific nanotechnologies embedded in specific applications, views on risks and benefits, and concerns about governance and responsibility of the key stakeholders in the nanotech enterprise in the USA. Key stakeholders in nanotechnology innovation, development, risk analysis, and management include *academic scientists and engineers* synthesizing novel materials and incorporating them in increasingly complex molecular devices and systems, *toxicologists* working to characterize the hazards of numerous manufactured nanomaterials and nano-enabled products in a large range of environmental and human health contexts, *industry leaders and workers* in businesses ranging from large multinationals to tiny startups and concerned with safety and quality control in larger volume production conditions while maintaining economic viability, and *regulators* attempting to decide a safe course forward that ensures public safety without impeding economic development. Simultaneously there exist multiple "publics," for example, those who are *members of NGOs* with specific active concerns about workplace safety, environmental contamination, consumer product safety, and democratic participation itself, as well as *lay members of the public* who have *implicated* (with or without their knowledge) *interests* in the course development takes and whose views on responsible development may affect market success or failure. Our research on these diverse expert and public stakeholders aims to provide evidence for decision makers that will overcome some of the problems with basing decisions solely on intuitive judgments (by publics or experts).

While the principle as stated aims to replace all inductive knowledge production with deductive system-based knowledge, we would argue that there is an essential place for systematic but nonetheless inductive interpretive qualitative research on the societal side. Thus, our work in CNS-UCSB has systematically conducted decision risk theory-based survey research on representative populations, but the systematic study of deliberative dialogue has been essential in the upstream context where, ironically for the purpose of this discussion, deductive survey data provide people's "fast thinking" intuitive judgments about benefits and risks, often affectively based if they are not well informed, but "slow thinking" deliberative thought and decisions only emerge in this upstream context in the context of longer, deeper deliberative dialogue (cf Kahneman 2011 re: *Thinking, Fast and Slow*). These same distinctions between fast, intuitive thought and slower deliberative thought can apply to experts as well, who can also demonstrate unsupported high confidence (see Kahneman's Chap. 22 on "Expert Intuition: When Can we Trust it?"). As he notes (p. 240), expert judgments are more likely to be sound when knowledge is acquired in predictable, "regular" environments with ample opportunities for practice. Rapid technological change in convergence may well overthrow those conditions. So, particularly in the context of potentially disruptive technological innovation and development, attention to qualitative research focused on knowledge production, dialogue, and "slow thinking" may also be important to the long-term success of the enterprise.

On the issue of whether innovation and entrepreneurs make our society more or less equal, many experts are on the fence, but our friend and colleague Vivek Wadhwa at Stanford/Duke/Singularity University and syndicated columnist at the *Washington Post* argues compellingly that by creating world-changing technologies that provide benefit for all, they are reducing inequality. This is premised, however, on their clear understanding that their achievements are based at least in part on others' contributions and that they have a moral obligation to give back (see Schumpeter's article in the Sep 20 2014 *The Economist* on "Entrepreneurs anonymous").

3. The third principle of CKTS is the enhancement of creativity and innovation via evolutionary convergence–divergence processes, wherein convergence combines existing principles and divergence generates new ones, that create added value in creativity, innovation, and outcomes. This dialectical process is evident in societal work on nanotech, and it is likely to be reproduced in the scale-up to CKTS.

   Thus, for example, the interdisciplinary field of science and technology studies (STS) has developed important insights through convergence of ideas within and across a number of social science and humanity disciplines. Its practitioners come from anthropology, communication, English, environmental studies, history, law, media studies, philosophy, political science, science policy, sociology, and women's and ethnic studies, among many others. This eclectic field has in turn contributed to the evolution of the societal science of nanotechnology, drawing on STS but also forging new collaborations and new fields, marked by the origin of new professional societies (e.g., the S.NET), journals (e.g., *Journal of Nanoparticle Research*; *Journal of Responsible Innovation*), and a robust set of publications and practitioners. The *divergence* from STS has arguably been an essential part of the reconstitution into societal and ethical issues of nanotechnology (SEIN), organizing a new set of collaborations across fields from business to electrical engineering, decision risk science and behavioral economics to global environmental sustainability. This new field is intrinsically international and requires the ability to move fluidly across and beyond disciplinary boundaries. Convergence on the order of CKTS will undoubtedly demand further morphing of societal disciplines to consider the changing conditions envisioned for individualized treatment, care, and education and yet strongly webbed interconnections across the globe.

   To consider but one convergence–divergence track, nanotechnologies' convergence with neuroscience on the scientific/technical side, in progress for some time (e.g., see Hays et al. 2013), is now being enhanced through the US BRAIN Initiative launched in April 2013 by President Obama with a strongly stated goal of "maintaining our highest ethical standards" (Fact Sheet: BRAIN Initiative | The White House.pdf Apr 02, 2013; downloaded on 2/6/14 from http://www.whitehouse.gov/the-press-office/2013/04/02/fact-sheet-brain-initiative). To do this, the US Presidential Commission on Bioethics was tasked with launching an assessment (still in progress), and the NNI societal science and ethics base offers a particularly apt template. However, to date, the Commission seems likely to focus on bioethics approaches alone and on issues of ethics research rather narrowly bounded, rather than the broader societal implications work of the NNI. Unless funding is ramped up very substantially, it is easy to anticipate that there will be little societal science in this initiative beyond the routine bioethics base (important though that is), in spite of well-advanced convergence on the technical side in areas such as cognitive enhancement. One form of evidence for this view about the skewness of convergence across technical vs. social issues is the insistence on the need for scientist autonomy from societal involvement in innovation decision making that was strongly evident at the Commission's hearings in Washington, DC, 10–11 February 2014 in response to testimony by NNI societal researchers Harthorn (director, CNS-UCSB) and Fisher (researcher, CNS-ASU). Another point of retrenchment (from a CKTS and societal point of view) was the contestation by the Commission of the introduction of the term "societal" to encompass issues beyond "ethics" by both societal nanotechnology experts giving testimony (http://bioethics.gov/node/2875).

4. The fourth principle of CKTS is the utility of *high-level cross-domain languages* to generate new solutions and support transfer of new knowledge. From a social science perspective, understanding and tracking new emergent modes of communication, both interpersonal and within systems, are also reflective of and conducive to new modes of interaction of the kind envisioned in the CKTS model. Here, too, societal work on nanotechnologies and the diverse communities of scientists and engineers engaged in their co-construction provide, for example, the analysis of modes of collaboration and the generation of new communities of scientific practice in the emergent/convergent technology context. These communities and the exchanges among them are critical to the invention and convergence processes.

   One example of this is the work by CNS-UCSB collaborator Cyrus Mody of Rice University in his award-winning volume *Instrumental Community: Probe Microscopy and the Path to Nanotechnology* (2011). In this volume, Mody (both a Harvard-trained engineer and Cornell-trained societal issues researcher) studies the way new scientific communities formed rather swiftly around new scientific equipment, in his case the scanning tunneling microscope (STM), and through their collaborative interactions across multiple disciplines, universities, and firms in conferences and other meeting places jointly developed new modes of practicing science, giving new meaning to the instrumentation and advancing entire fields, in this case, nanotechnologies. The social processes for integration of these fields warrant such study in addition to tracking the development of the kinds of hybrid linguistic practices. Gorman's (2010) volume on *Trading Zones and Interactional Expertise* draws attention to the kinds of interactional expertise needed for successful navigation of such emergent, interdisciplinary spaces, emphasizing that language alone is not enough for such expertise, which depends in much larger part on more subtle aspects of “tacit and situated knowledge” (Collins et al. 2010, 13). This argument also provides additional basis for not overthrowing all inductive research in the rush to validate decision making in convergence. The kind of tacit knowledge and understanding used by local level organizations and scaled up in convergence are far more readily studied by systematic qualitative research, often necessarily inductive in the initial stages.

5. The final principle in CKTS is the value of vision-inspired basic research embodied in “grand challenges.” This principle applies equally to societal science and innovation science. The crucial aspect from a societal benefit standpoint is that such basic research is inspired to solve pressing human societal and global environmental problems and as such needs to be developed within rather than outside the responsible innovation and development framework described above. Such work will necessarily be “upstream” but that is precisely where participatory engagement and dialogue are important. It is also essential that innovation scientists are socialized (i.e., educated, formally and informally) into modes of literacy and interaction with societal researchers, such that possibilities for two-way communication are welded into the template. Because an invention is “basic” does not mean it should happen in some boxed off space “outside” society.

   Indeed, both NNI societal centers, CNS-UCSB and CNS-ASU, have worked extensively to integrate societal understanding into the nanoscientific and nanoengineering research enterprise, and this work provides a record of interest and relevance to CKTS. Such work includes, at CNS-UCSB, systematic study of expert judgments about benefits and risks of nanotechnologies, e.g., for environmental remediation (Beaudrie et al. 2013), that indicates that even in the early days of innovation and basic research, experts attach values to different kinds of applications and that in theory anyway they can shift decisions and studies in directions that will foster such pathways. In addition, center organization and structure at UCSB has permitted extensive socialization of nanoscientists- and engineers-in-training into the motivations, languages, and practices of societal science and the precepts of responsible innovation through a dedicated S&E Fellows program. This has been one path toward convergence of technical with societal. Yet another at UCSB has been the consistent introduction of societal science into the interdisciplinary research space of the physical scientists and ecologists researching nanomaterial environmental toxicity in the NSF- and EPA-funded UC Center for Environmental Implications, where this author (Harthorn) has served as a group leader and member of the executive committee since the inception of the CEIN in 2008. CNS-ASU has a similar repertoire of “integration” activities. All of these would argue strongly against bracketing off “basic” research from its upstream societal nexus. Directing such work in paths that could lead to the solution of the kind of grand challenges for societal, human, and planetary well-being and development should not be regarded as a threat to the integrity of “basic” research but rather offers the promise that such work will contribute to core scientific knowledge production as well as fostering innovations for the betterment of the world and its inhabitants, human and others.

Summary/Conclusion

Normative ethical statements permeate the CKTS Report (Roco et al. 2013). Indeed, CKTS is defined in terms of what is good for society, using a normative framework of responsibility. In representations about CKTS, the technical system is bracketed top and bottom by ideas of doing good as the aim, via “societal benefit” and “human development” and taking responsible action in the form of “innovative and responsible society and governance” and “value system and morality” as the foundation. Societal researchers from the nanotechnologies research realm would applaud this encompassing of the science by society. Yet, the platform of societal research on nanotechnologies also offers a number of questions or cautionary notes on the nonproblematic delivery of such aims, beginning with the need to validate what constitutes “societal benefit” empirically and extending across all the basic principles offered for CKTS.

The opportunity to consider how to scale up from the knowledge of responsible innovation and development, governance, and participation gained from nanotechnologies’ R&D in the USA and abroad is a welcome one. The report (2013) reiterates throughout that “deliberate planning and concerted action” vis-a-vis ethical and societal implications are an essential component for success. This chapter has considered the key societal aspects essential to anticipating and realizing the visions for CKTS.

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Part VI

Convergence in Education

Reconceptualization of Education

R. P. H. Chang, Jennifer Shanahan, and Matthew Hsu

Contents

Abstract

The idea that one completes one's education – majoring in one field to prepare for a specific career and then leaving school to work until retirement – is

R.P.H. Chang (✉) • J. Shanahan • M. Hsu
Materials Research Institute, Materials Science and Engineering, Northwestern University, Evanston, IL, USA
e-mail: r-chang@northwestern.edu; j-shanahan@northwestern.edu; mhsu.northwestern@gmail.com

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obsolete. Educational institutions will need to transform themselves fundamentally to incorporate a new convergent culture that unites all fields while providing personalized instruction to meet the individual needs of each person, as those needs evolve over the lifetime. The new culture will be shared by new ecosystems of teachers and learners whose interactions will extend beyond the classroom to incorporate perspectives from all sectors of society. This chapter introduces a four-dimensional framework for developing and sustaining a convergence culture in education.

Introduction

What Is Convergence Learning?

Convergence technologies respond to complex systems-based challenges. The phenomenon of global climate change, for example, is the result of greenhouse gases accumulating in the earth's atmosphere. Causes include the burning of carbon fuels for electricity and transportation as well as construction and agricultural activities, forestry, industrial processes, and waste management. Effects include an increase in droughts, tropical storms, and coastal flooding, which are destroying the earth's ecosystems and threatening food and water supplies worldwide. Understanding and addressing the many causes and ramifications of climate change will involve the systems-based study of energy, environment, health, and many aspects of human behavior, from how we travel to what we eat – behaviors that are influenced by history, geography, cultural and aesthetic values, as well as by legal systems, and economic and environmental conditions. It will also require an understanding of how businesses, governments, and communities operate and are motivated to effect change.

Convergence learning derives its characteristics from those of convergence technology:

1. Knowledge intensive: Convergence learners must be prepared to acquire and retain larger amounts of information, beginning earlier in their learning careers and continuing over their lifetimes.
2. Systems based: Learners must be able to synthesize information from many sources, apply it in diverse settings and contexts, and understand how the individual parts of a system interact with each other to produce complex outcomes.
3. Fast-paced: The rapid evolution of convergence technologies calls for early and constant exposure to the latest research and applications and greater flexibility in knowledge acquisition and career training.
4. Collaborative: Because convergence technologies must incorporate many viewpoints and types of knowledge, students must learn to collaborate in diverse environments, transcend jargon, and leverage complementary perspectives.

5. Global: Because convergence technologies respond to global challenges, they require much higher levels of global coordination and collaboration. Learners must develop early awareness of global cultures, infrastructures, languages, geographies, economies, and comparative strengths in R&D.

What Is Convergence Culture?

Culture is defined as “the set of values, conventions, or social practices associated with a particular field or activity.” The field of convergence education is concerned with the development of global workforce, citizenry, and institutional networks prepared to solve convergence challenges in a collaborative mode. This chapter will discuss four axes of integration needed to foster a sustainable convergence culture at all levels of education:

1. The vertical axis represents integration over time – a continuum across grade levels and life stages to train a convergence-ready citizenry and workforce.
2. The horizontal axis represents integration across disciplines, i.e., how the physical and life sciences, technology, engineering, and mathematics (i.e., the “STEM disciplines”) must intersect with the social sciences and humanities to support the rapid development and widespread adoption of convergence technologies.
3. The third axis represents the crosscutting societal and economic relevance of convergence technologies, which motivates stakeholders from different sectors and disciplines to support and participate in convergence learning.
4. The fourth axis represents the integration of education settings and methodologies to support convergence learning inside and outside the classroom. This includes a blending of formal and informal methods and personalized or individualized learning.

This four-dimensional framework is illustrated in Fig. 1.

Each axis contains a set of associated values and practices that will evolve over time. Examples are described below.

Vertical Integration

Vertical integration means seeing education as a lifelong venture and a long-term investment. Educational content and practices must be conceived and implemented in the context of a continuum across grade levels and life stages, from elementary school into college, professional and civic life. Gaps in this continuum can dampen the return on educational investments. For example, although the USA spends more on education than any other developed nation (Organisation for Economic

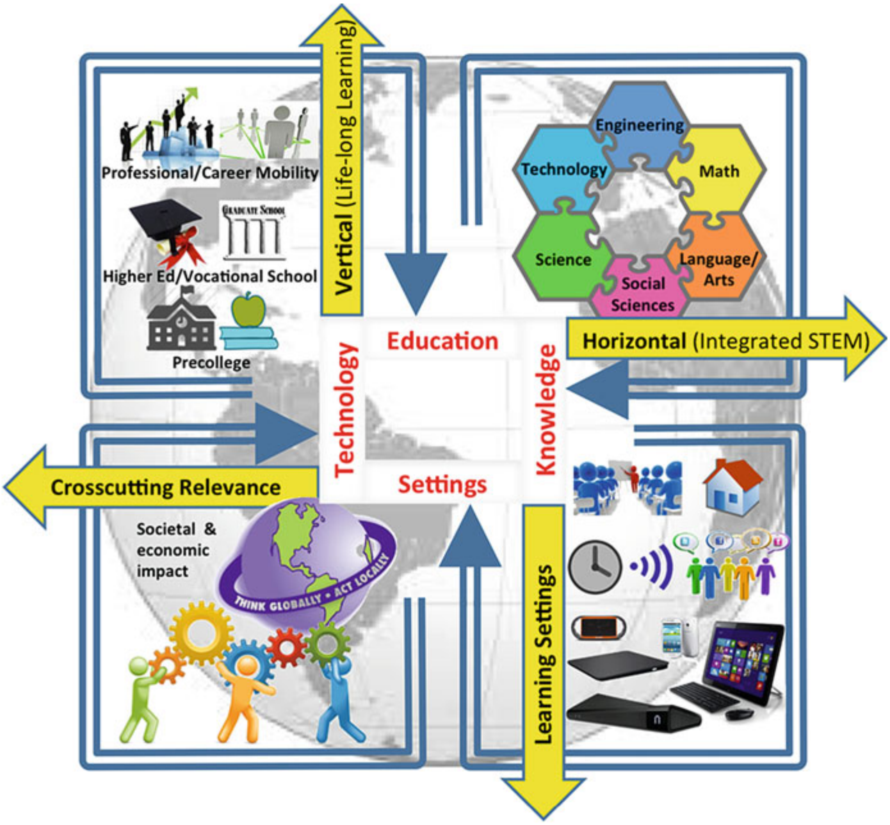

Fig. 1 A four-dimensional framework for convergence learning (Copyright R.P.H. Chang, Jennifer Shanahan, and Matthew Hsu)

Cooperation and Development 2013), its students consistently score below their international peers in math and science (National Center for Education Statistics 2014).

From one level to another, there may be gaps in *knowledge* (e.g., new research findings and technology applications may not be reaching the classroom), *capacity* (e.g., teachers may lack training and schools may lack resources to purchase up-to-date content), or *perspective* (e.g., high school teachers may not know what knowledge and skills their students will need to succeed in college and students may lack career awareness). Such gaps result in a pyramid structure (Fig. 2a) in which too many students leave the system before reaching higher levels of learning and too few become leaders and innovators who can support the convergence economy.

Convergence challenges require increased innovation and leadership across all sectors and segments of society. Therefore, convergence education must aim to

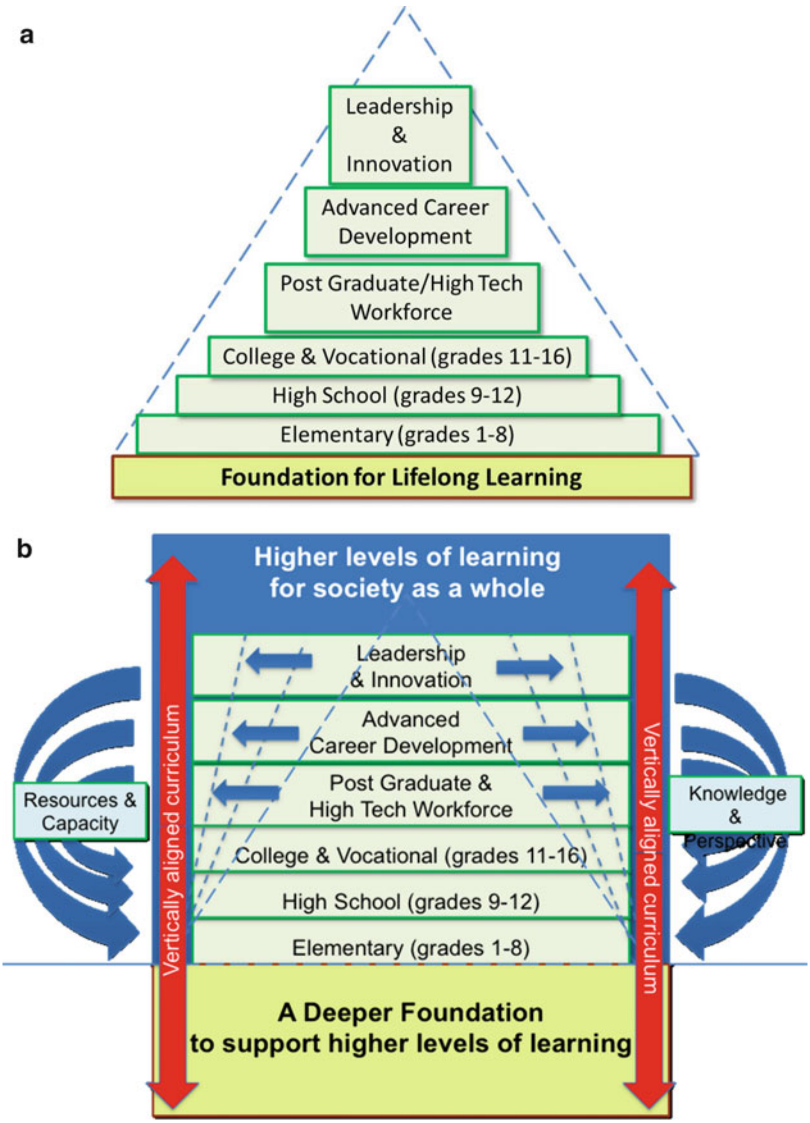

Fig. 2 (**a**) Pyramid structure: Although all learners start out in precollege (which is universal and compulsory), many do not finish high school, and relatively few will attain advanced degrees. Still, fewer will go on to become leaders and innovators in their professions and communities (Copyright R.P.H. Chang and Jennifer Shanahan). (**b**) Tower structure: Transferring knowledge, perspective, resources, and capacity from higher levels into lower levels will advance learning and integrate the curriculum across levels, aligning it with the needs of the future and creating a deeper foundation for advanced learning. Investing strongly at the precollege level (grades K–12) will prepare all students for the convergence economy (i.e., pull out the sides of the pyramid) and build a knowledge-based society from the ground up (Copyright R.P.H. Chang and Jennifer Shanahan)

increase knowledge and skills for *all* citizens and workers. The pyramid must be transformed into a tower (Fig. 2b), with sides pulled out to encompass all learners, and a deeper foundation that will support increased levels of learning for society as a whole. Both aspects of this transformation will require a strong focus on the precollege level, where the majority of the learners can be reached early in their careers and where knowledge and capacity can be increased *from the bottom up*.

This process will also require a cultural shift toward vertical collaboration: Academics and professionals must be willing to reach down into lower grade levels in order to strengthen the curriculum and raise the quality of instruction, while precollege educators must be willing to reach up into higher levels of study and practice to better understand the challenges their students will face in the future. The result of this cooperation will be an uninterrupted continuum of learning for the individual and consistent long-term benefits for society as a whole.

Several important aspects of vertical integration are discussed below.

Coherent Learning Trajectories

A civil engineering principle states that the taller a building is, the deeper its foundation must be. Convergence learners must not only acquire higher levels of knowledge than previous generations; they will also have to master it deeply enough to apply it in many different contexts and build upon its foundations for the rest of their lives. Yet the US precollege curriculum – often called "a mile wide and inch deep" (National Governors Association Center for Best Practices 2010) – does not prepare them for this challenge.

The typical progression of science education shows how disjointed the learning experience can be for students: Although the elementary curriculum allocates very little time for science instruction, K–5 students are exposed to a large number of science topics – in most cases by teachers who are unprepared to teach them in depth. As a result, they arrive in middle school (grades 6–8) without the background knowledge needed to grasp the still larger number of topics they are presented with. By the time they enter high school (grades 9–12), they are unprepared to succeed in high school level science. Whereas middle school taught science in an interdisciplinary way, high school introduces a series of seemingly unrelated courses in biology, chemistry, and physics containing disciplinary jargon they have never seen before. Many of their teachers hold college degrees in science and therefore have much higher academic expectations than their teachers in middle school. Meanwhile, the pressure is on for them to succeed on high-stakes tests and make important decisions about college and careers.

This lack of coordination wastes resources and fails students, particularly in terms of college readiness. One recent study found that two-thirds of science majors do not graduate with a science degree because they discover (too late) that they are unprepared to succeed academically (Stinebrickner and Stinebrickner 2014). This college readiness gap is not limited to science. According to another recent study, nearly 60 % of US college students are required to take remedial courses in English or mathematics (National Center for Public Policy and Higher Education 2010).

Building a Deeper Foundation: *Students could learn more, faster, and more deeply if foundational concepts were introduced earlier and systematically reinforced over time*. According to Michigan State University scholar William Schmidt, countries that are successful in math and science education pay much closer attention to the sequencing of topics and the pace of study, teaching a smaller number of "foundational concepts that make complicated processes understandable later on." This aspect of vertical integration is a "key conceptual shift" of the new Common Core State Standards for Mathematics (CCSSM), which call for "greater focus on fewer concepts" and "coherence across grade levels" (National Governors Association Center for Best Practices 2010). The Next Generation Science Standards (NGSS) issued in 2010 emphasize the study of "disciplinary core ideas" and present learning progressions outlining their study "over multiple grades at increasing levels of depth and sophistication" (NGSS Lead States 2013). "Increasing levels of depth and sophistication" are precisely what is needed to build a higher "tower of knowledge" as illustrated in Fig. 2b.

Foundational Concepts for Convergence Learning: Convergence learning trajectories will have to span grades K–16 and beyond, including vocational study and lifelong education to support career mobility and civic engagement, as discussed in the chapter by Anne Collins McLaughlin, "▶ Life-Long Learning." However, in the case of emerging technologies, there may not be agreement on what the foundational concepts are or how to introduce them to different age groups. The chapters by Chang, Shanahan, and Hsu, "▶ Precollege Convergence Education" describes the effort by the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) to identify core nanotechnology concepts and develop learning progressions for each of them. "One of these concepts was surface-area-to-volume ratio" (SAV) for which a partial learning progression is outlined in Fig. 3.

Nanostructured materials have very large SAVs, which give them many of their unique properties. Therefore, a strong grasp of SAV is essential to understanding nanotechnology. Given that the concepts of ratio and function are taught individually in middle school math, one would expect freshmen engineering students to readily grasp SAV and be prepared to study its applications. Yet most do not.

If SAV were introduced as an application of middle school math and reinforced throughout high school, students might master it deeply enough to begin performing nanotechnology research and development in their freshman year of college! This is an illustration of how deep mastery of foundational concepts (in this case, ratio and function) can accelerate the pace of learning and ultimately advance scientific discovery and technology development. The example cited here represents a 2- to 3-year advance in knowledge and skills acquisition. Undertaken consistently in US schools, this approach would significantly raise the starting level of vocational training, prepare future scientists and engineers to make the most of their time at research universities, and pave the way for the rapid adoption of convergence technology. To reap these benefits, foundational concepts will have

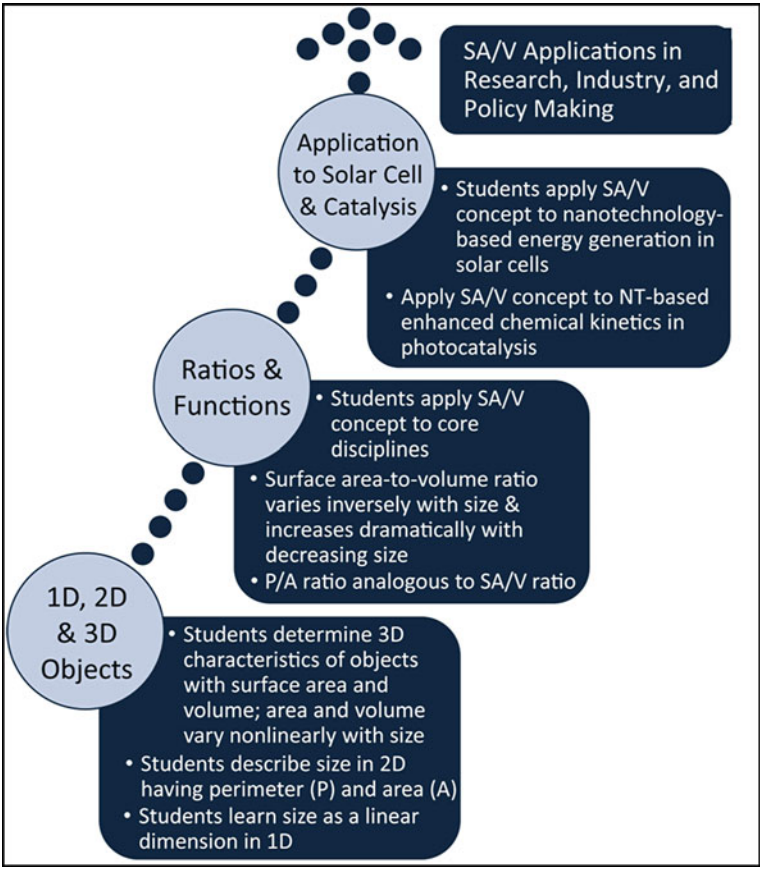

Fig. 3 Partial learning progression for surface-area-to-volume ratio (Copyright R.P.H. Chang and Matthew Hsu)

to be taught in the context of new laboratory research and technology applications, as described below.

The chapter by James Murday, "▶ Norms and Standards of Learning" discusses the development of *assessments and learning standards for emerging and converging technologies*, which are effectively moving targets. Adding to the complexity of the task, foundational concepts for convergence learning will have to be systems based, incorporating perspectives from STEM, the humanities, and the social sciences. This systems approach is discussed more fully in the section on Horizontal Integration.

Early Exposure to Emerging Research and Technology

Today's basic discoveries will become tomorrow's innovations. Convergence learning requires sustainable mechanisms for rapidly and systematically transferring emerging research and technology applications from laboratories and markets into classrooms.

Modular content is best suited for this purpose because it is more flexible than textbooks and far easier to update (Young 2014). The chapter by Chang, Shanahan, and Hsu, "▶ Precollege Convergence Education" describes a series of vertically integrated modules designed to transfer academic research into precollege classrooms (Materials World Modules). This successful model illustrates three essential elements for transferring new research into classrooms: First, new research must be grounded in foundational STEM concepts. This deepens understanding and supports linkages to learning standards, which is essential for teachers and schools. Second, content development must involve teachers, researchers, and practitioners from all levels. This simultaneously strengthens teaching capacity while ensuring that the resulting content will implement coherent vertical learning trajectories. Finally, content must engage students in hands-on scientific inquiry and engineering design work, which supports retention of foundational concepts and helps students understand that R&D is an iterative, collaborative process.

New mechanisms are also needed to transfer research into undergraduate classrooms. The visionary "Boyer Report" (Boyer Commission on Educating Undergraduates in the Research University 1998) calls on research universities to "make research-based learning the standard," including an inquiry-based freshman year and a "capstone" research experience to reinforce understanding. It also suggests ways to reward faculty who transfer their own research into classrooms and involve undergraduates in the research process.

Vertical Teacher Development

Convergence teachers will have to master a more rigorous curriculum, including advanced research concepts and the hands-on practice of scientific inquiry and engineering design as mandated by the NGSS. This presents a significant challenge given the lack of science background and professional development among precollege teachers, particularly those in grades K–8.

Contributions from academic, industry, and government labs are needed to improve teacher capacity. Teachers, like their students, must learn core concepts in depth so they can present them coherently to different age groups. They must also have more opportunities to perform laboratory research and transfer what they learn – concepts and practices – back into their classrooms. One successful model is the NSF-funded Research Experiences for Teachers (RET), which invites high school teachers to perform research alongside university faculty. There are currently more than 450 RET sites across the USA, many located in NSF-funded research centers (National Science Foundation 2014). This well-established model should be expanded to serve more teachers at all levels and incorporate the systematic development of modular instructional content as described above. Sites might also be established in industry and government labs.

This type of vertical collaboration will not only motivate teachers and improve the level of instruction; it will also help to build consensus on how to prepare students for college and the workplace. A recent report on college readiness cited *disconnected expectations* as the "overarching reason" why many students are unprepared for college – "There will be a gap between what high schools teach and what colleges expect as long as the two sectors do not develop expectations jointly" (National Center for Public Policy and Higher Education 2010).

Early Career Awareness and Skills Development

College is traditionally where students are encouraged to explore and prepare for potential careers. However, convergence careers will be more knowledge intensive and evolve more rapidly than those of previous generations, and to keep pace with these needs, convergence learning will have to offer earlier career awareness and skills development.

Career Awareness: Precollege students must be given opportunities to explore their own aptitudes in connection with different fields. These explorations should take place over a period of years to allow for an evolution of student interests and capabilities. Given time and perspective, students will be able develop the knowledge and skills needed for the jobs they want. In this way, vertical integration will let them optimize their career choices based on not only what they are currently "good at," but also what they are inspired and motivated to achieve. This shift alone will greatly improve the quality of the convergence workforce, which will be driven in large part by civic responsibility, i.e., the desire to help solve the world's complex challenging problems.

By getting an earlier start, students will also be able to improve the quality and focus of their college and vocational training. Currently, most students enter college without having chosen a major, and most will change majors at least once before they graduate. This exploration is time consuming and very costly: Two-thirds of college students graduate with some level of debt and the total national student loan debt exceeds $1.2 trillion, which accounts for 6 % of the overall US debt in 2013. With a career path and their own interests and aptitudes in mind, they can prepare to take more advanced courses and incorporate greater flexibility into their vocational training, including the interdisciplinary connections required for convergence careers.

Early Development of Workforce Skills: A recent study of career and technical education (CTE) in the USA conducted by the Organisation for Economic Co-operation and Development (OECD) found that the basic skills of US high school graduates are "relatively weak compared with many other OECD countries" (Kuczera and Field 2013). Meanwhile, ACT – the company known for its ACT college readiness assessment – recently conducted a national assessment of "work readiness" that tested mastery of three foundational work skills: "reading for information," "applied mathematics," and "locating information" among workers and job seekers possessing different levels of education (ACT 2013). The study found that “significant foundational skills gaps exist” between the skills of examinees and the skills needed for jobs. It also found that “higher levels of education do not always guarantee work readiness.” For example, fewer than half of examinees possessing a higher education could meet the “locating information” skill requirements for jobs that required higher education. This skill involves the ability to “locate, synthesize, and use information from workplace graphics such as charts, graphs, tables, forms, flowcharts, diagrams, floor plans, maps, and instrument gauges.”

Both reports recommend earlier career guidance and skills acquisition, including “authentic learning experiences that incorporate work readiness standards into K–12, postsecondary, and career and technical education” (ACT 2013). There is a growing trend in high school; career academies are being used to improve career linkages, build skills, and reduce dropout rates. The Rockford Public Schools recently implemented career academies in all of its high schools, where ninth grade students explore different career sectors before committing to a theme-based study track for grades 10–12. There are an estimated 2,500 career academies nationwide, each serving between 150 and 200 students in grades 10–12 (Kemple 2008). As more research emerges on their effectiveness, this model might be expanded to serve more students at younger ages and involve a wider range of institutions including research centers. Project-based learning (Boss et al. 2013) should be emphasized to ensure that students master skills as well as concepts. In addition to the career shadowing that such programs offer, precollege students might also be allowed to shadow undergraduate and graduate students so they can learn what will be expected of them in college-level degree programs.

Horizontal Integration

Solving convergence challenges calls for a flexible, highly integrated understanding of the STEM disciplines, the social sciences, and the humanities (Roco et al. 2013). Horizontal integration aims to improve connections among these disciplines, which have traditionally been taught and practiced separately. In his book entitled *The Innovators: How a Group of Hackers, Geniuses, and Geeks Created the Digital Revolution*, Walter Isaacson emphasizes the collaborative nature of innovation in the digital age, particularly the importance of interdisciplinary collaborations that “blend technology with humanity.” One of his most compelling examples was how the concept of computer programming was inspired in the 1800s when a mathematician observed the creation of tapestries on industrial looms (Isaacson 2014). This kind of insight will be vital to solving convergence challenges, which are inherently crosscutting and systems based.

Horizontal integration is not only needed to inspire the development of convergence technology but also to support its widespread implementation. For example, the United Nations has established the goal of reducing global CO_2 emissions by 70 % over the next 15 years (Intergovernmental Panel on Climate Change 2007). Meeting this ambitious goal will require unprecedented levels of global cooperation and planning. Every citizen will have a role to play, regardless of age or profession. Language skills, diplomacy, global awareness, and cultural literacy will become still more valuable. Economic development factors will come into play: History tells us that the first burst of CO_2 emissions came from the Industrial Revolution in Europe and the Americas, and today, the fastest growing economies are still the fastest growing producers of CO_2. Historical perspective will be needed, together with legal, political, economic, technical, and business expertise, to help these nations leapfrog their more developed peers in terms of CO_2 production. Designing efficient new technology that will be widely adopted by consumers and organizations around the world will require an understanding of business, economy, fine art (aesthetics), psychology, and sociology, including the influence of peers and social networks on technology adoption. Writing, visual arts, and other new forms of communication will be needed to educate, inspire, and inform consumers to use the new technology.

While vertical integration strategies focus on reinforcing core concepts over time, horizontal integration emphasizes the systems-based study of convergence themes that unify and integrate these concepts across disciplines. Horizontal integration supports convergence learning in three important ways:

(a) *Deeper, more flexible learning*: With the proper focus, repeated exposure to core concepts in different disciplinary settings can deepen understanding and make it more flexible, preparing students to apply knowledge in a variety of contexts.
(b) *New collaborative dynamics*: Each discipline, from chemistry to psychology, has its own well-established knowledge base, methodologies, and unique perspective, and each is continually developing new tools, theories, and concepts. According to the National Academies, blending these assets can "advance fundamental understanding or solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (Committee on Facilitating Interdisciplinary Research, Committee on Science, Engineering, and Public Policy 2004).
(c) *Systems thinking*, i.e., the ability to analyze how parts of a whole interact with each other to produce overall outcomes in complex systems goes beyond interdisciplinarity to help learners "see events in the larger context of a pattern that is unfolding over time" and "identify the leverage points that lead to desired outcomes" (Waters Foundation 2014). This type of critical thinking and problem solving will be essential in the convergence economy where systems-based research challenges will be the norm.

Status of Horizontal Integration

Higher education has been largely successful in transitioning to a horizontal approach, thanks to flexible curricula and policy guidance from federal sponsors. Over the last 25 years, sponsors like the National Science Foundation (NSF) and the National Institutes for Health (NIH) have encouraged interdepartmental collaboration and established hundreds of interdisciplinary research centers across the country. Examples include the NSF-funded Materials Research Science and Engineering Centers, which unite researchers from biology, physics, chemistry, and engineering, and the National Cancer Institute-funded Centers of Cancer Nanotechnology Excellence (CCNEs) and Physical Sciences Oncology Cancer Centers (PSOCs), which bring physical scientists and engineers into medical schools. Over the last 15 years, interdisciplinary research and education programs have begun to incorporate the social sciences as well. For example, the chapter by Carol Van Hartesveldt, "▶ Integrative Graduate Education and Research" discusses the successful Integrative Graduate Education and Research Traineeship (IGERT) program, launched in 1998 to provide interdisciplinary graduate education spanning science, technology, engineering, mathematics, and social sciences.

Investments like these have begun to produce changes to the academic research structure (e.g., hybrid schools and colleges like Berkeley's College of Natural Resources, which includes departments of Agriculture, Economics, Environmental Science, Policy, Management, Nutritional Science, and Plant and Microbial Biology), changes to the college curriculum (e.g., new undergraduate degree programs in areas like nanoscience and sustainability), and a convergence in methodologies between the behavioral/social sciences and the physical/life sciences (Roco et al. 2013.)

Changes like these are laying the groundwork for the true blending of minds and methods that convergence requires. In the words of one author, "Genuinely interdisciplinary researchers publish in or between several different fields, moving to and fro over time. The result is greater openness and transparency about the diversity of ways to understand and address particular problems" (Stirling 2014). According to a study by the World Technology Evaluation Center (WTEC), convergence will require "the adoption of high-level cross-domain languages to support transfer of new knowledge and to generate new solutions" (Roco et al. 2013). With this long-term ideal in mind, the chapter by Mark Lundstrom discusses interdisciplinary study as an intermediate step to developing a convergence perspective among graduate students.

Achieving this level of flexibility will require training from an early age. However, to date, horizontal connections have not yet permeated the precollege level, where disciplinary silos are still the norm and where several barriers impede horizontal integration. In the first place, precollege curricula are closely tied to learning standards and standardized tests and are therefore more rigid than those in higher learning. Second, precollege teachers have limited opportunities to collaborate with peers from other disciplines. Finally, vertical gaps separate most precollege teachers and students from the interdisciplinary research being performed in academic and industrial laboratories.

The first challenge is to integrate the precollege curriculum for teaching science, technology, engineering, and mathematics (STEM), which, according to a 2009 report by the National Research Council, "does not reflect the natural interconnectedness of the four STEM components in the real world of research and technology development" (Committee on Engineering Education 2009). The most glaring deficiency is the near absence of engineering from the curriculum. Without engineering, which constitutes both the "T" and the "E" in STEM, students do not learn how to apply math and science concepts to real-world challenges – the basis for innovation and technology transfer. The report found that in 2009, engineering education was only "slowly making its way into US K–12 classrooms" – a situation that persists at this writing.

Math deficiencies are another serious problem. According to a study by the Organisation for Economic Co-operation and Development, US high school students consistently score below their global peers in math and are particularly weak in performing math tasks with higher cognitive demands, such as taking real-world situations and translating them into mathematical terms. Math skills are critical to STEM workforce development in several respects: First, math self-efficacy beliefs (i.e., confidence) are a primary factor influencing a student's decision to major in STEM. Secondly, math deficiencies are a leading cause of student attrition from college-level STEM programs.

The "S" in STEM also needs attention. In most high schools, biology, chemistry, and physics courses are taught independently, without much coordination among them. This approach does not lend itself to understanding emerging research, which tends to be crosscutting. For example, two of the most impactful technological fields of the next century – nanotech and biotech – are inherently interdisciplinary, driven by the myriad properties of naturally occurring and man-made materials: structural, chemical, mechanical, electrical, optical, and so on.

Fortunately, new national learning standards are calling for a greater integration of STEM disciplines at the precollege level. For example, the three-dimensional Next Generation Science Standards, issued in 2013, incorporate engineering at all levels: Dimension 1 emphasizes the practice of scientific inquiry and engineering design, Dimension 2 defines "crosscutting concepts" that apply across science and engineering fields, and Dimension 3 defines "disciplinary core ideas" with "broad importance across multiple sciences or engineering disciplines." The Common Core State Standards for Mathematics (CCSSM), released in 2010, call for a more "rigorous" US math curriculum that "pursues conceptual understanding, procedural skills and fluency, and applications with equal intensity" – a goal that cannot be reached without stronger connections to science and engineering.

Understanding and addressing complex convergence challenges like climate change will require a broader definition of STEM integration that encompasses the social and behavioral sciences, humanities, and arts. Here, too, the new precollege standards are pointing the way. For example, the NGSS designate "societal and environmental impact" as a "core disciplinary idea," together with other ideas that are "relevant to the interests and life experiences of students." The Framework for 21st Century Learning prescribes a set of "interdisciplinary twenty-first century themes" like "global awareness" and "civic literacy" to unify and deepen understanding of core subjects and place them in a broader context. The Common Core State Standards for English Language Arts encompass literacy in science and technical subjects as well as history and social studies and require proficiency in "argumentative and informative writing" and communication that is "grounded in evidence."

Strategies for Horizontal Integration

Thematic curricula should be developed to teach convergence topics from a systems perspective. Curriculum development should involve horizontal (and vertical) teams of teachers, scientists, visual artists, engineers, writers, and business and policy experts. The convergence themes will attract participation from different sectors, and the collaborative development process will begin to break down the long-standing barriers in culture, methodology, and perspective that exist among these disparate groups.

Implementing the new curricula will require a cultural shift toward horizontal collaboration. This shift can be seeded through:

(a) Co-teaching of existing curricula using convergence topics as unifying themes: Originally used in special education, co-teaching is now being applied in mainstream classrooms, including those at top universities. Benefits of co-teaching include professional growth, support, and motivation for teachers, a greater sense of community in classroom and schools, smaller student/teacher ratios, and improved coordination.
(b) Project-based learning (PBL) challenges (Boss et al. 2013) that unify the thematic study of interrelated topics and bring teachers together in a collaborative mode. The highest level of co-teaching is team teaching, wherein both teachers share the planning and instruction of students in a coordinated fashion. Improved coordination will be especially important in reinforcing core concepts across disciplines rather than introducing redundancy and confusion.

One example that combines both approaches is the "expeditionary learning" at King Middle School in Portland, Maine (Edutopia 2010); students join collaboration teams to carry out school-wide projects that cut across STEM, the social sciences, and the arts; teachers work together to design project frameworks, provide background knowledge, and support student-led inquiry; class schedules are shifted to accommodate the goals of the project. Programs like this one have the potential to create a new philosophy of inclusion and trust among teachers from different disciplines, which will be needed to implement thematic curricula and pave the way for partnerships outside the classroom. Provided they are grounded in foundational concepts and coherent learning progressions, they can also advance learning and prepare students for success in college and the workplace.

Crosscutting Relevance to Society and the Economy

Convergence challenges, which involve driving questions from STEM and the social sciences, are relevant to stakeholders across all sectors of society and the economy. Governments, companies, academic institutions, community organizations, and individual citizens will all have an interest in and a role to play in solving them. This shared interest or "crosscutting relevance" will become the basis for new learning communities whose members consider convergence learning as essential to every aspect of the R&D cycle *and* are willing to contribute accordingly to ensure its effectiveness.

The new communities will be systems based and dynamic, with knowledge, capacity, and resources flowing in all directions. Members will frequently exchange roles, sometimes acting as teachers, other times as learners, and still other times as sponsors or advocates for the development and implementation of new convergence practices. These interactions will foster the vertical and horizontal integration needed for convergence learning. Here are some examples of contributions from (and benefits to) various sectors.

Public Contributions to Education and Technology Development

New technologies can have little impact unless they are widely adopted by the public. Whereas the academic and professional sectors are segmented, the public connects these sectors through a network of social, civic, and professional relationships. For this reason, the public can offer unparalleled perspective on what makes a new technology timely, effective, and successful.

Convergence professionals must learn to involve the public in every aspect of the R&D process to ensure the feasibility and appeal of new technology. Input from end users will provide the basis for "user-centered design" (Norman 1988), which will pave the way for widespread adoption. The public, motivated by civic responsibility, can be an important driving force behind the development and adoption of new technology. Cross-generational collaboration (Isaacson 2014) can play an important role in this process. For example, young people not only have unique perspective on what makes for the next must-have technology (e.g., iPhone) but as the inheritors of the future, they can be inspirational leaders in the adoption of new technology designed to solve global problems, particularly with new communication tools (e.g., social media) at their disposal. Meanwhile, older adults can inspire change by offering historical perspective and generational insight.

Employer Contributions to Convergence Learning

Employers clearly have a strong motivation to contribute to education. Historically, most of these contributions have been made in higher education where career development has traditionally taken place and where companies can simultaneously invest in basic research that supports their own R&D. Industry also performs collaborative research with university faculty through programs like the NSF-funded Science and Technology Centers (discussed in the chapter by Dragana Brzakovic, "▶ Academic Research Centers: Platforms for Convergence of Science, Technology, and Innovation"), which support "partnerships among academic institutions, national laboratories, industrial organizations, and/or other public/private entities." Although valuable, these contributions have proven insufficient to develop a strong S&T workforce in the USA. In a recent State of the Union Address, President Barack Obama lamented the workforce gap in science and technology where "business leaders can't find U.S. workers with the right skills" and where "there are twice as many openings as we have workers who can do the job" (White House Office of the Press Secretary 2012).

To address this serious gap, employers have begun to reallocate their resources to invest in precollege education, providing funding and in-kind support for teacher development, career mentoring, curriculum development, and the development of new instructional content that prepares students for college and career. Examples of these innovations are showcased on the Edutopia website funded by the Lumina Foundation.

This shift also comes in response to a crisis in public funding for education and vocational training. In recent years, state and local governments have slashed their budgets, leaving corporate, nonprofit, and federal sponsors to fill in the gaps (Lachman and Mai 2014). Meanwhile, because most public school districts are locally funded and managed, there are large disparities in curriculum, infrastructure, and teacher training nationwide. Women, African-Americans, Hispanics, Native Americans, and Americans with disabilities remain underrepresented in STEM relative to their percentage of the general population (National Science Board 2014). Companies with operations in the USA have a stake in eliminating these disparities to ensure a uniformly qualified workforce and educated consumer base nationwide.

Both the OECD report on CTE and the ACT report on work readiness have identified significant skills gaps for US high school graduates and call for collaboration among educators, employers, and industry leaders to narrow these gaps. Such cooperation would include the establishment of quality standards for certifications that would "anchor credentials in the needs of industry" (Kuczera and Field 2013) and incorporating "authentic learning experiences that incorporate work readiness standards into K–12, postsecondary, and career and technical education (ACT 2013)".

National Initiatives

Because the world's governments must lead the way in addressing global convergence challenges, they naturally have a stake in convergence learning. For example, education is a vital part of the US Global Change Research Program (USGCRP), mandated by Congress to "assist the nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." In addition to funding basic research, which is the traditional domain of the federal government, the program creates and disseminates resources for educators and the public at large, including climate change visualization tools produced by its 13 member agencies.

Global Cooperation

Global problems call for global cooperation. The innovators of tomorrow must be able to design products that will be embraced by consumers and institutions around the world. This will require the creation of global R&D teams with complementary expertise, perspectives, and resources.

Global research and education exchanges can shed light on many aspects of user-centered design including cultural variations in aesthetics, legal regulations, or environmental conditions. Some insights, such as the impact of a climate on a people's culture and the influence of tradition on consumer behavior, can only be gained by visiting a country. Currently, few American students study or perform research abroad, compared with the large numbers of international students who flock to US colleges and universities (Organisation for Economic Cooperation and Development 2013).

Students in all parts of the world must learn how the human capital, infrastructures, and research practices of a country define its comparative strengths and how these can contribute to shared convergence goals. Developing countries require special attention because they are important players in convergence challenges yet often lack the capacity to help solve them. A community approach is needed, together with new integrated learning settings that will allow teachers, learners, and collaborators in all parts of the world to gain global perspective and build global leadership capabilities.

Integration of Learning Settings and Methodologies

The characteristics of convergence learning call for new approaches that will accelerate and deepen learning, incorporate diverse perspectives, reach and engage all types of learners, and support advanced lifelong learning. Methodologies – new and existing – will have to support learning in a variety of different settings inside and outside the classroom.

Guidance comes from the Framework for 21st Century Learning, which calls for the establishment of "21st Century Learning Environments" that "enable students to learn in *relevant*, *real world* 21st *century contexts*"; "allow *equitable access* to quality learning tools, technologies and resources"; provide opportunities for "*group, team and individual learning*"; "support *expanded community and international involvement* in learning, both face-to-face and online"; and "create learning practices, human support and physical environments" that build twenty-first century skills (Partnership for 21st Century Skills 2011). This vision is very much in line with the vision of convergence learning communities described under Dimension 3.

Additional guidance comes from the "taxonomy of educational objectives" created by the educational psychologist Benjamin Bloom in the 1950s and revised by Lorin Anderson and David Krathwohl in the 1990s, which defines a progression

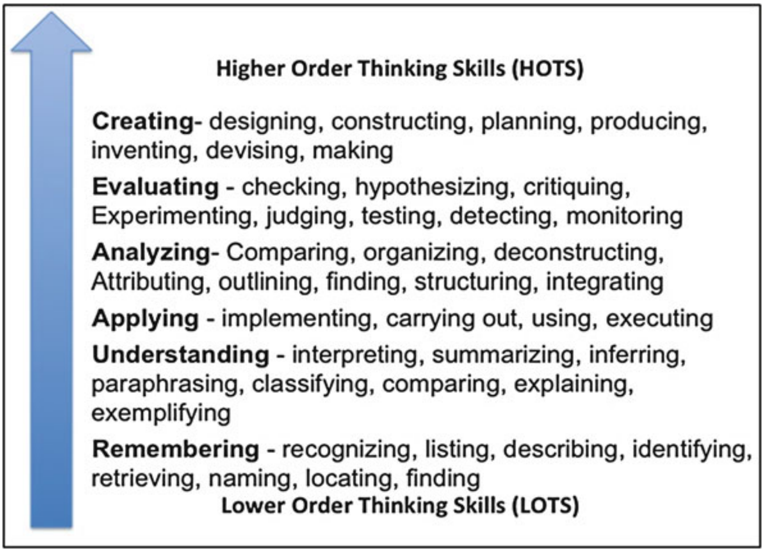

Fig. 4 Bloom's Revised Taxonomy based on research of Anderson and Krathwohl with subcategories of verbs that describe actions at each taxonomic level (Source: Bloom's Digital Taxonomy by Andrew Churches (2009))

of thinking skills from "lower order" to "higher order" and actions associated with each order (Fig. 4) (Churches 2009).

This model emphasizes the importance of vertical integration for teaching fundamental concepts in a deep and meaningful way. Because higher-order thinking is grounded in lower-order thinking, convergence methods should incorporate tasks from all levels. For example, lower-order thinking skills will be needed to acquire and classify large amounts of information from different sources and share it with others; higher-order thinking will be needed to apply knowledge in different contexts, test and critique its relevance to a given problem, conduct experiments, monitor results, and ultimately design and implement new technology.

The hands-on practice of scientific inquiry and engineering design must be a cornerstone of convergence learning. Science and engineering practices are core concepts that must be reinforced across grade levels. Project-based learning (Boss et al. 2013) grounded in scientific inquiry and engineering design (NGSS Lead States 2013) should be introduced early and continued into graduate school and beyond. Accompanying assessments must be developed to measure skills like asking questions, collaborating, and problem solving. The process of basic discovery and iterative engineering design allows students perform tasks at each level of the taxonomy, deepening their understanding and preparing them to perform the highest tasks – the creation of new ideas and products.

Interactive simulations and modeling tools are another means of engaging students in higher-order thinking. Researchers often use these tools to analyze multidimensional data sets, study complex concepts, and pursue "what if" scenarios that might take their work in new directions. The chapter by Douglas Fisher, "▶ Online Courses" discusses how computer-simulated laboratories can improve the effectiveness of massive open online courses. The chapter by Janet Kolodner, "▶ Cyberlearning" discusses how these and other types of technology can enable new forms of educational practice, according to research performed at the boundary between cognitive science and computer science. The chapter by Chang, Shanahan, and Hsu, "▶ Precollege Convergence Education" describes how interactive learning tools can help motivate students and teach them advanced concepts.

Convergence learning will combine formal and informal methods to educate learners inside and outside the classroom. Formal methods (e.g., lectures, lab work, and reading assignments) are generally used as part of the classroom curriculum and followed by assessments. Informal methods (e.g., games and museum exhibits) are generally used outside the classroom and not assessed. The chapter by Chang, Shanahan, and Hsu, "▶ Precollege Convergence Education" discusses the use of interactive games – an informal method – to enhance the formal study of nanotechnology concepts by middle and high school students. The chapter by Larry Bell, "▶ Informal Science Education of Converging Technologies" discusses the use of informal methods for public education, outreach, and engagement that will be so vital to the development and adoption of convergence technologies. The *new learning communities* described in Dimension 3 will adopt other informal methods to engage its members, e.g., career mentoring boards, community blogs, innovation forums, and social media. Combined with classroom study, these tools will help educate a generation that can collaborate vertically, horizontally, and globally.

Self-direction and self-efficacy (belief in one's own abilities) are the foundations for independent lifelong learning (OECD 2003). The intersection of learning methods and environments should build these by expanding students' decisions and letting them take greater responsibility for their own learning. For example, project-based learning encourages students to take the lead and set their own pace, while hands-on scientific inquiry and engineering design lets students design useful products that solve real-world engineering problems. Digital content delivered on mobile devices broadens access and lets students decide when and where to study. Interactive multimedia lets students with different learning styles choose learning tools that appeal to different senses (e.g., auditory, visual, or tactile) and employ different methods (e.g., narrations, animations, modeling) to help them grasp complex concepts. *Personalized learning platforms*, discussed in the chapter by Susan Singer, "▶ Learning in a World of Convergence", will engage diverse learners on their own terms, allowing them to tailor content to their own interests, study at their own pace, and use the tools best suited to their personal learning styles.

Concluding Remarks

There is evidence of a growing trend toward convergence learning at all levels.

The precollege level, the natural starting point for seeding the new culture, is adopting three new sets of learning standards – NGSS, F21, and the Common

Core State Standards – that together constitute a framework for convergence learning. These standards refer to one another, are specifically linked, and in many cases are being implemented together: 24 US states have adopted at least two of the standards, and six states are leading the way in adopting all three. These standards emphasize all four dimensions and many of the strategies described in this chapter.

Meanwhile, there is a growing movement to transform STEM education to STEAM education where “A” represents the arts. Several nations including South Korea have already made this shift, and in 2013, the International Conference on Transnational Collaboration on STEAM Education was held in Malaysia with papers published in the new “Journal of Transnational STEAM Education.”

Building on its investment in STEAM, South Korea has gone on to establish a new Graduate School of Convergence Science and Technology at Seoul National University as described in the chapter by Y. Eugene Pak, “► Convergence Science and Technology at Seoul National University”.

Bloom’s Taxonomy of Education Outcomes has been further revised to account for the growing role of digital technologies and the vital importance of collaboration in today’s classrooms (Churches 2009).

Certain elements of the envisioned convergence communities are falling into place. For example, regional STEM hubs involving academic, government, and industry partners are becoming a reality in 2014. A multi-sector network of businesses, universities, federal agencies and states, museums and corporations, universities and school districts, nonprofits and foundations, and others has been established after 2012 to “produce 100,000 excellent new STEM teachers by 2021”. Long-lived federally research programs like MRSEC, STC, IGERT, and RET have established national networks that can serve as the foundation for the new communities.

Going forward, the development of these communities might be seeded in a more focused way by establishing a series of regional hubs around the world. On the ground, these hubs might host regional experts (e.g., teachers, academics, industrial engineers, government researchers) and provide the necessary infrastructure support (e.g., labs, IT support) to rapidly turn their ideas and research findings into new instructional materials, curricula, and teaching practices. Each hub could also operate online to test and disseminate its products, provide teacher training, and collaborate other hubs around the world.

The hubs would produce immediate and long-term impact: The task of developing new content and curricula would help diverse partners establish a collegial rapport. Teachers and schools would be attracted by research-based instructional content and professional development that would help them meet the new national STEM standards. Companies and community organizations would have meaningful opportunities to participate in education and workforce development and interact with their customers and stakeholders. Open online communities would be established to allow students, teachers, companies, and the public to join discussions, participate in initiatives, and communicate with peers around the world.

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Academic Research Centers: Platforms for Convergence of Science, Technology, and Innovation

Dragana Brzakovic and John H. Cozzens

Contents

Abstract

This chapter contains a brief survey of a representative set of established academic research centers programs, which provide platforms for the convergence of science, technology, and innovation in the academic world. Three programs are discussed: Science and Technology Centers supported by the National Science Foundation (US), Centers of Excellence supported by the Danish National Research Foundation, and the Centres for Science and Engineering Technology supported by the Science Foundation Ireland, as well as the impact they have had on the research landscapes within their purview. The description of the aforementioned academic research centers programs includes their center models and evaluation processes. Two representative examples of each program's centers are used to illustrate a broad range of research areas and

D. Brzakovic (✉)
Science and Technology Centers, Office of Integrative Activities, National Science Foundation, Arlington, VA, USA
e-mail: dbrzakov@nsf.gov

J.H. Cozzens
Division of Computing and Communication Foundation, National Science Foundation, Arlington, VA, USA
e-mail: jcozzens@nsf.gov

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organizational structures and to elucidate developing trends. Next, the common and distinctive features of these programs are delineated with an emphasis on the role that academic research centers play as agents of change and, more importantly, the all-pervasive role of their knowledge transfer models as platforms for convergence and how these fit within the context of the Convergence of Knowledge, Technology, and Society. Finally, the last section summarizes some of the emerging trends that reveal how centers respond to the evolving interaction between scientific research, and societal needs, and identifies the pièce de résistance, the emerging model of what can be termed a “center without borders” – a dynamic center model that facilitates amassing resources as needed – to attack some of the most challenging problems facing society.

Introduction

In the ever changing world of science, discovery happens in various ways, sometimes through pure serendipity, e.g., the discovery of penicillin, and other times through hard work driven by expected outcomes, e.g., the discovery of radium. The research agenda within a country or a discipline may be dictated, top down, typically by government programs (e.g., EU frameworks), or developed bottom up by individual investigators driven by their intellectual curiosity. Large research projects and teams, an invention of the twentieth century, are driven top down and enabled by sizeable investments. Two of the most notable – the Manhattan and Apollo projects-included significant research efforts but were in essence outcome-driven engineering projects. As history has taught us, large projects such as these require immense infrastructure (both physical and human), precise coordination, and strong leadership to ensure delivery of the final product within a very tight timeline. Most importantly, these large endeavors require significant financial resources, which can only be underwritten by public sector/governments but may be augmented when appropriate by the private sector or philanthropy.

Other well-known models of large research efforts are associated with the area of high-energy physics. These involve large facilities, e.g., CERN or SLAC, where experiments require the participation of large numbers of scientists and engineers. In these cases, the research teams are driven by lofty scientific goals and work under more flexible timelines. The cost of the facilities and experiments is generally underwritten by the public sector, sometimes involving global cooperation. Yet another model of a team effort, also funded by the public sector, is exemplified by the US National Labs (e.g., the Jet Propulsion Laboratory) and Research Institutes (e.g., the Max Planck Institutes), which provide highly productive research environments coupled with high-end facilities. These institutions tend to be mission driven and are accountable to the parent organization and general public.

A different type of team research model, adopted by the private sector and associated with innovation, relies on smaller dedicated groups. This model is characterized by research teams, sometimes self-assembled, functioning in environments built to intellectually challenge while providing significant resources that are not tied to immediate outcomes. Historically, Bell Labs epitomized this approach; contemporary counterparts include, among others, Microsoft Research. However, nowadays the private sector favors teams focusing on specific problems closely aligned with the organization's goals, with the expectation that the research teams will show progress within a specified timeframe.

A less structured research team model is found in academic institutions. The academic world has historically played an important role in scientific discovery. It has laid the foundations for much of the "pure" science and was and still is the training ground for the next generation of scientists. Generally, a member of academia divides his/her time between different research projects and teaching duties. In order to enable the formation of larger and stable research teams within academic environments that can pursue complex research questions, many governments have introduced mechanisms for providing larger and longer range funding of (multidisciplinary) research efforts. These funding schemes support team structures usually referred to as **centers**. A typical academic research center comprises 15 or more senior researchers who are joined in the effort by students, graduate and undergraduate, and by many postdocs. These centers become the source of new ideas and unique training environments, which, in turn, change their immediate academic culture and impact the national and sometimes even global research scene.

This chapter discusses three examples of academic research centers programs and their impact and is organized as follows: first the three programs are described, followed by the summary of their common characteristics and differences. The most prominent features shared across centers – their role as agents of change, their knowledge transfer models as convergence platforms – are illustrated by two examples from each program. Finally, centers are analyzed in the context of the Convergence of Knowledge, Technology, and Society (Roco and Bainbridge 2013) – followed by a discussion of developing trends.

Academic Research Centers Programs within the National Research Funding Milieu

This section focuses on the three academic research centers programs: The Science and Technology Centers supported by the National Science Foundation (US), Centers of Excellence supported by the Danish National Research Foundation, and the Centres for Science and Engineering Technology supported by the Science Foundation Ireland. Each program description includes a brief history of the corresponding funding agency, discusses the agency's raison d'être for creating a specific center program, and then summarizes the processes utilized to select centers and evaluate their impact. Two illustrative examples of each program are highlighted in Table I. These examples epitomize each program's vision for a center and illustrate important (defining) characteristics that are discussed in ensuing sections, including various modes of collaboration and knowledge transfer models. The motivation behind selecting the particular programs was, apart from the authors' firsthand experience with the three programs, to demonstrate that center programs not only aspire to fulfill national priorities but also to establish scientific preeminence globally.

The **National Science Foundation** (**NSF**), the oldest of the three agencies, was founded in 1950 in response to a need to coordinate research activities across the United States and was initially conceived as the primary funding source "to promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense." Over time, NSF has taken on added responsibilities – promoting research in engineering and social sciences and supporting undergraduate and graduate education, and its mission has evolved into the primary funder of nonmedical basic research. Currently, NSF supports about 24 % of federally funded basic research conducted at US academic institutions. Most of the research is supported in the form of individual investigator grants to academic institutions. A small portion of the budget is allocated to larger research efforts, namely, center-like activities and large facilities. NSF's investments in academic research are complemented by mission-oriented departments/agencies most notably, the Department of Defense, the Department of Energy, the National Aeronautics and Space Administration, and the National Institutes of Health.

Centers gained prominence in NSF's portfolio in the late 1980s, with Materials Research Science and Engineering Centers, Engineering Research Centers, and the Science and Technology Centers (STC) programs, becoming the Foundation's mechanisms to respond to challenges to US dominance in basic research. The STC program was the only center program across US federal agencies open to all areas of basic science and engineering research and has steadfastly retained that status. This program was developed in response to President Regan's state of union speech in 1987, which announced "comprehensive proposals to enhance our competitiveness, including new science and technology centers and strong new funding for basic research." From their inception, STCs were driven by research grand challenges requiring a team approach and longer-term funding. In addition, these centers were required to establish partnerships with stakeholders for the purpose of knowledge transfer, thus, ensuring that the research maintained societal relevance. The first cohort of 11 centers was announced in 1989, followed in 1991 by a second cohort of 14 centers.

The STC program underwent multiple evaluations during the period 1995–1996 (Fitzsimmons et al. 1996; National Academy of Public Administration 1995; National Academy of Science 1996). These evaluations culminated in the recommendations by the NSF's governing body, the National Science Board, to continue the program with some minor modifications to the program requirements and NSF oversight. The most significant change was the emphasis on partnerships, which was reflected in a program name change to Science and Technology Centers: Integrative Partnerships. The most recent review of the STC Program was by the American Association for the Advancement of Science (Chubin et al. 2010). The early program evaluations and this recent review have found significant strengths in the program, the primary ones being the ability of STCs to respond to scientific grand challenges, take appropriate risks in research, and allow participants to change the mode of research.

Since the name change, the STC program embarked on funding the next generation of centers, starting in 2000, and yielding, to date, 25 new centers. STCs are funded at a level of US $4–5 million/year for a period of up to 10 years. Awardee selection involves a 2-year, multiphase peer review process which includes pre-proposal review by multidisciplinary panels, full proposal review by domain experts and a multidisciplinary panel, site visits, and the final “blue-ribbon” panel review. At each stage the number of proposals is narrowed. NSF manages STCs under cooperative agreements, and the primary oversight tools are annual site visits by teams of external experts and NSF staff.

The **Danish National Research Foundation** (**DNRF**) was founded in 1991 with the objective to “promote and stimulate basic research at the highest international level at the frontiers of all scientific fields.” This foundation is an independent funding body with full discretion for managing its funds. DNRF complements other funding mechanisms in Denmark, including the Danish Council of Independent Research, which funds single investigators, and the Danish Innovation Foundation, which focuses on application-driven research, innovation, and technology. In addition, private foundations have played significant roles in funding research in Denmark, the most notable being the Novo Nordisk and the Lundbeck Foundations.

From their very inception, the Danish Centers of Excellence (CoE), DNRF’s flagship program, were designed to be the catalyst for strengthening the Danish research enterprise and the promoter of the internationalization of Danish research. This program supports researchers with outstanding performance and leadership skills and provides them with long-term funding and considerable autonomy regarding their research activities. DNRF’s philosophy is very simple: provide the best research environments for the most talented researchers. The Foundation established its first 23 CoEs in 1993/1994, followed by 9 new CoEs in 1997/1998. Since then, six additional competitions, in approximately 3-year intervals, have been held, yielding 67 additional centers. Having funded approximately 100 centers, DNRF has promoted and established a research-oriented culture that affords studies of difficult problems, with a focus on scholarly excellence, and the ability to take appropriate research risks.

The scientific breath of the DNRF’s portfolio is immense, ranging from topics such as the medieval literature to nanostructured graphene. Many of the centers work on topics of great immediate importance to society, e.g., climate change and human health; others concentrate on basic research, e.g., mathematics and dark cosmology. In selecting the centers, DNRF employs a two-stage selection process: the pre-proposal stage in which the DNRF Board of Trustees members review applications and the peer review stage for full proposals followed by an interview of the proposed center leader by the DNRF Board. Centers are funded for a period of up to 10 years at the level of approximately US $1.5 million/year. The annual oversight is relatively minimal, and centers are reviewed in depth, midterm (around year 5) by an external site visit team.

An individual center's success, as well as the Foundation's as a whole, is viewed through the assessment of research quality. This in turn relies on bibliometric analyses of publications, namely, numbers of publications in high impact journals and citation indices. The most recent evaluation of DNRF provides detailed analyses of how the CoE's publications compare relative to the European and US standards (MSIHE 2013). It is interesting to note is that when it comes to publications in journals such as Nature and Science, the cumulative publication record of CoEs compares favorably with the best US institutions. An additional measure of DNRF's success is that many of their CoEs have attracted significant funding from other national and EU sources. On the human resource development side, CoEs have been very successful in attracting foreign Ph.D. students (in 2012, approximately 40 % of their 700 students were foreign). Additionally (in 2012), the Foundation supported over 500 postdocs, with 62 % of these of foreign origin. More importantly, DNRF's CoEs have elevated the quality and visibility of the Danish research culture, which, in turn, has increased an influx of high-profile expatriate and foreign researchers.

The **Science Foundation Ireland** (**SFI**) was established in 2000 as a sub-board of Forfás (Ireland's policy advisory board for enterprise, trade, science, technology, and innovation) with the express goal to fund research in biotechnology and information and communication technology. These areas were identified by a study commissioned by the Irish Government in 1998 as strategic investments in the future growth of the Irish economy and scientific enterprise. SFI's portfolio has since expanded to include energy-efficient technologies. SFI started with a portfolio of program activities ranging from individual investigator support to large research centers. Particular attention was given to academic researchers with strong ties to the private sector. Thus, from its inception, SFI assumed an instrumental role in chartering Ireland's research and development strategy as it links to economic development. The SFI's investments are complemented by the Industrial Development Agency, which aims at attracting foreign investments to Ireland, including research and development activities, and Enterprise Ireland, which promotes innovation and supports the creation of innovative companies. Together, these three agencies bridge research, technology, innovation, and economic impact, including job creation.

SFI started with a large investment in Centres for Science and Engineering Technology (CSET), which were funded for up to 10 years at the level of approximately US $6 million/year. The program goals included nurturing cutting-edge research, establishing linkages between academia and industry, fostering the development of new companies, and facilitating the investments of large multinational companies in Ireland. In order to help academia develop effective management structures to bridge the cultural divide between academia and industry, SFI has provided the centers with a high-level governance model. Center selection is a two-stage review process: peer review at the pre-proposal stage and site visits for the invited full proposals. SFI makes its final selections based on all the materials that are generated throughout the review process. The awardees are subject to extensive oversight which includes quarterly and annual reviews and in-depth mid- and end-term reviews. Having established that the first-generation centers, which started in 2003, strengthened international visibility of the Irish research enterprise and established strong links with the private sector, SFI decided to sustain its initial investments in centers. In addition, SFI leveraged further investments by requiring stronger government-industry co-funding collaboration; industry currently provides at least 30 % of the funding for existing centers.

SFI's investments, in particular, the CSET program, have undergone various evaluations; these evaluations confirmed that the centers have a multifaceted impact (Indecon 2008; Forfás 2014). The centers have ensured a critical mass in particular research areas; they have increased the reputation of Irish science in the EU measured by an increase in collaboration with other partners across the EU and have increased their funding base as evidenced by the influx of funding from the EU and other sources. CSETs have reported significant numbers of high impact publications, innovation successes, patents, and licenses. In addition, Irish universities have reported an increased ability to attract researchers of the highest caliber due to improvements in research capabilities. CSETs have also changed attitudes in industry regarding university researchers. However, the jury is still out on the actual impact that CSETs had/have on the Irish economy. In order to ensure a more demonstrable impact on the Irish economy, SFI's call for proposals in 2012 emphasized criteria pertaining to attracting foreign investments, tech transfer, start-ups, and tangible societal benefits.

Academic Research Centers Programs: Similarities, Variations, and Contrasts

The objective of each program is to fund world-class, most frequently, multidisciplinary teams of scientists and engineers, who share common research goals that require long-term funding and a team approach. The way research success is measured is driven by the program's mission. On one end of the spectrum, DNRF measures success by high impact publications and the visibility of their centers on the international scene; on the other end, SFI looks for strong industrial linkages and a track record of discovery translating into market utility; the NSF model embraces both extremes.

The three programs recognize the importance of value added and expect centers to show that the whole is greater than the sum of its parts; in other words, center members must justify the program's investment by showing that what they are achieving goes beyond what they could achieve as single investigators. One of the measures that can be used to demonstrate/track value added is the level or extent of collaboration of the researchers working in very disparate disciplines. This collaboration across disciplines also opens new research pathways (Bishop et al. 2014) and enables research risk, sometimes high risk-high return research undertakings (Chubin et al. 2010). Value added is further enhanced by the education programs and by requiring that the centers build pathways to stakeholders.

The complexity of the organizational structure of a center and how its activities are integrated is determined by expectations that go beyond research itself. DNRF's centers tend to develop strong center cultures and identify with a single institution and are usually organizationally lean. SFI's centers require appropriate organizational structures to establish linkages between academia and industry. NSF's STCs mandate partnerships among academic institutions and with stakeholders and tend to employ complex organizational structures and decision-making processes. STC partnerships have the advantage of enabling shared facilities and student mobility; however, establishing the cultural identity of a virtual center is an onerous task.

Academic Research Centers as Agents of Change

In many ways centers are agents of change on their own campuses, from lessening barriers between departments and disciplines to changing how the next generation of scientists is trained. This is largely due to the necessity of involving multiple disciplines in solving the societal and scientific "grand challenges" that drive center formation. It is worth noting that breaking disciplinary barriers is important in solving many problems, but, at the same time, it challenges established academic structure (Llerena and Meyer-Krahamer 2003). Typically, in large center efforts, the early years are characterized by complementarity in disciplinary contributions and attempt to develop a common language that enables communications among disparate disciplines. Next, the team starts systemic integration across the original disciplines in order to solve the problem at hand. The scientific challenge underlying center formation most frequently requires yet another step of team integration – the development of new conceptual frameworks that transcend individual disciplinary perspectives. In short, using standard definitions of disciplinary enterprises (Stember 1991), center research teams undergo a transformation from multidisciplinary to transdisciplinary, or in the Convergence of Knowledge, Technology, and Society terms, this evolution exemplifies convergence.

While the nature of the problem largely determines the team's composition, disciplinary compositions may be different, even in cases when centers work on similar problems, because they take different technical approaches. In some cases, one of the drivers for a center is the establishment of a new discipline, e.g., the Center for Brains, Minds, and Machines, a relatively new STC, states as one of its goals the formation of a new discipline, the science and engineering of intelligence – a synergistic combination of cognitive science, neurobiology, engineering, mathematics, and computer science. Often the progress of disciplinary interactions is reflected in the education program, where a center in its early years may champion new courses embracing methodology from a few disciplines, followed by the development of courses teaching a new discipline, and culminating in the establishment of a new degree program during the center's maturity phase.

In order to help research teams efficiently overcome disciplinary boundaries, a new field, rooted in organizational psychology and called the *science of team science*, is gaining attention. This new field started in 2006 and is formally defined to be “a branch of science studies concerned especially with an understanding and managing circumstances that facilitate or hinder the effectiveness of team science initiatives” (Stokols et al. 2008). The researchers in this new field are developing frameworks for the evaluation of team efforts such as seen in academic research centers, which are of great interest to funding agencies and the scientific community at large because they have the potential to ensure accountability in these rather large investments and, at the same time, aid in the formation of new centers.

Knowledge Transfer Models as Convergence Platforms

The three programs consider the investments they make in their centers significant; thus, funding is accompanied by expectations that the centers will demonstrate their relevance to the program’s mission and, more broadly, the society at large. At the center level, the program’s mission shapes how centers identify stakeholders in their research and establish knowledge transfer pathways to these stakeholders. Potentially there are three types of stakeholders: (i) industry, (ii) scientists in other disciplines, and (iii) policy makers and/or society at large. Different models of knowledge transfer pathways are discussed in the following and illustrated by representative examples of centers summarized in Table 1.

The SFI centers, including APC and Insight, target the private sector as the primary recipient of knowledge transfer. The linkages between academia and industry are clearly emphasized in the program description and institutionalized by requiring significant funding matches from industrial partners. The willingness of the private sector to co-fund a center ensures relevance of the center’s research agenda to industrial needs, and, hence, successful centers will likely have significant economic impact. While NSF and DNRF do not mandate industrial involvement, some STCs and CoEs have been very effective in developing intellectual property and commercialization (Chubin et al. 2010; DNRF 2013). Working with the private sector requires effective communication mechanisms to bridge the cultural divide between academia and industry. The dynamics of academia-industry cooperation has been studied during the past 25 years, and the effectiveness of established models is relatively well understood (Boardman et al. 2013).

In modern science, a discipline frequently benefits greatly from developments in other areas of science, e.g., new theory, methods, or instruments. When communications between the two very different disciplines are well established and are bidirectional, both disciplines can be transformed. CENS is an example where the research team consisting of computer scientists and electrical engineers selected the environmental scientists as the primary knowledge transfer partners, and the resulting bidirectional communications enabled seminal results in both disciplines. This targeted impact on other disciplines is to be contrasted with the approach followed by SYM which is, at this stage, immersed in theoretical development; it is addressing a very important albeit difficult problem – the classification of symmetry deformations in an invariant-theoretic manner – using tools at the confluence of topology, algebra, and noncommutative geometry. What will constitute their

Table 1 Representative centers funded by NSF, DNRF, and SFI

Alimentary Pharmabiotic Centre (APC)
Funded by SFI, 2003–present
Center website: http://www.ucc.ie/research/apc/content/
Lead institution: University College Cork + three academic partners and industrial partners
Center profile: 57 senior faculty in medicine, biology, biochemistry, food science, and pharmacology
Research focus: investigation of the role of the gut microbiota in human health and disease
Center for Embedded Networked Sensing (CENS)
Funded by NSF, 2002–2012
Center website: http://www.cens.ucla.edu
Lead institution: University of California at Los Angeles + four academic partners
Center profile: 48 senior faculty in computer science, engineering, biological sciences, natural and agricultural sciences, and statistics
Research focus: building the theoretical foundations for the next generation of sensor nets that were deployed in variety of monitoring applications, including habitat monitoring and seismic sensing
Centre for Ice and Climate (CIC)
Funded by DNRF, 2007–present
Center website: http://www.iceandclimate.nbi.ku.dk/
Lead institution: University of Copenhagen
Center profile: 13 permanent core faculty in geoscience/glaciology and biology/evolutionary and population genetics
Research focus: studying ice cores and developing models that explain observations and predict ice sheet response to climate change
Center for Remote Sensing of Ice Sheets (CReSIS)
Funded by NSF, 2005–present
Center website: https://www.cresis.ku.edu/
Lead institution: University of Kansas + four academic partners
Center profile: 25 senior researchers in engineering-electrical, mechanical and aerospace, geoscience/glaciology, computer science, and mathematics
Research focus: development of technology and computational models to understand ice sheet dynamics in Greenland and Antarctica
The Insight Centre for Data Analytics (Insight)
Funded by SFI, 2013–present
Center website: http://www.insight-centre.org
Lead institutions: Dublin City University + seven academic partners
Center profile: academics from five previous research centers in a broad spectrum of (sub) disciplines in computer science, engineering, and mathematics
Research focus: to conduct research in data analytics that has significant impact on industry and society "by enabling better decision-making"
Centre for Symmetry and Deformation (SYM)
Funded by DNRF, 2010–present
Center website: http://sym.math.ku.dk/
Lead institution: University of Copenhagen

(*continued*)

Table 1 (continued)

Center profile: 15 senior faculty in mathematics – subdisciplines: algebraic topology, algebra and number theory, geometric analysis and mathematical physics, noncommutative geometry, and operator algebras
Research focus: to "understand the mathematics behind symmetry and deformation"

contribution to the broader scientific community remains to be seen, perhaps new mathematical tools or a derivative application of their classification to contemporary problems in totally different disciplines, e.g., computer vision. Historically, in cases of theoretical work, most notably mathematics, pathways to other disciplines follow later only after the theory is fully appreciated. Case in point: pioneering work by Joseph Fourier in the late 1700s, leading to what is known today as harmonic analysis, found practical applications in the second half of the twentieth century in the areas of signal processing and telecommunications.

The most vexing problems facing modern society, such as those related to climate change, the environment, water resources, and energy, call for deep scientific studies to achieve a full understanding of the underlying mechanisms and finding solutions to mitigate these problems. Furthermore, these efforts should also provide unbiased albeit compelling scientific evidence to policy makers and ideally empower the general public. Both CIC and CReSIS are examples of centers that are valuable resources in understanding the impact of climate change, an issue of great concern to policy makers and the public alike. In order to accentuate this role, CIC has developed an outreach program about climate change, its causes, and its potential effects, via its web site, and provides general public education and science popularization through video documentaries. Similarly, CReSIS has developed an extensive public education program dealing with climate change and its impact and is utilizing various electronic media outlets to reach the general public.

Some of the operative processes that are enabled and occurring within the centers discussed above exemplify the notion of Convergence of Knowledge, Technology, and Society (CKTS), defined by Roco and Bainbridge (2013). The CKTS dynamics between convergence – "the escalating and transformative interactions among seemingly different disciplines technologies, communities, and domains of human activity to achieve mutual compatibility, synergism, and integration and through this process to create added value and branch out to meet shared goals" – and divergence, which is the usage of the accumulated knowledge to branch out into new discipline(s), product(s), or new knowledge, translates into the integration of research and knowledge transfer components of a typical center program.

CENS is an example of a center that after 10 years of STC funding not only successfully accomplished its goals but also was instrumental in creating two new disciplines: mHealth or mobile health, the practice of medicine and public health supported by mobile devices, and participatory sensing, citizen science enabled by mobile phones, by developing early prototypes and demonstrating the feasibility of these new mobile modalities, hence, new, exciting research directions for the cognate communities to pursue. CENS's early works – building and deploying sensor networks in a variety of monitoring applications and enabling these new disciplines – exemplify convergence-divergence under CKTS. It is interesting to note that yet another CENS spin-off phase – intellectual property and a start-up company – followed later. A very different instance of the converge-divergence evolution was followed by APC, a first-generation CSET, which early in its lifetime spun-off Atlantia Food Clinical Trials Ltd., a company that "provides a comprehensive end-to-end solution for human intervention studies, and specializes in trials for functional ingredients in foods, nutraceuticals, medical foods, dietary supplements and infant formula." In a more mature phase, APC's research findings have been translated into technology opportunities and are in the process of (or are available for) commercialization. These, an example of which is a safer infant formula, are handled through licensing and marketed by various venues including their web site.

The notion of convergence in established centers may take different forms through their lifetime. To wit, CIC and CReSIS established long-term, ultimately very successful collaborations as measured by personnel exchanges and joint publications; most recently, they have started sharing technology. This fusion of ice core technologies and radar may be viewed as convergence at a higher level, the culmination of which could lead to a major breakthrough in climate modeling, a new subdiscipline of glaciology, and perhaps even new tools for conducting similar research. Insight is yet another example where established centers had to align their research agendas, in this case, formally, by establishing a new center encompassing the original ones, in order to respond to diverse research challenges which no center alone could begin to solve on its own. These two cases of convergence demonstrate that the academic research centers' models have sufficient flexibility to enable the evolution of research team structures and assemble adequate resources to respond to societal grand challenges.

Academic Research Centers: A Prelude to the Future

Looking at the research landscape worldwide, centers have clearly permeated the academic world. Most of the developed and developing countries have established center programs (OECD 2014). Judging by the proliferation of center programs after 25 years of experimentation, centers have proven their value to the modern science. However, centers are dynamic and continue to adapt to changing environment around them; the remainder of this chapter discusses some of the emerging trends on how centers respond to the issues facing modern society and contemporary science.

Centers as a means of attracting talent. Center programs in Denmark and Ireland were initially viewed as a vehicle to stop and reverse the national brain drain. Not only did this approach work, but the new centers also started to attract high-profile science leaders from around the world. Their stature, in turn, attracted younger faculty and students, thus ensuring that these centers became hubs of excellence.

The importance of centers in the race for the top researchers lies not only in the funding that centers provide but more in the human infrastructure they afford and the visibility they aspire to achieve. However, the race to offer to the top researchers large and long-term funding is also a threat to the very existence of centers because relocation of a center leader may disintegrate the research group.

Megacenters. The academic community is becoming more organized as it attempts to attack very complex problems. Consequently, many of the new centers are comprised of a number of large, tightly connected research teams or subcenters, approaching what one might call a megacenter. Case in point is SFI's Insight center, which is a conglomerate of five past centers, involving a critical mass of researchers at the lead and major partner institutions. The megacenter structure empowers researchers with very large physical and human infrastructure at the expense of increased organizational complexity and difficulties in name branding. From the funder's perspective, a great advantage with this model is that the groups function relatively autonomously, and if any group is underperforming or not willing to change direction, it may be cut out without jeopardizing the whole organization. The concept of a megacenter is challenging both for the center leadership and for the funding agency, and, as time progresses, it will be interesting to watch how multiple research groups, each with an established identity, morph into a new organization.

Centers without borders (*geographical or otherwise*). Historically, science was internationally competitive, and a high national standing in this race was a matter of national pride. Now, the views that the "the world is flat" and everything is linked (Barabasi 2014) have started to pervade the academic and science worlds. The big societal challenges, e.g., climate change, health, diminishing water resources, etc., are calling for large efforts around the globe. Some areas of science have always had a global flavor, e.g., ocean sciences and geosciences in general; case in point is the long-term collaboration between CRESIS and CIC. The ability to establish collaboration between research groups and facilities without imposing strict structural requirements is a particularly attractive model for establishing global cooperation. This model supports a large-scale effort, which may equal or even surpass megacenters, but because the components are only loosely and informally coupled, these centers without boarders do not require complex management and oversight or complex communication channels connecting participants. This trend is clearly a win-win proposition, both for many researchers and society at large.

Sustainability issue. An issue that has haunted the center concept from the very start is sustainability. Centers as research hubs develop infrastructure, both physical and human. Since each of the programs tends to limit the funding term, the issue becomes – in which cases and how – to sustain parts of the infrastructure beyond the life of a center. The STC and CoE programs are silent on this issue, leaving their centers to seek support from other funding sources after their terms end. SFI has for the moment taken a view that industry-academic trust building is a slow process and that it is premature to let its centers function on their own after 10 years of initial success. Considering that centers are large investments, each of the programs needs to periodically reexamine and modify, as appropriate, its sustainability policy, in particular, relative to the physical infrastructure developed by its centers.

A center program is generally developed in a historical and geographical context, meaning that it is designed to respond to national needs at a specific time. In many ways formulating requirements for a center program is a balancing act between attempting to impose structure and accountability, which is counterproductive in academia, and allowing flexibility, which promotes creativity. Defining an ideal center program is an exercise in futility, considering the fact that each program is driven by the political and economic factors which lie outside the science and the academic worlds. Finally, center programs and the centers they spawn are inexorably tied and should "feed" one another in an obvious manner, namely, a (good) centers program invariably produces good centers, which, in turn, suggest "better practices," which, in turn, lead to refinements of the original centers program.

Centers offer the advantages of critical mass coupled with the ability to strategically morph in response to new challenges. The literature on best center practices or at least good practices is very limited; however, the consensus is that centers need strong leadership, appropriate communication channels among members, and adequate resources. Among the developing trends, the model of a center without borders provides a mechanism to leverage and optimize the fulfillment of these requirements. It finesses many of the inherent problems with the megacenter model and is flexible enough to accommodate virtually all of the prevailing center models. Moreover, it may be the most viable way to assemble the physical and human infrastructure needed to attack the real grand challenges such as alternative-nonpetroleum-energy sources that do not pollute and destroy our planet.

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Assistive Technology in Education

Francis Quek, Yasmine El-glaly, and Francisco Oliveira

Contents

Abstract

This chapter overviews the state of research in assistive technologies that support teaching and learning for *individuals with blindness or severe visual*

F. Quek (✉)
Department of Visualization, Texas A&M University, College Station, TX, USA
e-mail: quek@tamu.edu

Y. El-glaly
Faculty of Science, Port Said University, Port Said, Egypt

College of Computers and Information Technology, Taif University, Taif, Saudi Arabia

F. Oliveira
Ceara State University, Fortaleza, Brazil

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impairment (IBSVI). Education, learning, and information are culturally defined and designed for efficient communication and access for humans with typical visual and spatial capabilities. Understanding the unintended roadblocks to IBSVI brought on by such culturally defined elements of instruction and information is critical to assisting IBSVI to participate in the education and learning milieux. We divide the assistive technology challenges to the support for classroom instruction and for individual access to informational media. We address different aspects of each of these challenges and discuss various approaches to these aspects.

Introduction

Imagine if everyone else were endowed like the basketball superstar Michael Jordan in his prime. What kind of a world would we live in? The entire built-up world and cultural expectations would be designed around 2 m-tall individuals with tremendous dexterity. Stairsteps would be high enough to require significant effort for most readers of this chapter to scale, shelves would be too high for us to reach, and even the dimensions of keyboards, phones, and books would concomitantly enlarged. Furthermore, interhuman interaction would be designed where we would expect to hand things to one another across larger distances (most of us would become klutzes, dropping things that are routinely handed/tossed to one another), and we would find most objects for everyday use to be too awkward heavy to handle. The authors and readers of this chapter would, in short, be "disabled" in this world.

The point of the previous paragraph is that we are *embodied beings* and that the cultural world is designed for this embodiment. *Individuals withblindnessor severevisual impairment* (IBSVI) are "otherly embodied" along the dimension of visual perception. Many of the barriers faced by IBSVI arise not only from the natural world but from the cultural expectations designed into the world we construct and the means by which we communicate and inform. This is especially true for teaching and learning that are almost entirely culturally constructed and has concomitant implications for technology to support for learning. These implications extend to the understanding of the expectations built into the way we communicate concepts and design information and provide impetus for technology convergence between cultural understanding, cognitive science and interactive, multimedia, and signal processing technologies to address assistive technology needs. Furthermore, disability can be seen as a situational construction. In a noisy room, our ability to listen to a conversation may be compromised, and in low-light or under competing attentional load, our visual ability may require technological assistance.

This chapter focuses on two general needs for teaching and learning: support for classroom instruction and support for individual access to information through reading.

Instruction and Classroom Support

Society's interest in nurturing an educated populace and workforce has, to a large part, been supported by public/government education systems. Classroom instruction is the de facto configuration for providing instruction within the public education framework. In this section, we discuss technologies that support classroom instruction and learning. We divide this discussion under three general headings: visual aids for accessing classroom presentations, instruction material, and technology aimed at the teaching of specific courses.

Access to Teaching/Learning Material

One issue faced by IBSVI in classroom situations is the need to access individual information while attending to joint instruction. Sighted students can, for example, read screen menu layouts, while the instructor is guiding the class through the use of a computer system. IBSVI students may similarly access the menu system through screen reader like the popular JAWS software but will have to receive the information either in audio or through some kind of tactile reader (we will cover tactile readers later in our general discussion on reading). For audio, covert individual access may involve the use of over-ear headphones. Technology investigations to ameliorate the problem of headphones impeding classroom speech include the use of new bone-conduction devices in conjunction with auditory graphing software that was presented by Chew and Walker (Chew and Walker 2013). The drawback to such solutions in general is that of intramodal competition where the audio channel becomes overloaded.

Another challenge faced by IBSVI in the classroom is the need to take notes in class. A solution is to have human-sighted note-taking aides take class notes for the IBSVI. Apart from the labor intensivity of such approaches, notes are typically "personal self-communication." Notes taken by someone else are not typically as useful. One approach to this problem is embodied in the note-taker project (Hayden et al. 2011) designed to support students with low vision or legal blindness in inclusive classrooms. The approach employs cameras whose focus, magnification, and tilt can be controlled by the IBSVI student who can then take notes either by typing or with a stylus. The approach also represents a more general class of screen magnifiers (including handheld optical devices) for students with residual vision. The drawback with such approaches is the competition of attentional and activity resources placed on the IBSVI student to control the camera, attend to the instruction, and take notes. Also such approaches are not usable by individuals with total blindness.

A third requirement for classroom access is that of access to graphical information that accompanies instruction. Low-cost approaches are available to produce static tactile raised-line graphics on paper using embossing processes similar to printing with dot-matrix printer capable of creating raised indents on embossable paper (e.g., https://viewplus.com/product/vp-spotdot/). Alternatives to these include the use of aural and haptic feedback using such devices as pen tablets, audible bar graphs, and force-feedback devices. Ladner and colleagues (Jayant et al. 2007a) approach the problem as one of translating visual graphics into tactile forms through analyses and reformulation that involves human workflow practices.

Support for Classroom Discourse

An important aspect of support for classroom instruction for IBSVI is that of supporting the multimodal aspects of discourse in instruction as illustrated in Fig. 1 where three channels of communication are evident: (1) the vocal presentation by the instructor, (2) the graphic that carries the mathematical concepts being discussed, and (3) the pointing gesture that allows the instructor and student to share a focus into the illustration co-temporally with the vocal utterance. The speech channel is not normally impeded for IBSVI, and the graphical access was address previously. Quek and Oliveira (Quek and Oliveira 2013) employ a haptic glove interface to furnish the IBSVI with awareness of the deictic gestures performed by the instructor over the graphic in conjunction with speech. They present a series of studies where they show how their Haptic Deictic System (HDS) can support learning in inclusive classrooms where IBSVI receive instruction alongside sighted students. The approach employs machine vision to track the pointing gestures of instructors into graphical presentations and the reading point of IBSVI students as they read an embossed raised-line graph that mirrors the instructors' graphics. A haptic glove with a pattern of embedded vibrotactile devices activates in real time to inform the readers where they have to move their reading point to access the

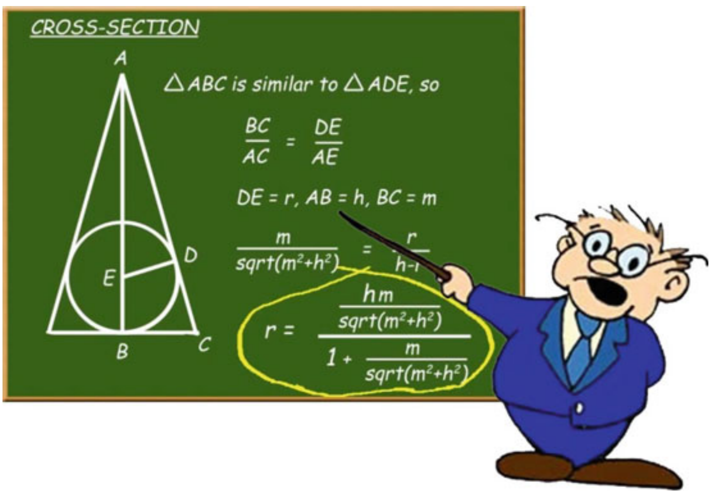

Fig. 1 Illustration of mathematics instruction

points of instructional foci of their instructors. The authors show how the introduction of the HDS was advantageous to all parties: IBSVI, instructor, and sighted students. The HDS created more learning opportunities, increased mutual understanding, and promoted greater engagement. Their approach differs from others as they formulate the problem as that of situated discourse, while prior work had focused on the act of reading or acquiring information. Their discourse analysis shows that it is possible to introduce technology to mediate interactions in inclusive regular classrooms and still have the conversants focused on the lessons' objectives.

Technology Aimed at the Teaching of Specific Courses

The classroom and instructional aids discussed thus far are generally applicable to broad ranges of subject matter. In recent years, there has been the surge of technology to assist the teaching/learning of specific courses. Howard, Park, and Remy (Howard et al. 2012) used a Wii remote controller as a haptic display paired with sound feedback to convey a robot positional information to a programmer who is blind. Students found the haptic device helpful in feeling the movement of the robot; they also found the audio feedback more helpful than the haptic feedback. The addition of the haptic feedback helped blind programmers to understand the robot's actions. Mohammadi and Murray (Mohammadi and Murray 2013) developed a sound-based network packet tracker for Cisco Networking Academy and successfully tested with IBSVI pupils. The NavMol software helps students who are blind to navigate through molecular structures and chemical reactions guided by sound (Fartaria et al. 2013), enabling collaboration between blind and sighted students and their teachers in inclusive classrooms. The Musibraille software enables music composition via a version of Braille conceived for that purpose (Borges and Tomé 2014). The application embeds a voice synthesizer and a small screen reader, and it's been used in inclusive music classes throughout Brazil, also enabling inclusive classroom collaboration.

Support for Individual Access to Information Through Reading

Support for reading is a critical segment of assistive technologies to support IBSVI in learning. We can divide the domain of reading support under five headings: (1) character-based tactile reading, (2) audiobook readers, (3) computer screen readers, (4) mathematics text, and (5) digital tactile graphics.

Character-Based Tactile Reading

Braille represents text as raised dot patterns laid out spatially on paper. Braille gives IBSVI the opportunity for self-paced reading and rereading of information on a page. The layout and spatial cues make it easy to find information and to compare data content. Modern Braille printers are able to emboss Braille documents through a simple printing process, giving individuals and institutions the ability to prepare paper-based Braille. Braille readers engage in an active process, pausing and thinking as they read; however, reading Braille requires continuous practice. A problem is that only 10 % of IBSVI in the USA can read Braille. This is because of the difficulty of learning Braille, especially for individuals with late blindness. More importantly in the USA, inclusive education where IBSVI learn alongside sighted students is mandated by law. While inclusive education addresses many social problems for IBSVI, it has the side effect of eliminating the Braille reading culture of previous schools for the blind. Furthermore, Braille books are large in size and cumbersome to handle. Amazon.com, for example, lists the print version of "Harry Potter and the Order of the Phoenix" at 870 pages and lists the Braille version as 14 volumes on thick stock paper measuring $11'' \times 11.5''$. A typical page has only 40 characters across and a maximum of 25 lines. This makes Braille literature unwieldy and not easily portable. This threatens to leave IBSVI behind in a growing "information divide" as the amount and rapidity of information access increase for individuals in general.

Refreshable Braille displays (RBDs) that can render tactile Braille dots provide dynamic access to text. These technologies approach the digitalization, portability, and mobility problems of Braille books; however, they eliminate the capability of Braille to provide spatial referencing because the size of the displays is relatively small. They typically feature displays with just one line of Braille text in blocks of 20, 40, or 80 characters. While reading one line at a time is not as passive as in listening to audible text, the information is still represented in temporal sequential format. The reader cannot develop a mental map of the page she reads and faces many of the text-locating problems endemic to audiobooks. At this time, RBDs are still expensive solutions for widespread use.

Various research groups worked on the idea of conveying Braille characters to IBSVI readers by vibrotactile modality using mobile and wearable devices. Piezo-electric actuators under the touchscreen of a mobile device were used for reading one Braille character at a time by generating tactile feedback. The Body-Braille (Ohtsuka et al. 2008) system uses six vibrating motors on the human's body to represent one Braille character, while UbiBraille (Nicolau et al. 2013) attaches vibration motors to six rings worn by the users around the fingers. The advantages of these vibrotactile Braille methods are that they are convenient for individuals with blindness and deafness and that they use inexpensive devices. However, they require training to be learnt by IBSVI, in addition to previous knowledge of Braille. Apart from UbiBraille that was used by two participants to read sentences, most of these systems have been demonstrated only for reading a character at a time.

Audiobook Readers

Audiobook readers are a popular solution for reading textual material because they have negligible learning curves. OCR and text-to-speech technology also provide a means to scan and read printed documents audibly. While these technologies are well suited to leisure reading and dissemination of information, the experience they enable is different from active reading, primarily because they provide no spatial access to the rendered text. Audio format provides IBSVI with information in the form of linear ephemeral stream that overloads IBSVI's working memory. A fundamental reason for this is that information is typically designed for access by sighted individuals with ability to scan material spatially. In short, information media are designed so sighted readers can scan recently read material for contextual refresh, and the information is often formulated with the implicit assumption of such capability. Because audiobooks endemically obliterate spatial layout, IBSVI are left with the tremendous cognitive load of maintaining all contextual information in memory while reading. Interviews with IBSVI who feel comfortable using both audio and Braille pointed out that audio is ideal for recreational reading, while Braille is mandatory for active reading. Abandoning Braille for audio for IBSVI, like converting print to audio for sighted population, leads to virtual illiteracy. Braille advocates stress that auditory learners must read and write, in either print or Braille, to meet the competitive employment needs.

Computer Screen Readers

Screen reading technologies constitute our third category of reading support for IBSVI. Screen readers are designed to interact with on-screen computing systems. Modern operating systems include screen reading as part of their universal access technology, e.g., Windows' Microsoft Narrator and Apple's VoiceOver. There are also popular commercial screen readers such as JAWS. This assistive technology has been extended to the touch devices, which are largely inaccessible to IBSVI. These different types of screen readers have two main functions: reading the screen content and navigating the screen. Screen readers have usability problems (Parente 2006), especially when the content of the screen is designed with the assumption that it will be visually read. Browsing web pages by IBSVI, for example, using screen readers leads to more probing and takes longer than for sighted users. Screen readers process pages sequentially, which leads to information overload. The navigation function on desktop screens is achieved by keyboard shortcuts, which are typically different combinations of two keys. On touchscreens, IBSVI can navigate the screen by touch or alternatively connect the touch device to a keyboard. Screen readers do not provide IBSVI with feedback regarding their location on the screen of both desktop and touch devices. In touch devices, the spatial awareness problem is reduced; however, much more accuracy is needed in locating place because any unintended touch could lead to undesired interaction. Finally, screen readers are not built to support active reading, and they do not provide IBSVI with the needed mental model of the page. Research on music and earcons (Asakawa et al. 2002) has addressed auditory representations for spatial layout in browsers. Changes in music were used to represent colors, thus helping the user to differentiate the context of content during navigation, and highly contrasting earcons (separate audio components such as rhythm, pitch, intensity) were used to represent text, images, and links to reduce a listener's confusion.

The main problem of accessing digital documents by IBSVI is the lack of easy access to the document structure. To address this problem, El-Glaly et al. presented STAAR system (El-Glaly et al. 2012) that combines static tactile overlay with touch slate device and audibly renders touched words, allowing the IBSVI reader to fuse spatial information from the static landmark overlay with the textual content of the page in audio. The STAAR system features a dynamic speech-touch interaction model that interprets the reading intent (estimating what the IBSVI intends to read next) to help to guide the reader to avoid straying by incorporating a "sonic gutter" that overlays sonic cues over the audio text rendering (El-Glaly and Quek 2014). Studies with the STAAR system showed that IBSVI were able to develop and maintain a mental model of the pages they read.

Mathematics Text

Mathematic equations are translated for IBSVI to read in one of the following formats: tactile, haptic, audio, or a hybrid of these formats. The main difference between plain text and mathematics is the multidimensionality of mathematical information. Various approaches to this approach either linearize the mathematics expressions or provide renderings that attempt to preserve the spatial relationships of expressions that contain mathematical information.

An approach to linearizing mathematics expressions is by extending Braille with Nemeth code that uses the same six-dot rendering as Braille. DotsPlus is another solution that offers tactile representation for mathematical information (Barry et al. 1994). DotsPlus uses Braille for alphabets and numbers, combined with raised images. The raised images are used to represent easy to recognize symbols, e.g., plus and minus signs. The advantage of DotsPlus is its ability to keep some of the original document structure, leveraging the understandability of the reading material.

A second approach is to convey mathematics expressions in audio. MathML, for example, is an XML application that is used to describe mathematical information in addition to saving its structure. MathML could be read by special types of screen readers such as Math Genie (Gillan et al. 2004). Another technique for audibly expressing math equations is the Audio System for Technical Reading (AsTeR) (Raman 1994). This software employs a voice synthesizer and an audio sound generator to read aloud the math information. It uses different pitch voice to indicate superscript and stereo effects to read data in tables.

In Toennies et al. (2011), the authors explained how they employed a haptic touchscreen to convey mathematical information through aural and/or vibratory tactile feedback. They also conducted user studies to test the effect of using only audio, only haptic, and audio/haptic feedback. Interestingly, their results showed that both audio and haptic are valuable.

Digital Tactile Graphics

Typical science and engineering books contain different kinds of graphs such as charts and diagrams. To enable IBSVI access graphs, they are translated into tactile graphics. It was shown by studies that tactile graphs give faster and more accurate access to the data than Braille and electronic tables (Watanabe et al. 2012). This is because the tactile perception is the best modality for graphical image understanding (Gardner 2002). As discussed earlier, Ladner et al. provide an excellent discussion on the practice of the reformulating graphical material for IBSVI access through a sequence of workflow steps, e.g., scanning, tracing, and adding Braille label (Ladner et al. 2005). The first step of the process typically involves the processing of the graphical data to extract a reformulation that is amenable to tactile output. Accessibility specialists who create tactile graphics may use general image editing software such as Photoshop or CorelDraw or special software that support tactile rendering of images. Jayant et al. describe Tactile Graphics Assistant (TGA) that automates these steps to various degrees to produce a layout that can be embossed (Jayant et al. 2007b). Similarly, Wang et al. describe an approach whereby semantic image categorization and segmentation and semantic-driven image simplification are employed to reformulate documents for tactile presentation (Wang et al. 2007). For output, user studies showed that raised-line pictures were better for IBSVI in performing discrimination, identification, and comprehension (Krufka and Barner 2006). For obtaining high-quality tactile graphics, the American Foundation for the Blind published a list of characteristics of discriminability in the components of a graphic (Hasty and Presley 2006) (e.g., that lines are perceived the best if they are straight and solid). In addition to pure tactile rendering, other researchers have combined tactile and audio output for graphical rendering.

Conclusions

Much of the challenge faced by IBSVI in education and learning arises from the fact that classroom instruction and information media are culturally determined. In the classroom, the students have to have access to multiple streams of information simultaneously. They have to be able to attend to the instructor's speech, access the presentation material being used, and read the individual material relating to the instruction (e.g., an open textbook on the desk) and the embodied behavior of the instructor. Each of these elements represents opportunities for assistive technology support. For individual reading and learning, reading material and information are designed for consumption by humans with typical visual/spatial perceptual capabilities. To date, Braille that was invented in 1824 is still one of the best options to provide IBSVI access to both the spatial layout and the elemental contents (the words) of documents. Refreshable Braille arrays are still too limiting to support spatial access, and audiobooks are spatial information poor. There have been many approaches to supporting access to mathematics expressions and material as well as graphics. None of the solutions advanced thus far have fully solved these problems of access. There are many open problems yet to be addressed in assistive technologies to support teaching and learning for IBSVI that present opportunities and rationale for convergence of technologies and sciences.

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Convergence Science and Technology at Seoul National University

Y. Eugene Pak and Wonjong Rhee

Contents

Abstract

Having achieved a prominent economic status, Korea is now facing a new phase of global competition. To cope with this challenge, technology convergence has been identified as a key strategy for sustaining innovation and continuing economic growth. This chapter introduces convergence movements of Korea including national government's planning and funding of strategic convergence programs, local government's investment on technology clusters, and Seoul National University's founding of the Advanced Institutes of Convergence

Y.E. Pak (✉)
Advanced Institutes of Convergence Technology, Seoul National University, Suwon, South Korea
e-mail: genepak@snu.ac.kr

W. Rhee
Graduate School of Convergence Science and Technology, Seoul National University, Suwon, South Korea

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Technology (AICT) and the Graduate School of Convergence Science and Technology (GSCST). AICT and GSCST were founded on the basis of Gyeonggi Province's investment and Seoul National University's reputation, and the description of the two institutions, as a group, is the main focus of this chapter.

National Government's Convergence Activities: Planning R&D Directions

Korea has witnessed an unprecedented economic growth over the past several decades, transforming itself from agricultural to industrial and now to information society. As an outcome, the economy has grown from one of the weakest in the world in the 1960s to the world's 15th in 2013. Per capita income has increased 330 times from $79 to $26,000, and exports amount to 3 % of the world trade, totaling at $540 billon. Much of the current economy is driven by the exports in manufacturing areas including electronics, automobiles, heavy machinery, construction, and materials. Electronics, such as memory semiconductor, cellular phone, and flat panel display, makes up more than 20 % of the exports and is by far the strongest with the advanced technologies (Pak 2002, 2007). In addition to hardware goods, Korea is becoming increasingly stronger in exporting software contents through a phenomenon called the Korean Wave or "Hallyu" (Tuk 2012) that includes global sales of Korean dramas, movies, and pop culture. This is considered to be an immeasurable marketing asset for boosting exports of manufactured goods, particularly to Asian countries.

Despite her manufacturing strength, Korea is being challenged by many countries that are rising as star players of manufacturing, and Korea's leading position is continually being challenged. To address the issue, the current government, under the banner of "Creative Economy", is gearing up with a convergence strategy to meet the grand socioeconomic challenges. Here, the convergence is considered as the convergence of knowledge, technologies, and industries. Because Korea has been an innovator in Information and Communications Technology (ICT), the convergence efforts are mainly based on the cooperative framework to strengthen the connection between the ICT and the traditional industries.

In 2008, the National Science and Technology Council of Korea came up with the "National Convergence Technology Development Plan" (National Science and Technology Council 2008) in collaboration with seven other ministries. The plan included programs to promote interdisciplinary, interindustry, and international collaborations. It was created to foster technology convergence at the national level and to lead the next generation of technological revolutions in the fields of medical health, safety, energy, and environment. Ultimately, the goal was to create new growth engines that can create more jobs.

In 2011, the National Science and Technology Council was officially launched from the 2008 plan with administrative power to control each Ministry's R&D budget. The Korean government decided to invest $8 billion over 3 years for the promotion of technology convergence, and the law makers passed the "Industry Convergence Promotion Law" in 2011 (National Law Information Center 2011). The objective was to promote new ideas and convergence efforts across the industry and to create new markets. As a result of these efforts, new investments are being made in biosimilars, photovoltaics, and service robots. In addition, smartphones, e-Tag RFID, and smart ship technology are acting as a springboard in generating new services. This promotional law also boosts support for SMEs through industrial convergence support centers. Universities are also being supported with funding to create educational programs for training of future workers versed in technology convergence.

What is Convergence Technology?

Convergence technology can be defined as a "technology of creating new results by combining various existing technologies." This definition can broadly include skills, methodologies, and processes that enable more innate and intimate convergence of technologies. South Korea's Ministry of Science and Technology, in their Basic Plan for Comprehensive Development of Convergence Technology (Korean Ministry of Science and Technology 2007), defined convergence technology as "an innovative new technology created by the fusion of interdisciplinary fields and technologies for the purpose of resolving economic and social issues of the future." Under this plan, the convergence technology includes the fusion of information technology (IT), biotechnology (BT), nanotechnology (NT), environmental/energy technology (ET), space technology (ST), and cultural/contents technology (CT) as its main subjects by considering domestic level of science and technology as well as economic and social interests. This is a domain of the convergence of knowledge, technology, and society defined in Roco et al. (2013), which is the extension of the initial technology convergence report (Roco and Bainbridge 2003).

Local Government's Convergence Activities: Cultivating Innovation Clusters

The convergence effort as a national agenda must be aligned with the efforts of the local governments and the educational institutions to take its full effect. Korea has nine provinces, and Gyeonggi Province is the one that surrounds Seoul, the capital of Korea. Seoul and Gyeonggi together are home to more than 50 % of Korea's population, and much of Korea's industry and intellectual infrastructure are located in Seoul and Gyeonggi Province. To this end, the local Gyeonggi Province has been actively participating in sharing the vision set forth by the central government. Masterminded by the Gyeonggi Institute of Science and Technology Promotion (GSTEP), the Gwanggyo and Pangyo Techno Valleys were built in Gyeonggi Province to create innovation and convergence clusters for research, education, and business. These recently established clusters, which combine features of research center, business incubator, and learning institution, have chosen to specialize in the convergence of key technologies deemed crucial to the future competitiveness of the Korean economy.

Gwanggyo Techno Valley

Located in the provincial capital city of Suwon, the Gwanggyo Techno Valley (GTV) is home to SNU's AICT and GSCST as shown in Fig. 1. Also located in the Valley are Korea Advanced Nano Fab Center (KANC), Gyeonggi Bio-Center, Gyeonggi Small and Medium Business Support Center (GSBC), and Gyeonggi R&DB Center (Gwanggyo Techno Valley Brochure 2012). These institutions on a single campus make up a comprehensive infrastructure to conduct convergence technology research and business development. Located in GTV are about 240 venture start-ups and SME's R&D centers. GTV is close to large multinational companies such as Samsung, Hyundai, SK, and KT as well as many high-tech SMEs. Strategically located 30 km south of Seoul, GTV can act as a corridor or link pin connecting other technology clusters situated near Seoul and in other parts of the country.

Pangyo Techno Valley

The Pangyo Techno Valley Project is a nonprofit public project to strengthen national competitiveness and to secure self-sufficiency of Pangyo New City by laying the foundation for knowledge industries that will develop national growth engines related to IT, BT, NT, CT, and other advanced convergence technologies (Pangyo Techno Valley Brochure 2013). It is a strategic national project initiated by the Korean central government and executed by Gyeonggi Province to create a state-of-the-art technology complex, as shown in Fig. 2, just 14 km south of Seoul. The goal is to make the Pangyo Techno Valley Korea's best ICT and BT-based R&D innovation cluster, much like the Silicon Valley, by investing a total of $5 billion by the end of 2015. This is in line with the current administration's Creative economy vision to step up the economic growth. By the end of 2015, a total of 1,000 companies armed with advanced technologies will be doing R&D and business in the Valley (As of 2014, 870 companies have settled in Pangyo Techno Valley that is built on 661,000 m^2 (163 acre) site). Large- and medium-sized companies will account for 50 %, and the remaining 50 % will be ventures and small-sized companies. To strengthen R&D capacity and to improve business conditions of the high-tech companies that have moved to the Valley, Gyeonggi Province is planning to supply public support facilities, a global R&D center, and an industry-academia-government lab R&D center. AICT, situated only 16 km away, will play a major role in the R&D function as well as in training the Valley scientists and engineers through a newly established AICT educational center called ConTech Academy whose activity will be explained in a later section.

Fig. 1 Advanced Institute of Convergence Technology (*AICT*) and Graduate School of Convergence Science and Technology (*GSCST*) located at Gwanggyo Techno Valley

Fig. 2 New buildings in Pangyo Techno Valley

Seoul National University's Convergence Activities: Delivering Research and Education

Seoul National University (SNU) has been recognized as a prestigious institution in Korea since its foundation in 1946, and it has grown into one of the world's leading research universities in the past couple of decades. Gyeonggi Province recognized the potential synergy between SNU's prominence and Gyeonggi's cluster strategy and initiated a discussion on collaboration in 2005, even before the central government's convergence planning was started. The discussion matured in 2006, and SNU and Gyeonggi provincial government made an agreement to establish a research and educational institution devoted to the development and application of convergence technologies, the first of its kind in Korea. The research arm was named the Advanced Institutes of Convergence Technology (AICT), and the education arm was named the Graduate School of Convergence Science and Technology (GSCST). They are co-located in the Gwanggyo Techno Valley in Suwon 30 km away from the main SNU Seoul campus and opened in 2008 and 2009, respectively.

Advanced Institutes of Convergence Technology (AICT)

AICT was established as an independent nonprofit research organization whose infrastructure was built by the Gyeonggi Province while research and management functions are being carried out by SNU. AICT's goal is to become a world-class convergence research institute for the discovery and creation of key technologies to improve future economy, society, and culture. This is to be accomplished through diverse synergistic convergence of new technologies, such as NT, BT, IT, ET, and CT, as well as through convergence of new technologies with existing industries and academic disciplines. From the planning stage, emphasis was placed on AICT's role in carrying out convergence-oriented R&D with the purpose of bringing commercial impact to local industry. AICT functions as a stimulator driving up global R&D network and collaboration, promoting exchange programs with foreign and domestic organizations. Another important function is to lead the efforts to increase the public awareness of the convergence technologies through diverse programs such as forums, symposia, and youth programs. AICT also acts as an incubator for start-up companies with technology transfers from SNU and AICT. Aiming to train qualified professional experts in technology convergence, AICT maintains close collaborative relationship with SNU's GSCST and is gearing up the synergy in all research activities. While AICT has its own research and management staff, many of the AICT's institute and center directors are faculty members of GSCST. AICT's organization chart is shown in Fig. 3.

Research Activities and Organization

Research activities at AICT are organized around four convergence research institutes under which are total of 26 research centers, each with the goal of

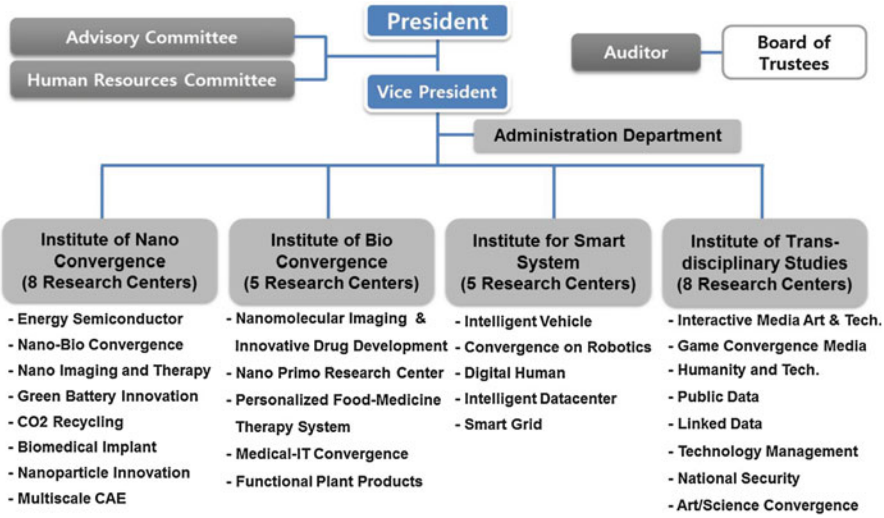

Fig. 3 Organization chart of AICT

becoming a pioneer in the convergence technology research. Research areas and objectives are shown in Fig. 4. Centers that can share underlying technology disciplines are grouped together under an institute so that convergence of similar disciplines can readily occur. This, however, does not limit the convergence activities with research centers under other institutes. In fact, once a common research theme or a new convergence platform is identified, all interested centers are encouraged to participate. The organization is made flexible so that merging and launching of new centers can readily occur for the purpose of strengthening the current research effort or initiating a new research topic.

Research centers in the Institute of Nano Convergence conduct research on LEDs, organic solar cells, nanobiosensors, and nanomaterials that can have energy and biomedical applications. Marine-organism research in reducing the atmospheric carbon dioxide content and multiscale CAE simulation research for designing innovative engineering materials are also being carried out.

Research centers in the Institute of Bio Convergence conduct research on a variety of innovative bio-health-related topics which include discovery of biomarker for detecting new diseases, application of nano-imaging technology as a source of new pharmacologic development, personalized food-medicine therapy system, medical-IT convergence technology, and mapping of the newly discovered mammalian circulatory system. Research on producing functional natural products from plants is also being conducted.

Research centers in the Institute for Smart Systems are focusing on developing the next generation of smart cars, electric-powered personal mobility vehicles, and surgical and rehabilitative robots for the elderly and disabled. Research in digital human technology, based on human body motions, and smart grid research as a future platform for convergence of energy and ICT are also being carried out.

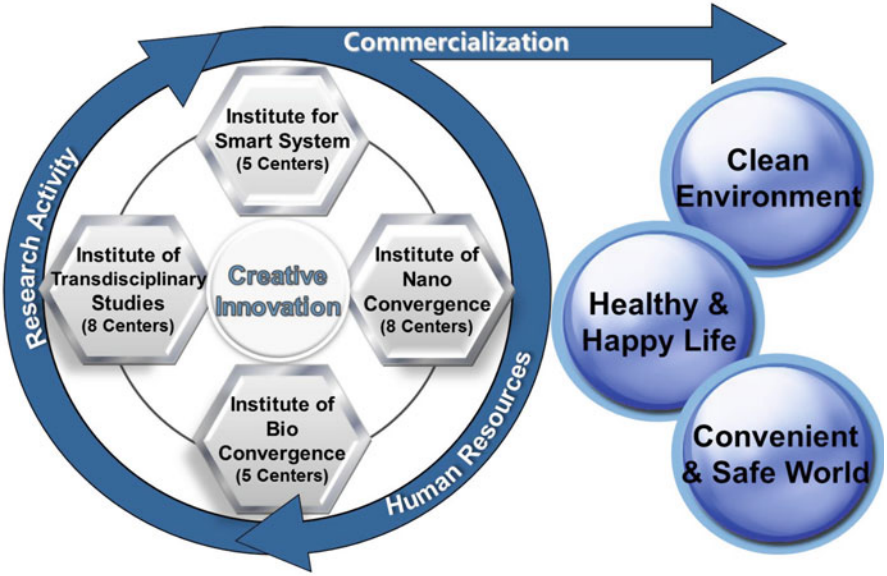

Fig. 4 Research areas and objectives of AICT

Finally, research centers in the Institute of Transdisciplinary Studies lead the mission of combining cultural and contents technology with various disciplines that include interactive media art technology, educational and medical game convergence contents, convergence of humanities, art and social sciences, big data research analyzing public data, and public safety research. Dissemination of the management of technology (MOT) methodologies to local industries for improving their research efficiency is also being done. The institute aims to conduct research to acquire a better understanding of methods that result in an information-technology-human convergence.

Convergence and Industry Friendly Environment

One of the key catalysts for activating convergence is setting up a proper physical environment and an organizational infrastructure. Locating the research institutes away from the main SNU campus has the advantage of starting a new organizational structure with minimal or no boundaries between disciplines or departments. Such a configuration encourages fresh thinking outside the traditional boundaries and allows new ideas to develop from intermixing of traditional disciplines which is further enhanced by experts working in many jointly appointed teaching and research positions (Mroczkowski 2011).

With that goal in mind, AICT is designed to be an open organization welcoming the best and the brightest who want to realize his or her vision through convergence activities with other researchers. Also welcome are the faculty members from the main SNU campus or from other universities who may want to take academic research further into commercialization by converging with other fields or disciplines. Through a process of providing seed funding, AICT incubates convergence technology ideas that can grow into large projects or convergence platforms. One successful example is realized by the Bio Convergence Institute Director who wanted to go beyond the basic academic research done on main SNU campus. He obtained a joint appointment with AICT and organized a team of experts converging on the main theme of key technology developments for fast and low-cost pharmaceutical drugs. As an outcome, this convergence team was able to acquire a 10-year $140 M government grant with $5.7 M matched by the local government to establish the BioCon (Bio Convergence) research hub. Interested pharmaceutical companies participating in this process became partners in establishing this convergence research hub whose members include researchers from other participating organizations. This also attracted an investment from overseas accelerating the commercialization process from basic technology developments.

In order to create an environment that not only encourages research excellence, but also to promote the mind-set of creating commercial values, AICT has expanded its participating research staff to include people with extensive industrial experience. AICT has a system of inviting and welcoming former executives from industry who have accumulated vast technical and commercialization knowledge along with the firsthand experience on technology management. They bring to AICT years of valuable experience in creating research projects that have industrial relevance. They can also provide consulting and guidance in technology management to the local SMEs. Through this open invitation policy, a former President of Hyundai Motors with a legendary reputation was invited to run the Intelligent Vehicle Platform Center. This center is to conduct R&D in preparing for the future demand in automobiles including the personal mobility vehicles. A technology management and innovation guru who was once CEO at Samsung Advanced Institute of Technology was invited to head the Technology Management Solution Center to transfer technology management and innovation expertise to the local industries, particularly to SMEs. This in part is done through running a short executive training program. A successful venture start-up CEO in the mobile games area who retired early was invited to enhance the computer game research activities at AICT. She was also delighted to be sharing her experience with researchers and students who aspire to start venture companies. A traditional university setting would have much difficulty in bringing industry people on board as they would not meet the usual academic requirements such as journal publications. Through this open policy, AICT is creating an environment that naturally encourages the convergence of different philosophies and modes of operation that are usually practiced differently in academia and industry.

To facilitate the burgeoning of convergence ideas and to take them further into action, AICT has created an exploratory convergence research space called Convergence Base Camp. This is a space dedicated to the realization of convergence platforms providing office and lab spaces conducive for convergence. The camp space also includes meeting rooms, demonstration showcase exhibit areas, and a supporting mechatronics workshop. These functions are all gathered in one space to encourage close interactions. This first trial space is offered to the researchers from different centers with ideas and expertise to work on the convergence of IT, media arts, music, audio visual technologies, and robotics. It is expected that a larger project or a convergence platform, such as miniature humanoid robot that can mimic the intricate dancing moves of Korean pop stars, will organically grow out of this camp.

To encourage and support researchers to spin off companies from their research outcome, AICT has a venture start-up program that provides infrastructural and R&D support along with favorable licensing agreements and flexible leave of absence policy. So far, three companies have spun off in nanotechnology areas relating to nanomaterials for electronic devices, high-performance LEDs, and medical implants.

Planning of Convergence Research

At AICT, the governance of convergence research is being developed to encourage the generation of new ideas among researchers through creativity, innovation, and communication. At the same time a common goal or a vision is strategically set forth so the convergence becomes more focused and team-oriented.

Effective planning of convergence research can be done in two ways. One is a top-down approach based on a big picture and a long-term view, taking into consideration the mega trends of the society and technology. Convergence goals or platforms should be carefully identified so that they will serve as an effective convergence point for a specific problem solving or as a technology demonstrator that can show potential commercial impact. Assessment of in-house technical capabilities and outsourcing needs is carried out to build the right team of core people. To this end, a strategic planning group is put in place to work closely with the institute and center directors. As an outcome, three large research themes were chosen that reflect the mega trends of the global and the Korean society. These are "Healthy & Happy Life," "Clean Environment," and "Convenient and Safe World." Champion projects representative of these themes are selected and given full support so that they can blossom into convergence platforms for further development and commercialization. Some representative convergence platforms addressing these themes are introduced in a later section.

The other method of convergence is bottom-up approach encouraging close interactions among researchers with freedom to test and try out new ideas. This type of convergence is best done through human network and interaction. To this end, AICT holds Convergence Research Forum once a month with a designated main theme such as Wellness and Healthcare, Intelligent Digital Solutions, Green Nanotechnology, Media Art and Science, Novel Therapeutic Approach, Safe Korea Smart System, Industry-Academia Collaboration Model, and Gwanggyo Collaborative Drug Discovery Program. At this forum, AICT research center members and interested company workers come together to present and discuss technical and related issues so that innovative convergence research topics can be identified. AICT provides initial seed funding to try out new convergence ideas generated from these forum meetings. This forum also acts as a venue for planning and team building in response to RFPs for large government research funding that emphasize technology convergence.

Public Education and Promotion Programs by AICT

As a nonprofit research organization with the support from local government, one of AICT's important agenda is to educate the general population including researchers, industry groups, government personnel, and even high school and college students. AICT has developed a variety of programs and is currently running the following educational and public relations programs.

SNU&G ConTech Academy

Catering to the continuing education needs of about 800 companies located in the Pangyo Techno Valley, AICT established a corporate need-tailored education center called ConTech Academy. The emphasis is placed on technology convergence, hence the name ConTech Academy, which also phonetically symbolizes contacting or connecting industry with academia. Unlike the traditional college educational system, the curriculum is developed according to the demands of the companies and corporate students who can choose from available subjects that are judiciously tailored according to their needs. Companies can also request for specifically tailored private courses. AICT is in dialogue with the Ministry of Trade, Industry and Energy (MOTIE) to make this into a government-accredited program at the graduate school level with strong emphasis on industry-oriented problem-solving contents based on convergence technologies. This program will be expanded to include high school teachers who are increasingly being challenged in teaching with newly revised textbooks that have convergence science and technology contents.

World Class Convergence Program (WCCP)

This 6-month-long executive program aims to help CEOs and CTOs of SMEs to become world-class corporate leaders so that they can make a leap forward in leading the world-class company through the use of convergence technologies and technology management methodologies. The program offers exposure to state-of-the-art technology trends, technology management tools, and problem-based learning sessions to address the real-world issues in effectively growing an enterprise.

International Symposium on Convergence Technologies (ConTech Symposium)

AICT holds ConTech International Symposium annually inviting domestic and overseas luminaries to address global technological and societal issues. Aiming to tackle technological and societal issues through multidisciplinary exchange and collaboration, a grand challenge theme is chosen each year such as Improving the Quality of Life, Smart and Humane World, Smart Mobility, and Global Challenges for Wellness. This symposium can also link AICT with overseas institutions to find international collaborations in addressing these issues. Representatives from academia, industry, and government funding agencies are invited so that a common vision can be shared in developing meaningful government research funding programs. Through this forum, AICT's future research direction can also be effectively identified. ConTech symposium has marked its status as a venue for the promotion of convergence technologies to industry and general public.

Cultural Concert for Convergence

This open concert is designed to educate the public about convergence in the areas of science, technology, and humanities by inviting publicly well-known speakers to give a series of lectures on Friday evenings. The lectures are preceded by cultural events such as musical concerts or performing arts. This program is particularly popular among the local high school students who can get personal exposures to the lecturers of national fame.

Internship Program for College Students

Two-month-long internship program is offered twice a year, during summer and winter breaks, to students who have finished first year or beyond in college. Selected students acquire hands-on research and on-the-job training experiences. A popular activity among the students is the brown-bag seminar where professors and researchers from AICT and GSCST give interesting and informative talks on the topics of their research.

Seoul National University's Youth School for Convergence Science

Targeting high school students in Gyeonggi Province, it is designed to promote creativity in the youth and to rear them as global leaders by providing them with early opportunities to experience convergence research activities. This program includes series of lectures and hands-on laboratory experience so that the students can gain better understanding of the topics and methods of convergence science and technology.

Short Course on Convergence Science and Technology

This 2-day short course is aimed at educating the workers of the government and public agencies. It is designed to enrich their science and technology convergence awareness and to provide information on domestic and overseas convergence activities so that they can contribute effectively to the current issue resolution and policy making.

Open Campus Industrial Convergence Idea Contest

Cosponsored with the Ministry of Science, ICT, and Future Planning, this contest is aimed at fostering the spirit of collaboration among different industries in encouraging new generation of young people for creative convergence thinking. Awards are given to students with best convergence ideas, and AICT provides support in developing these ideas into real patents.

Graduate School of Convergence Science and Technology (GSCST)

In the midst of rapid growth in a knowledge-based economy, demand is rising for field-oriented experts with interdisciplinary integration of knowledge not only based on physics, mathematics, chemistry and biology but also based on cultural, social, life, and medical sciences. Creative experts are sought in the fields of newly emerged convergence technology such as nanotechnology (NT), information technology (IT), biotechnology (BT), and cultural/contents technology (CT).

GSCST opened in 2009 with the following missions: (1) act as a knowledge-producing base on a global standard, (2) lead the development of new technologies for future industry, (3) cultivate creative experts with international competitiveness, (4) develop new technologies for industries through promotion of academic-industrial cooperation, (5) train field-oriented experts, (6) nourish experts with both interdisciplinary integration of knowledge and practical professionalism, and (7) foster creativity as well as field expertise in the new convergence technologies such as NT, IT, BT, and CT, thereby promoting the creation and the development of new industries.

Organization

GSCST consists of two departments: the Department of Transdisciplinary Studies and the Department of Molecular Medicine and Biopharmaceutical Sciences. Organization chart of GSCST is shown in Fig. 5.

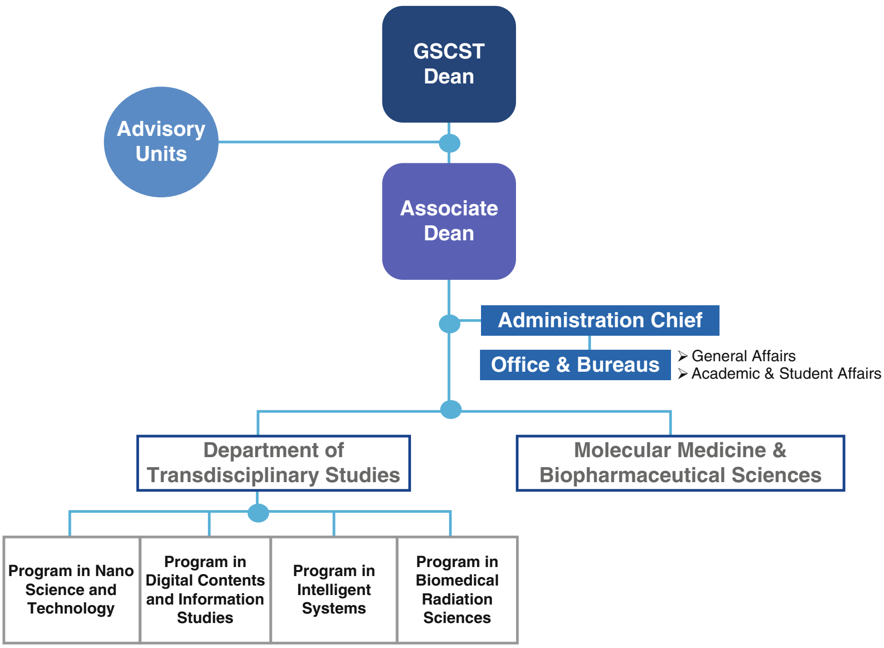

Fig. 5 Organization chart of GSCST

Department of Transdisciplinary Studies

The Department of Transdisciplinary Studies consists of four programs that cover NT, IT, BT, and CT areas.

a. Program in Nano Science and Technology
   Nanoscale science, engineering and technology (NSET) encompasses a wide range of traditional academic disciplines such as physics, chemistry, biology, electrical engineering, material science, and mechanical engineering. This characteristic presents both promise and challenge. NSET is capable of overcoming limitations of current science and technology, and in the course of its development, it will greatly improve the ways to obtain and process information, diagnose and treat diseases, and deal with energy and environmental issues. The challenge is to identify, in a timely fashion, new opportunities arising where traditional science and engineering disciplines converge and be capable of turning those opportunities into reality. The mission is to produce engineers and scientists who possess a solid understanding of the principles of nanoscience and are capable of making real-world impact by overcoming the scientific and technological challenges. The department offers interdisciplinary teaching and research in the following three loosely defined areas: nanophysics and nanodevices, nanomaterials and nanochemistry, and nanobiological science.
b. Program in Digital Contents and Information Studies
   Digital technology is a core aspect of every interdisciplinary study and academia-industry collaboration. Information is the key component in shaping the modern world and human perspectives. Information convergence study, based on the behavioral theory of information needs, provides a wide understanding of human needs for information flow and system applications. The *Digital Contents Convergence Program* addresses the radical changes in the information-oriented society that have greatly affected and altered social behavior and structure. In order to prepare for such changes, "information-convergent" approaches need to be taken by converging what was once regarded as independent fields of study, including information science, computer science, communication study, humanities, and design-related studies. Recent research topics include convergence in user experience, human-computer interaction, data science, signal processing, music, audio, and computer game.
c. Program in Intelligent Systems
   The Intelligent Convergence Systems Program combines mechanical engineering, software engineering, human engineering, electrical and electronics engineering, intelligence system engineering, computer engineering, business, and industrial design. It seeks to establish intelligence convergence system that links "human-engineering-market," foster practical experts who can apply the knowledge to reality, cultivate experts with professional knowledge and creative synthetic thought process, and produce leaders with engineering knowledge as well as personal attainments. Recent research topics include convergence in robotics, computer systems, vision, and connected cars.

d. Program in Biomedical Radiation Sciences
   The Biomedical Radiation Sciences Program performs a wide range of cutting-edge interdisciplinary academic study encompassing radiology, biophysics, radiopharmacology, radiochemistry, nano-molecular imaging, and imaging science and exploits the new biomedical science fields by converging a variety of traditional academic majors such as medicine, physics, pharmacy, chemistry, nuclear engineering, electrical engineering, materials engineering, and mechanical engineering. Curriculum of Radiation Biomedical Sciences focuses on the training of creative interdisciplinary specialists based on the expert knowledge of radiation and biomedical sciences.

Department of Molecular Medicine and Biopharmaceutical Sciences

The Department of Molecular Medicine and Biopharmaceutical Sciences (MMBS) aims to become the world's top-ranked program in molecular medicine and biopharmaceutical science through collaborative research with the distinguished scholars of the world. The department was originally established as a World Class University (WCU) project. WCU is a higher education subsidy program of the Korean government that invites international scholars who possess advanced research capacities to collaborate with the Korean faculty members and to establish new academic programs in key growth-generating fields. MMBS is a collaboration effort among the College of Pharmacy, the College of Medicine, and the GSCST convergence program. It offers a graduate program to train professionals for translational research that combines fundamental knowledge in medical life sciences with applied fields such as pathophysiology, clinical trials, and clinical medicine.

GSCST's Convergence Education

At the time of founding, GSCST was one of the early, if not the first, educational institutions in Korea to focus on convergence of multiple disciplines. Challenges included developing new classes and cultivating open culture that can provoke communication and cooperation among students and researchers from different disciplines. The challenge is ongoing, but some of the programs and trials turned out to be effective, and they are explained below.

Introduction to Convergence Science and Technology

This is a first year course for the new M.S. and Ph.D. students. The class has two main goals. The first is to teach the concept of convergence in the context of history of science and technology. Historical development of reductionism is explained, and the limitation of the approach is discussed for the complex modern life. Then, examples of overcoming the limitation are studied where approaches such as design thinking, technology sensing, and recognizing inventions are discussed. Students form groups to exercise the learning through team projects. The second goal is to introduce research activities at GSCST. Faculties of GSCST are invited to talk about their research on nano-convergence technology, digital content convergence

Table 1 Research areas of smart humanities program

Area	Examples
Health technologies	Nano-molecular chemistry and imaging, biomedical imaging, nano-neuro photonics, cognitive science, radiological physics, and biomarking
Humane technologies	Humanoid, next-generation computing, digital contents, user experience, human computer interaction
Sustainable society	Nano-matrix, organic LED, nanotube, nanofiber, energy harvester, high-power battery
Smart and secure environment	Information retrieval, convergence with design, robotics, social analytics, system data analysis, internet of things

technology, intelligent convergence systems technology, and biomedical convergence technology.

Interdisciplinary Project Design

This is a recently created class to promote teamwork and collaboration among the graduate students. This class is run for each of the programs of GSCST, and achieving effective convergence and teamwork across multiple programs is still an ongoing challenge. In the case of Program in Digital Contents and Information Studies, students from different research disciplines are encouraged to identify a common problem or a research topic that can be investigated and studied together as a group. The course provides support through other students' and faculty members' feedbacks, resulting in regrouping or recruiting of necessary team members. The process is iterated until satisfactory teams are formed.

BK21+ and Smart Humanities

BK21+ is a government program that provides funding for M.S. and Ph.D. education. It is a highly selective national program – only a few graduate programs are selected in each discipline and the funding size is large enough to cover a significant portion of the graduate students' tuitions and stipends. Because of GSCST's leadership and experience in convergence education, it won this educational program in the convergence category. GSCST's mission for this program is to provide convergence education with a focus on "smart humanities" whose research areas are listed in Table 1. Smart humanities is defined as human-centered convergence that is developed through environment-friendly sustainable science and technology, and the four focus areas are shown in Fig. 6.

Technopreneurship

The Internet and maker movement (e.g., 3-D printing and development based on cheap and easily accessible manufacturing components) are making innovation, prototyping, and commercialization possible not only for large manufactures with capital and resource support but also for individuals and small groups. Accordingly, the recent entrepreneurship is moving toward technopreneurship that fully

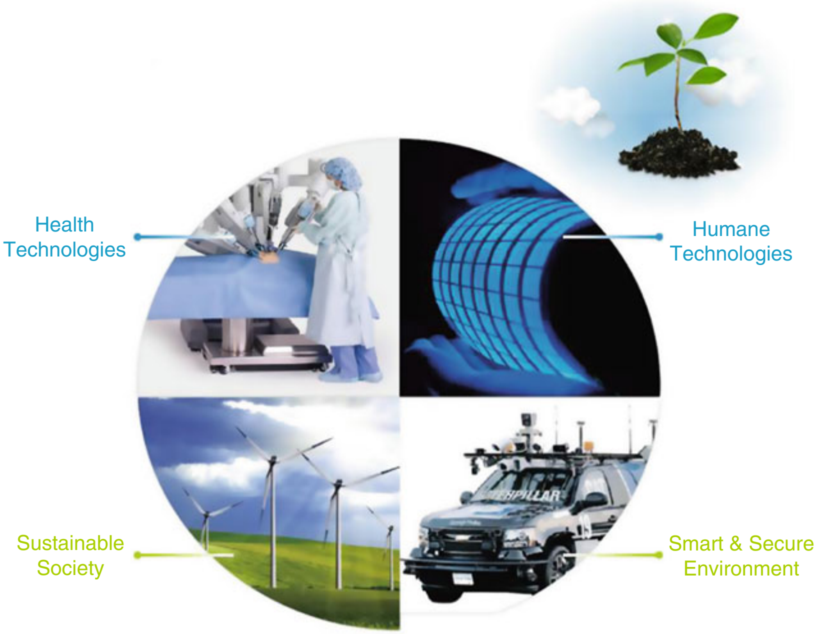

Fig. 6 Four focus areas of smart humanities

exploits the accessibility of this technology. This means that creativity is becoming increasingly important component of innovation and that individuals and small entities are becoming the main characters of innovation success stories. GSCST encourages its faculty members and students to transfer their research results to the industry. This can be in the form of start-ups or technology transfer whose support system is provided by AICT. GSCST provides a class on entrepreneurship where the goal is not only to teach basic knowledge on running a start-up but also to help students acquire a proper mind-set in becoming an entrepreneur. The class emphasizes that not everyone needs to become an entrepreneur, but everyone should learn and understand the fundamental strengths of entrepreneurial thinking.

GSCST: Lessons Learned

GSCST has been accumulating an extensive experience in convergence education and convergence research since its opening in 2009, and some of the important advantages and difficulties have been identified. As expected, GSCST's broad spectrum of research topics turned out to be a good stimulus for promoting new research topics. Easy access to the experts in near or far disciplines have been helpful, and arguably the daily interactions and casual discussions have been the most important for keeping eyes and minds open for convergence research. Also, the program has attracted students with diverse backgrounds, allowing students to see different approaches on similar research topics. Occasionally, the student diversity forced their advisors to learn new disciplines, naturally promoting convergence. Because of the program's convergence-oriented goals, GSCST has been encouraging its members to freely choose and alter their research topics. Having a flexibility does not necessarily lead to innovation, but at least it has greatly lowered the barrier for investigating new directions. As for the difficulties, two of the most important ones were recognized. First, convergence among weakly related disciplines has been challenging. An expert from nanomaterials and an expert from human-computer interaction can discuss their research topics, but they would rarely come up with a common research topic that they could collaborate on. Without a strong connection, it has been difficult to apply a systematic approach, and the convergence effort often ended up being opportunistic. Secondly, convergence and innovation indeed requires enough time and resource, and this has been a major issue for early career faculties. Most of the GSCST faculties were hired during their early careers because of their adaptiveness and research potential. Seoul National University's promotion and tenure system, however, was not flexible enough to allow sufficient time and resource for high-potential convergence research, and the faculty members had to focus on short-term outputs. In turn, this meant that the young faculty members had to focus on their original research topics to manage the risk of failing. Fortunately, the situation has greatly improved because most of the young faculties have been promoted in the past few years, but allowing exceptions and providing appropriate supports are necessary factors to consider for other institutions that are planning to establish a new program on convergence.

Representative Convergence Research at AICT and GSCST

Since its foundation, AICT's convergence research centers and GSCST's research labs have been coproducing a broad spectrum of research results. Samples of the representative and unique results are listed here.

Emergence Center for Personalized Food-Medicine Therapy System

This research group has been working on the development of personalized food-medicine therapy system that combines the traditional medicine and personalized treatment (Fig. 7). The research aims for the convergence between Korea's traditional preventive medicine and modern scientific understanding of human health though personal genomics. With the traditional philosophy that medicine and food have the same origin, chocolate candies, for example, were developed that can prevent cavities while being good for diet as well. These have been commercialized and are currently being sold on the market.

Intelligent Vehicle Platform Center

Intelligent automobile is another excellent example of a convergence platform bringing together mechanical technology with electronics and wireless

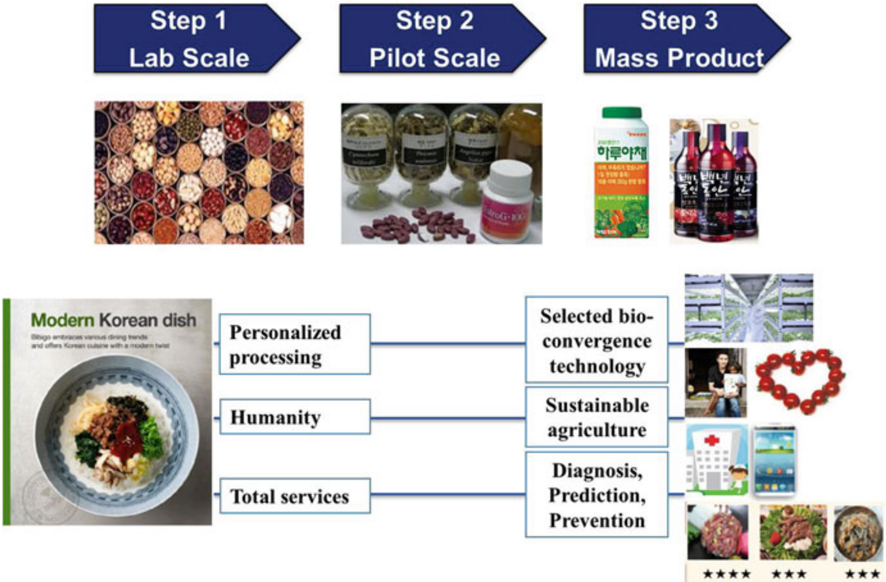

Fig. 7 Research goal of the Emergence Center for Personalized Food-Medicine Therapy System

Fig. 8 Smart personal mobility (*SPM*) project of Intelligent Vehicle Platform Center

communication technologies. Upcoming electric autonomous vehicles and smart personal mobility platforms (SPM) for the aging population will have even more diverse convergence technologies that include totally new power train concepts and electronics interfaces. A future SPM platform that can navigate autonomously was

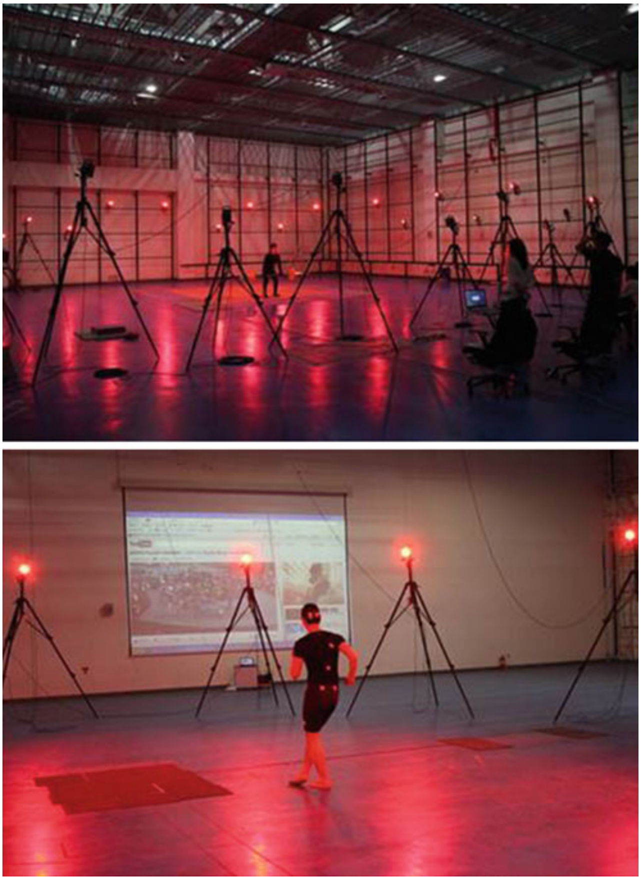

Fig. 9 AICT's motion capture facility and dancing motion analysis

successfully demonstrated by a team of researchers at the Intelligent Vehicle Platform Center (see Fig. 8).

Digital Human Research Center (in Collaboration with Dynamic Robotic Systems Lab of GSCST)

The research group has been focusing on the analysis of digitalized human movements in biomechanics and robotics. An exemplary project is on the analysis of dancing motions followed by synthesis of new dancing motions. As Korean songs and dances gain a worldwide popularity, like Psy's "Gangnam Style", creation of new dancing motions for a virtual character or a robot has become an interesting research area. The research group utilizes AICT's motion capture studio facility that has the largest number of motion capture cameras in Korea and performs analysis of human motions for character animation or humanoid robots (see Fig. 9).

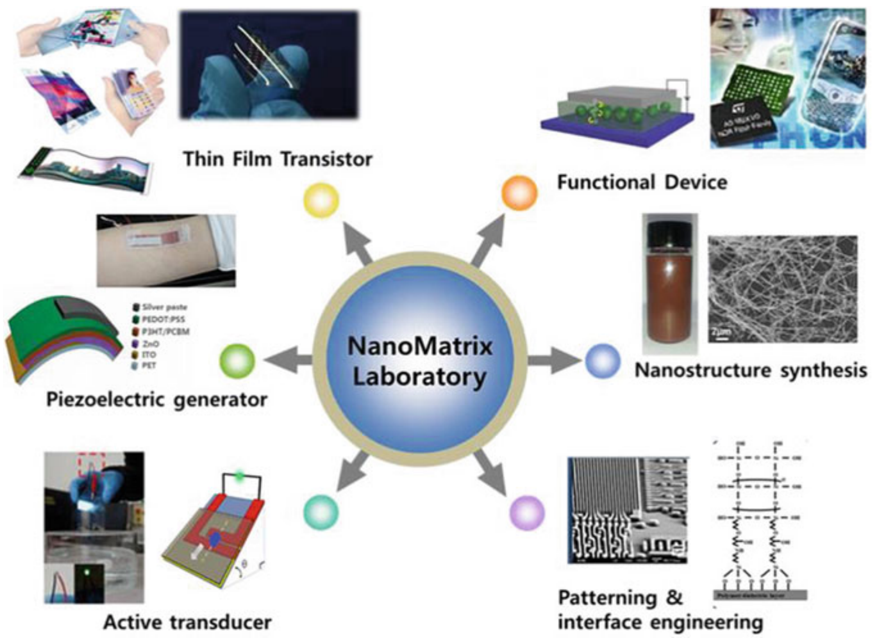

Fig. 10 Research topics of Green Battery Innovation Research Center

Center for Interactive Media Art and Technology (in Collaboration with Music and Audio Research Group of GSCST)

The group has dozens of researchers with diverse backgrounds, but one common attribute is that all the members have genuine interests in music and related research. The group has been performing convergence research between music and many other topics including data science, haptics for instruments, human mood classification, recommendation system, and movies.

Green Battery Innovation Research Center (in Collaboration with Nano-Matrix Lab of GSCST)

This group has been working on nanotechnolgy topics including patterning, thin-film transistor, memory device, battery, and energy-harvesting device (see Fig. 10). One of its latest and greatest research findings was about electric energy generation by adopting a transducer to convert the mechanical energy from various water motions (such as a few drops of water). Just thin layers of special materials were needed for the demonstration, and the result was covered in The Washington Post and the Fox News.

Concluding Remarks

As innovation in each stand-alone discipline becomes more difficult to achieve and at the same time expertise from different disciplines becomes readily available, the convergence practice has become more common and often a requirement for innovation. This chapter introduced Korea's convergence activities with a focus on Seoul National University's research and educational efforts through AICT and GSCST programs. Convergence activities can be effectively planned and performed if they are executed in concert at the national government, local government, and academic/research-institution levels. Identified key success factors are: Firstly, the central government should show leadership in addressing the grand challenges, including a long-term vision, workable strategies, and funding plans. Secondly, the local government should provide appropriate environment and infrastructure conducive for creative convergence activities along with the funding for convergence research. Gyeonggi Province's technology cluster strategy was proven to be effective for bringing many technologies and businesses together in one location and creating synergy through convergence. Lastly, the academic and research institutions should produce tangible results, which can be achieved through diversity and flexibility that encourage convergence and innovation. Furthermore, the institutions are responsible for delivering education and training not only for the skilled workers and professionals but also for the general public. Overall, the diversity and openness are important components for science and technology convergence, and furthermore the humanities, arts, and social sciences play essential roles for a broader success.

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Cyberlearning

Janet L. Kolodner

Contents

Abstract

The history of learning technologies has computers mostly playing the roles of tutors, expert resources, and testers, with learners acting more as consumers than producers. Modern understanding of the processes involved in development of deep understanding and masterful capabilities suggest that more active and engaging roles are required for such learning. New technologies make it possible to imagine how managing and organizing such activities can be made manageable and engaging. In FY 2011, the US National Science Foundation set up a new program called Cyberlearning: Transforming Education (later named Cyberlearning and Future Learning Technologies) focused on this challenge.

J.L. Kolodner (✉)
School of Interactive Computing, Georgia Institute of Technology, Atlanta, GA, USA
e-mail: janetkolodner@gmail.com

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This chapter defines *cyberlearning*, presents the context under which the Cyberlearning program was founded, presents trends identified over the first 4 years of the Cyberlearning program, and my vision of how to achieve technology's most vital possibilities in fostering development of deep understanding and masterful capabilities.

Cyberlearning and the Context for NSF's Cyberlearning Program

In their 2008 report (Borgman et al. 2008), a task force commissioned by the US National Science Foundation (NSF) suggested that the time was right for NSF to invest in a program that would lead the way toward the future of learning technologies. In that report, they coined a term for what they were proposing: "*Cyberlearning*" *meant learning that is mediated or guided by interactions with the computer and done in an environment where both the computer and human agents can provide the help, or scaffolding needed, to foster deep understanding and masterful capabilities*. The meme "cyber" in the name, the report said, should not simply be thought of as referring to computers but should be construed the way Norbert Weiner used the term when he coined the term "cybernetics" – to guide. Cyberlearning, as defined in this report, would be about using computers and people together in the right ways to foster learning; the Internet could provide access to education and learning opportunities; simulation, modeling, and other immersive technology would provide opportunities for learners to explore and make sense of phenomena, while the computer and human agents in the environment would help learners make sense of those experiences and learn from them; the computer would provide resources that learners need as they are learning at the times when they are relevant and useful for activities learners are engaging in, with the computer and human agents sharing responsibility for helping learners needed make sense of those resources and deeply integrate what they are reading or experiencing with other things they know; and the computer would collect and interpret data that would help teachers and other mentors and the computer itself to assess understanding and capabilities in ways that could ultimately lead to adapting learning experiences to the interests and experiences of targeted learners, bridging experiences in and out of school, and assisting learners in finding, connecting to, and collaborating with others with similar interests.

NSF took up the challenge, and the Cyberlearning: Transforming Education (http://www.nsf.gov/pubs/2010/nsf10620/nsf10620.htm) program was established in Fiscal Year 2011. It was since renamed Cyberlearning and Future Learning Technologies (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504984). The program, a joint effort of several NSF Directorates, had/has a threefold mission: to take advantage of what is known about the processes involved in human learning along with what technology makes possible to (i) help us imagine the roles technology might play in fostering and assessing deep understanding and masterful capabilities, (ii) learn how to design and use technology to achieve those goals, and (iii), in the context of the experiences people can have when interacting with such technologies and the data they can collect, advance our understanding of how people learn – the processes involved in getting to deep understanding and masterful capabilities and the influences on those processes – and how to foster, assess, and design for such learning.

Addressing these challenges requires the combined efforts of those who can imagine new technologies and the roles they might play in fostering learning, who are expert at how people learn, and who are expert technology inventors and developers. Over 4 years of NSF's Cyberlearning program, the program's awardees have created new ways of immersing learners in phenomena and situations they couldn't experience without technology, have designed ways to access and manipulate limited lab resources from afar, are designing ways to use augmented reality to help learners see into the past and see invisible natural phenomena, and are investigating how to systematically foster learning while engaging in citizen science endeavors, how to turn maker spaces into learning environments, and more. In each project, they are also uncovering the pedagogical moves, approaches, and strategies that are necessary for technology to effectively play roles in fostering deep understanding of natural and historical phenomena and mastery of the skills and practices involved in STEM (science, technology, engineering, and math) endeavors, historical inquiry, argumentation and explanation, communication, collaboration, language learning, and more. Each project team is also studying learning as it develops in these new kinds of environments. Some are learning about how understanding and capabilities develop when new kinds of experiences and support are available; others are learning new things about learning that can be learned only through analysis of the data that can be collected when learners are interacting regularly with technology.

The Cyberlearning program lives within an ecosystem of programs across NSF Directorates. CISE (Computer and Information Science and Engineering) funds research that supports the creation of new hardware and software technologies and new means of interacting with computers and integrating computers into communities, laying the groundwork for design and development of technologies for supporting learning. EHR (Education and Human Resources) funds research on learning in formal and informal learning environments, and SBE (Social, Behavioral, and Economic Sciences) funds research on human development, cognition, and learning, much of which can inform the design of new learning technologies and approaches. EHR also funds research and development leading toward new tools, resources, and models for learning, many of which are technological, and so forth. NSF has a long history of funding such endeavors.

The Cyberlearning program was designed to play a special role within this ecosystem of programs; it asks researchers to collaborate across disciplines to imagine the learning technologies that will be commonly used 10 or more years out and to create that future. Solicitations (cited above) ask researchers to think in terms of new "genres" (types) of learning technologies for the future rather than aiming toward implementation of applications for learning particular disciplines. The solicitations ask researchers to imagine and design new technologies, ways of using technology to foster or assess learning, ways of integrating technologies with each other, ways of integrating technologies into learning environments, and ways of configuring learning environments.

The timing for this new program was opportune. Between 2010 and 2014, a bumper crop of new hardware and software capabilities were developed and/or became available – tablet computers were just becoming affordable during the summer of 2010 and have become ubiquitous during the years since then, screens on cell phones have gotten better and bigger in that time, broadband has been greatly enhanced, the technologies that make augmented reality possible have become mature, touch screens of all shapes and sizes have made it to the market as have devices for health and activity sensing, software for authoring virtual worlds has become easier to use and more accurate, miniaturization of components has made sophisticated but easy to use robotics kits and electronic components available to use in making and design, Khan Academy and YouTube have made the Internet a place to access instructions and explanations for all kinds of things academic and nonacademic, MOOCs emerged as a way to provide access worldwide to undergraduate and graduate courses, and more.

The Cyberlearning program gave/gives those who want to work across disciplines and outside of tradition the license to not only dream about what is possible but also to apply for funding to an NSF program specifically aimed at what learning technologies could be if the current constraints of the education system are eased.

Cyberlearning Evolves with Technology Possibilities

When the first solicitation for the Cyberlearning program was published, the aim was to fund research that would lead toward anytime, anywhere access to resources, materials, and others, personalization of materials, inclusiveness in STEM and other areas of learning for those who are not served well in the present educational system, and better understanding of learning, fostering, and assessing learning with technology and designing for learners. This was just as iPads were coming on the market and the Khan Academy was gearing up. Anytime, anywhere access and social networking were becoming ubiquitous; there was no need to aim research directly toward some of those original aims. Rather, the big issues in designing the learning technologies of the future seemed to be in learning how to appropriately integrate them with each other, how to configure them to foster learning, and how to integrate the ensuing technological genres with curriculum activities. The Cyberlearning program, therefore, came to focus, almost from the beginning, on how to transform technologies designed for productivity or entertainment into learning technologies.

As well, because a big aim of the Cyberlearning program was to contribute toward transforming education and because the program was about aiming toward future possibilities, it was clear from early on that funded projects needed to go beyond simply focusing on cognitive issues in fostering and assessing learning. Design of learning technologies in the 1970s through 1990s was largely based on what was known about the cognition of learning. That literature tells us that deep understanding requires considerable time on task, abundant opportunities to try things out, and get feedback, time for iteration toward understanding and capability, and revisiting of what has been learned over a variety of contexts (Anderson 1981; Bransford et al. 2000; Schank 1982). We know, as well, that learners need to connect what they are learning to what they already know and have experienced; they can only build on the mental models they already have.

But more is known now about learning that can be used to inform the design of the next generation of learning technologies. We know now that understanding involves complex considerations of what makes sense. Iterating toward understanding includes expressing, debugging, and refining one's understanding and self-explanations, often aided by interactions with peers and more knowledgeable others. Iterating toward development of masterful capabilities involves the same kinds of complex reasoning and interactions with others. Learning is not a solitary or purely cognitive activity (see, e.g., Vygotsky 1978). As well, we now know that our bodies play powerful roles in helping us learn and in helping us express what we know, through the metaphors we use in understanding (Clark 1997; Lakoff and Johnson 1999), the gestures we use and observe others using to express meaning, our use of multiple senses as we experience scenarios and phenomena, and more – called *embodied cognition*. And because getting to deep understanding and masterful capabilities takes a long time and can be fraught with difficulties (and tedium), such deep learning can only happen if learners are motivated to sustain their engagement over long periods of time and through the hardest parts.

Furthermore, we see in our schools on a regular basis that many students turn off and tune out when they don't know why they need to learn something or how it will be important to their lives. These learners won't put in the time or energy to engage in sense-making activities and practice that are needed to develop understanding and capabilities. As well, what people need to learn in the twenty-first century is different from what they needed to learn in previous centuries. Communication and collaboration skills are more important than ever, as is the ability to be adaptive and flexible in the ways one uses what one knows and identifies what else one needs to learn. And learners, who are our citizens, need to both be competent and feel confident in these capabilities to succeed when required to perform outside of what they know well.

The challenges in fostering learning, then, are not simply cognitive challenges; it is important, as well, to consider social, cultural, and other influences on individuals and collectives when designing ways to help them learn, and it is important to not only help learners know things but also to help them *develop the skills, practices, attitudes, and dispositions they need to be productive and successful in our complex world*. The Cyberlearning program became a go-to funding program for researchers who were designing ways of using technology to address learning life skills and practices; help young people develop new pro-social and productive habits, habits of mind, and dispositions (and, ultimately, identities); and learn complex skills and practices that are important across disciplines.

Trends and Challenges

In the first 4 years of the Cyberlearning program, a variety of trends emerged from funded efforts that are indicative of the ways computers and people will be working together to transform the learning experiences of the next generation and of our generations' lifelong learning, and I will continue by writing about several:

(i) From computer as expert to computer as afforder of expressive experiences
(ii) From games and simulation to immersion and role-play
(iii) From computer as resource provider to computer as manager of help-giving agents
(iv) From collaboration and cooperation to community learning
(v) From individual tools to platforms integrating tools

From Computer as Expert to Computer as Afforder of Expressive Experiences

A major focus in learning technologies for the past 40 years has been development of computer tutors that can tutor students in academic subjects as a human tutor can do (Anderson et al. 1995). In such systems, the computer plays the role of disciplinary expert, usually posing problems for a student to work out. The computer system provides hints to the student about how to go about solving the problem, a congratulatory statement if the student solved the problem correctly, short descriptions of what the student did right, and statements about what the student did wrong; such systems choose problems for a student to solve and resources for them to read and interact with that will help the student move forward. Such approaches have helped students learn some targeted content very well standardized tests (Anderson et al. 1995).

But what is known about encouraging active engagement over long periods of time suggests that more playfulness and expressivity is needed to address the nation's educational challenges. Activities in which learners are making things work or helping others learn have affordances for engaging learners over long periods and providing opportunities for iteratively refining one's understanding (Papert and Harel 1991). Expression can be in the form of designing and building working models or animations, storytelling, acting out roles, and more.

Scratch (http://scratch.mit.edu/), for example, and its descendants (e.g., Scratch Jr., http://www.scratchjr.org/) allow children as young as 4 or 5 to design working models and animations. Scratch is extensively used online from home as a space for creative design, and in the process of sharing their designs with others and discussing (online) their ideas and how they programmed them, participants begin to develop expert programming skills. Teachers, usually in middle school, ask students to use Scratch to animate scientific and historical processes. The process of animating, examining one's animation and comparing it to what one expected or wanted to show, and iteratively refining the animation provides learners an opportunity to debug their understanding of what they are trying to express so that others can understand.

NetLogo (https://ccl.northwestern.edu/netlogo/), a cousin of Scratch, is designed to support modeling of natural, designed, and social processes. The interface helps learners express the causal connections in processes they are modeling. As with Scratch, when learners run their models, they compare what they see in animations with what they were expecting to see and then refine the process rules and causal connections between the elements until the outputs they see are what they expected. The structuring of process rules and causal connections the software provides helps learners discuss the processes they are modeling in the kinds of language scientists would use, e.g., the language of causality, influences, and emergence. One particular descendent of NetLogo, called SiMSAM (http://sites.tufts.edu/simsam/), is being designed to help young learners (grades 4 through 8) make explicit connections between their naive conceptions of natural processes and current scientific understanding of those processes.

The advent of small componential electronics that can be sewn or glued into craft projects (e.g., Arduino (http://www.arduino.cc/), Arduino Lilypad (http://lilypadarduino.org/)) makes it possible to extend expressive computing beyond a school focus on STEM (science, technology, engineering, math). Maker spaces are springing up in schools, libraries, and science centers around the world to provide a place where families or groups of friends can go to make things together. The most sophisticated of these have woodworking, metalworking, and laser-cutting tools that expert designers, engineers, and craftspeople might use (see, e.g., FabLabs (http://fab.cba.mit.edu/)), but less sophisticated ones almost always include laser cutters and 3D printers. People in the spaces help each other use the tools and materials and imagine what they will make, and those who build things in maker spaces are often participants in maker faires (https://makerfaire.com/) where they have a chance to show off their creations to others and discuss the ins and outs of making things work.

Learning is not systematic in maker spaces, however. Participants experience many electronic, physical, and mathematical phenomena, but they are not always experiencing those things in ways that are most productive to learning. To address this, some NSF grantees are exploring what it takes to make a maker space into a learning environment (http://cehd.gmu.edu/news/stories/makerspaces01). Software is being designed to help participants identify phenomena and begin to wonder about them and to connect participants to others with similar interests; the challenge, of course, is to do this in a way that does not detract from the fun and playfulness of these spaces.

Identifying the help someone needs and providing that help is quite difficult when learners are in charge of what they express. In some attempts to address this difficulty, researchers are triangulating across learner behaviors and reported goals and difficulties to identify indicators of confusion and progress (e.g., http://www.nsf.gov/awardsearch/showAward?AWD_ID=1319938&HistoricalAwards=false, http://www.nsf.gov/awardsearch/showAward?AWD_ID=1418352&HistoricalAwards=false). Another way to close this gap is to design ways of distributing responsibilities for providing aid across computer, peers, and teacher. Ashley, Litman, and Schunn (http://www.nsf.gov/awardsearch/showAward?AWD_ID=1122504&HistoricalAwards=false) do this for providing help with argumentation by using the structure provided to students as they put arguments together for two purposes – to provide guidance to students and to constrain the computer's analysis. The computer is then able to critique and provide help with the structure of an argument, while peers and teacher help with the content itself.

From Games and Simulations to Immersion and Role-Play

Simulation has long been used as a means of allowing learners to observe phenomena and scenarios that would be off-limits because of size, speed, danger, or accessibility (Honey and Hilton 2012). Advanced interactive capabilities (e.g., augmented reality, whole-room projection, multi-touch screens, realistic and real-time rendering) make it possible to allow learners to go a step farther – to embed themselves in such situations. Once learners can be embedded in situations they could not have experienced otherwise, they can also take on roles they could not easily take on otherwise – as, e.g., scientists, engineers, policy advisors, and journalists – and carry out activities authentic to those roles with the resources and tools that are available to their professional real-world counterparts.

For example, in Tom Moher's RoomQuake (Moher 2008; http://www.evl.uic.edu/moher/roomquake/), the elementary school classroom is outfitted with sensors, effectors, and equipment that allow students to be seismologists. The scenario controller keeps track of the locations of seismic plates in the classroom; it moves the plates to create *roomquakes*, which the children experience as the noise of a big vibration and the classroom's seismograms coming to life. Acting as seismologists, students read the seismographs, find the epicenters, and calculate the intensity of each.

Harvard's ecoMUVE (Grotzer et al. 2013) is a virtual environment where learners immerse themselves in an ecosystem. The fish in the pond are dying, and it is their mission to figure out why. The graphics are sophisticated, and there is a feeling of being there. Learners "walk around" the watershed area to learn what activities going on in the neighborhood might be affecting the pond's chemistry, and they can have "conversations" with those they encounter. They immerse themselves in the pond (at different levels and augmented with different magnifiers), and they examine the fish, plant life, and microorganisms under the water. They can magnify, measure, and count the organisms as well as watch them interact with each other, and they can collect much environmental data – both current and past. The computer provides tools for visualizing what they can't directly see, taking measurements, and analyzing the data.

Or immersive might be done by augmenting a real-world environment. CI-SPY (Singh et al. 2014) is designed to help students learn the history of school desegregation through visiting a local site, the Christiansburg Institute, important to that history. Using CI-SPY, they are able to examine what life was like in that place in previous generations and make observations and collect data from across historical eras. As historians do, they plan for data collection before going to the site, they collect data at the site, and they bring it back to examine and make sense of.

Immersion in a situation allows more of the senses to be involved in experiencing a phenomenon, allowing for richer representations to be formed. Immersion allows, as well, first-person perspective on phenomena rather than simply a third-person perspective. A ride on a molecule, for example, is far different from watching a molecule move around. Standing or sitting at the bottom of a virtual pond and watching the life swim by is a different perspective than watching from the outside.

Of course, having a rich experience does not guarantee learning from it. It becomes the teacher's responsibility and the responsibility of curriculum materials (some embedded in the technology and some outside the technology) to make sure that the conversations and other activities that will lead to learning from such activities are carried out well.

In the most engaging of immersive environments, immersions are the venue for undertaking missions – the kinds of challenges that put a learner into a role he or she can connect with and become passionate about. When such challenges require learning targeted text and becoming masterful at targeted skills and practices and are exciting and complex enough to engage learners over long periods of time and to require sense-making discussions as a natural progression toward achievement, children learn deeply, discipline is less of a problem, and test scores go up (see, e.g., Kolodner et al. 2003).

From Computer as Resource Provider to Computer as Manager of Help-Giving Agents

From the beginning of the infrastructure of the World Wide Web, people have been putting resources on the web that others can use to learn. The Khan Academy's (https://www.khanacademy.org/) website has one of the largest collections of educational videos, aimed at content targeted in schools. University of Colorado's PhET (http://phet.colorado.edu/) efforts include hundreds of interactive simulations that can be integrated into curriculum and/or used to help with making sense of science content. Resources such as these serve many useful purposes, but thinking about computer networks only as a repository for resources limits imagination about what other functions the computer can take on.

The computer as manager of help-giving agents is a function many researchers are currently focusing on. Help-giving agents can take several forms; in any of their forms, they are somewhat different from a computer tutor. A computer tutor has full control over the learning activities of the learner as he or she is learning some particular content and skills, and computer tutors are designed specifically to focus on the cognition of learning certain content.

But expressive technologies and immersive environments used in contexts of asking learners to undertake missions and achieve big challenges require a different type of help for learners, and researchers are working on learning the best ways to implement this help in the form of specialized agents. One agent might alert an interested learner about the life of a scientist who engaged or engages in research in the area the learner is investigating. Another might notice when a learner is excited about some practice or content and tell about the kinds of careers in which one gets to do that kind of thinking. Or, as Paul Feltovich et al. (2001) have suggested, a cognitive prosthetic could engage with a group of learners as a slightly more sophisticated group member scaffolding their sense-making while participating as a peer. Other agents might be specialized to particular content. In SimCoach (Swartout et al. 2013), for example, a simulated retired sergeant major, civilian, aviator, and battle buddy each give advice from their particular perspective and based on what would be their roles in the life of an advisee. A set of help-giving agents in one of the virtual or augmented environments mentioned earlier might share responsibility for such tasks as highlighting what it is important to observe, aiding data collection, aiding visualization and interpretation of data, making connections to the real world, moving a conversation forward, and helping collaborators focus in productive ways as they are making sense.

A particularly important role for such an agent is one masterful teachers play as they facilitate whole-class discussions together – managing *accountable talk*. Accountable talk (Michaels et al. 2008) means expression at a level of appropriate rigor for the discipline (and the age/development of the learners), in a way that is respectful and inclusive of others and in a way that moves the group's sense-making forward. When a help-giving agent can help small groups of students engage in accountable talk, the whole-class discussions will generally be at a higher level. Giving the computer this capability requires expertise in computational linguistics, socio-cognitive processes, and education practice.

Help-giving agents are sometimes implemented as friendly looking avatars that might be quite sophisticated in the ways they express themselves verbally and with gestures. What they look like is less important than the functions they carry out, but for some applications, the most natural-seeming ones, and the best conversationalists, researchers believe, will be best accepted by learners (see, e.g., Swartout et al. 2013). A challenge in making such avatars work well is managing their friendly gesturing, deistic gesturing, and gesturing for purposes of explanation so that the three complement each other well (http://www.nsf.gov/awardsearch/showAward?AWD_ID=1217215). When such avatars have voices, there are also challenges in making voices natural and expressive enough. Overall, however, the biggest issues in designing help-giving agents are in identifying with accuracy when it is appropriate to do their job; identifying the right times and ways of giving help so as not to interrupt a learner's flow and train of thought, principles for merging different kinds of help-giving into single agents; and managing the interactions with such agents so that they are a help and not an annoyance.

From Collaboration and Cooperation to Community Learning

Early in the days of the Internet, researchers were helping learners to collaborate with each other productively while learning. Some software helped learners find experts (e.g., CoVIS (http://www.covis.northwestern.edu/)) and peer interested in similar issues. Some helped learners contribute to conversations in productive ways (e.g., CSILE (https://www2.ed.gov/pubs/EdReformStudies/EdTech/csile.html), Guzdial and Turns 2000).

More recently, the focus in computer support for collaborative learning includes, as well, support for community learning – learning across a collective. CSILE, for example, mentioned earlier, has been replaced by Knowledge Forum (Scardamalia and Bereiter 2006; http://www.knowledgeforum.com/), which includes facilities for not only keeping a conversation going but for restructuring notes to make new threads that lead to new or alternate conclusions, looking across conversations to notice new possibilities for moving collective learning forward (http://www.nsf.gov/awardsearch/showAward?AWD_ID=1122573&HistoricalAwards=false), and helping learners in one place take advantage of the conclusions and conversations of groups of learners in other places (http://www.nsf.gov/awardsearch/showAward?AWD_ID=1441479&HistoricalAwards=false). As augmentation to several Citizen Science efforts, researchers are focusing on helping participants keep track of what their collective knows and use that knowledge to pursue their own interests and tasks (http://www.nsf.gov/awardsearch/showAward?AWD_ID=1441527&HistoricalAwards=false; http://www.nsf.gov/awardsearch/showAward?AWD_ID=1227530&HistoricalAwards=false).

From Assessment to Data Mining and Learning Analytics

The computer has long been used as a tool for assessment. The original CAI programs counted what learners got right and wrong and chose the problems they would see next based on solutions to previous problems. Intelligent tutoring systems are able to dig deeper into learners' understanding, tracking more explicitly what learners understand, and are capable or not capable of as they are solving problems.

Such assessment is more difficult when learners are working on open-ended tasks and when they have more personal choice about what to pursue. Additional challenges arise when we think about the many different ways learners might be expressing themselves and when we take into account that not all the learning that needs to be assessed is content learning. Also important to be able to automate help-giving activities and to keep a teacher informed about a learner's progress is to extract from learners' activities and behaviors the project and collaboration practices they are learning, their proclivity toward taking on responsibilities and using what they know at appropriate times (called *disposition*), and their overall abilities to flexibly use what they are learning. Such tracking requires more than simply interpreting the interactions learners have with the computer. Some of their interactions will be with peers and some with objects in their environments. Tracking growing dispositions requires being aware of what the opportunities are in the environment for applying what they are learning.

The fields of learning analytics (http://solaresearch.org/) and educational data mining (http://www.educationaldatamining.org/) are addressing these issues. These new fields are grappling with such issues what the indicators might be of growing dispositions, how to interpret a learner's boredom or identify excitement, and what data to collect and take into account to be able to predict the potential insights a learner might have and the help that might be given to make those insights happen. They collect big data from learning environments – both the data that comes from interactions with the computer and video data showing learner behaviors. They might also, in some circumstances, collect conversational data. The fields are in their infancy, and we are just beginning to see researchers in those fields take on the kinds of challenges that can only be addressed using big data sets.

From Individual Tools to Platforms Integrating Tools

It is typical in academic research for a single researcher to focus on a single function of technology for learning – providing certain kinds of help, supporting collaboration, a particular approach to modeling, and so forth. But transition of ideas from research to practice requires integrating tools in platforms that make it easy for a learner to move fluidly from one function to another. A science investigation, for example, may require collecting data from a setup in the real world, charting it, and graphing it, looking across the charts and graphs of others who have collected similar data and synthesizing across, charting the data in several different ways to make sense of it, and reporting out conclusions with justifications. An infrastructure that makes it easy to move data and representations across the tools used for that big variety of functions will be easier to integrate into classroom activities than individual tools that each have their own conventions.

Such integration goes beyond issues of technical interoperability; the suite needed for middle-school life science will share functionality with the suite needed for middle-school physical science and the suite needed for high-school biology, but they will not be exactly the same, and there is much intellectual challenge in identifying the suites needed for each, how to manage fluid movement between tools in each suite, and how to manage look and feel across suites of tools. Research in learning technologies is beginning to include design of such suites. EcoMUVE and RoomQuake, discussed above, both provide examples of integrated suites of tools, but each is specific to its disciplinary content and activities. Several other projects focus on more general-purpose suites of tools. InquirySpace (http://concord.org/projects/inquiryspace) focuses on integration of tools inquiry science in high school. Fred Martin's iSense (http://isenseproject.org/news) is designed to allow middle-school and high-school students to share and analyze data across sites. Kemi Jona's iLab (http://www.ilabcentral.org/) is focused on supporting high-school teachers and students as they engage in remote lab activity.

One more approach to integration is the massive online open course (MOOC; http://tech.mit.edu/V133/N2/mooc.html). A MOOC is massive – available to hundreds of thousands or millions of students at the same time. It is online – one listens to lectures and works out problems within the online infrastructure the course uses. It is open – one does not have to be enrolled in a degree program to take one of these courses nor does one need to pay if one does not want credit. And it is a course – 6–15 weeks of lectures with associated resources, problem sets, and assessments. In general, MOOC platforms are designed with integrated functionality for watching lectures, working on problem sets, collaboration, and more. But experience has shown that access to such courses does not necessarily mean that learners will remain engaged in a course and be able to learn from it. The community of researchers and developers in the area of MOOCs has many challenges ahead of it: how to organize content so that learners can pick and choose which parts of courses they want to participate in and how to take advantage in MOOCs of the affordances technology provides for fostering deep understanding are among those big challenges.

The Future

While some of these new types of learning technologies are available to small sets of learners now, most have been implemented for research purposes only, and only the crowdsourced citizen science projects are widely available. New ways of using technology for learning have the potential to transform classrooms into spaces where teacher and students make sense together of experiences they are having with phenomena as they are addressing real-world issues of personal importance to them. This was John Dewey's (1938) dream but was never possible except at a small scale. It's hard to manage a classroom of students when they are working on open-ended problems; it's uncomfortable for teachers when they cannot answer questions that come up that they were not expecting; it's impossible to get close to scenarios and phenomena that are far away, dangerous, too small to see or too large to explore, go by too quickly or take too much time to experience, or are simply invisible, making it impossible to explore them and investigate what happens in natural contexts; teachers cannot give advice simultaneously to multiple small groups of students working together; and so forth.

Technology provides ways of making Dewey's dream more of a reality, putting in place schools that are more attuned to the interests and learning needs of students, helping youngsters learn practices for the twenty-first century, connecting formal and informal learning activities, and supporting the learning wants and needs of the adult population.

But that requires, first, awareness of and imagination about what is possible and how to get there. I challenge my colleagues to do the kinds of work that will help others to have such imagination. This will mean going beyond implementations and research on the small pieces. It will require demonstrations at large scales of integrated technology platforms that invite exploration and creative pedagogy, with those platforms further integrated with excellent curriculum that affords playful but productive engagement and is governed by pedagogy that values collaborative exploration, expression, playfulness, and rigorous sense-making, all at the same time. When such technologies and associated curriculum materials and pedagogy are designed such that they can be integrated into the lives and learning environments of learners in ways that foster curiosity, support synthesis and sense-making, and scaffold practices and skills, we will be able to make real change happen in our educational systems and help learners both succeed at achieving goals and succeed at learning in the context of achieving those goals.

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Informal Science Education of Converging Technologies

Larry Bell

Contents

Abstract

The term "informal science education" is used to identify a wide variety of ways in which people learn about science outside of the formal educational process. While museums may have a tradition of preservation of objects for academic study, science and technology centers, which grew up everywhere in the second half of the twentieth century, focus on engaging the public in science. Driven initially by how phenomena could be put on display like objects in a museum, science museums developed a more explicit role in informal education, which has continued to evolve over time. Today's theoretic underpinnings of informal education in science museums are a convergence of the practices of the field with educational research and social science research. Educational research has identified the types of learning that are supported by informal educational experiences, and

L. Bell (✉)
Museum of Science, Boston, MA, USA
e-mail: lbell@mos.org; lb369@comcast.net

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different theories of knowledge and learning have suggested different approaches in developing museums. With the emergence of educational challenges for science museums on topics of current scientific research and technological development that raise questions about the societal and ethical implications of the choices we make, research in the social and political sciences has converged with educational research and the practices of the field. This convergence enables informal education in science museums to grapple not only with core principles of science but also with the presence of science in society and with public policy issues related to science and technology. Emerging engagement in the science of science communication holds promise for further expanding and refining informal education approaches for building bridges between the world of science and technology and the many publics whose lives are influenced by it.

Introduction

Even as convergence of knowledge and technology has transformed the work of scientists and engineers in seemingly different disciplines for the benefit of society, a similar convergence has occurred in informal science education. In its broadest conception, the term “informal science education” is used to identify a wide variety of ways in which people learn about science outside of the formal educational process. The National Research Council report *Learning Science in Informal Environments*: *People*, *Places*, *and Pursuits*, published in 2009, noted that:

> Contrary to the pervasive idea that schools are responsible for addressing the scientific knowledge needs of society, the reality is that schools cannot act alone, and society must better understand and draw on the full range of science learning experiences to improve science education broadly. Schools serve a school-age population, whereas people of all ages need to understand science as they grapple with science-related issues in their everyday lives. It is also true that individuals spend as little as 9 percent of their lives in schools. (National Research Council 2009, p. 12)

The NRC report notes that scholars of informal education trace its roots in the USA to the late eighteenth century and institutions such as libraries, churches, museums, lyceums, and Chautauquas – all places where people gathered for learning, lectures, dialogues, debates, scientific experiments, and entertainment. In the mid-nineteenth century, people went to world’s fairs to be exposed to a showcase of developments in science, technology, and industry. In the twentieth century, several world’s fair sites provided permanent homes for science and technology museums – Chicago’s Museum of Science and Industry, Seattle’s Pacific Science Center, the New York Hall of Science, and San Francisco’s Exploratorium among them. Early science museums in the USA drew inspiration from the Deutsches Museum in Munich, Germany, and were developed in Chicago, Philadelphia (The Franklin Institute), Boston (Museum of Science), and Saint Louis (Saint Louis Science Center). The great success of these and other early hands-on interactive science centers led to a worldwide explosion of science center development in the late twentieth century, and by the twenty-first century, the US-based Association of Science-Technology Centers listed nearly 400 such centers in their US database (www.astc.org) and another 100 from other countries, altogether hosting 95 million visits worldwide in 2013. Science and technology centers represent just one type of environment in which informal science learning takes place, but it is a significant one. The Association of Science-Technology Centers was founded in 1973, hosts an annual conference attended by over 1,500 leaders in the field from 42 countries, publishes a bimonthly magazine, and offers a variety of professional development and support services for the field.

While learning outside of school has taken place throughout human history, the field of informal science education was essentially defined by the creation of the Informal Science Education (ISE) funding program at the National Science Foundation in 1983. While funding for "public understanding of science" existed at NSF before that, the ISE program identified educational television, radio, and film projects; after-school programs; and science museum exhibits as components of informal science education. With grant funding came the requirement to use evaluation to assess and improve the impact of informal educational materials and activities (Robelen 2011). And with evaluation came the need to better identify learning outcomes consistent with research on learning in early childhood, particularly for children's museums and science museums with young audiences.

Informal science education is sometimes described as a craft because the community is seen as highly expert in what it does, but its "skills are rooted more in practice than in theory–a description that also fits formal education in schools" (Matterson and Holman 2012, 2.2). When you look across the wide range of practitioners of ISE, it is easy to see why this would be the case since the technical expertise needed for making television shows, designing exhibits, and running after-school programs for elementary school students varies considerably. Even in the specific case of developing an exhibit, a wide range of expertise is needed. Funded by the W. K. Kellogg Foundation in the 1980s, The Field Museum in Chicago developed a training program for exhibit development that identified three kinds of expertise and related responsibilities for an exhibit team:

Curator: The curator provides the scholarly expertise based on knowledge of the collection. As a subject matter specialist, the curator is responsible for establishing the overall concept of the exhibit.

Designer: The designer is responsible for the visual appearance and coherence of the exhibit. The designer's expertise assures that the material is set out in an appealing, understandable, and attractive manner.

Educator: The educator establishes the link between the content of the exhibit and the museum audience. The educator is a communication specialist who understands the ways people learn, the needs that museum audiences have, and the relationship between the museum's program and the activities of other educational institutions, including schools. The educator plans evaluation activities that will examine the exhibit's success in meeting its intended objectives and communicating with visitors (Munley 1986).

The Field Museum's training was instructive because the three team members they focused on had not only different expertise, but also different underlying values they brought to the development process, which sometimes, perhaps even often, resulted in conflicts during the creative process. Since the time of these Chicago trainings, science museum exhibit development teams have recognized a number of additional key players with different expertise to contribute to the work–project managers, fabricators, maintenance technicians, different types of designers (three-dimensional, graphic, and technical), evaluators, accessibility experts, and more, depending upon the nature of the project. It takes the convergence of skills and expertise from a variety of fields to develop a successful exhibition in which visitors will learn about science and technology on their own without additional guidance.

The informal science education field is itself diverse in the types of programs and institutions involved. Television and media projects may take similarly complex teams, but various programs that take place on the floor of a museum or in an after-school setting may be developed and implemented by a single individual or small group of individuals with similar expertise. In these cases, convergence may not yet be a reality but rather a future potential. Although an individul in this kind of position must often be a "jack-of-all-trades" with a wide range of expertise converging in a single person.

Real learning takes place in informal educational environments. Such environments are quite varied. Many of the practitioners of informal science education are highly skilled but work like craftspeople learning their methods from each other and improving their technologies on the job through both inspiration and trial and error. Some convergence with educational research has occurred since the 1980s, but new goals for informal science education to engage the public in new research areas like those associated with the convergence of nanotechnology, biotechnology, information technology, and cognitive science require twenty-first century informal science educators to engage also with knowledge from the fields of social and political science and with researchers studying the science of science communication. This convergence of these three areas of research – informal education, social and political science, and science communication – with the practice of informal education is the main focus of this chapter.

Convergence of Informal Science Education and Educational Research

In 2009, the National Research Council published *Learning Science in Informal Environments*: *People*, *Places*, *and Pursuits*. This report reflects on the theoretical perspectives on knowledge and learning that have guided an outpouring of research on the mind and the brain. These include behaviorist, cognitive, and sociocultural perspectives, each of which looks at learning differently. Behaviorist approaches focus on repetition and reward to support acquisition of simple skills that accumulate to become more complex concepts and behaviors. Cognitive theories may see learners as actively constructing knowledge and understanding in subject matter disciplines in connection with lived experience but primarily as individuals. Sociocultural theories focus on how knowledge and skills are developed in the context of the communities in which the learners are embedded. No grand convergence of these theoretical perspectives has guided the development of informal learning environments, but each has had influence in different areas and aspects of design.

The *Learning Science in Informal Environments* (*LSIE*) report constructs an integrated framework that brings about the convergence of learning theory with informal educational practices. Drawing principally from cognitive and sociocultural theories, *LSIE* proposed an "ecological" framework that integrates relationships between individuals and their physical and social environments. The framework uses people, places, and cultures as lenses to examine learning.

An example of convergence of theories of knowledge and theories of learning through a **people-centered lens** is the work of George Hein in the 1990s (Hein 1998). Hein saw behaviorist and cognitive theories applied across a range of learning experiences in ways that reflect a range of theories of knowledge – from seeing knowledge as objectively independent from the knower to the view that knowledge is individually and socially constructed. Mapping learning theories and theories of knowledge as two independent and orthogonal variables, Hein identified four quadrants with different approaches to informal education (Fig. 1).

If you think that knowledge exists objectively outside of the knower and that learning comes incrementally through repeated and progressive exposure to known content, you might organize a series of classroom lectures or the display of objects and information about them in what Hein calls a didactic, expository approach. The focus is on the knowledge and orderly presentation of it within the learning environment. This is typical of the traditional natural history museum in which minerals, shells, anthropological artifacts, stuffed animals, or other specimens are displayed in orderly and informative ways.

If you think that learning indeed happens in this way but that the knowledge learned is really a set of constructs in the mind of the learner, then you might take a more behaviorist approach providing rewards for progressive responses from the learner that are in line with learning goals. Programmed learning and computer games are examples that reward progression to higher and higher levels, and some museum exhibit and program activities have employed this question-answer-reward approach. It is quite typical for video and computer games to reward achievement with increasingly interesting and challenging levels of interaction.

If you think that knowledge does indeed have a reality external to the knower but that learners reconstruct that knowledge from their own experiences, then you might develop a discovery museum. This has been the dominant model in hands-on science and technology centers, in which exhibit developers construct experiences that will allow visitors to discover natural phenomena in the biological and physical world. Since the learner must construct knowledge that has objective

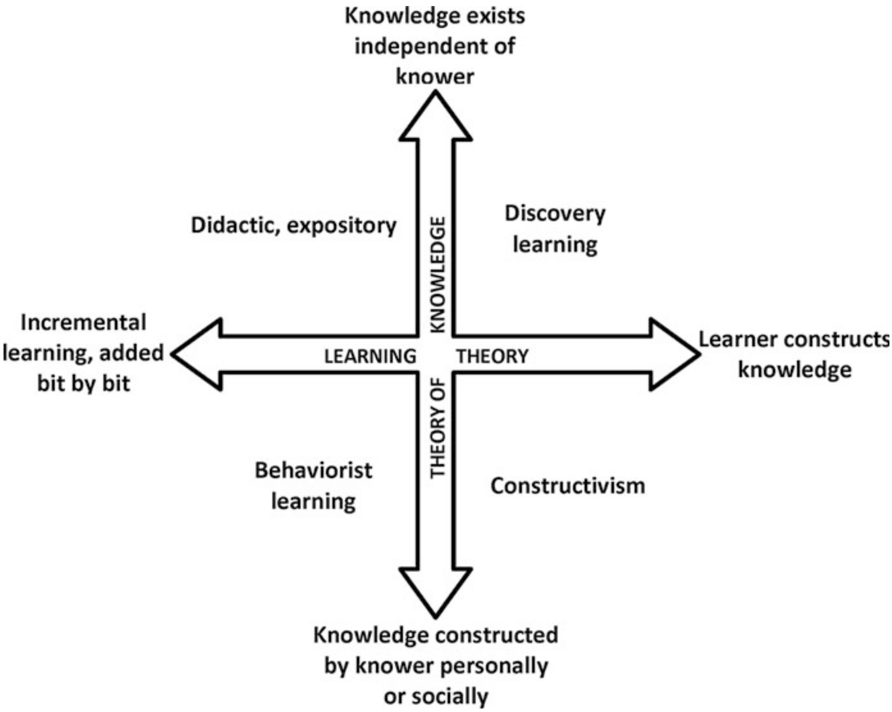

Fig. 1 Four domains of informal learning based on theories of knowledge and theories of learning (Redrawn with permission of George Hein)

reality, formative evaluation may be used to ensure that the designed learning experiences successfully lead visitors to the specific objective knowledge that is the goal of the learning experience.

If, however, you think that the knowledge that learners develop is really a set of constructs that are unique to the individual constructing it or to the social group with which individuals construct their understanding, then you might develop what Hein calls a constructivist museum. In such a museum, you might expect that different visitors will learn different things from the same experiences because they bring different knowledge with them at the outset. Open-ended, self-directed, multiple-outcome activities allow visitors to construct new knowledge that is most relevant to them. Hein clearly identified this quadrant as the one that reflects his views on the way that people actually learn and on the nature of what they learn.

Constructivist approaches are valuable for a wide range of learning objectives in science and technology, but they are inescapable for engaging the public in consideration of the societal implications of science and technology and especially in areas of new technological development where personal and societal values drive decisions as much as scientific evidence does. (The next section will discuss this further.).

Another component of the LSIE ecological framework, the *place-centered lens* (pp. 36–38), acknowledges the resources and practices associated with a wide variety of physical environments in which people learn. The awe of the Grand Canyon or Denali National Park, the night sky in the country far from city lights on a moonless night, a walk in the forest or along the rocky ocean shore at low tide, a plot of soil in the backyard or in a window box all provide unique opportunities for learning. Informal educators and naturalists make use of these unique opportunities all the time. Exhibit developers, after-school/out-of-school educators, media producers, and developers of online environments explicitly design settings to foster place-centered learning. Informal learning spaces have artifacts, materials, tools, practices, and supports that facilitate unique learning experiences. Such a space can be thought of as a "cabinet of wonders" – a world of fascinating scientific curiosities concentrated in a relatively small space eliciting one reaction after another and thereby constituting a unique place of learning and fun in the minds of the participants.

At the core of creating such learning spaces is the idea of experiential learning, which was most prominently proposed by John Dewey in his 1938 book *Experience and Education*. In 2012, George Hein documented how Dewey's ideas influenced museums, the 1973 establishment of the Education Committee of the American Association of Museums, and the 1981 launch of the Journal of Museum Education (Hein 2012). Science and technology centers are typically designed to be navigated freely – visitors choose their path and which activities they participate in. They may also be designed to serve a diverse range of visitors of different ages, backgrounds, and interests.

The *culture-center lens* described in the LSIE report reveals that all learning is a cultural process in which learners access and express their own ideas, values, and practices through their social affiliations. Out-of-school contexts can create social environments in which children become motivated and competent in areas in which they are failing in school. The Computer Clubhouse, for instance, which was originally developed at The Computer Museum in Boston and is now headquartered at the Museum of Science, is a creative and safe out-of-school learning environment where young people from underserved communities work with adult mentors to explore their own ideas, develop new skills, and build confidence in themselves through the use of technology. There are now 100 Intel Computer Clubhouses around the world. In a 2013 survey (SRI 2013) of Computer Clubhouse alumni, 97 % said the Clubhouse was the most important source of support in their lives for setting high goals and expectations for themselves. The Clubhouse has many success stories, and as one alumnus put it, "It was like a big family. My experience there made me more interactive with people. It's not only a great place for learning but for networking with great people while having fun" (http://www.computerclubhouse.org/alumni/steve).

The outcome of the NRC's work in 2009 to cut across various educational theories and to explore people, place, and culture lenses was to converge on a set of six interdependent strands that describe goals and practices of science learning (Fig. 2).

Strands of Informal Science Learning

Learners who engage with science in informal environments . . .

Strand 1: Experience excitement, interest, and motivation to learn about phenomena in the natural and physical world.

Strand 1: Come to generate, understand, remember, and use concepts, explanations, arguments, models and facts related to science.

Strand 3: Manipulate, test, explore, predict, question, observe, and make sense of the natural and physical world.

Strand 4: Reflect on science as a way of knowing; on processes, concepts, and institutions of science, and on their own process of learning about phenomena.

Strand 5: Participate in scientific activities and learning practices with others, using scientific language and tools.

Strand 6: Thing about themselves as science learners and develop an identity as someone who knows about, uses, and sometimes contributes to science.

Fig. 2 Strands of informal science learning (National Research Council 2009, p. 43)

These six strands have become a solid foundation upon which to plan, develop, and assess learning in informal environments. They represent the convergence of educational theory and research with the practice of informal education.

Knowledge of this convergence of educational research and informal educational practice was important to the development of educational experiences for the public on the topic of nanoscale science, engineering, and technology at the outset of the work of the NISE Net in 2005 because front-end evaluation showed that less than half of the industrialized adult population of the USA, Canada, and the UK had heard of nanotechnology and not more than 20 % could provide some sort of definition. Furthermore, interest in nanotechnology among the public was quite low compared with other emerging and current technologies. In addition, the informal science education community did not have decades of experience developing exhibits, programs, and media in the domain of nanoscale science, engineering, and technology, and there was no large extant base of such materials to learn from and to use as a basis for further designs. Hence, NISE Net developers had to find new ways to design informal educational materials to communicate new concepts to the public and to be attractive and feasible to the ISE and research communities. The larger ISE community itself had little expertise, experience, or incentive to do nanoscale education for the public. NISE Net was starting from scratch in developing institutional capacity and readiness to implement nanoscale education. So traditional informal educational practice needed to be supported by formative evaluation activities that measure educational achievement of new ideas, concepts, and approaches in the context of goals aligned with the strands of informal learning described by the *LSIE* report.

Convergence of Informal Science Education and Social and Political Science

In the late 1980s, the Museum of Science in Boston developed a series of exhibits that were organized around science thinking skills rather than traditional content areas. The underlying notion was to stimulate visitors in the construction of knowledge in ways similar to those used by scientists. In retrospect, this work can be seen as focusing explicitly on Strand 3 in the *LSIE* report (which had not been written yet) with the intent of generating pathways to the kinds of learning identified particularly in Strands 2, 4, and 6. The broad themes of this long-range exhibit plan and the associated scientific activities were the following:

- *Seeing the Unseen* (observation)
- *Finding the Pattern* (classification)
- *Making Models* (description)
- *Testing the Theory* (experimentation)
- *Putting It to Work* (application)
- *Playing with Ideas* (imagination)

When The Computer Museum in Boston closed in 2000 and organizationally merged with the Museum of Science, the latter organization began to examine the content and thinking skills that should be part of a new focus on technology. For technologies, thinking skills include innovation and engineering. With engineering comes a new set of issues noted in the 1989 report *Science for All Americans*, published by the American Association for the Advancement of Science (AAAS):

> Engineering decisions, whether in designing an airplane bolt or an irrigation system, inevitably involve social and personal values as well as scientific judgments. (AAAS 1990, p. 40)

"Social and personal values" are not among the typical content areas in most hands-on, interactive science museum exhibits, not in the list of science thinking themes adopted in Boston, and not in the six strands of informal science learning in the LSIE report. Furthermore, an experiment in building value-laden issues into science museum programming conducted by The Franklin Institute between 1991 and 1996 found that

> . . .presenters were uncomfortable with issues-related programming, preferring "concrete" science that did not venture into politics. The changing nature of points of view on the subject also evoked some concern, as did the fact that the topic. . .raises questions that cannot be answered definitively. (Mintz et al. 1995)

Despite this reluctance, the need to venture into issue-related programming in science museums grew with the publication of the National Research Council's report *Technically Speaking* in 2002.

> As far into the future as our imaginations can take us, we will face challenges that depend on the development and application of technology. . ..To take full advantage of the benefits and to recognize, address, and even avoid the pitfalls of technology, Americans must become better stewards of technological change. Present circumstances suggest that we are ill prepared to meet that goal. (Pearson and Young 2002, p. 12)

Calling for widespread "technological literacy," the *Technically Speaking* report describes the need as comprised of "an understanding of the nature and history of technology, a basic hands-on capability related to technology, and an ability to think critically about technological development" (Pearson and Young 2002, pp. 11–12). The first two of the components of this definition of need were fully within the existing experience and toolset of science museums, but the third was not.

Dialogue and Consensus Conferences

Forum programs derived from Danish Citizen Consensus Conferences introduced a different type of programming into informal science education in museums. A solution to the conundrum of how to introduce social and personal values, and questions that cannot be answered definitively, into educational programs in museums came when three scientists (Steven Katz, Patrick Hamlett, and Jane Macoubrie) from North Carolina State University (NCSU) reported on their experiments with citizen consensus conferences about genetically modified foods at the annual meeting of the AAAS in 2002. Citizen consensus conferences were used by the Danish Board of Technology (DBT) to provide input to the Danish Parliament from citizens about new technological developments. DBT provided a panel of citizens with background information on the technology in question, access to experts for technical information, a deliberation process, and the opportunity to write and present a final report. The panel of ordinary citizens brought their common knowledge, personal experiences, and societal and personal values to the deliberations. The whole process was typically carried out over 2–3 months.

The team at NCSU had experimented with a similar process both to acquire the input the citizens could provide and to learn about the consensus process itself. Some in the informal education community saw the overall concept as a potentially engaging educational experience for their own audiences. The Museum of Science conducted a series of prototype forum programs on variations of the consensus conference format with total program times from 2 to 8 h. Attendees found it an interesting experience and enjoyed both learning about new topics and hearing the diverse views of different people on the issues raised.

While conducting this kind of deliberative dialogue with the public was new to science museum educators, there were other organizations that did it all the time. *National Issue Forums* (NIF) is a network of civic, educational, and other organizations and individuals, whose common interest is to promote public deliberation in America. The *National Coalition for Dialogue and Deliberation* (NCDD) is a network of nearly 2,000 innovators who bring people together across divides to discuss, decide, and take action together effectively on today's toughest issues. The *Public Conversations Project* (PCP) has worked in the USA and around the world since 1989 facilitating dialogues on a wide range of contentious issues in order to prevent and transform conflicts driven by deep differences in identity, beliefs, or values. These groups and others like them do not necessarily focus on issues related to science and technology, though science and technology often come into play, and they provided models of public engagement that science museum educators could learn from.

Public Engagement with Science

Public engagement with science emerged within the informal science education community in the USA as a different way of engaging the public, in 2009 when the NSF-funded Center for the Advancement of Informal Science Education (CAISE) developed the report *Many Experts*, *Many Audiences*: *Public Engagement with Science and Informal Science Education* (McCallie et al. 2009). That report notes that public engagement with science (PES) is an approach that developed during the prior decade within academic settings and the science policy arena.

> . . .Public Engagement with Science (in related) literature and practice has a specific meaning that is characterized by mutual learning by publics and scientists – and, in some cases, policy makers. This orientation contrasts with a one-way transmission of knowledge from "experts" to publics. Specifically, PES experiences allow people with varied backgrounds and scientific expertise to articulate and contribute their perspectives, ideas, knowledge, and values in response to scientific questions or science-related controversies. PES thus is framed as a multi-directional dialogue among people that allows all the participants to learn. PES activities in the context of informal science education may – but do not necessarily – inform the direction of scientific investigations, institutions, and/ or science policy. (McCallie et al. 2009, p. 13)

Many in the science communication and public policy arena have argued that to do this, there is a need to engage the public in multi-directional dialogue about science-related societal and public policy issues in a way that allows scientists to learn from the public as well as the public to learn from the scientists (Barben et al. 2008).

> We need to move beyond what too often has been seen as a paternalistic stance. We need to engage the public in a more open and honest bidirectional dialogue about science and technology and their products, including not only their benefits but also their limits, perils, and pitfalls. (Leshner 2003, p. 977)

ISE professionals are uniquely situated to inspire and mediate the types of interactions between scientists and publics that are critically needed today. Science centers already engage scientists as advisors and speakers, partner with them in outreach activities of all kinds, and provide training and opportunities to practice science communication skills. ISE institutions are skilled at communicating science to the public and are seen as trusted conveyors of controversial scientific topics. Thus, they are well positioned to facilitate conversations among diverse stakeholders about socio-scientific issues – societal issues that are informed by science. Despite this potential, ISE programming that explores the full benefits of PES is still limited (Kollmann 2012).

The Museum of Science conducted a survey in 2011 to explore the prevalence of PES activities in the work of the ISE community. Over 150 organizations submitted descriptions of 201 projects – ranging in format from art and theater to festivals to on-site research. Analysis of these case summaries found that most commonly, projects had public awareness, knowledge, or understanding goals and public engagement or interest goals to a lesser extent, but projects were much less likely to include goals for the scientists' involvement (Iacovelli et al. 2012). Despite high levels of interest in PES in the ISE community indicated by the responses to this survey and field-wide goals such as those in the Science Centre World Congress *Toronto Declaration* in 2008 ("We will actively seek out issues related to science and society where voices of citizens should be heard and ensure that dialogue occurs"), very little robust PES was happening in US science museums as of 2011.

Social Science Content

Informal educators for the most part were taught science concepts and processes in school, in a way that appears to have an objective, rather than subjective, basis. But when societal and personal values come into play, for many science educators the content is unclear. What values? Whose values?

In 2005, NSF funded the Nanoscale Informal Science Education Network (NISE Net) to increase public awareness, knowledge, and engagement with nanoscale science, engineering, and technology. The idea was to create collaborations between informal educational institutions and nanoscale research centers in order to raise the capacity of both types of organizations to engage the public in learning about nano. Tying all of these local partnerships together would be a national network infrastructure. The Museum of Science, the Science Museum of Minnesota, and the Exploratorium partnered to win the award from NSF to establish the NISE Net.

NISE Net developed a wide range of educational materials including tabletop and classroom hands-on activities, theater and stage presentations, media, exhibits, and a wide range of training materials, guides, and other resources. A group of five institutions worked together to develop, test, and deliver forum programs that engaged visitors in dialogue and deliberation about such topics as who should be involved in shaping future development and regulation of nanotechnology, under what conditions should nanotechnology applications in medicine and personal care products be made available to the public, and how should nanotechnology research fit into domestic energy policies in the near future. These forum topics went beyond even the novel physics and chemistry of nanoscale science and led informal educators to find social scientists, political scientists, and ethicists at their local universities to make presentations and help with the planning of the program content.

At the same time that NSF funded the NISE Net, it also funded two centers for nanotechnology in society, one at the University of California at Santa Barbara and one at Arizona State University. The latter became heavily involved in the work of the NISE Net and provided the critical missing component of the public engagement work – the science and society perspective and content drawn from the social and political sciences that is missing from the backgrounds of most informal science educators.

In 2007, a team of researchers and educators in the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) presented a draft of a document that was later expanded into *The Big Ideas of Nanoscale Science and Engineering*: *A Guidebook for Secondary Teachers* (Stevens et al. 2009). The draft primarily covered eight big ideas in physics, chemistry, engineering, and mathematics and only one big idea about science, technology, and society. Later that year, a team of researchers at the Center for Nanotechnology in Society at Arizona State University developed a parallel document *Nanotechnology and Society*: *Ideas for Education and Public Engagement* (Miller et al. 2007). This guide included ten big ideas:

- *People make nanotechnologies*
- *People live with*, *in*, *and through technologies*
- *Technological and social change are closely connected*
- *There are many ways to design*, *implement*, *and use a given technology*, *and many technological solutions to a given problem*
- *Technological systems are frequently highly complex*, *interdependent*, *and difficult if not impossible to predict*
- *Social and technological change can be incremental – or disruptive – and it can be hard to forecast which*
- *New technologies are often controversial and may create new risks*
- *Our technological imagination shapes our future*
- *People already play an important role in governing new technologies*, *and they can play an even bigger roles*
- *We need to be more reflexive about how we assess nanotechnology*. (Miller et al. 2007)

Researchers from the Center for Nanotechnology in Society (CNS) at ASU argued for societal and ethical implications content to be included not only into forum programs but also added to the more traditional educational formats used in science museums to communicate physical and biological science concepts. Forum programs require a longer time commitment that traditional museum experiences for both participants and facilitators, and so while highly impactful, they generally reach much smaller audiences than do short educational activities that take place in the exhibit halls as part of a normal museum visit.

So CNS researchers and NISE Net educators collaborated to develop a set of resources, educational activities, guides, training materials, and workshops centered on the theme of Nanotechnology and Society.

> The Nano and Society project of the Nanoscale Informal Science Education Network (NISE Net) is designed to empower museum educators and visitors to explore the relevance of nanotechnology in our lives. The project builds upon the fundamental scientific concepts, tools, and processes related to nanotechnology that are central to many of NISE Net's other educational materials and programs. It then considers how new nanotechnologies may affect people and the societies they live in and create. These technologies will open up new possibilities, shape our relationships, promote the values of those who build them, and through a variety of systems affect many different parts of our society and communities. This project is different from many other museum programs because it seeks to encourage visitors not just to think about science and technology, but to participate in the conversation. To achieve this, it encourages conversations that can help museum guests think through what their values are, better understand how other people think about values, recognize the expertise they have, and increase their confidence to contribute to the broader discussion about these technologies. At its core, this project aims to illustrate that while new nanotechnologies will help shape our future, people everywhere have opportunities to influence what that future looks like. (Wetmore et al. 2013, p. 5)

In developing educational materials for informal educators to use with museum visitors and training on how to use the materials, CNS researchers and NISE Net educators concentrated on three big ideas revising and combining elements from the earlier list of ten.

Nano and Society: Big Ideas

1. **Values** shape technologies.
2. Technologies affect social **relationships**.
3. Technologies work because they are part of **systems**:

1. **Values shape technologies**.
   (a) Our values shape how technologies are developed and adopted:
      - Technologies reflect the values of the people who make them.
      - Individuals choose technologies to advance their goals, hopes, and dreams.
      - Companies build technologies that can be sold for a profit.
      - Governments fund technologies in an effort to benefit their economy and their citizens.

   (b) The adoption of technologies benefits some people more than others:
      - With any technology, no matter how useful, there are winners and losers.
      - Technologies can be used to promote one group's values and interests over other groups.

- Technologies can lead to conflicts over values, among groups, or even within an individual.
- Some of these effects are deliberate and some are unintended.

2. **Technologies affect social relationships.**
   (a) Technologies often change the relationships between people:
   - Technologies affect the way we interact with family members, people in our community, and people around the world.
   - People negotiate with each other and with new technologies to maximize their own values.

   (b) New technologies are often accompanied by changes in cultural norms:
   - We are all actively involved in developing acceptable behaviors related to technologies.
   - These new norms will not reflect everyone's values equally.
3. **Technologies work because they are part of systems.**
   (a) Technologies are part of larger systems that include technological, political, social, and environmental components.
   (b) Many people and groups are involved in the development and adoption of new technologies.
   (c) We affect the development and use of technologies through our actions and choices (as consumers, citizens, voters, workers, parents).
   (d) In order to understand the role that technologies play and the effects they have, we need to think about the ways they are connected to systems and people (NISE Net 2012).

Anticipatory Governance

Engaging the public in learning about and participating in dialogue and deliberation about future and emerging technologies is a reflection of a broader theoretical construct presented by David Guston of Arizona State University's Center for Nanotechnology in Society as "anticipatory governance." Guston defines anticipatory governance as "a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible."(Guston 2008) In pursuing anticipatory governance, Guston suggests activities that encourage and support scientists, engineers, policy makers, and other publics to reflect on their role in nanotechnology through an awareness of their own position as a participant with a specific set of roles and responsibilities in a field of other actors. Those roles call for the ability of a variety of lay and expert stakeholders, both individually and through an array of feedback mechanisms, to collectively imagine, critique, and thereby shape the issues presented by emerging technologies before they become reified in particular ways (Barben et al. 2008).

So the argument from the social and political science community to the informal science education community is that while few members of the lay public need to know about chemical bonds or planetary mechanics, they do need to know about how the decisions we are all making today or failing to make will impact our future, and we as educators need to know how we can help people develop the knowledge and skills the public needs to effectively play the roles that the future depends upon.

The Science of Science Communication

A new area of convergence for informal science education is the science of science communication. The NSF-funded NISE Net project created partnerships between science museums and university-based research centers. A central tenet of this arrangement was that the museum staff knew a lot about engaging the public but little about nanotechnology, and the researchers knew a lot about nanotechnology but little about engaging the public. The NISE Net project created a lot of educational materials that the university partners could use in their educational outreach activities, and it also provided training to NanoDays presenters and others from university research centers on how to use the materials. This led to a variety of activities throughout the network but most specifically at the Museum of Science and at the twice-annual meetings of the Materials Research Society (MRS) that focused on science communication professional development for mostly early career scientists.

At MRS, these professional development activities took the form of seminars on communicating through presentations, posters, working with the media, and in writing. These seminars were quite popular and became a staple of MRS meetings. The Museum of Science developed science communication training specifically for students in Research Experiences for Undergraduates (REU) programs and for graduate student participation in outreach events like NanoDays. Materials to conduct these two activities were developed and posted in the NISE Net library of educational materials at www.nisenet.org for all to use, and workshop helped to spread their use in the field. At the same time, the Pacific Science Center launched the Portal to the Public project, which was designed to assist informal science education (ISE) institutions as they seek to bring scientists and public audiences together in face-to-face public interactions that promote appreciation and understanding of current scientific research and its application. Starting with three science centers in 2007, the Portal to the Public network grew to 30 science centers by the end of 2013 (www.pacificsciencecenter.org/Portal-to-the-Public).

This work and the public engagement work discussed earlier drew the attention of ISE practitioners to two Sackler colloquia conducted by the National Academy of Sciences in 2012 and 2013 on the science of science communication. While informal science educators were aware of a body of research about science education, the research on science communication was fairly new to the field. Organizers of these colloquia and editors of the public volume of proceedings argued that beyond the discipline specific research field being communicated to the public and educational research that has informed informal education in the past, the research of psychologists, sociologists, decision scientists, and communication scientists can play a central role in informing successful science communication.

> Although scientists may know more than anyone about the facts and uncertainties, applications of . . . science can raise complex ethical, legal, and social questions, regarding which reasonable people may disagree. As a result, if scientists want to be effective in their communication, they must understand and address the perspectives of interest groups, policy makers, businesses, and other players in debates over decisions that require scientific expertise.
>
> . . .the stakes are too high to rely on intuitive theories and anecdotal observations about communication. It would be foolish to ignore the best available scientific evidence. The social, behavioral, and decision sciences have documented the many ways in which intuitions about others and about the effectiveness of communication can go wrong – and how those biases grow with the distance between the parties. The unique ways of looking at the world that make scientists such indispensable sources of information may also distance them from nonscientists. Making the most of what science has to offer society requires the give and- take of two-way communication with laypeople. . .. Ineffective communication can be costly to science as well as to society. (Fischoff and Scheufele 2013, pp. 14031–14032)

The extent to which science museums in the decades ahead see themselves as facilitating communication between scientists and a variety of publics, informal educators becoming familiar with and putting into practice the findings of research on science communication will become increasingly important.

Informal Education and Ubiquitous Information: Convergence of Education and Informatics

Informal science and education is enhanced not only by social sciences but also by the ability to communicate across fields, communities, and places using the Internet, large data bases crossing the fields, and methods of interaction between diverse groups. The evolution taking place in ISE would not be possible without modern means of communication and methods of finding information. ISE and social sciences are enabled quantitatively and changed qualitatively because of the new computer and informatics tools.

Educational media – television and radio – have been key contributors to informal science education. As early as the 1950s, *Watch Mr. Wizard* and *The Bell Laboratory Science Series* brought science to public audiences' homes across America, and numerous shows continued that work into the twenty-first century. *Cosmos*, *Scientific American Frontiers*, *MythBusters*, *3-2-1 Contact*, *Bill Nye the Science Guy*, and *Nova* are just a few television shows that have engaged audiences with science.

With the emergence of the World Wide Web in the 1990s and its subsequent growth, the public has a new major source of resources for informal science education. In formal education, universities have put entire curricula online and even offered degrees for online students. As of 2014, however, relatively little research existed on informal science learning through online environments. The Center for the Advancement of Informal Science Education (CAISE) Informal

Science Evidence Wiki is a source of information about current research in this area.

> For attentive, motivated, and knowledgeable audiences, science-related blogs likely enhance learning, build relationships with users, and visibility for a project or initiative.... However, blogs face many barriers in reaching younger audiences and unmotivated audiences, requiring dedicated resources, informed strategies, and staff to be effective.
>
> Over the past few decades, digital games on computers and mobile devices have grown in popularity as a teaching and learning tool....Research into digital games (however) is still in its relative infancy, and researchers' findings often conflict with those of others in their field.
>
> A large body of research exists on how to design formal educational software for non-mobile devices ... but there is considerably less information on how to design effective educational software for mobile devices, let alone informal educational software for mobile devices. The ways in which mobile devices are used differ along several important dimensions, which suggests that merely adopting lessons learned from more traditional desktop-based classroom software may not be effective.
>
> Recent research investigated the question of how learning from combined use of related, multiple media platforms (known as cross-platform learning) compares to learning from a single medium ....using the PBS school-age mathematics series Cyberchase, found that combined use of the Cyberchase television series and online games produced more consistent improvement in children's mathematical problem solving than use of either medium by itself....Moreover, the study found that, compared to children who played online Cyberchase math games without also watching the TV series, children who used multiple media also employed significantly more mathematically sophisticated strategies to play the online games....These points also suggest intriguing possibilities for convergent media, in which the narrative and explanatory power of video, the participatory strength of interactive games, and the in-person support provided in hands-on media can be combined in a single experience. (CAISE, Informal Science Education Evidence Wiki)

One early experiment with convergence between informal science education and informatics was the Science Learning Network project funded by NSF and led by the Franklin Institute in Philadelphia. The project involved six science museums and the global information technology company Unisys.

> With the goal of integrating the resources of informal educational institutions with the power of telecomputing, the (Science Learning Network's) theory of action incorporated a multi-pronged approach to supporting inquiry science teaching and learning in K-8 public schools.... SLN (provided) important images of the ways that museums, schools, and teachers move forward with integrating technology into their educational missions. (Blanc et al. 1998)

When the Experience Music Project (EMP) opened in Seattle in 2000, developers showed an unusually high regard for information in the context of artifacts and hands-on interactive museum environments. Perhaps this is not surprising with the realization that Microsoft co-founder Paul Allen was at the center of the project. In addition to the artifacts, labels, and hands-on activities, EMP provided all visitors with headphones and a digital audio tour guide worn over the shoulder. Recorded exhibit tour guides were not uncommon at the time, often providing narrative explanations of exhibit artifacts. (Charlton Heston who played Moses in the film

The Ten Commandments narrated the recorded tour for the Ramses the Great Exhibition.) But the data base for EMP's tour guide was more extensive than a recorded narrative. You could access audio recordings made with the various instruments on display in the galleries or by the artists whose personal artifacts were on display. You could also bookmark items in the EMP Digital Collection that you want to access later in your tour or at home on the museum's website. A seeming world of information was at your fingertips throughout the tour.

With the explosion of handheld mobile technology both in terms of capacity and distribution, visitors today can indeed have a world of information at their fingertips. For instance, *DIY Nano* is an iPhone app created by the Lawrence Hall of Science for the NISE Net (www.nisenet.org) that connects visitors to a variety of videos, hands-on activities, and the whatisnano.org website.

In 2013, the Museum of Science in Boston opened a new exhibition about health and human biology called the Hall of Human Life (HHL). Emphasizing that research in human biology and health was being revolutionized by the convergence of biology and information technology, the exhibition is built upon a base of information provided by its visitors. Visitors get bar-coded wristbands as they enter the exhibition and use them to activate a series of link stations in five themed environments – Communities, Time, Organisms, Food, and Physical Forces – where they collect or enter data about themselves anonymously into the exhibition database. Visitors' experiences are personalized as they see the shape of their own foot arch and compare it to others or measure how many calories they use up while walking at different paces and with different strides. They test their ability to recognize faces, to balance themselves, to pay attention, and to explore how they relate to their families and how their circle of friends changes their brains. Visitors to the HHL can then later access their data online at home or in their classroom.

In addition to the kinds of information resources that science museums, media, and community programs might use directly with their public audiences, online information systems now form the backbone for online collaboration, mutual learning, and distribution of educational resources throughout the professional communities of informal science educators. Here are just a few examples of the many that exist in 2014:

http://informalscience.org The Center for the Advancement of Informal Science Education (CAISE) works in collaboration with the National Science Foundation (NSF) Advancing Informal STEM Learning (AISL) program to strengthen and advance the field of professional informal science education and its infrastructure by providing resources for practitioners, researchers, evaluators, and STEM-based professionals.

www.howtosmile.org is an online tool that allows educators to search, collect, and share high-quality, hands-on science and math activities.

www.nisenet.org houses an online library of 500 informal educational resources focused on various aspects of nanoscale science, engineering, and technology.

www.ngcproject.org provides extensive resources aimed at encouraging girls to pursue careers in science, technology, engineering, and mathematics.

Impacts of Convergence on Informal Science Education

Informal education identifies its domain of impact as outside of school time learning, meaning beyond the hours of 9 AM to 3 PM (or whatever normal school hours are), beyond the months of September through June (or whatever the school year is) and beyond the ages of 5–22, or however long an individual continues in formal education. The audience includes preschoolers, children of all ages with or without their families, and adults for whom formal education is a distant memory. There is a wide range of goals associated with informal education and these audiences, but at the outset of the Nanoscale Informal Science Education Network, two that emerged that have ongoing relevance for all fields of science and technology, but especially for those that are emerging and show great promise for the future, are the following:

- To help youth and their families see a role for themselves in the future that is unfolding in the new and emerging fields of scientific research and technological developments
- To help adults make informed decisions about the development and application of future technologies that are not clouded by misperceptions and unwarranted fears

The convergence between informal educational practice and educational research has helped guide the development of out-of-school experiences that are engaging and stimulate many types of learning, while at the same time has broadened our concept of what learning includes. This has been particularly effective in providing engaging learning experiences for children that stimulate their curiosity, generate a sense of excitement about learning science, and help them think of themselves as someone who can know something about and contribute to science and technology.

The convergence between informal educational practice and social science research has broadened the content for informal education from basic physics, biology, chemistry, astronomy, geology, engineering, and other fields of science typically taught in school to issues of the impacts of science and technology on people and society more broadly as well as the corresponding impacts on science and technology of people and society. This has been particularly helpful in supporting the needs of adult audiences in understanding the relevance and implications of technological development.

The emerging convergence between informal educational practice and research in a collection of disciplines related to the science of science communication is yet to be fully realized. The promise it holds is to support informal education organizations like science museums in facilitating fruitful dialogue between members of various scientific communities and members of various publics. The form of that facilitation might include organized engagement events, training for scientists in communication practices, or other mechanisms to support two-way communication and to build mutual respect and trust.

The convergence between informal education practice in science museums and research in education, in the social and political sciences, and in the science of science communication has changed the roles that museums can play within society: from the cabinet of curiosities to the informal learning environment, from science content to science thinking skills, from public understanding of science to public engagement with science, and from a venue for informal learning to a facilitator of increased capacity for public engagement with science within the scientific community.

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Integrative Graduate Education and Research

Carol J. Van Hartesveldt

Contents

Abstract

Driven both by the increasing pace of scientific discovery and the development of new technologies, strategies for graduate education are emerging to prepare students for collaborative work across disciplines. Outstanding graduate students are attracted to research problems of relevance to important social goals and are capable of combining disciplinary depth with interdisciplinary breadth without prolonged time to degree, as shown by the National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) program. Programs that intentionally prepare graduate students for interdisciplinary work typically include an interdisciplinary curriculum with participation of faculty from several different areas to help students learn the language and culture of another discipline and structured settings in which students learn to collaborate across disciplines and work in teams to solve research problems. Activities beyond the classroom help students to negotiate disciplinary divides in other ways. The departmental/disciplinary organization of most universities is a challenge for both students and faculty seeking disciplinary flexibility in education. To encourage a new ecosystem supporting interdisciplinary education and

C.J. Van Hartesveldt (✉)
National Science Foundation, Arlington, VA, USA
e-mail: drcjvh@aol.com

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research, universities are creating new organizational policies to provide both the flexibility and the rewards and incentives for faculty to work and educate across disciplines. Funding agencies are adapting their own organizational structures to find new ways to accommodate interdisciplinary research and education.

Introduction

The increasing pace of scientific discovery and the development of new technologies have stimulated new strategies for interdisciplinary research and education. While there are many terms that have been used to describe research across the disciplines, including multidisciplinary, transdisciplinary, convergent (Stokols 2014), and even postdisciplinary, the term "interdisciplinary" as defined by the National Academies (CFIR 2004) will be used in this chapter to represent all collaborative approaches to research and education across the disciplines. The National Academies' definition is as follows: "Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (CFIR 2004, 2). As disciplines themselves evolve, what is defined as interdisciplinary changes over time, as researchers borrow the techniques and expertise of fields outside their own to solve new research problems. Interdisciplinary research has led to new disciplinary fields, such as neuroscience, nanoscience, and bioinformatics, for example. Thus, topics that are considered "interdisciplinary" now may be considered "disciplinary" in the future.

A doctorate in the science, technology, engineering, and mathematics (STEM) disciplines is a research-intensive degree, during which students learn both the conceptual and technical aspects of conducting research in a particular field to create new knowledge. The traditional model for disciplinary education is the "apprenticeship" model with a research advisor, undertaken in a department where disciplinary depth is acquired. The doctoral student is expected to work as an individual to produce an original scientific investigation of a research problem, traditionally within a discipline, which serves as the dissertation. However, as the scope of the scientific research needed to solve important problems broadens, graduate students increasingly need the skills to create new knowledge in topics that cross disciplines. The kind of education to be discussed here is interdisciplinary doctoral education that *intentionally* prepares graduate students to work across multiple disciplines and become capable of conducting interdisciplinary research, rather than providing circumstances in which students may *incidentally* acquire these skills. The opportunities and challenges for interdisciplinary doctoral education for students, and the roles in this area for faculty, universities, and federal funding agencies, will be the topic of this chapter.

Numerous calls for reforms in graduate education (Wendler et al. 2012; NRC 2012) have included recommendations that graduate students get more academic breadth (COSEPUP 1995; CFIR 2004). Four studies published after the COSEPUP report had similar recommendations, including encouraging interdisciplinary work in graduate school (Carney et al. 2006). Still other reports have strongly recommended that graduate education have an interdisciplinary component (CFIR 2004; Derrick et al. 2012; ACS 2013; Murday et al. 2013), in order to foster the pursuit of creative research as well as to build career skills.

The National Science Foundation made awards in its Integrating Graduate Education and Research Traineeship (IGERT) program from 1998 to 2013; IGERT was the only federally sponsored training program that intentionally fostered doctoral education with an interdisciplinary theme across all the STEM disciplines. Called "America's hallmark grant program for interdisciplinary training" (Gamse et al. 2013, 8), IGERT has been the subject of considerable examination and evaluation, and thus examples and findings for this program provide much of the substance for this chapter.

Each IGERT project had at its heart an interdisciplinary theme chosen by its faculty, who designed a graduate education program to prepare students to carry out collaborative research on topics related to the theme. Examples of interdisciplinary theme categories include nanoscience, sustainability, clean energy, sensors, and human and social dimensions of new knowledge and technology, to name a few (Brown and Giordan 2008). Many of these forward-looking themes are related to the interdependence of the natural and human systems as well as vision-inspired research, two of the principles of convergence (Roco et al. 2013). IGERT had many other goals including professional development for students, increasing diversity, global engagement, and changing the culture of graduate education at the institution. As it evolved, IGERT added innovation as another important skill for students to develop so that the interdisciplinary research they conduct might be used for the benefit of society, in the spirit of convergence.

IGERT: A Model for Interdisciplinary Graduate Education

Interdisciplinary graduate education programs can be designed in many ways, depending upon the goals of the program. Faculty fashion their programs to give students the interdisciplinary skills and experiences they think most appropriate for the interdisciplinary research to be done. IGERT faculty created a variety of programs, all of which offered students a curriculum and activities designed to provide them with both the personal and professional skills to carry out interdisciplinary collaborations. In spite of the wide variety of interdisciplinary themes in IGERT programs, there was considerable consistency in the kinds of activities that were incorporated into the projects. In almost every IGERT project, faculty designed interdisciplinary courses intended to help bridge the disciplines involved in the project. These courses were challenging for faculty to design and for students to negotiate. Creating a graduate-level introduction to multiple disciplines so that the course was neither too difficult nor too easy was both an exciting and a trying experience for faculty, and one that raised many issues. Sometimes prerequisite courses were recommended, raising issues both of the suitability of an out-of-discipline course for a graduate student (imagine a biology student taking an undergraduate engineering course) and whether the student would get graduate credit for an undergraduate course in a field outside his or her discipline. Students were concerned about their lack of background for that part of the curriculum that was in new disciplines for them (Hrycyshn 2008). Notwithstanding the considerable effort that went into the initial design of interdisciplinary courses, most IGERT faculty revised them after the first time they were offered. Those projects that empowered graduate students to help design or redesign and implement the interdisciplinary curriculum got a double benefit: the faculty members were relieved of some of their workload, and the graduate students (who knew firsthand what was needed) were energized by taking ownership of their education. Even though interdisciplinary courses were demanding for both faculty and students, both thought that these courses were an important part of interdisciplinary preparation for graduate students (Gamse et al. 2013).

In addition to interdisciplinary courses, most IGERT projects have used team research projects to prepare their students for research on topics within the project's interdisciplinary theme. Team research projects generally took place early in graduate student training. These projects were seen as useful in helping students to apply multidisciplinary approaches in a research setting, as well as offering a setting for students to learn to communicate their research to those in other disciplines (Gamse et al. 2013). Team research projects carried out in nonacademic internships focused on solving real-world problems with colleagues from different disciplines and backgrounds and helped to build career skills and networks. The value of interdisciplinary team research in the graduate curriculum has been recognized outside the IGERT program. The ACS report (2013) stated that critical skills in graduate education include communicating complex topics to various audiences, learning new science and technology after academic training, collaborating on global teams, managing projects, and understanding the ethical conduct of research. According to the ACS, "The most all-encompassing approach to these needs is to significantly enhance interdisciplinary collaboration among the students" (ACS 2013, 12). However, there remains a tension between the perceived need for graduate students to become highly independent researchers, especially in academia, and the need for them to learn how to work on research in teams (Gamse et al. 2013).

Other informal mechanisms that IGERT projects employed to better enable students to work with those outside their own disciplines were summer "boot camps" with hands-on activities, winter sessions, informal science cafes, shared office space, open laboratories and shared lab space, lab rotations, interdisciplinary laboratory and field experiences, and attendance at a professional conference outside their home discipline. IGERT projects have differed in their training mechanisms in part because IGERT faculty have interpreted the challenges of educating in an interdisciplinary theme in a variety of ways, including educating students to become experts in more than one field, to have mastery of one field and being able to work with researchers in another, and/or to know and use the techniques of multiple disciplines (Carney et al. 2006).

Another common element of IGERT projects and other interdisciplinary graduate education programs is cross-mentoring, or student mentoring by faculty outside their home department. Cross-mentoring is another way for students to learn the language and culture of another discipline outside the classroom. IGERT participants often commented on the importance of learning the language of other disciplines, as have others (CFIR 2004). Some in IGERT reported that it could take up to a year to learn each other's disciplinary language, and to learn that the same words could mean different things in different fields. Communicating across disciplines was an important key to success, although it could be frustrating. Beyond learning a new language, students and faculty also learned the differences in each other's "cultures," including how research questions are posed, the way courses are taught, and the milestones for graduate student progress in a field outside their own.

One measure of confidence and preparation in disciplines outside the home department is the interdisciplinary nature of the topic of the dissertation. IGERT students reported using more disciplines than non-IGERT students in their dissertations (Carney et al. 2011). It is informative to compare dissertation outcomes of IGERT students with those of the graduate students educated at NSF's Science and Technology Centers (STCs), which are Centers that are directed at large, complex, and frequently interdisciplinary research problems and that also include education as a part of their missions. IGERT students responded that they drew on at least two disciplines in their dissertation research far more than STC students (Martinez et al. 2011).

In addition to interdisciplinary skills, all IGERT projects emphasized the need for disciplinary depth. With few exceptions (Murday et al. 2013), there is general agreement that graduate students should develop depth in a discipline whether or not their program includes interdisciplinary training (Derrick et al. 2012; ACS 2013). Disciplinary depth gives students a recognized expertise to bring to an interdisciplinary research problem, as well as a disciplinary home if they seek a career in academia. Skeptics wondered whether it would be possible for graduate students to acquire sufficient disciplinary depth while also being involved in activities to build interdisciplinary breadth. However, both IGERT faculty and students have reported that IGERT students were as well prepared to know their own discipline in depth as non-IGERT students in the same field. While acquiring both disciplinary depth and interdisciplinary breadth, as well as transferrable skills, IGERT students completed their doctoral degrees in slightly less time on average than comparable non-IGERT students (Carney et al. 2011). Nonetheless, the question of the appropriate balance between depth and breadth continues to be an important issue in doctoral education in general and interdisciplinary graduate education in particular.

Interdisciplinary research themes are attractive to both undergraduate and graduate students (CFIR 2004). Three quarters of both IGERT and non-IGERT doctoral students reported having been drawn to an interdisciplinary graduate education (Carney et al. 2006). A higher percentage of IGERT students found interdisciplinary graduate education to be of interest, and in that regard they could be considered a “different breed” of graduate student (Carney et al. 2011, 76). A percentage of IGERT students were attracted to the institution they attended because of the IGERT program. Many of the IGERT projects featured research on the kinds of societally relevant broad, complex real-world problems that require expertise in more than one traditional discipline. These kinds of research problems and the education to address them both inside and outside academia may appeal to more diverse students than those who have applied to graduate school to study a single discipline (Derrick et al. 2012). IGERT diversity was reported as roughly equivalent to the national averages for the disciplines represented in IGERT (Carney et al. 2011), although when data were analyzed by race, ethnicity, and gender and compared with national data by field of study, IGERT projects’ diversity overall was either equal to or exceeded the relevant national data in well over half of all fields (Brown and Giordan 2008).

IGERT interdisciplinary themes were not only attractive to prospective graduate students, they were attractive to excellent prospective students. IGERT students were consistently considered better qualified than non-IGERT students by faculty (Carney et al. 2006; Brown and Giordan 2008), even though neither the IGERT students’ GRE scores nor grade point averages were higher than those from comparable single-discipline graduate students. However, IGERT faculty perceived that IGERT students were more independent, more creative, more willing to take risks, more highly motivated, and better focused than single-discipline graduate students (Van Hartesveldt and Giordan 2009).

The risks inherent in a nontraditional degree program may be attractive to some students but not to others. Prospective students must be confident that they can meet all the requirements of a nontraditional degree, attain the degree, and succeed in obtaining the kind of employment that they value. Much of the perception of risk results from the fact that graduate education is highly oriented toward and controlled by departments that represent single disciplines. Departments traditionally recruit and admit graduate students, assign them research advisors, set the requirements for graduation, and allocate departmental resources such as teaching assistantships and travel funds. In addition to these departmental assets and actions, departments also help their students to establish a sense of professional identity and intentionally or unintentionally promote a career path to a faculty position. The disciplinary emphasis within departments is reinforced by the fact that individual departments are often associated with professional societies. Students pursuing an interdisciplinary program may lack a clear sense of professional identity, and their interdisciplinary program may not give them as strong a support group as a disciplinary/departmental program. A career path to a faculty position, if that is what is desired, may not appear as clear. In addition, students pursuing an interdisciplinary option may not be seen as worthy of departmental funding, since they (or their advisors) may not be viewed as “belonging” sufficiently to the departmental discipline, and they may not be given teaching assistantships if it is thought that they do not have sufficient content knowledge within the discipline to be effective. In summary, the university's organizational structure, particularly at the level of the department, is a force to be reckoned with for anyone trying to operate outside its domain. It is not surprising that faculty saw graduate students willing to work outside the confines of a department as a "different breed."

An interdisciplinary graduate education can be judged as successful only if it prepares its graduates for desirable careers. On average about half of all doctoral degree holders will be working outside academia (Wendler et al. 2012), with the percentage varying according to field of degree. For graduates who will work outside academia, an interdisciplinary graduate education provides many of the skills that employers value, including the ability to work in teams, the ability to apply knowledge in one area to solve problems in another area, and good communication skills, among others (Wendler et al. 2012). When student career expectations are limited to tenure-track faculty positions in a single-discipline department, in spite of the decreasing availability of these positions (Golde and Dore 2001), then student success may depend upon departmental valuation of publications in particular journals or research on disciplinary topics. However, academia is changing, albeit slowly. Cluster hiring is being used at some universities to build interdisciplinary faculty teams focused on broad, complex research questions. This is one way that the university can establish a focus on particular areas of interdisciplinary research in areas of national priority with likely federal funding. Examples of universities currently engaged in substantial cluster hiring include North Carolina State University, the University of Florida, and Notre Dame University.

To what extent were IGERT students successful in obtaining employment, and to what extent has their interdisciplinary training carried through into their careers? IGERT graduates have reported having little difficulty in finding employment, and most thought that their IGERT training had given them a competitive edge (Carney et al. 2011). The area of their education considered of highest value by IGERT graduates was their interdisciplinary training, followed by communication skills and professional networks. In spite of broader training and opportunities for internships outside academia, the degree to which IGERT students worked in the various employment sectors is about the same as that of non-IGERT graduates (Carney et al. 2011). About half of IGERT graduates surveyed continued to draw upon the disciplines they used in their dissertations in their careers, and about half were using new fields; the latter suggests that IGERT students developed the transferrable skills to become involved with new disciplines. IGERT graduates with positions in academia have been very active in supervising interdisciplinary student research projects, establishing interdisciplinary courses, and creating interdisciplinary programs of study (Carney et al. 2011). Thus the IGERT program not only affected the institutions where the graduate students were trained but also the educational institutions where they found employment. The multiplier effect of IGERT graduates on higher education is a powerful force for change.

Interdisciplinary Graduate Education: Organizational Challenges

Both interdisciplinary research and education are driven by the faculty, who conduct the research and develop and teach the curricula. Doing exciting new research and providing students with an effective education for the future have their own incentives and rewards, including attracting adventurous, outstanding students who want to be working on the cutting edge of important research and the opportunity to do new research and have new avenues for funding, and to work with new collaborators. However, these incentives and rewards cannot substitute for measures of faculty success within the organizational hierarchy of the university. Many have recognized that the university must work to remove barriers and provide incentives and rewards to the faculty who take on research and education outside the auspices of their department (e.g., CFIR 2004). When faculty initiate and carry out interdisciplinary graduate education programs, they will likely be developing cross-departmental curricula, team-teaching interdisciplinary courses, participating in informal activities to build rapport and community among faculty and students, and mentoring and serving on dissertation committees of students outside their home departments. If the faculty's interdisciplinary activities are added on to a full disciplinary assignment, they may suffer from overload. In addition, evaluation of the quality of teaching and curricular development is difficult; evaluation of the quality of interdisciplinary courses and informal activities is even more difficult but essential if interdisciplinary education is to thrive. The work that faculty do outside the department may not be fully appreciated inside the department, and may even be considered a detriment, particularly when tenure and promotion are considered.

The academic department is the traditional home of the faculty, responsible for faculty recruitment and appointments, space and teaching assignments, tenure, promotion, and raises. Departments are also typically the locus of graduate student admissions and decisions regarding assignments of teaching assistantships, the second largest source of external support for graduate students (NSB 2014). Thus, the attitude toward interdisciplinary research and education in the department where a faculty member has his or her appointment is critical for one planning to work across departments. Faculty with appointments in traditional departments assigned to teach disciplinary undergraduate courses may find a tension between their disciplinary and interdisciplinary identities. If they do not teach disciplinary undergraduate courses, their graduate students may not be appointed on teaching assistantships. Faculty members need clear consistent messages from university administrators from the top down to every hierarchical level, including that of the department, outlining their assignments. They may also need help from their administrators in developing research and education programs across colleges and departments (Van Hartesveldt and Giordan 2009).

It has been said "the traditional academic departments at universities and colleges are…discouraging interdisciplinary collaboration…" (Murday et al. 2013, 252) and that the "basic organizational structure of most higher education institutions is all but incompatible with interdisciplinary education and research" (Borrego et al. 2014, 337). One American university, Arizona State

University, has reorganized its structure in order to promote interdisciplinary collaboration (Crow and Dabars 2014). Abroad, Seoul National University has formed the Graduate School of Convergence Science and Technology, in which separate academic departments are loosely divided into four programs (Murday et al. 2013). Much as in IGERT, in each program all students take an introductory course in subjects that cross disciplinary boundaries and participate in a project that is carried out by teams of students from different academic backgrounds. However, in the U.S.A., most universities continue to work within their disciplinary organizational frameworks to overcome their barriers to interdisciplinary research and education in order to attract top faculty and outstanding graduate students.

Creative ways that universities may give graduate students more academic flexibility begin at the time of admissions. In the ACCESS program at UCLA, graduate students may be admitted to graduate study in an interdisciplinary field, then select their home department and research group later; at the University of Florida, students may also be admitted to an interdisciplinary program and decide on their department later. Arizona State University gives students multiple admission options including both traditional and interdisciplinary doctoral programs (Van Hartesveldt and Giordan 2009).

At some universities, graduate students are admitted through traditional departments but then may choose a program that gives them greater breadth. While some interdisciplinary programs become free-standing doctoral programs, creative university administrators have established a variety of mechanisms for students to gain interdisciplinary breadth and the credentials to recognize it, each tailored to that university's unique mission, organizational structure, and culture. Introductory courses may be shared across departments. A matrix design for interdepartmental interactions is employed at Michigan State University, the University of Minnesota, and the University of Idaho. Some of the new credentials that are offered and examples of the institutions that offer them include a Designated Emphasis (University of California-Davis), a dual-title degree program (Pennsylvania State University), Interdepartmental Degree Programs (University of Michigan), the Student-Initiated Degree Program (University of Michigan), and the Interdisciplinary Ph.D. program (University of Maine). Certificates, minors, and specializations or concentrations have also been used as credentials that attest to a student's breadth (Van Hartesveldt and Giordan 2009).

Universities stimulate interdisciplinary research and graduate education by establishing interdisciplinary centers and institutes and by building teams ready to tackle problems requiring interdisciplinary expertise by gathering together interested faculty or by cluster hiring. Some interdisciplinary cluster hires or centers naturally evolve into interdisciplinary departments, which may establish their own graduate programs. Interdisciplinary centers and institutes set the stage for incidental interdisciplinary graduate education but are not sufficient per se for intentional interdisciplinary graduate education. One interesting outcome of cluster hiring to build collaborative research groups is that it may include faculty from industry, who can provide graduate students with valuable teamwork and collaboration skills, along with information about careers outside academia that graduate students may not get elsewhere. Typically, graduate students get their career advice from the faculty, who primarily encourage them to prepare for faculty positions (Wendler et al. 2012).

Roles of the Federal Funding Agencies in Interdisciplinary Graduate Education

The federal funding agencies have played an important role in stimulating interdisciplinary graduate education for the past 50 years. For example, the National Institute of Mental Health used interdisciplinary training grants in what is now behavioral neuroscience to stimulate the growth of that field long before neuroscience became a discipline. As discussed above, the IGERT program was established at NSF in 1998. In 2005, the Howard Hughes Medical Institute-National Institute of Biomedical Imaging and Bioengineering established the HHMI-NIBIB Interfaces Initiative to stimulate interdisciplinary training for graduate students in the biomedical sciences and to have a broader impact on graduate education in the institutions that were granted the awards. Each of these programs has influenced interdisciplinary research and education both for the students trained in them and at the institutions of higher education where they were located.

While it is difficult to tease out the effects of training programs such as IGERT on universities from other simultaneous influences on research and education, at least one study has indicated that on campuses with multiple IGERT awards, IGERT has affected attitudes and practices (Borrego et al. 2014). IGERT has been given credit for raising awareness of interdisciplinary research and education on campuses and thus stimulating the first step in institutional change. Programs like IGERT have had an effect on university policies on faculty hiring, workload, promotion, and tenure (Borrego et al. 2014). Policy changes that have taken place at universities with multiple IGERTs include changes in listings of interdisciplinary courses, eligibility of advisors to serve on dissertation committees outside their departments, faculty credit for cross-mentoring, and coauthored doctoral dissertation chapters.

Federal agencies not only influence graduate education by funding training grants but also by funding fellowships and research assistantships. Each of these funding mechanisms has its place in graduate education, and the mix of these mechanisms has both intentional and unintentional consequences for graduate education. Traineeship programs like IGERT and the HHMI-NIBIB Interfaces Initiative condition their funding on educational and institutional innovations in interdisciplinary education. Some fellowship programs require particular curricula or offer students internships or other special training to broaden their research and career perspectives. However, research assistantships typically lack educational requirements or goals for the education of those holding them, beyond what students learn in the course of working on the research project on the grant to which they are appointed. About 70 % of graduate students supported by federal funds are supported on assistantships on research grants, while only about 10 % are supported on fellowships, about 10 % on traineeships, and the rest by other mechanisms (NSB 2014). Decades ago it was lamented that STEM graduate education seems to be a "by-product" of the nation's research policies (COSEPUP 1995). One unintentional consequence of the significant amount of funding for research assistantships is that it could reinforce the single-discipline, apprenticeship model of education. It has been suggested that if the federal funding agencies are to have a significant influence on the quality of graduate education through their awards, then the mix of funding for training grants, fellowships, and research assistantships should be better balanced (COSEPUP 1995; Biomedical Research Workforce Working Group 2012; ACS 2013; NRC 2012). Another way to increase the influence of federal funding on graduate education would be to incorporate educational goals for graduate students in research assistantships. For example, an individual development plan (ACS 2013) could be required for every graduate research assistant appointed on a research grant, just as it is for every postdoc appointed on an NSF or NIH award.

The current balance for funding mechanisms for graduate students affects not only the quality or type of education but also the quantity of doctoral degrees earned in a field. While fellowships and traineeships have defined programs and defined budgets that control the numbers of supported students, there is no such control on research assistantships – these are determined independently, one grant at a time. Because research assistantships are such an important source of funding for STEM graduate students, the numbers of research grants awarded and the numbers of research assistantships funded on those grants greatly influence the number of doctoral students trained in a field, and thus the number of degree holders seeking employment. The Biomedical Research Workforce Working Group (2012) found that the number of holders of the doctorate in the biomedical sciences is greater than the employment opportunities for them and has recommended that NIH shift its graduate student funding allocation from predominantly research assistantships to fellowships and traineeships, without an overall increase in numbers. The recommendation is controversial because graduate students are so intricately involved in the biomedical sciences research enterprise.

Like the organization of the traditional university, those federal funding agencies that support basic research in the STEM disciplines are organized around disciplinary topics, including the structure of the organizational hierarchy, the budget process, and the review processes. NSF is an example of an agency that faces the same challenges as the traditional university regarding the promotion of research and education across disciplinary boundaries. Strong leadership from the top is usually needed to establish programs that cross NSF's directorates. In the past, bold new initiatives to solve important societal problems could garner additional funding, giving NSF leaders a strong incentive to collaborate. In a fairly flat-funding environment, these incentives may be fewer if funds for interdisciplinary research and education programs subtract from disciplinary budgets.

Federal funding agencies like NSF thus mirror universities in their disciplinary hierarchies and allocation of funding through organizational structures organized around disciplines. Because universities depend substantially on federal funding, changing the culture of graduate education must be accompanied by, and can only be achieved by, changing the cultures of funding agencies. Funding agencies that support basic science currently have a traditional disciplinary structure over which transitory interdisciplinary initiatives are overlaid. Many of the challenges in promoting interdisciplinary research and education at federal funding agencies reflect the challenges found in academia, including the policies underlying the funding allocations, "ownership" of the venture, and the influence of important constituents or stakeholders. Because the federal funding agencies primarily fund research, graduate students are not considered as their primary focus, and graduate education is expected to take place outside the purview of the research grant. However, interdisciplinary graduate education cannot be taken for granted. It must be intentional, so that the graduate students of today will become the adventurous, creative next generation of scientists and engineers that will solve the complex research problems of tomorrow.

Closing Comments

Graduate education is influenced by many interlocking factors including the organization of the institution where they study, faculty members and their rewards and incentives, and the federal agencies that fund graduate students. Together these factors constitute the ecosystem for graduate education, and each has a critical role to play. The value of interdisciplinary research in solving large-scale problems is well recognized in industry, but universities and funding agencies lag behind in implementing the changes in policies that would support it. The value of preparing graduate students to carry out interdisciplinary research lags even further behind. Yet clearly interdisciplinary graduate education drives new interdisciplinary research, drives institutional change, and drives the future of research and education where interdisciplinary degree holders go. Interdisciplinary graduate education is one force that can help to drive convergence ecosystems to the next level.

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Learning in a World of Convergence

Susan Rundell Singer

Contents

Abstract

Convergence challenges traditional learning systems at all levels. Structurally there is the need for deep disciplinary learning coupled with the ability to work across fields, that is, the need to speak "convergence creole." Learning about new concepts, mastering new approaches to solving problems, and gaining competency with an ever-changing suite of tools and instruments require the ability to be a lifelong learner. A convergence of research in education, learning science, cognitive science, computer science, education technology, and related fields is creating new approaches to personalize learning and provide just-in-time resources for the lifelong learner. Progress in five key areas is creating new opportunities to align effective education and workforce development:

Developing "convergence creole": Major reframing of precollege and college education in science and engineering has the potential to support the development of learners who can effectively solve convergence problems. The

S. Rundell Singer (✉)
Biology and Cognitive Science, Carleton College, Northfield, MN, USA
e-mail: ssinger@carleton.edu

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focus on a few core ideas within a discipline to develop expertise is interwoven with understanding crosscutting concepts and science practices.

Learning anytime, *anywhere*: From massively open online courses to simulations, games, and virtual reality environments, there are emerging models for learning that are no longer tethered to place. These new tools allow for more efficient and effective personalized learning.

Leveraging technology to understand convergence learning: While the learning sciences are advancing rapidly, much of the work has focused on specific disciplines or more global approaches to how people learn. As online learning environments emerge, the accompanying research agenda for large and complex data sets they generate have the potential to accelerate the understanding of effective teaching and learning across disciplines.

Developing intrapersonal and interpersonal skills: Working across disciplines places demands attention to fostering growth of intrapersonal and interpersonal skills that are vital for collaborative problem solving. The emerging field of team science is providing insights into how to support individual development and create environments for productive synergies across disciplines.

Defining and measuring successful learning in a convergent world: Measuring and documenting the success of learners working across disciplinary divides may be enhanced by personalized learning environments, which provide rapid and ongoing feedback on performance. Both assessment and credentialing will require new infrastructure to support lifelong learning and fluid movement among disciplines.

The success of innovation in education for convergence depends on the ongoing convergence of a broad range of fields to design and develop effective learning environments.

Introduction

Early scientists and learners moved fluidly among our now siloed disciplines. For example, Leonardo da Vinci's study of dandelion and maple seed dispersal purportedly inspired his parachute designs. Twentieth-century science and science education often delved deeply into single disciplines and clearly demarcated domains of expertise. In the 1970s, science education research diverged from traditional approaches by staking the claim that the disciplinary context was core to the work. Yet, even with the rapid growth and advances within disciplines, fields have converged to yield breakthrough advances. Biophysics and biochemistry arose through convergence, as did evolutionary and developmental biology to give rise to a field now known as evo-devo. Likewise, both convergence and divergence are reflected in the infrastructure of university departments even within fields. Parsing life science departments based on organisms (e.g., departments of botany, microbiology, and zoology) gave way to departments focused on molecular and cellular biology versus ecology and evolution, as new tools and approaches drove the field. Nanotechnology, genomics, and other emerging areas offer new territory for convergence and further challenges for educating the next generation.

Meeting today's grand challenges in science and engineering requires deep disciplinary expertise and fluency across multiple disciplines, coupled with the creativity of da Vinci. Learning in the world of convergence challenges traditional education models and structures. As learners and researchers engage in convergence work, the need for just-in-time tools and resources to bridge knowledge and methodological gaps is driving new learning environments. Technology-enhanced learning and social media open the door for personalized learning to aid and inspire synergistic work across domains. The needs extend far beyond the ability to integrate concepts and practice. Team science demands interpersonal and intrapersonal skills to complement cognitive skills. Innovation requires increasingly entrepreneurial thinking and a culture that values and supports failing forward. Learning environments in a convergent world blend formal with informal learning, virtual with bricks and mortar environments, school with workplace, and traditional research environments with course-based experiences. Simply extending and applying promising practices in interdisciplinary learning is insufficient to prepare learners who will use nanotechnology to accelerate unraveling the mysteries of genomes, translate the clingfish's ability to grip and pull 300 times its weight into a super adhesive, bioengineer batteries to address the global energy challenge, and push the boundaries of engineering and molecular biology to develop innovative cancer treatments or feed the world. Just as convergence demands "vision-inspired" research (see Roco et al 2013), new learning environments must be "vision-inspired."

Developing "Convergence Creole"

Convergence work demands the broad ranging thinking and engagement of historically notable intellectuals including Jean-Jacques Rousseau, whose work influenced the development of modern education, political philosophy, sociology, and even botany, and Ralph Waldo Emerson who engaged in novel approaches to manufacturing pencils and conducted field research to test Darwin's theories of evolution while establishing a literary legacy. The challenge, however, is the complexity and sophistication of advances in science and engineering today, resulting in vast bodies of knowledge, conceptual frameworks, resources, and tools, requiring "convergence creole," the ability to fluently engage with experts in other disciplines.

Cognitive psychologists have shown that expertise is domain specific, gained over 10 years or 10,000 h of deliberate practice (Ericsson 2006). More than ever, educational systems are challenged to guide learners in developing deep, lasting understanding within a field. Understanding a bit of everything will not prepare learners to be creative contributors to convergent problem solving. Yet, deep understanding within a field is not enough either. Developing "convergence creole" is a conceptual challenge, not merely the ability to translate words across disciplines or adapt useful methodology. Individuals with distinct disciplinary expertise must think synergistically and creatively together. Understanding and making explicit the differences in how knowledge is acquired and meaning is constructed in distinct fields can facilitate conceptual collaborations.

An integrated approach to learning science, technology, engineering, and mathematics (STEM) in primary and secondary school has been proposed by some as the way forward, as opposed to the increasingly discipline-focused structure of science and math learning as a learner advances through the precollege years. For example, C-STEM (Communication, Science, Technology, and Mathematics) uses teacher professional development and learner competitions at all levels to inspire the next generation of innovators in C-STEM areas through real-world, integrated problem solving (cstem.org). As engineering design is increasingly woven into precollege curriculum, there are research gaps to fill if the potential of an integrated STEM approach in enhancing conceptual learning and transfer of learning across STEM domains is to be fully realized.

The National Research Council (NRC 2014c) study of STEM integration in grades K-12 provides an analysis of the still limited research and offers constructive guidance for advancing the work. While learning science research indicates that building connections and leveraging prior knowledge can advance conceptual understanding, too much integration can impede learning because of split attention and the limits of working memory (i.e., how many thoughts one can hold and work with at a given moment). Sorting out what is best learned through integration and what is more effectively learned in a traditional disciplinary context will be essential to develop convergent thinkers.

Several studies on coordination of mathematics and science learning underscore the essential role mathematical modeling plays in STEM learning. As learners become fluent in expressing the behavior of natural systems, physical or biological, as mathematical models, their conceptual understanding increases. The promise of mathematics as a universal language, cutting across disciplines, is enticing in the world of convergence.

Both the integrated STEM study and the *Discipline-Based Education Research* report, focused on undergraduate learning, call attention to the role of disciplinary representations in STEM fields (NRC 2012a, c). Consider a phase change diagram in materials science, the range of molecular representations chemistry, and evolutionary trees in biology. These complex representations are shorthand for complex ideas, accessible primarily to experts. Extensive reliance on representations within STEM fields extends the "convergence creole" to include "representational fluency," in addition to understanding definitions, concepts, and methodology. A growing body of evidence on how to support visual learning and development of expertise in using representations is an important resource in the "convergence creole" tool kit (Mayer 2014).

For learners to effectively make connections across disciplines, they need support from instructors who make the connections explicit. Learners are unlikely to make those connections, those integrated cognitive moves, on their own, even in rich, integrated STEM environment. Integrating STEM concepts in engineering and other applied learning contexts, especially real-world problem solving, can positively impact learning if there are sufficient instructional supports in place and the connections are made visible to the learner. Studies investigating at a range of approaches for aligning STEM learning, through parallel, sequential, and other approaches, reveal promise for mathematics learning enhancing STEM learning, including the role of mathematical modeling previously mentioned. There is less compelling evidence that an integrated STEM environment supports mathematics learning, but caution in arriving at a conclusion is urged in light of the small number of studies (NRC 2014c).

Research findings on integrated STEM learning at the undergraduate level are also limited (NRC 2012a; Singer 2011). As the learner moves from the primary grades through postsecondary education, the need for deep disciplinary understanding undergirding the ability to make integrative conceptual moves grows. Indeed, historically the undergraduate years have focused on building domain-specific expertise with the output being a degree in a specific discipline and the presumed outcome, expertise in the field of study. Universities like Evergreen State College that have fully integrated learning are the exception.

Given both the potential and the challenge of an integrated approach to STEM learning from grades K to 16 and beyond in preparing a generation ready to productively contribute to convergence, the current alignment of STEM standards and approaches to STEM learning are particularly promising. The NRC (2011a) *Framework for K-12 Science Education* is based on research on learning, which indicates that effective learning can be maximized when instruction integrates disciplinary core ideas, crosscutting concepts, and science/engineering practices. The tension between discipline and "convergence creole" is masterfully handled by focusing on no more than four core ideas in any of the science disciplines and fully integrating the crosscutting concepts and practices. The core ideas are both central to the discipline and teachable/learnable in a progression from kindergarten through high school graduation. Moving beyond "mile-wide and inch-deep" disciplinary coverage to deeper conceptual understanding of what matters most is a signal change in STEM education. State college and career standards, including the *Next Generation Science Standards* (Achieve 2013), informed by this research-based framing also support "convergence readiness." Indeed, the *Next Generation Science Standards* maps the science performance expectations onto the mathematics performance expectations in the *Common Core State Standards in Mathematics* (National Governors Association 2010). The opportunity to build on this integration of the three strands, core disciplinary ideas, crosscutting concepts, and science/engineering practices, extends into higher education through the newly revised Advanced Placement (AP) curriculum and initiatives within disciplines at the undergraduate level.

Initiatives within the life sciences demonstrate the unique window of opportunity to align precollege and postsecondary learning to support the development of learners equipped for the challenges of creatively working across domains. Given the convergence of STEM domains on life science-related grand challenges and the observation in *A New Biology for the 21st Century* (NRC 2009) that the new biologist may actually be a physicist, engineer, or computer scientist, the work of the life science education community is promising. In addition to the new AP Biology curriculum, in place for the past two years, the National Science Foundation has supported a multiyear, national initiative, *Vision and Change in Undergraduate Biology*, to recreate the undergraduate biology curriculum in light of the vast changes within the discipline (Brewer and Smith 2011). In parallel, the Association of American Medical Colleges and the Howard Hughes Medical Institute have rethought the preparation of future physicians (AAMC and HHMI 2009). A mapping exercise across these K-16 efforts reveals that all these efforts have brought a laser sharp focus onto a similar, limited number of core disciplinary concepts to guide instruction. Similar consilience is seen with intersecting sets of cross-disciplinary concepts and science practices. With respect to science practices, modeling as a way to capture science processes appears in all the documents and in the Common Core State Standards for Mathematics. Several of the life science professional research societies have further applied these core concepts and developed learning objectives for their subfields (e.g., cell biology, plant biology, and genetics). There is a perhaps surprising degree of agreement that K-16 learning can and ought to undergird convergence science by building deep disciplinary understanding around central disciplinary concepts, complemented by a robust understanding of core concepts shared across the disciplines.

Implementation of an integrated approach to STEM education is in the early stages. The Council of State Science Supervisors through the Building Capacity for State Science Educators (BCSSE) supports and provides professional development for states in working with the NRC Framework for K-12 Science Education and the NGSS, convening participants from 43 states. At the undergraduate level, the HHMI-funded National Experiment in Undergraduate Science Education (NEXUS) is a response to the challenges raised in the *Vision and Change* and *Scientific Foundations of Future Physicians* reports. Teams of university faculty are working to integrate the other sciences and mathematics into life science learning. The physics community has risen to the challenge of integration, and the American Physical Society convenes physicists and life scientists to develop Introductory Physics for Life Scientists (IPLS) courses that teach relevant and fundamental physics concepts to life scientists, explicitly making connections across disciplines to enhance development of transfer skills. In 2014, a Gordon Research Conference on the “Complex Intersection of Biology and Physics” was held to address the different ways physicists and biologists view the nature of science and how they can best meet the needs of biologists in learning relevant physics.

Based on current understandings of how learning works, learners who understand shared concepts across STEM disciplines are building the connections necessary to transfer their learning across domains. The emphasis on integrating shared science and engineering practices into conceptual learning is likely to prepare learners who can do far more than adopt a tool from one field of work to solve a problem in another. The foundation is in place to develop learners fluent in convergence creole, but operationalizing the approach across formal education is a challenging aspiration. Success depends on a broad range of factors, including a more robust grasp of what it takes to teach and learn integrated STEM, improving mathematics learning at all levels, providing effective supports to teachers at all levels, and developing effective strategies for widespread implementation of evidence-based approaches to integrated STEM.

Learning Anytime, Anywhere

The "where" learning is occurring may be changing even more rapidly than "what" is being learned. Boundaries are blurring between formal and informal learning, face-to-face and technology-enhanced environments, traditional research and course-based research, and academic civic engagement and citizen science. Learners are engaging with STEM learning anytime and anywhere, with a relatively small percentage of their time committed to traditional classroom learning. Rich environments to support education for convergence are emerging.

While structured and supported approaches to integrated STEM learning in the early years can lay a foundation for effective learning across disciplinary boundaries, contributing to convergence research will require lifelong learning and integrating knowledge and approaches from varied sources. This type of learning rapidly becomes personalized learning, requiring just-in-time access to a missing puzzle piece in a complex problem. Informal learning provides opportunities for learners to develop lifelong integrative skills. Consider the International Genetically Engineered Machine (iGEM) competition (igem.org). High school and collegiate learners are given a kit of biological parts they use to meet a synthetic biology challenge. Projects have ranged from building a bacterial biosensor that detects a range of arsenic levels to cost-effective red blood cell substitutes built from bacteria. Participants begin building the same convergence skill sets as researchers in the National Science Foundation funded Synthetic Biology Engineering Research Center (Synberc). For example, they develop a range of tools, such as smart fermentation organisms that detect and respond to changes in their environment. The iGEM participants are engaged in convergence thinking while developing essential team skills, discussed later in this chapter.

Whether still in a learning environment or in the workplace, the need to collaboratively engage those with expertise in complementary fields is accelerating. The Koch Center at MIT hosts the Engineering Genius Bar, a place where biologists can tap into their engineering colleagues' thought processes and tools (NRC 2014b). What social media options might be available to create virtual Genius Bars to engage experts nationally and globally?

Innovative, online learning modules will become increasingly valuable as an engineer or scientist identifies and seeks to rapidly fill a gap in knowledge. An engineer improving the use of nanochannels to identify structural variations in genomes may stumble upon a unique pattern of variation and want to learn about its potential biological significance. Ideally a genomics researcher on the same floor steps in as tutor and collaborator, but interactive, up-to-date learning modules on cutting-edge topics could partially substitute if an expert is not nearby or provide sufficient background to get the individual up to speed so the face-to-face time is more effective and productive.

Virtual environments can serve as cognitive tutors, providing guided learning for complex problem solving. Cognitive tutors are adaptive, providing feedback and modifying tasks based on the learner's performance. Adaptive learning can accelerate a learner's progress by moving rapidly through areas of competence and specifically targeting and building understanding in areas of less expertise. Building flexible learning tools is particularly important to support convergence education so learners from a range of backgrounds can acquire new skills more rapidly by building on their prior knowledge. To date, building a cognitive tutor is a time-consuming process, requiring cognitive task analysis, the breaking down of the overall competency into hundreds of small competencies. Efforts are underway to use technology to automate the cognitive task analysis and increase the rate at which cognitive tutors can be built.

The use of simulations and gamification, an approach to supporting problem solving using the mechanics and thinking of computer games, shows increasing promise for skill building and could be adapted to support development of fluency across domains (NRC 2011b, 2012a). Over 110 million interactive science simulations designed and refined through an ongoing research effort at the University of Colorado at Boulder have been downloaded and used globally (phet.colorado.edu). At the secondary school level, Radix is an example of a massively, multiplayer online game that is being used in biology and mathematics courses and integrated into an ongoing research study on learning through gamification (radixendeavor.org/). The challenge in building games is the cost structure. Radix, for example, is a Gates Foundation investment.

Beyond conceptual learning, there is a need to interface with tools used in disciplines where one acquiring fluency, but may not have direct access. This work has been developed most extensively for training in defense and for middle skills workforce development through certificate and associate degree programs. For example, the NSF-funded Center for Nanotechnology Education and Utilization at Penn State (cneu.psu.edu/abHomeOf.html) can provide remote access to learner thousands of miles away to their atomic force microscope and scanning electron microscope. Likewise, the NSF National Center for Welding Education and Training (Weld-Ed; weld-ed.org/) uses a physically interactive simulator to develop and assess welding competency with newer materials. Throughout the country, undergraduates are collaborating to unravel genomes through a range of programs, including the Howard Hughes Medical Institute Science Education Alliance (SEA, hhmi.org/programs/science-education-alliance) where participants isolate and analyze the genomes of newly discovered bacteriophages, viruses with bacterial hosts. Dozens of programs like SEA engage learners in collaboratively working on problems. Crowdsourcing through Foldit (fold.it/portal/) engages game players in a protein-folding game that is far more than a game. The collective, asynchronous efforts of a virtual team of players unlocked the structure of a protein related to AIDS that had baffled traditional researchers for a decade. Understanding the structure was key to designing an effective AIDS drug and resulted in a publication in a premier science journal *Nature Structural and Molecular Biology* in 2011.

Virtual reality environments have the potential to also support learning where multiple cognitive domains must be utilized while also integrating other aspects of learning, such as managing stress responses in a flight simulator. Consider the Office of Naval Research's futuristic Project BlueShark. The user slips on gloves and a headset with a range of sensors and inputs and is soon working virtually on an aircraft carrier or fly above the deck. Undergraduates at the University of Oklahoma learn about offshore oil rig drilling after settling into the seat of a virtual rig on campus.

Technology-enhanced learning environments show promise, but have a long way to go to be truly effective personalized learning resources. Much is known about how K-16 students learn science and engineering that can be effectively integrated across learning environments (NRC 2011a, b, 2012a). While the potential is great, far more current online learning environments simply scale less effective approaches, including traditional lecturing, than utilize Radix or BlueShark learning environments.

Leveraging Technology to Understand Convergence Learning

Although more is known about learning within specific science, mathematics, and engineering disciplines than about interdisciplinary and convergence learning, work on supporting interdisciplinary learning is emerging (Kezar and Elrod 2012). Technology-enhanced learning environments can advance our understanding of convergence learning, as well as provide personalized, just-in-time learning. The field of learning analytics, which develops tools and analytic methods to learn from large-scale, complex learning data sets such as online courses, is emerging in response to the opportunity to accelerate research about personalized, technology-enhanced learning (Pea 2014). In 2013, the *Journal of Learning Analytics* was established. Learning analytics tackles data sets generated by thousands and even tens of thousands of users with an aim to maximize learning, one learner at a time.

Learning analytics has the potential to disaggregate data based on demographics at a grain size not possible in a traditional classroom. For example, how might learning in a similar digital environment be different for an undergraduate engineering and biology majors interested in applying their skills to a synthetic biology problem? While existing learning science research can inform the design of the environment, a continual improvement cycle in the digital world can advance progress rapidly. For example, A/B testing allows the researcher to provide two different environments to two groups of similar learners at scale to determine which approach is more effective and for whom. The more effective approach is integrated into the learning environment and the research team is off to design the next experiment and further refine the resource.

A core skill for success in a world of convergence is the ability to transfer understanding and knowledge from one context to another. Indeed, transfer has been considered the holy grail of science education. Far too many undergraduates learn about energy in a biology course, a chemistry course, and a physics course and leave believing that these are different and unrelated concepts. Following how learners use and apply learning from course to course is challenging in both K-12 and higher education. The ability to follow learners in the online world as they move between courses offers unique opportunities to both study and experiment with approaches to enhance transfer. Think of the ability to transfer as acquisition of "convergence creole." One promising approach is the Core Concept Catalog (MC3) that is being developed at MIT (oeit.mit.edu/gallery/projects/core-concept-catalog-mc3). This is an architecture that allows concept mapping and exposing conceptual models within and across disciplines. The value of such architecture is the opportunity to compare and intervene in learning experiences, online, within, and across fields.

Building a robust learning analytics field to support personalized learning is, in of itself, an example of convergence. Education and learning expertise, computer science, data privacy policy, data science, law, social statistics, machine learning, and artificial intelligence are all at the nexus of effective personalized learning at scale. The policy and privacy issue are substantive and on par with the technological challenges of creating a robust environment to support one learner at a time, at scale.

Developing Intrapersonal and Interpersonal Skills

The broad range of expertise needed to address the complexities of today and tomorrow's grand challenges demands effective teamwork. Integrating teamwork complements progress in the cognitive domain and building deep disciplinary expertise coupled with the fluency to work across fields, bringing the relevant tools, knowledge, conceptual frames, and strategies together to solve problems. While these cognitive skills are essential ingredients, success will be limited if the participants lack both the intrapersonal and interpersonal skills to successfully maximize the contributions of all team members. A framework for developing these skills can be found in the NRC (2012b) *Education for Life and Work* report.

Within the intrapersonal domain, three clusters of competencies support learning: (1) intellectual openness, (2) work ethic aligned with conscientiousness and perseverance, and (3) core self-evaluation. Within the intrapersonal domain, the roles of motivation in learning and metacognition (being aware of one's thinking) are critical as convergence demands lifelong learning. Research on a number of social-psychological interventions that affect learners' beliefs about their learning can have a positive effect on their success. For example, middle school children whose math lesson includes the message that working hard, not simply being good at math, leads to success out perform children who are just taught the math skills. Increased persistence in college has been found when incoming college students viewed videos from upperclassman discussing how their grades improved over time. Likewise there are numerous reports of success using interventions that reduce “stereotype threat,” a self-fulfilling prophecy that individuals will do poorly because they belong to a specific demographic (e.g., women drivers or girls solving mathematics problems).

Motivation can have cultural dimensions, for example, the belief that one is good or poor at mathematics versus the belief that success in mathematics is the result of hard work. Addressing global challenges requires global participation and a growing number of technology-enhanced learning environments aim to develop relevant competencies for worldwide populations. While cognitive dimensions of these learning environments may translate with relative ease across cultures globally, greater understanding of motivation and other dimensions of both the intrapersonal and interpersonal domains are needed.

Metacognition is increasingly important as the emphasis on self-directed learning increases. Consider an engineer working on bio-based energy solutions who is delving into an online resource on photosynthesis. Ideally the learning environment would provide a highly adaptive cognitive tutor that builds on the engineer’s prior understanding. Yet realistically not all resources will have that amount of structural support. The engineer needs to rely on her ability to understand her own learning and monitor her learning. Experts are particularly good at metacognition within their domain of expertise. Again, the need to develop the ability to transfer skills across domains will be critical and less is understood about the transferability of metacognition.

The interpersonal domain aligns with two clusters in the NRC (2012b) report: (1) teamwork and collaboration and (2) leadership. Success in these clusters aligns with a broad range of skills including communication, collaboration, empathy, and social influence. Research in this domain is emerging in the context of the science of team science. Team science considers individual factors and the characteristics of teams, including size, members, and proximity, as well as other factors that affect a team’s effectiveness in achieving its goals. As advances are made in understanding the core competencies needed to be an effective team member, inclusion of the knowledge in the construction of learning environments will more effectively support learning about and working with convergent problems. The importance of the intrapersonal and interpersonal domains challenges the status quo of many learning environments where lecture is the primary mode of instruction. For technology-enhanced learning environments, there will be unique challenges to effectively integrating the social context of learning.

Researchers in the Language Technologies Institute at Carnegie Mellon bring together fields ranging from human-computer interactions to linguistics to learning science to ask questions such as how conversational constructs may predict group learning outcomes. Convergent research in these areas may lead to virtual learning environments that more effectively develop skills to support team-based solutions to complex problems.

Increasingly, self-organizing groups are forming to learn from online platforms. These range from “meetup” groups that can be located through a search engine on the edX.org platform that hosts massive open online courses (MOOCs) to clusters of graduate students, postdoctoral fellows, and faculty using an online course on implementing effective teaching practices, hosted by the Center for the Integration of Research, Teaching, and Learning (cirtl.net/), for professional development. Interactive tools, including Classroom Salon (classroomsalon.com), allow learners to remotely and asynchronously read and annotate a journal article or other document. An engineer and a chemist can make their expertise and perspectives visible to each other while critically evaluating a key finding from a third field that could advance their convergence project. These virtual groups provide rich data sets to mine with the goal of understanding particularly effective ways learners from distinct backgrounds productively engage each other to create new knowledge and tools.

Defining and Measuring Successful Learning in a Convergent World

Assessing learning within a discipline is a challenge, with measuring integrative moves across disciplines being even more so. At the K-12 level, an assessment framework has been proposed that includes strategies for assessing a learner's ability to weave together science practices, core ideas, and crosscutting concepts in the context of their shorter- and longer term learning experiences (NRC 2014a). Developing valid measures of performance at all levels of learning, measuring progression over time, and using assessment data to promote learning are grand challenges at many levels.

Collectively, what is measured is what is valued. Unless assessments can be developed to adequately assess the problem solving, transfer, and critical thinking skills essential for success in working on convergent problems, developing innovative learning environments, tools, and resources will be for naught. That is, assessment is the proverbial tail that wags the dog. Progress in clearly identifying and measuring the cognitive, intrapersonal, and interpersonal skills needed for success in contributing to convergence needs to be accompanied by high-quality assessment.

Personalized learning, utilizing online environments, offers opportunity for assessment that can more rapidly improve learning, as well as document the learner's proficiency. Research shows that enduring learning occurs when the learner retrieves and works with what has been learned. Taking frequent quizzes enhances learning far more than rereading material. Online environments can be built to include frequent, iterative feedback. Think about a computer game where the user has to build skills and solve problems in order to get to the next level. The feedback is continuous. This, in addition to personalizing the tasks to build on the learner's prior understanding has been key to the success of cognitive tutors.

In addition to the "how" of assessment, the need to develop understanding on a just-in-time basis for different fields and tools suggests a different model for assessing and documenting competency is also needed. Emerging efforts to document competency with stackable credentials, whether they be badges or certificates, are particularly relevant in preparing and providing lifelong learner for a convergence workforce. Progress is being made in middle skills job areas, including welding certification, IT certification, and the National Association of Manufacturers' endorsed Manufacturing Skills Certification System. LinkedIn, a social media site for business, now includes tools to link certifications to the user's profile. Developing stackable credentials for advanced degree holders is a viable, but not yet tapped, approach to documenting an individual's "convergence creole" fluency.

Summary

Preparing the next generation of lifelong learners who can contribute to solving the grand challenges facing this world requires a significant transformation of current education at all levels. This is, in of itself, a convergence problem to be solved and will require the best thinking and efforts across the education sciences, social sciences, computer science, and the science, mathematics, and engineering fields. Key challenges to be addressed are:

- Effectively integrating a deep understanding of core ideas within a discipline with learning about crosscutting concepts and science practices in the way science and engineering is taught from the early grades through graduate education.
- Vertically integrate precollege and postsecondary learning for greater coherency and impact.
- Create adaptive, personalized learning environments that allow individuals to master new areas, in cognitive, intrapersonal, and interpersonal domains, as needed.
- Leverage new learning environments to accelerate findings on interdisciplinary learning and team-based learning.
- Develop effective assessments to measure the critical skills for success in problem solving and create new credentialing mechanisms to document the broad portfolio of expertise individuals will acquire over a lifetime of learning.

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Life-Long Learning

Anne Collins McLaughlin, Jing Feng, and Richard Pak

Contents

Abstract

As the number of persons over 65 makes a meteoric rise worldwide, there is a need for convergence of many fields to best prepare systems and technology that support older adults. These adults constitute a special population with capabilities, limitations, needs, and motivations that can only be addressed through interdisciplinary innovations. We situate the needs of older persons in an adaptation of the hierarchy of needs, first proposed by Maslow in the mid-twentieth century. Using such a framework can help create a culture of convergence between fields in cognitive/behavioral science, medicine, and engineering to ensure that new technologies are well designed for lifelong learning and fulfillment to the point of self-actualization – not just basic life support.

A.C. McLaughlin (✉) • J. Feng
Department of Psychology, North Carolina State University, Raleigh, NC, USA
e-mail: acmclaug@ncsu.edu; jfeng2@ncsu.edu

R. Pak
Department of Psychology, Clemson University, Clemson, SC, USA
e-mail: richpak@clemson.edu

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"Aging is not lost youth but a new stage of opportunity and strength."

Betty Friedan (1921–2006)

Introduction

The mid-twenty-first century will witness a demographic shift never before seen as for the first time the number of persons over the age of 65 will outnumber those under the age of 14. Those older persons will live longer than prior generations, and it is crucial that we prepare cultural and technological systems to allow them to contribute both to society and to fulfillment in their own lives. **Development of such systems will depend on the interdisciplinary contributions of many fields, including areas of psychology, medicine, engineering, and computer science, with a need for convergence of these fields to assure usability, adoption, learning, and enjoyment**.

As long as humans have used tools, there have been adaptations for aging, from the walking stick to the personal emergency beacon. Systems tend to focus on making up for a decline, such as a walker, or supporting life, such as a pacemaker. Although low-level systems are necessary, it is important to also design for the higher-level motivations of older persons. Maslow's hierarchy of needs illustrates the type of needs that may be addressed by technology while also directing research and development into currently unfulfilled needs.

Maslow developed the original theory in 1943 to categorize different motivations of human behavior. It is a hierarchy because the motivations to fulfill various needs occur at different levels. The lowest levels of the hierarchy must be fulfilled to some minimum of satisfaction before the individual is driven to fulfill the higher levels. A truly whole individual has all lower-level needs met and is free to follow motivations at the highest level, that of self-actualization. In Maslow's hierarchy, the most basic level was physiological need (shelter, food, water), rising to safety, then love/belonging, esteem, and finally self-actualization, where morality, creativity, and problem-solving can occur. The hierarchy of needs appears in many theories, including theories of nursing, where nurses provide for the lowest levels of the hierarchy (physiological need) to allow for the higher levels to emerge, and technology adoption by older adults, where Thielke et al. pointed out technologies are not adopted because designers do not consider the needs of older users. We have adapted this hierarchy to describe the needs of older adults as they may be fulfilled by advancements in science and technology with a focus on *allowing* the highest needs to emerge (Fig. 1).

In the adapted hierarchy, the first level is health or the absence or amelioration of disease, where much past work on technologies for older adults has occurred. Life-threatening conditions, such as heart attack or stroke, influence the goals of technologies at this level. At this level is also basic self-care, such as food, water, elimination, and hygiene. Higher in the hierarchy is well-being, defined by the

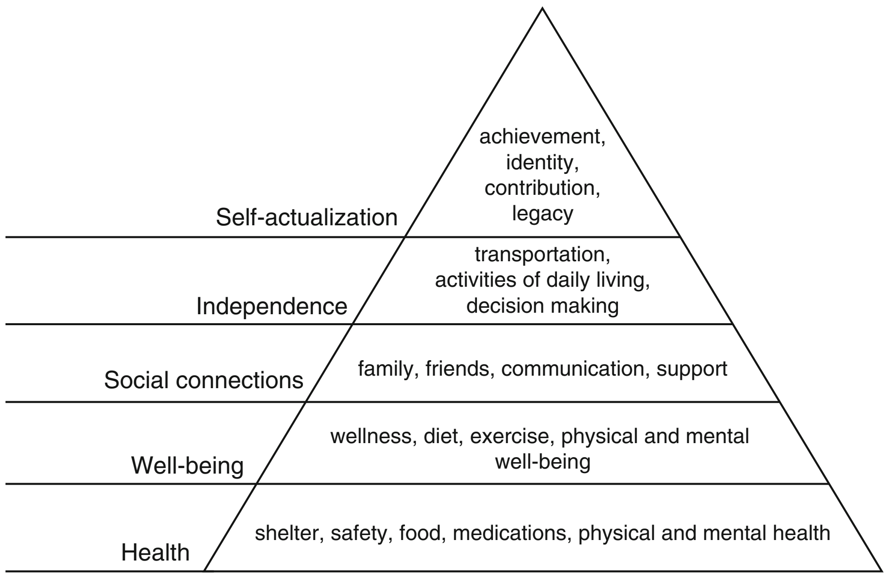

Fig. 1 The hierarchy of older adult needs, inspired by Maslow's hierarchy of needs (1943)

Centers for Disease Control and Prevention (CDC) as a holistic perception that life is going well, followed by social connections to family and friends, independence in areas the individual perceives as important (this could be transportation or home activities), and finally, self-actualization. In Maslow's original hierarchy, self-actualization allowed for creativity and contributions outside the self. We preserve this definition, adding in feelings of identity and achievement, remaining active in society outside of the self, presiding over a legacy, and promote the top of the hierarchy as a near and far future goal for the convergence of science and technology for lifelong learning. Although research and development of technologies for older adults spans the hierarchy, existing technologies have traditionally focused on lower-level needs with relatively few innovations addressing higher levels of the hierarchy (e.g., technologies to support basic life and health but few to support well-being, social connections, or self-actualization).

Age-Related Change

Maslow did not originally conceive of the possible implications of biological aging in the hierarchy of needs, although aging is intertwined with needs such that younger people's needs may be lower on the pyramid (striving to get by on one's own) while older people's needs may be higher up (well established and looking for self-actualization). But age-related changes naturally could have a deeper effect altering the specific needs at each level. Because of normative age-related changes in cognition and perception and increasing life span, older adults' needs will be different than people of other age groups (e.g., health needs are likely to be increased for older adults compared to healthy younger adults). Thus, we must understand the various changes that tend to occur with age. Note the use of the term "age-related," as these changes vary and assuming all persons of a particular age have reductions in their capabilities is a stereotype. Further, persons should be considered in their *limitations* and *capabilities*. Not all age-related change is decline; there are areas where older persons tend to excel compared to younger, and good design can take advantage of those capabilities. Age-related changes are typically divided into the following categories: movement changes, sensory changes, cognitive changes, and emotional changes. We provide a brief overview of each.

Movement changes tend to include slower reaction times, less speed and control over fine movements, and changes in gait and joints. Interestingly, it has been found that reaction time does not change much with age – it is only for reactions that depend on a decision that tends to slow. For example, when driving it is not the response time needed to move the foot suddenly to the break that slows, but it is the decision based on the environment that tells the foot to move to the break that can slow. Such differences can be serious, because although older persons are less likely to be in an accident per mile driven than middle-aged drivers, those who are have a 150 % higher chance of serious injury or death than a younger person.

Age-related changes in movement can also affect use of personal technologies such as input devices (mouse, keyboard, touch screens). The need to double-click a mouse button or click and drag on a screen using a mouse can be frustrating, and a few adaptive technologies exist at the hardware and software levels. For example, a trackball is easier to use than a computer mouse; a touch screen can be effective (providing the display is designed to be used with a touch screen with adequate target size). However, despite research on older adult preferences and difficulties with input devices, few adaptations and no new input devices have been created for this audience, making it an area with adequate science, but surprisingly little convergence with engineering or commercialization. Software adaptations for usability are more extensive, such as "sticky" icons that draw the mouse cursor to them as it comes near or automatic changes in gain as a cursor approaches a target. However, aside from turning off double-click, these adaptations are not in widespread use; thus it is unsurprising that a 2014 Pew report found that having physical difficulties correlated with less technology use and use of the Internet.

In addition to changes in movement, older adults also experience declines in sensory abilities. The main changes in aging vision are reduced contrast sensitivity, yellowing of the lens, and near-/farsightedness. Contrast sensitivity refers to the ability to detect differences between overlayed objects or text. Older drivers face risks when driving at night or in glare, though antireflective coating on glasses and high-definition lenses can reduce glare. In general, interfaces such as e-readers or tablets designed for older users should have the capacity to accommodate to personal contrast sensitivity level. In addition to declining contrast, the lenses in the eyes become increasingly yellow. Seeing through yellowish lenses, older persons experience deterioration in the ability to distinguish blue from purple and green from yellow. When interfaces are coded using these colors, older persons may not see the difference in the shades of the colors. Last, as near and far vision changes, older adults often use bifocals to correct both their near and far visions without the need to change between glasses. While bifocals provide some convenience, the use of bifocals (and trifocals, progressive glasses) increases the risk of falling by 31 %, even among regular wearers.

Hearing loss is another aspect of sensory changes. About one in every three older adults age between 65 and 74 experiences hearing loss, and nearly half older than 75 years have problems with hearing. Hearing loss makes it difficult to interact with friends and family members as frequently asking people to repeat themselves feels embarrassing, thus older adults who have difficulty hearing tend to withdraw from conversations and other social activities, reporting increased isolation and loneliness. The highest and lowest pitches are the most likely to be lost, raising considerations when designing sound communications such as alarms for older adults.

Older adults also experience decreased sensitivity to light touch and vibration, due to the decrease of density of skin receptors in advancing age. It is difficult for them to tell the exact location on their skin where light touch is taking place and also to distinguish two simultaneous light touches at different locations on the skin. The ability to distinguish two touches, discriminate tactile gaps, and identify the orientation of a line by touch deteriorates with age. While the deterioration on the sense of touch is prevalent across the entire body, the rate on fingers is much slower than on other parts of the body (about 20 % decline in forearms and 80 % decline on average across the whole body). These age-related changes place important concerns when designing advanced tactile interactions on a computer interface (e.g., cell phones and tablets) and on warning systems in an automobile (e.g., whether to present tactile warnings such as vibrations on the driving wheel or the seat belt) for older adults. Making use of better preserved capabilities among older adults (e.g., vibrations on hands rather than other parts of the body) can make the signals from the interface much more perceivable.

On the cognitive level, the ability to focus on important information while ignoring others tends to decline with age. This deterioration, however, is greatly reduced when older adults are given information about what and where to ignore and if all information to be ignored is similar. For example, to make a website more senior friendly, the designer could present text on a webpage in a large font with little distracting information. Further, the topic of interest should be emphasized, with high contrast between the target information and the background. Other information can be temporarily hidden or shown in a uniform visual appearance (e.g., same color, font). Another tactic is to avoid situations that are particularly difficult for older users, such as multitasking (e.g., conversing and using a GPS while driving).

An insidious negative effect comes from stereotype threat or behavior change due to knowledge that their performance may conform to a stereotype about their age. It is insidious in that it most strongly affects older persons who place great value on their memory or cognitive abilities and it is rarely acknowledged as a cause of cognitive failures, particularly by designers, who may signal stereotypes about aging through their designs. When under stereotype threat, older adults exhibit more memory errors, more input device errors, and various other mistakes that provide a feedback loop that a new system cannot be learned or is not worth the effort of learning. Stereotype threat is a possible explanation as to why technologies labeled for older persons tend not to succeed – older user do not wish to think of themselves as needing such items.

Thus far, examples of age-related changes in cognition have been of decline; however, some abilities improve with age. Knowledge, sometimes referred to as crystallized intelligence or wisdom, tends to improve until late in the life span and affects many domains such as vocabulary, reasoning about interpersonal relations, verbal and written communication, and maintaining “institutional memory” for past eras and events. Knowledge can decline at older ages, but this is frequently associated with a phenomenon called “terminal drop,” where many abilities change in the months preceding death, rather than associated with normal aging.

Older persons also tend to have better control of their emotions and report higher emotional well-being than their younger counterparts. The most popular theory explaining this finding is Carstensen’s socioemotional selectivity theory, which posits that older persons, who have a realization of their limited lifetime, seek positive interpretations of events and avoid situations or interpretations that are negative. Most research findings are consistent with this claim, making the stereotype of a depressed and lonely older adult inaccurate. However, such emotional well-being can come at a cost when avoiding negative emotions, which means avoiding learning or use of a helpful system or technology. For example, in a typical experiment on this topic, learners are asked to memorize words or images presented on a screen. Older persons have been shown to remember far fewer words or images associated with negativity (such as an injured person or the word “lonely”) compared to younger adults, even while their memory for positive items is relatively the same as younger persons. Unfortunately, many important topics where science, technology, and policy converge have negative aspects.

One of the most important considerations for older adult use of new technology is their motivation to do so. In many cases, lack of adoption or use is not a function of inability but due to a lack of perceived benefit. This difference is critical – unfortunate stereotypes of aging suggest to designers that older persons will not benefit from their products because they “are too set in their ways” or “you can’t teach an old dog new tricks.” In actuality, older persons are highly able and learn *when they invest the resources and effort needed for learning*. New technologies often do not appear to offer enough benefit above systems already in use to warrant the investment of resources. For example, consider the benefits of email over the telephone: email can be asynchronous; pictures are easily sent over email; emails can be reaccessed later rather than only from memory. If these benefits are not clear, then email appears to be more effortful than a phone call. After all, email requires a computer, being near a computer to communicate, typing, understanding file hierarchies for attachments, avoiding spam and viruses, storing email addresses rather than a phone number from a book, an Internet connection, a password, and reading on a screen. In an evaluation of cost versus benefit, many rational humans would decide the benefits do not outweigh the costs compared to using a phone. Thus, the benefits of a new technology must be clear and substantially high to expect rational older adults to exert the effort and resources necessary to overcome the associated costs.

Social support appears to be crucial for successful aging, as older persons who report strong social networks score better on tests of cognition and have lower incidence of depression. However, the types of desired social support interaction tend to change with age. For example, older persons tend to desire strengthening existing connections to others, rather than seeking new connections. Thus, a message board full of strangers may not fulfill their needs, at least until those strangers are introduced as friends or demonstrate their utility via their knowledge.

Traditionally, older audiences for game and social technologies have been ignored, despite Pew reports that 23 % of persons over 65 report playing digital games and that number jumps to 40 % when considering 50–64. These numbers are bound to increase by the mid-twenty-first century as, in 2014, persons turning 60 were 23 when the first Star Wars movie debuted and 29 when the Apple Macintosh personal computer was introduced. These will be people who have spent most of their lives interacting with abstract technologies, such as spreadsheets, word processing, file systems, printers, and networks. One of the biggest challenges will not be to interest these older adults but to design interfaces that are learnable, accessible, and enjoyable to encourage participation in future technologies such as augmented, virtual/mixed realities, 3D printing, citizen engineering, and citizen science.

In sum, age-related change is well studied, but less well applied in the design of technologies and systems for older users. Armed with a general understanding of age-related change, we apply that knowledge to three case studies of technology for older adults and discuss the current state of the technology and the potential of the technology once the fields of cognitive, behavioral, and social science converge with engineering, industrial design, and other areas.

Robotics

One convergent technology that can address multiple levels of need is robotics. Robots are in increasing use in the home, and there is active research examining robots as caregivers (basic life support), robots that encourage healthy behaviors and perceptions of wellness (well-being), enhance social connections by keeping older adults company (social connections), and enhance older adults' ability to maintain employment (independence). Viewing human-robot interaction through the lens of the hierarchy of needs illustrates challenges and opportunities for future researchers, drawing upon the expertise of social scientists, computer scientists, engineers, programmers, and gerontologists. Key issues that cross needs and point out the need for strengthened multidisciplinary work are social acceptance of robots, human behavior with autonomous systems, and appropriate function allocation.

When it comes to *health* and *well-being*, most current work in human-robot interaction has focused on robots as caregivers for older adults. The proportion of the population considered older is quickly approaching a point where there will not be enough caregivers for those that need it. A major issue with technology at this level is the nature of human behavior with autonomous systems such as robots: as the reliability of the robot increases (e.g., it properly diagnoses, reliably notifies caregivers), users can depend on the technology, leading to complacency. When the robot inevitably fails at a task, the user must resume control. However, long-term interaction with reliable automation can lead to skill degradation. In addition, because the user was not in the loop of a highly automated task, they will have reduced awareness of the situation and will not effectively be able to "take over" when the robot fails. Thus, key issues at this level will be finding the right balance of task allocation between the robot and the human so that the user can reap the positive aspects of robots (reduced task load) but not the negative aspects (skill degradation, loss of situation awareness). Proper function allocation is an issue that requires input from psychologists, who can contribute ideas of human capabilities and limitations, and engineers and programmers who build the robot with specific capabilities and limitations. The proper allocation of tasks between the robot and the human is an open question. One technique that could be used is more participatory design of robotic systems: involving older users in all phases of the design process from inception ("what should the robot do?") to testing, release, and revision.

When basic needs are met, the individual can focus on *social connections*. Existing work has examined the use of robots to either act as companions for older adults or to help facilitate older adults' communication with family and friends. However, many challenges exist in the use of robots for this higher-level need. Perhaps the biggest one is of initial acceptance and eventual adoption, an issue often unaddressed by those creating the robot helper. A common attitude among engineers seems to be, "if you build it, they will come," implying that there will be a market for advanced social companionship robots. However, as decades of research on technology adoption has shown, acceptance and adoption are not inevitable for new technology and can seem counterintuitive (i.e., some technologies are rapidly adopted while others are not). This problem of adoption by older adults may be exacerbated by the fact that outside of specialized research labs, most commercially available social companion robots are not targeted to older adults but more for novelty purposes (e.g., Sony's AIBO pet) and thus will not accommodate older users' unique capabilities and limitations outlined previously. In addition, when it comes to convincing older adults of the benefits of robots to enhance social companionship, it may be prudent to remember socioemotional selectivity theory discussed previously when "marketing" products; that is, is the robot to keep you from being lonely (negative connotations) or to enhance and strengthen existing social bonds with distant friends and family?

Even when robots are adopted, subtle issues come into play that may affect use. As robots and many automated technologies appear to have agency and can display seemingly advanced autonomous behavior, users may attribute too much capability or set high expectations that cannot be met. For example, although a robot appears to be listening intently or expressing emotions that may be appropriate for a situation, it does not think or feel. However, Nass repeatedly found that users respond to the social cues given by an affective technology as though the robot or system had human feelings. This often resulted in frustration or anger when a technology, that gave affective cues, was unable to perform at a humanlike level. Thus, it is important to better understand how to calibrate user expectations of a technology. This is important because it may determine whether a user becomes frustrated with the technology and eventually abandons it.

All of the issues described also apply to the use of robots to enhance independence. Independence could mean staying at home longer or staying productively employed past the traditional age of retirement. Research on smart homes, or houses with pervasive and automated support technology, shows that technology can enhance the ability of the older adult to stay in their homes instead of moving to an assisted living facility. For example, robotic helpers can carry out autonomous tasks such as loading the dishwasher or cooking. The GIRAFF+ robot is being fitted with sensors to monitor activity but also allows communication with family or caretakers through the robot, and other robots exist that guide walkers or other assistive equipment through the home. The major issues with any smart home technology will center on function allocation (i.e., what needs to be monitored or automated), user acceptance, and balancing the tradeoff between utility and privacy.

Similarly, one way of maintaining independence is by remaining employed longer. However, due to age-related changes, an older adult may be at a disadvantage for some work tasks. The future of human-robot collaboration to enhance older adults' independence in the workplace is not hard to imagine; it is occurring today in many factories as humans work with robots to assemble cars, airplanes, or complex microelectronics. In those examples of human-robot collaboration, such as the commercially available Baxter manufacturing robot, the worker is usually younger to middle aged. For older workers, the aforementioned issues of human-automation interaction, function allocation, and social acceptance are magnified. Extant research has shown that older adults, compared to other age groups, react differently to automation (and robots) compared to other age groups. One such difference is that older adults tend to be more wary of adopting automation than other age groups. When they do adopt automated technology, they ironically tend to be more complacent, or over-trusting, of automation. These issues cut across needs and domains and as of yet are unsolved. However, multidisciplinary research efforts can provide some answers that may smooth relations between the older user and the robot.

Automobiles

Convergence should also take place in vehicle technology. Older drivers keep their licenses for longer than before, and the number of older drivers is projected to increase from 34 million in 2010 to 57 million by 2030. However, cognitive deterioration can affect driving safety. For example, older drivers tend to miss pedestrians or other vehicles in a visually cluttered environment, have trouble juggling multiple tasks such as remembering turns while driving, and have slower reactions to sudden hazards. As a result, older drivers are more crash-prone, particularly in situations such as making a left turn, driving on a busy road, traveling in an unfamiliar environment, and driving at night. Fast-evolving automobile technology such as advanced warning systems and autonomous functions can help to improve driving safety and mobility of older drivers. However, the successful deployment of technology requires consideration of older drivers' needs at each level of the older adult hierarchy.

Addressing the level of *health*, advanced automobile technologies can help older drivers to improve their driving performance and safety. For example, collision prevention systems can warn a driver when the distance between vehicles is too short. Safety experts expect collision prevention systems to reduce the likelihood of rear-end collisions by 20 % and the severity of the collisions by 25 %. Lane departure systems provide warnings when drivers leave their lanes unintentionally. Given that older drivers in general take longer to react, advanced warnings may provide the extra time that older drivers need to avoid a crash. Similarly, at intersections, older drivers may miss a stop sign or a red light due to declining attentional abilities. In-vehicle intersection warning systems can augment the safety-critical information and provide an advanced alert to the driver.

While many emerging in-vehicle technologies have the potential to benefit older drivers, designing technologies without considering older adults' limitations and capabilities can reduce their effectiveness. For example, if a warning sound is too weak for an older driver to hear, the warning system may be of little use. If it is too loud, it may grab attention away from safety-critical actions. When multiple warning systems do not work collaboratively, such as many alarms issued closely in time, an older driver would not be able to react effectively to them.

Among older adults, mental health is closely connected with the maintenance of their driving privilege. Loss of driver's license can causes devastating consequences in the *well-being* of older adults by triggering depression, physical health, and social function declines; loss of license correlates to four to six times higher likelihood of death in the following few years. Fortunately, recent advances in the development of brain training techniques through mental and physical exercise can help older drivers to stay cognitively fit in advancing age. Cognitive training tools such as useful field of view (UFOV) can improve older drivers' attentional functions and subsequently better driving performance, driving safety, and more years of driving privilege. The development of effective and appealing brain training tools such as digital games is an area that warrants much research endeavor and convergence between cognitive science and technology.

With the ability to drive, it is easier for older adults to age in their own homes, allowing *independence* and *social connections* from earlier years to remain. Loss of the ability to drive often means that an older adult will need to depend on family members or friends to carry out daily tasks such as grocery shopping and visiting health-care providers. Given that older persons tend to nurture and rely on existing social connections rather than making new connections, home and community are particularly meaningful to an older person's social life. Losing the ability to drive makes it difficult to participate in social activities if places are not within walking distance or if walking is difficult and can lead to greater loneliness and isolation. Thus, driving is not just a way to keep mobility; it is also a symbol of *independence* and personal freedom. Well-designed smart vehicle technologies and effective cognitive training techniques can help older adults maintain their driving ability and mitigate restrictions on driving due to age-related cognitive declines (e.g., enable older drivers to drive safely at night and in busy traffic).

While specific in-vehicle technologies described in the above sections can aid older adults with driving, however, it is important to note that a vehicle that is marketed as a "senior car" is likely not going to be well received by older drivers. No driver enjoys a stereotypical image of incapability on himself/herself. Therefore, careful considerations have to be taken at all levels of the proposed hierarchy rather than merely focusing on the lower levels.

Medical Systems

Health maintenance and management of chronic conditions is a challenging task for persons of all ages, and 40 % of older patients must juggle five or more prescriptions. On top of this self-care, older adults are likely to be the caregiver for a partner, including all of his or her medications and devices. These high demands are further complicated by the age-related changes in sensory abilities, cognition, movement, and emotions that were discussed earlier in this chapter. As with assistive robotics and automobiles, older adult use of medical systems and devices spans the hierarchy of needs, and each level of the hierarchy requires research and development to help older persons achieve their full potential.

When considering basic life support at the level of *health*, the design emphasis tends toward high levels of automation. Just as humans should not need to concentrate on breathing or sweating, they should also not need to think about monitoring a pacemaker, artificial heart, or artificial pancreas. The convergence areas for these forms of technology may seem to trend toward medicine and engineering, rather than human factors or other areas of psychology and cognitive science. However, considering the capabilities and limitations of older users/patients is still critical for these technologies. For example, almost 9 out of 10 pacemakers are implanted in patients over 64. Learning to live with such life-supporting technologies requires motivated effort, both in changing behaviors and in continuing to learn about other new technologies that affect pacemakers. For example, induction stovetops are a recent invention and highly safe, particularly for a person who has memory issues with turning off a stove. However, anyone with a pacemaker must keep a 2-foot minimum distance from an induction stove. Thus, even at the life support level, design and development must take into account the learning needs, desires, and abilities of the older user. In another life-supporting device, fall detection, it may appear as though missing a fall would be worse than a false alarm. After all, no technology is perfect, and the criterion for detecting a fall must be chosen. However, false alarms could prevent use of the device due to fears of embarrassment or being perceived as less independent. This may explain why, although such devices have existed for many years, so few older adults use them – some estimates are less than 5 % of those who might benefit use them. Clearly, such dramatic rejection of the technology is due to more than cultural lag.

The bulk of medical systems for older adults are aimed at improving or maintaining *well-being* in the hierarchy of needs. This can mean teaching management of conditions, preventing conditions, or assisting with fitness or rehabilitation. There are many questions concerning medical systems, both at the engineering and design levels. For example, sensor technology is still being developed and improved for health issues such as blood glucose measurement and aerobic exertion. These engineering improvements often result in an easier-to-use design – when blood glucose can be measured using light through the skin or continuously through a pair of contacts, the step of taking blood or operating a meter is obviated. When a wearable can measure steps or heart rate and deliver the information wirelessly, there is no longer a need for proprietary displays or large equipment. However, it would be a mistake to conclude that improved engineering always equates with better design. Will the user need to remember to check his or her glucose levels? What serves as a reminder? Will the activity monitor be "gamified" as is common with such applications? How will an older person be motivated or unmotivated by a competitive aspect? Is the expectation of a smartphone as a display realistic considering a Pew report found that although 77 % of older adults had a cell phone in 2014, only 11 % owned a smartphone? Convergence in the study of technology solutions, human behavior, and human ability is needed.

In many cases, the appropriate designs and products can precede the engineering required to create them, making the eventual convergence of different forms of science and engineering seamless. For example, currently there is no device that can automatically detect the nutritional/caloric/carbohydrate content of a plate of food (although promising developments are underway at GE). It is possible to individually enter food items or ingredients, with a general estimate of amount or weight, into many applications or websites to get this information – information crucial to diabetes management. However, the potential benefits of such a device can be explored before its development. For example, one question might be whether instantaneous feedback on the variable of interest (calories, nutrition, carbohydrates) can help older persons learn to serve appropriate portions when such feedback is not available. Another question might concern the design of the device display – is it as effective a learning tool if the information is abstracted to a computer screen, or does more learning occur when information is displayed "on" the food via mixed/augmented reality? What format/amount/type of information best promotes learning? How should the level of automation in a device be decided? – too little automation provides less benefit over traditional assessments, but too much automation might act as a crutch that prevents learning.

Social connections are generally beneficial to aging – indeed, strong social support correlates with higher physical and cognitive functioning in older persons.

This result even holds when those social connections involve conflict – the presence of others in our lives is important for health. Having social connections and support has even been strongly linked to medication adherence – a difficult problem considering the large number of medications typically taken by those over 65. Thus, not surprisingly, social support is often a component, if not the goal, of medical devices for older persons. For example, blood glucose meters can send measurement information directly to health-care providers or family members. Such transfer of information may have two beneficial outcomes: (1) sharing the mental load of managing the condition with others and (2) strengthening or making more frequent their communication with others regarding their condition. However, enabling social interaction through medical devices is not a panacea and, in some cases, may not be desirable. One of the aspects of social connectivity through medical devices that needs exploration is informed consent. Do older users understand who may view their health information? Do they understand the degree of security offered by various transmission options (wireless, bluetooth, encryption)? Privacy is a complex area often overlooked by those creating devices with social connectivity, yet it is the most widely cited concern and barrier to adoption for older adults. Psychologists, designers, and engineers all need to work together to make systems transparent and controllable in their privacy settings.

Independence through technology has been a goal for many years, from the studies performed in living laboratories, such as the Georgia Tech Aware Home or the Mayo Clinic HAIL lab. These smart homes have been test-beds for the effectiveness of convergence, bringing together disciplines for the common goal of enabling independence for as long as possible. From memory aids to home automation to ambient displays of health and activity, researchers have contributed knowledge that is beginning to result in commercial products, such as prepackaged sensors, tracking, and communication devices that keep an independently living older adult in touch with family or health-care providers. For example, in one study using home sensors, remote heart rate monitoring resulted in a 60 % drop in hospital readmissions.

Conclusion

When considering the success of a new technology for older adults, it is important to consider two facets of the hierarchy for an individual: first, does the technology *satisfy* the need at a certain level or levels? Second, what is the *importance* of that level of need to the older person? Indeed, David Lester found that different measures developed to assess placement in the hierarchy focus on these different outcomes and both must be considered.

Fulfilling the lower levels on the hierarchy of older adult needs with systems such as robotics, transportation, and medical systems will allow older adults to pursue the highest state, one of *self-actualization*. The sources of creativity, identity, and contribution are as various as older adults themselves; thus it is the freedom from other needs that enables self-actualization, rather than any particular convergence of science and technology. One of the issues with technology innovation and design for older persons has been the focus on the lowest levels of the hierarchy and associating those levels with aging – the need for help with self-care, monitoring activity to keep those with illnesses from wandering, and the assumption that there will be memory issues. It is true that these needs must be met, but we would like to promote a focus on technologies that support higher levels in the hierarchy. In a chapter on nursing for healthy aging, Kathleen Jett wrote that she "was asked to speak to a group in a nursing home about death and dying. To her surprise, the room was not filled with staff, as she had expected, but with the frailest of elders in wheelchairs. Instead of the usual lecture, she spoke of legacies and asked the silent audience, 'What do you want people to remember about you? What made your life worthwhile?' Without exception each member of the audience had something to say from 'I had a beautiful garden' to 'I was a good mother' to 'I helped design a bridge.' Meaning can be found for life everywhere – you just have to ask." In seeking to improve possibilities for healthy aging through innovations brought about by convergence, designers must consider the whole person. Instead of focusing on "fixing" an age-related problem, reframe the development of an innovation as meeting a need so as to *allow* higher levels of need to arise and be met in turn.

In sum, convergence of science and technology is required at all levels of the older adult hierarchy of needs. Through three case study areas, we have illustrated the impact design and engineering it can have on the lives of older persons as well as questions yet to be explored. Using the older adult hierarchy of needs as a cohesive theory of motivation could help to create a convergence culture: unify the focus of new innovations across interdisciplinary fields, create a shared language of goals for technology, and ensure the inclusion of human capabilities, limitations, needs, and desires.

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Norms and Standards of Learning

James Murday

Contents

Abstract

Converging technologies present challenges to each of the stages in education – primary/secondary, community/technical college, undergraduate, graduate, and continuing. Three case studies – computer and information science and engineering, materials science and engineering, and nanoscale science and engineering – are discussed to examine various approaches to standards and norms.

J. Murday (✉)
Office of Research Advancement, University of Southern California, Washington, DC, USA
e-mail: murday@usc.edu

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Introduction

Any realization of goals for accelerating the impact of converging technologies will require (a) competent scientists/engineers that can provide the technical know-how, (b) informed business/government leadership that is ready to implement change, and (c) a public that is sufficiently knowledgeable to assess the relative benefits and detriments. Science and engineering technical education is only part of the equation. At the same time, education must develop skills such as problem solving, critical thinking, design, communication, collaboration, and self-management, e.g., skills that can be transferred or applied in new situations. This transferable knowledge includes both domain-content knowledge and procedural knowledge of how, why, and when to apply this knowledge to solve problems. Further, with longer life spans and employable years, adults will need access to the new knowledge via some form of continuing education (NRC 2012b; Organization for Economic Co-operation and Development (OECD) 2005; NSF 2008; Cargill and Van Tyne 2009; Murday et al. 2013).

The presently accepted education norms for science and engineering primarily address the traditional academic disciplines such as biology, chemistry, physics, and mathematics.

But nature does not parse its phenomena into the traditional academic disciplines, which have been human-imposed taxonomies to organize material in a way more readily grasped by the student. Further, one explicit role of science is to establish the underlying bridges/communalities among those traditional disciplines toward an ultimate goal of a unified knowledge framework (i.e., in the context of this book, to foster convergence). As such, convergence does not attempt to create something from nothing; rather, it fuses existing disciplinary perspectives into a new whole that transcends their sum.

Evolution of Education Norms and Standards

There are at least seven different communities that purvey education, each associated with a different stage in the education process:

Primary/secondary	Grades K–5/6–12
Community college (CC)/technical college (TC)	Grades 13–14
Undergraduate (BS/BA, MS/MA degrees)	Grades 13–18
Graduate (PhD degree)	
Continuing education (CE)	
Informal science education (ISE)	

The content of those various learning venues is guided by different sources of norms and standards.

Any modification to education content requires one to (a) be more efficient in the education process to add the new material without deleting other information,

(b) delete some material previously deemed important, or (c) add time to the education process. The evolution of education over the last century as reported in US Census Bureau's "The Educational Attainment in the United States" shows evidence for the last approach as necessary in the preparation of functional citizenry:

Grade school (K–8)	Required beginning in the early 1900s and was for free
High school (9–12)	Required beginning in the early 1920s and was for free US graduates grew from 30 % in 1940 to 90 % in 2013
Technical (13–14)	Optional; but in 2010 some US states are exploring making it free, which is a step toward recognizing it as "required" for functional citizenry in the twenty-first century
Undergraduate (13–17)	Optional; but US population with a bachelor's degree has grown from 5 % in 1940 to 30 % in 2013
MS degree	7 % of US population in 2013
PhD degree	1 % of US population in 2013

Education is not only a desired and necessary endeavor, but also a huge business (~$1 trillion/year in the USA) with incumbent bureaucracies. Any bureaucracy resists change due to inertia, inconvenience, threat, and cost. For K–12 education, the situation is made worse by its highly decentralized nature – control is generally at the lower levels. Any proposed change is subjected to many independent decision wickets, resulting in geographical nonuniformities. So economy of scale is hard to achieve. As a result, updates of science and engineering education are periodic with time frames measured in decades, in contrast to change in useful knowledge, which is made in years. For instance, at the K–12 level, at the request of the National Governors Association, the National Academy of Sciences published ideas toward national standards in 1996 and then again 17 years later in the Next Generation Science Standards (NGSS) (Achieve 2013). NGSS better reflects issues important to converging technologies – engineering is now formally incorporated into the standards, and emphasis is put on the interdependencies between the traditional disciplines.

Case Studies

"Converging technologies" is too broad and complex a topic to yield a simple, universal algorithm that would guarantee its successful incorporation into education. So three case studies are explored below to illustrate relatively recent convergence events that are dramatically affecting both academics and society – computer/information science and engineering (CSE), materials science and engineering (MSE), and nanoscale science and engineering (NSE) – or generically XSE where X denotes the specific topic.

Figure 1 provides a timeline with selected key events in the histories of the three XSEs.

Fig. 1 Important events in the selected XSE evolutions

The Advanced Research Projects Agency (ARPA) initiated funding programs in the early 1960s that keyed the growth of CSE and MSE that is evident in Fig. 1; National Science Foundation (NSF) programs followed shortly thereafter. While Department of Defense (DOD) funding was helpful in accelerating NSE, the influence was less pronounced, with NSF providing equivalent influence.

Because new science and engineering knowledge is largely generated at research universities, the early manifestations of any XSE in the education system tend to show up in college/university programs. Table 1 tracks the evolution of XSE departments and the BS/PhD degrees granted. About half of the BS MSE awardees continue on to a PhD and are presumably employed as researchers in academia and

Table 1 XSE evolution at US colleges/universities[a]

	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
Departments											
CSE	1	5		50		100		160	210	230	260
MSE	1	10	30						70		60
NSE										1	2
PhD degrees											
CSE		–	–	–	200	300	700	1000	850	1100	1700
MSE		–	40	130	150	150	300	500	400	500	650
NSE										5	10
BS degrees											
CSE		90	1500	5000	11,000	39,000	28,000	25,000	38,000	55,000	40,000
MSE		700	800	700	1300	1300	1200	1100	600	750	1000
NSE											

[a]The numbers cited in this table must be viewed as approximate since there are uncertainties in identifying appropriate assignments to the XSE designations. With the exception of NSE, the degree information is derived from NSF report 13-327. The NSE PhD degrees are the output of a single school, CNSE at SUNY-Albany (there are many other PhD degrees granted in the traditional disciplines that address the nanoscale)

industry where PhDs are expected. A BS in CSE clearly has greater viability in the workforce beyond the research and development communities.

Case Study 1: Computer and Information Science and Engineering (CSE)

Information science and technology is credited with transformative changes in human history; the advent of written language and its subsequent inexpensive replication by the printing press are two notable examples. Information technology (IT) – computers, wired and wireless digital networks, electronic data and information, IT devices and systems, and software applications – today provides indispensable infrastructure for activities across all facets of society. CSE is now credited with enabling another sociological revolution comparable to the industrial revolution (NRC 1999).

The explosive growth in IT over the last 50 years can be traced to investments made by the Federal agencies in the early 1960s. While government R&D investment was critical to the early CSE program, the large commercial market is now supported by industrial R&D, with government contributions largely constrained to basic research.

CSE education is the topic of a 1996 paper (Tucker et al. 1996); there is also a history of computing sciences accreditation (Engel et al. 2010). These two publications form the basis for this section. The importance of CSE education has been emphasized in three major national academy reports (NRC 1992, 1999, 2011). Efforts to define CSE standards at the university/college level began in the late 1960s/early 1970s with guidelines being explored by the Association for Computing Machinery (for computer science), the IEEE Computer Society (for computer engineering), and the Data Processing Management Association (for business applications). Since 1968 approximately every decade has seen new computer science curricular guidance, the latest being CS2013 (ACM 2013). Beginning in 1970 the ACM Special Interest Group on Computer Science Education (SIGCSE) has organized an annual symposium. The SIGCSE Web page and the NSF Computer Science Courseware Repository both contain links to information on a variety of course materials that are available at different institutions.

At the community college level, in 2003 NSF initiated an Advanced Technology Education (ATE) center "Broadening Advanced Technological Education Connections (BATEC)." Its primary focus is public post-secondary education (community college and university) in the fields of computer science, information technology, computer networking, and data analysis. It also works on workforce development issues at the high school, community college, and four-year levels.

There is general agreement that CSE should be included in K–12 education (ACM 2010), but the Next Generation Science Standards only mention the important role for computer models and simulations and do not address CSE per se. The Computer Science Teachers Association does have 2011-revised K–12 computer science standards, upgraded from the 2003 ACM model curriculum for K–12 computer science education. Independent of the NGSS, a number of US states are actively considering K–12 computer standards.

There are four journals that focus on CSE education:

Mathematics and Computer Education Journal initiated in 1967 by an independent
Computer Science Education initiated in 1988 by Taylor and Francis
Journal of Computational Science Education in 1994 by Shodor
Transactions on Computing Education initiated in 2001 by ACM

Case Study 2: Materials Science and Engineering (MSE)

Materials have had a profound impact on society as witnessed by the naming of specific historical ages after them – Stone, Bronze, Iron, Plastic, Silicon. Future successes will require unprecedented advancement in our (a) understanding of how structure/composition dictates properties and performance and (b) ability to manipulate at the atomic level composition and structure to fashion desired properties (NSF 2008).

Two papers on MSE education have been published (Östberg 2005; Schwartz 2010); they form the basis of this section. As with CSE, the growth of MSE can be traced back to initial ARPA and NSF investments in the 1960s. But beginning in the mid-1950s, departments had already began to identify "materials science" and by the 1970s, stimulated by the Defense Advanced Research Projects Agency (DARPA) and NSF centers programs, the name "materials science and engineering" appeared on many engineering school rosters.

MSE represents the integration of earlier academic subsets of metals, ceramics, and polymers and the more recent subsets of functional materials, composites/ metamaterials, and biomaterials. All of those subsets explore variants on properties of connected atoms and have a common dependence on materials structure, properties, processing, and performance (NRC 1975; Schwartz 2010). These four aspects, in conjunction with design and experimental/statistical/computational methods, comprise the generalized MSE. But while materials underlie essentially all manufactured goods, the number of jobs associated with materials expertise is largely constrained to the academic and manufacturing communities. These are not the larger-scale job opportunities seen in CSE.

As with CSE, no one professional society organization has clear leadership in materials science and engineering although the Materials Research Society (MRS) was formed in 1973 toward that goal. At universities, curricular content, methodology, and interaction with other engineering education entities are left to local departments with some guidance by the University Materials Council (UMC), which was formed in 1997. The UMC is comprised of US and Canada departments that share best practices and generally agreed upon, broadly defined undergrad curricula. Issues of accreditation are addressed by a joint effort of the Minerals, Metals and Materials Society (TMS), the American Ceramic Society, and the

Materials Research Society (MRS); accreditation is implemented through the organization ABET.

At the community college level, many of the NSF Advanced Technological Education (ATE) programs deal with MSE, but in 1996 NSF funded the National Resource Center for Materials Technology Education (MatEdu) to encompass high-quality modules both in traditional and new advanced materials technologies focused at the technician level. MatEd offers classroom-ready modules of labs and demos for use by educators, industry, and the general public.

While MSE is not a specific focus in the NGSS K–12 standards, the topic is reasonably well represented in the form of learning about materials properties (NSF 2008).

There is one journal that addresses MSE education: Journal of Materials Education begun in 1979 by the International Council on Materials Education.

Case Study 3: Nanoscale Science and Engineering (NSE)

NSE is a relatively recent occurrence, coming some 30 years after CSE and MSE. In that it addresses materials at the nanoscale, one might view NSE as a part of MSE. So why does it warrant a separate case study? The nanoscale provides new properties not seen at smaller/larger size scales. But more importantly, the nanoscale compels integration across disciplines that do not necessarily characterize themselves as materials people, e.g., biology, chemistry, and physics. In parallel, nanostructure-enabled information technologies provide sufficient computational power to address materials behaviors at the nanoscale from first principles. This raises more realistic expectations for materials by design enabled by (a) gaining understanding of nanoscale properties and (b) modeling/simulation capability integrating first principles and continuum models. In contrast to CSE and MSE, NRC studies have not guided the convergence; rather a Federal government-wide effort, the US National Nanotechnology Initiative (NNI), has generated those studies.

While the NNI has education in its goals, NSF is the only agency with a significant education investment. NSF was given a mandate to address science and engineering (S&E) education in the early 1990s. So NSE is different than CSE and MSE in that an NSF investment in education was explicitly built into the beginning of the National Nanotechnology Initiative (Murday et al. 2011). It is too early to determine how much this strategic investment has accelerated NSE education relative to the CSE and MSE examples. The status quo has been recently examined in two publications (Jones et al. 2013; Winkelmann et al. 2014).

There is no lead professional society to drive NSE education, and there has yet to be an ACM (CSE) or UMC (MSE) equivalent. The graduate/undergraduate curricula have been evolving largely at NSF-funded centers that span traditional academic departments. NSE work is being recognized in form of a minor or concentration associated with a traditional academic discipline. That is beginning to change. Similarly to CSE and MSE, the focused Federal investment in NSE in the last decade spawned three NSE departments – State University of New York

Albany's College of Nanoscale Science and Engineering, University of California San Diego's Nanoengineering, and the Joint School of Nanoscience and Nanoengineering at North Carolina A&T and UNC Greensboro – that explicitly award degrees in NSE.

At the CC/TC level, there are three nanoscale-focused ATE centers; each of those centers is working with local industry to determine the best curricula to make students better qualified for employers' needs. Nanotechnology Applications and Career Knowledge (NACK) (at Pennsylvania State University, PA), begun in 2007, partners with education institutions across the USA to promote a model for broad nanotechnology education and preparation. Nano-Link (at Dakota County Technical College, MN), begun in 2008, promotes nanotechnology education at multiple grade levels by providing comprehensive resources for students and educators. Northeast Education and Technology Education Center (NEATEC) (at Hudson Valley Community College, NY), begun in 2010, expands the pipeline of K–12 students interested in semiconductor and nanotechnology career options.

In 2006 NSF funded a "Big Ideas and Learning Goals in Nanoscience" workshop that defined materials appropriate for K–12 education and resulted in a textbook offered by the National Science Teachers Association (NSTA). A subsequent workshop in 2010 examined the NSE opportunities in the context of the Next Generation Science Standards (Murday et al. 2011). Since the NGSS has only a scant reference to nanotechnology, the challenge is to identify the NSE-based concepts/demonstrations that can help the curricula development in support of the NGSS physical sciences, life sciences, earth and space sciences, and engineering/technology/applications of science standards.

There is one journal that addresses NSE education: Journal of Nano Education begun in 2009 by American Scientific Publishers.

Challenges Specific to the Various Stages of Education

K–12 Level

The timely introduction of the new knowledge base associated with converging technologies into K–12 education is important, as the impact on society is pervasive. The CSE case study highlighted the extreme difficulty in making this happen. K–12 norms are largely defined by state/local school districts, but draw heavily on studies by the national academy (NRC 1996, 2012c).

1. Because of the huge K–12 enterprise and the tendency toward local control, it is expensive (time and money) to establish a coherent, accepted set of standards for any topic. The ongoing efforts in the various US states to adopt the Next Generation Science Standards (NGSS) illustrate the difficulties involved. The problem is more critical for XSE where rapid progress in societally pertinent knowledge happens on time frames short compared to the evolution of new standards. Nonetheless, it is important to incorporate converging knowledge into

this level of education to (a) avoid adding additional years later in the education process and (b) ensure all persons have at least some rudimentary understanding.
2. It is expensive (time and money) to train the teacher workforce in new technologies and to keep them up to date with the field. To facilitate the process, new channels of communication and support are needed between college-level and pre-college educators (Tucker et al. 1996).

CC/TC Level

Technician and support personnel increasingly come with 2–4 years of post-high school education (Schwartz 2010). This is likely a key reason some US states are considering free CC/TC education.

1. CC/TC institutions have multiple functions, one of which is to address education needs for local enterprises. It is necessary for CC/TC to reach out to the local industrial base to ascertain what the new skill sets are required for its XSE technicians.
2. Cost of lab work with converging technologies is frequently beyond CC/TC budget constraints. In the NSE case study, this challenge has been met in part by formal programs utilizing research university facilities [the NSF ATE projects at the University of Minnesota (with Nano-Link) and Pennsylvania State University's NACK], but this approach is not easily scaled up. There is need for improvements in remote access to high cost instrumentation.
3. About 50 % of US students who get 4-year degrees start in CC/TC institutions. XSE poses special problems, especially for non-S&E majors who will take only survey S&E courses (i.e., those more likely to happen in the first 2 years of college education). Articulation agreements can be difficult when the college/university curricular approach to an XSE is in a continual state of flux.

Undergraduate College/University Level

> This 21st –century scientist must have a skillset that allows him or her to probe and explore problems, to find and critically evaluate information, to work productively as a member of a team and to effectively communicate research findings to others. To meet this challenge it will be imperative for the higher education system to design, implement, sustain, and evolve undergraduate and graduate education programs that effectively promote student learning that transcends traditional disciplinary boundaries and that promotes a culture of scientists who see convergent approaches to complex scientific questions of the future as one critical strategy. (NRC 2014; NSF 2008)

Academic research is predominantly done by PhD students, so graduate education tends to adapt first to convergence driving forces. Undergraduate education moves next since (1) the scientists/engineering faculty driving the research are also engaged in teaching at the undergraduate level; (2) college level students (compared to K–12) have a sufficient science/engineering foundation to cope with the breadth implicit in converging technology; (3) commercialization of converging technologies requires not only scientists/engineers capable of that commercialization, but also those individuals who will become the savvy business and government leaders who can accelerate the commercialization; and (4) an XSE savvy population can facilitate more educated risk/benefit decisions on innovative technologies.

1. Undergraduate education has standards set by professional science and engineering societies (NRC 2012a), with ABET as an example of an organization that implements adherence to those standards (ABET 2014). For XSE, with its convergence of interests among different traditional academic disciplines, this is a particular challenge since there tends not be a one predominant professional society. Another key challenge for convergence is the marriage of the research endeavors where understanding of the sciences is being extended, and that understanding employed through innovative engineering practice toward the solution of society problems. This marriage of science and engineering disciplines also challenges standards/accreditation (Schwartz 2010). In part to meet this challenge, the ABET new EC2000 MSE standards are akin to ISO standards, i.e., state what they want to accomplish, show evidence that this has been accomplished, and describe what is being done to effect continuous improvement – not require uniformity of course work; ability to apply and integrate knowledge to solve problems; and ability to utilize experiments and statistical and computational methods.
2. Undergraduate engineering education is becoming a preengineering degree (NRC 1992, 2005). Professional engineering societies have been exploring the use of ME/MS for professional certification. This raises the question for the need to accredit and certify the new ME/MS degree programs. For XSE, this is difficult because (a) no single outside organization is fully engaged in all aspects of XSE and (b) the diversity of student backgrounds attracted to XSE requires a variety of "remedial" coursework.
3. Any XSE curriculum faces constant evolutionary pressure to integrate new critical developments. This is already challenging for the research universities that have faculty engaged in the XSE research and even more so for those schools whose faculty is not so engaged.
4. Many universities/colleges, especially those who would be heavily involved in XSE, value research and fund-raising by faculty at the expense of sound and effective teaching. Federal funding tends to emphasize XSE-like topics, i.e., provide new monies to the university. This can cause a problem because of the strong link between availability of Federal funding and faculty selection in academic departments. As faculty evolves horizontally into an XSE, it can lose vertical (traditional) discipline learning important to segments of industry. This can lead to accreditation problems (Cargill and Van Tyne 2009).

5. There is always tension at the undergraduate level to provide an appropriate balance of practical skills and fundamental knowledge. “Practical skills” are determined by the needs of the student’s ultimate employers. For XSE, those skills tend to evolve quickly. So the tendency is to provide the education basis for later careers by emphasizing fundamental principles and effective knowledge. Nonetheless, there is evolution of courses to incorporate the new knowledge. As courses addressing older, more specialized topics are phased out, and especially when local faculty expertise is lost, e-courses offer an approach to coping.
6. XSE knowledge, with its impending impact on societal technologies, must be imparted at some level to *all* students. That information is frequently incorporated into “service courses” for non-majors, which need to be strongly supported and continually upgraded. Further, because students come to XSE with a wide range of learning styles and backgrounds, faculty need to look for opportunities to develop teaching methods, lab materials, and technologies that appeal to as broad a collection of students as possible (Tucker et al. 1996).

Graduate College/University Level

Graduate education programs are unencumbered by accreditation issues, so each department is different, depending on factors such as the local environment, thesis advisor, lab facilities, and degree of collaboration. Nonetheless there is need for education to instill the skill sets required by the eventual employers. While the case studies illustrated that CSE education clearly must address a wider range of potential employment options compared to MSE and NSE, at the PhD level the XSE education will tend to be more research position oriented.

Today, major technological breakthroughs occur within just a few years, which approach the typical time scale for completing a PhD thesis. Graduate students could face a situation where the technical skills that they learned at the beginning of graduate school become obsolete by the time they graduate. This accentuates the need for student training in more general capability, including the ability to think, how fast they learn, and how they find and disseminate information to solve problems (ACM 2013).

Continuing Education Level

The rapid evolution in science and engineering, especially in XSE, makes it preposterous to envision an education scheme that could be “complete” for more than one or two decades past the end of “formal” education (Östberg 2005). Thus, it is necessary to initiate approaches to informal and continuing education. Professional societies, in concert with the business communities, are a logical place to determine what new courses need to be offered.

Summary/Conclusion

Convergence in science/engineering/technology poses both opportunities and challenges for education. Based on the case studies above, for any XSE there tends to be some similar needs (Tucker et al. 1996; Murday et al. 2011):

- A resource center for course and curriculum development
- A library of educational tools and demonstration software
- A clearinghouse for student opportunities
- A "virtual university" to support distance education

The concurrency of NSF attention to both education and research, starting in the 1990s, provides an opportunity to accelerate the incorporation of XSE materials into the education system. The NSE case study, which reflects an experiment in process, will provide some insights into this new paradigm. But NSF tends to migrate its investments toward new topics on a 10-year time frame, and the MSE and CSE case studies both show the need for attention over much longer time frames.

Beyond Federal investment in research and education, converging science and engineering requires continual attention and evolution by the various professional societies. One clear problem that shows up in all three case studies was the absence of a clear professional society leader for an XSE. This slows the development of appropriate university/college standards and curricula. That, in turn, affects change in the CC/TC and K–12 curricula.

In order to incorporate the new understanding inherent in XSEs, without adding time to the formal education process, it will be necessary to revise the K–12 curriculum on a timelier basis. While the Next Generation Science Standards provide a framework that may make this easier, the failure to incorporate CSE shows how difficult this task is.

Given longer life spans and careers, along with the education needs imposed by XSEs, there are major opportunities and challenges for continuing education.

On a positive note, one might hope that the advances in CSE will lead to reductions in the cost for changes in education. For instance, an electronic textbook can be updated continually at lower cost as compared to its printed predecessor. Similarly online training for teachers promises easier, more effective use of their time, and potentially it can be individually tailored to the person's specific learning idiosyncrasies.

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Online Courses

Douglas H. Fisher

Contents

Abstract

This chapter summarizes and speculates on the future of massive open online courses, which are courses offered by educational institutions to anyone with a computer and Internet connection. The pedagogy, technology, and policies surrounding interactive courseware offered to the world illustrate and drive convergence and divergence processes of knowledge, technology, and society.

Introduction

Massive open online courses (MOOCs) are prototypically courses that are offered online and free of charge to anyone in the world with access to a computer and an Internet connection. There has been animated discussion on how MOOCs will change the higher-education landscape, by reducing costs of higher education, by

D.H. Fisher (✉)
Vanderbilt Institute for Digital Learning, Vanderbilt University, Nashville, TN, USA
e-mail: douglas.h.fisher@vanderbilt.edu

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raising expectations of teaching quality, by giving many an opportunity for a college education who would not otherwise have had one, by accelerating the learning sciences with big data, by winnowing out many colleges and universities who cannot add perceptible value to low-cost online education and training, and by turning colleges into assembly lines of skill-based education. Even as many have anticipated a revolution, with these and other pros and cons, many have pointed to a gentler evolution in which MOOCs and their descendants will add bang for the buck to a campus-based education (Hollands and Tirtthali 2014).

MOOCs vary in content and format, but as the name suggests, they share broadly understood characteristics.

Massive refers to the number of students taking the course, which is generally taken to be in the thousands and tens of thousands.

Open suggests that anyone can gain access to the course, though not necessarily free access.

Online indicates that the main medium is through an Internet connection between a MOOC hosting platform and an individual's computer.

Course suggests a construct much like a campus-based multi-week course – with an instructor, a syllabus, lectures and readings, and formative and summative assessments of participants.

MOOCs entered the public eye when Stanford University offered three of them in machine learning, database, and artificial intelligence to students around the world for free in fall 2011. These courses each boasted enrollments of about 100,000 and more. Within months, various Stanford faculty members had founded Coursera and Udacity, MIT and Harvard had established edX, and other MOOC hosting platforms (e.g., iversity, Udemy) grew as well.

These courses did not burst out of nowhere. Stanford and other institutions, such as MIT and the Indian Institute of Technology, had been putting their course materials, notably lectures, online for years. YouTube had played host to brilliant lessons by "amateur" teachers, which were watched by thousands of learners each. Khan Academy is best known of the video tutorial "homespun" platforms, but many ad hoc sites of excellent tutorial content preceded it.

George Siemens and Stephen Downes are credited with offering the first *so-called* MOOC, "so-called" because McCauley et al. (2010, p. 10) state that other very large, online, open courses had been previously staged. Siemens and Downes' *Connectivism and Connective Knowledge* MOOC in 2008 (*CCK08*) included an "anchoring" cohort of University of Manitoba students taking the course for university credit, with over 2000 online students joining the course for free. The utilities of a global online population for the benefit of a formal student cohort and vice versa are attributes that are now being further explored with MOOCs, so it is notable that the juxtaposition of formal and informal learning was at the core of the very first so-called MOOC. Another important characteristic of CCK08 was the emphasis on social connectedness (McCauley et al. 2010; Fini 2009), with students encouraged to create and share knowledge across the many media available over the Internet and aggregated daily over RSS feeds. Indeed, the extent, form, and diversity of social interactions between students are potential dimensions for distinguishing MOOCs in fundamental ways. The term connectivist MOOC (or cMOOC) has been coined to refer to a course like CCK08 with rich content and social connections.

The prototypical MOOC of today does not possess the rich social and content interconnectivity of CCK08. Rather, more typically, a MOOC hosting entity (e.g., Coursera, edX) partners with educational institutions, to provide syllabi, lectures, assessments, and other content for an online course. The prototypical MOOC is a translation of a traditional campus course with adaptations to accommodate large numbers of students. These have been referred to as eXtended-course MOOCs or xMOOCs.

This chapter summarizes the forms that MOOCs take and the ways that MOOCs are used, speculates on how MOOCs might change in form and function in an exciting and uncertain future, and touches on the roles of MOOCs in suggesting, illustrating, and driving convergence and divergence processes of knowledge, technology, and society.

> Convergence is actually part of a dynamic and cyclical convergence–divergence process …. This process can provide a structure and specific improvement methods for the creative-innovation-production chain. The convergence phase consists of analysis, making creative connections among disparate ideas, and integration. The divergence phase consists of taking these new convergences and applying them to conceptual formation of new systems; application of innovation to new areas; new discoveries based on these processes; and multidimensional new outcomes in competencies, technologies, and products. This convergence–divergence process is reflected in the coherent chain of ideas from the ancient to modern eras, in the evolution over time of knowledge and technology, and in the development of human organizations and industries. (Roco et al. 2013, p. 3)

The coarse-grained descriptors of MOOCs (e.g., cMOOC, xMOOC), encouraged by initial divergence, are giving way to finer-grained multidimensional characterizations that will encourage both convergence and divergence of MOOC formats.

Learning at Large Scale

MOOCs are driving development of supports for open education of massive numbers of students. For example, discussion forums are the primary mode of communicating among MOOC students, teaching assistants, and instructors. Because of the massive numbers of students, MOOC discussion forums can become unwieldy quickly, thus motivating ongoing research and development into MOOC search and recommender capabilities.

Handling a massive number of student assessments (e.g., assignments, exams, quizzes) in a timely and reliable way is also a major challenge. Currently, many kinds of assessments (e.g., exams, computer programming assignments) can be graded automatically (i.e., by computer) in a manner that is better than the worst of human graders used in traditional settings, but is undoubtedly not as good as the best of such graders. Consider, for example, that grading a computer program may involve grading the correctness of the program, which computers excel at, but also aspects of style, where good human graders have an advantage over both computer graders and poor human expert graders. MOOCs have also accelerated research and development on peer grading and review, where students assess each other's work (e.g., Kulkarni et al. 2013). While peer assessments may work well in the average and best cases, there is plenty of room for improvement, and in the worst cases, peer assessment is downright disheartening to students (Suen 2014).

Conferences and workshops have been established to address issues of learning by large populations, and researchers and practitioners are rapidly enriching the potential design space of MOOCs and improving the tools for discussion, grading, review and commentary, and other functions (e.g., Learning at Scale 2014). The conferences themselves manifest processes of divergence and convergence, as like-intended venues spring up, support like-intended scholarship, which may later become differentiated and/or synthesized, as illustrated by the fields of educational data mining and learning analytics (Baker and Siemens 2014), for example.

While many of the tools being used in MOOCs are more suitable for some disciplines (e.g., computing, mathematics, language comprehension) than others (e.g., written and other artistic composition), it is increasingly difficult to make cursory judgments about what is possible to do given the fast pace of research and development. Still, MOOCs are potentially a good basis for longitudinal studies of how available technology both enables and limits certain functionality. For example, if peer assessment is the only tool one has available for conveniently grading multimedia essays at scale, will MOOC education technologists use it despite its drawbacks?

There has been much written about the large "dropout" rate in MOOCs of today, with the percentage of students who complete a MOOC falling off sharply as a MOOC progresses. Typically, only a small percentage of students who enroll in a MOOC actually complete it (DeBoer et al. 2014). High "dropout" rates are unsurprising under a freely open model, with relatively impoverished scaffolding to support student learning, but again, learning at scale research and development is rapidly expanding what is possible and desirable to do in the descendants of today's MOOCs. Educators are also focused on different qualities and quantities of student engagement (DeBoer et al. 2014; Dillenbourg et al. 2014). For example, "dropout" rate may not be a sensible descriptor of MOOC successes and failures if it is unconditioned on the goals of learners who enroll in a MOOC.

MOOCs exist within what is a potentially rich design space, which is part of a larger design space for online and distance education generally. What distinguishes MOOCs from the backdrop of other online and distance education programs won't be addressed in depth in this chapter, but what educators have learned in other distance education settings (Woolf 2010) or will relearn will surely drive the definition of descendants of today's MOOCs.

Institutional Motivations for MOOCs

Some may wonder why universities would go to the trouble of creating MOOCs, which can require many hours of faculty and staff time and tens of thousands of dollars to create and maintain (Hollands and Tirtthali 2014). One reason, perhaps the dominant one for many institutions, is that universities view MOOCs as a means for learning about new technologies and pedagogies, which will better insure that they will play robustly in the uncertain future of higher education. MOOCs also promise to increase student bang for the buck, which can be done by decreasing "the (net) buck" (e.g., through revenue, reducing staff costs) and by increasing the bang (e.g., by providing lifelong learning to alums at nominal cost). There are additional reasons that some institutions embrace MOOCs relating to institutional teaching, research, and outreach missions (Hollands and Tirtthali 2014; Cyrus 2013; Dasarathy et al. 2014).

As elaborated in a later section, MOOCS and the content and infrastructure of MOOCs can be turned inward, for education of campus students. Lectures and materials prepared for the world are often of higher quality than materials prepared for twenty or thirty campus students only. Moreover, global students will vet, correct, and otherwise refine material before it goes to campus, and global students can themselves be resources for campus students. For example, imagine finding the world's greatest teaching assistants for campus classes by drawing from the very best of the global cohort that takes a MOOC. Such nontraditionally affiliated teaching assistants may be highly incentivized through nontraditional (though meaningful) compensation packages.

Universities may be also interested in the research possibilities of MOOCs (Fisher and Fox 2014), which are often taken to mean the learning analytics and educational data mining research that can proceed with "big data" from MOOCs on student learning behaviors (Woolf 2010; Bienkowski et al. 2012), but can also be research in areas of human–computer interaction design (e.g., for online labs that will accompany MOOCs) and other educational research in areas such as formative assessment. The possibility of cultural affordances and blending in MOOCs' global, multicultural cohorts suggests the unprecedented potential for research of cultural convergence and divergence, yet another example of MOOC enabled longitudinal study.

Outreach is the third area that potentially benefits from MOOCs. Many educational institutions may have excellent national reputations, for example, but through MOOCs can accelerate their international reputations. MOOCs also provide benefits to larger communities, from regional to global, which satisfy an altruistic desire by many. The intended audiences for MOOCs can be tailored to institutional interests. K-12 students (and teachers thereof) in public, private, and homeschools are a common special audience of interest who can be reached through MOOCs, and so are alums of the institution. In contrast, retired people are probably underappreciated as a potential MOOC audience.

The reasons of education, research, and outreach are clearly synergistic, with MOOCs outwardly providing formal and informal (outreach) learning opportunities and also being "laboratories" for research. All things considered, some institutions may determine that it is more cost-and-quality effective to explicitly design and implement education for the globe, which is then turned inward, than to create education explicitly for a campus, which is then turned outward.

Not surprisingly, as disruptive technology, MOOCs are affecting universities in divergent and convergent ways. Cyrus (2013) describes the way that one university perceived and responded to early MOOC imperatives (e.g., institutional robustness), by realigning organizational units and personnel on a provisional basis, largely a process of convergence. In turn, many universities have probably followed Cyrus' institutional exemplar, by later founding new organizational units to manage MOOC production. It will not be surprising that after experience and reflection, there are further realignments, perhaps with consolidation across organizational units (i.e., convergence) at some institutions and/or divergence through distribution and differentiation of MOOC production across academic units in other cases.

In general, the MOOC case study illustrates that while the convergence–divergence cycle may look nonoptimal relative to attaining some result, within human organizations it may be the best approach given limits on human foresight; organizational change studies are an additional example of research suggested in the MOOC arena.

Changing Roles and Boundaries

As noted, MOOCs are the latest incarnation of education for the masses. The focus of discourse around MOOCs is usually about students, but how will public-facing education at scale affect instructors, academic expectations, and boundaries between institutions and between disciplines?

One implication of massive, public-facing education is likely to be that instructors will start treating learning objects, such as homework exercises, assignments, exam questions, exam keys, and the like, as intellectual output that requires citation. There appear to be no studies on how often instructors cite learning objects that are created by others, largely because teaching typically happens behind closed doors and password-guarded learning management systems. Normative behavior is likely to change under MOOCs. After all, with current MOOCs, accusations by students on suspected honor code violations by other students can be scathing, and accusations against instructors using the content of others without citation may be just as scathing. Ideally, prescribed practice will become citation of teaching and learning objects, both in public-facing practice and in private campus practice too.

Besides avoiding punitive outcomes, citation will bring positive outcomes to creators of learning objects, and to this end, it may be desirable to standardize citation practice and formats. Such practices will shine light on divergence and convergence in educational practice and may drive such processes. MOOCs may also accelerate the reuse and citation of other learning objects, which may be underutilized in spite of their high quality (Cohen et al. 2013). To the extent that it is the educational practices that most undergraduates observe and not the research practices of their instructors, the scholarship of education could still have larger impacts on student perceptions of community and collaboration in the academy.

There are still greater implications of public-facing education. Fisher and Fox (2014) illustrate that as far back as 2012, there were MOOCs sufficient for learners to acquire the rough equivalent of a bachelor's degree in computer science, starting with introduction to programming, through all the traditional core course requirements, advanced electives and technical society, mathematics, and liberal arts components. Moreover, there were options on the paths that students could take through the courses so as to personalize their curriculum, with multiple options for equivalent courses at all levels. The possibilities have only grown since 2012, not just with increased richness in computer science, but with curricular level options emerging in other disciplines as well. On the Coursera (2014) platform alone, at time of writing, computer science has been differentiated into overlapping areas of "Artificial Intelligence" (39 courses), "Software Engineering" (57), "Systems & Security" (37), and "Theory" (48). The remaining 884 courses, from 116 Coursera partners, in 20 languages, include 47 in the "Music, Film, and Audio," 110 in "Biology & Life Sciences," 141 in "Business & Management," 154 in "Social Sciences," 77 in "Physical & Earth Sciences," and 160 in "Humanities."

The ability to personalize, endorse, and share curricular pathways opens opportunities for crowdsourcing the best curricular pathways for different learners, who have different learning goals and learning styles (Fisher and Fox 2014; Woolf 2010). The beginnings of these possibilities are seen with the many MOOC aggregators that can be found via Web search (e.g., CourseTalk, CourseBuffet, Knollop), which include recommender capabilities and educational social networks. These curricular pathways span MOOCs from different educational institutions.

What can happen "organically," bottom-up through crowd sourcing, can also happen through deliberative design. Across-institution teaching collaborations are now emerging, with instructors at different institutions tightly collaborating in the creation of single MOOCs, such as a collaboration of five institutions on "An Introduction to Evidence-Based Undergraduate STEM Teaching" (CIRTL MOOC 2014) and more loosely collaborating in the design and implementation of MOOC sequences, with soft dependencies between MOOCs (Dasarathy et al. 2014). These across-institution collaborations will contribute to the development of scholarly communities growing around education practice, just as it has long existed in research, a topic touched on earlier. The pragmatic advantages of such collaborations are several. For campus students, the output of across-institution teaching collaborations results in courses that the expertise at any one institution was insufficient to offer, a topic addressed in the next section. For all learners, affiliated or not with established institutions, curricular level constructs, such as deliberatively designed MOOC sequences, are likely to be more cohesive curricular pathways than pathways that result from happenstance.

Much of the exploration with MOOCs will involve across discipline exploration. Consider that 25 conceptually overlapping topic labels (e.g., "Biology & Life Sciences") on the Coursera (2014) platform are applied 1921 times to a total of

884 courses, so on average there are 1921/884 = 2.17 labels per course. This is a very rough proxy for interdisciplinary connections found in these courses and the barest glimpse at the potential that MOOCs motivate and enable for longitudinal research on convergence and divergence processes on disciplines.

Importantly, across-institution teaching may accelerate the dismantling of disciplinary stove piping. Imagine a faculty member in artificial intelligence at one institution who wants to co-teach a course on artificial intelligence applications to ecology, but there were no willing or able co-instructors at the same institution. The online medium considerably grows the pool the candidate co-instructors for truly across-disciplinary instruction. The possibilities of richer mixing of instructors across disciplines may have implications for softening and changing disciplinary boundaries, and it may be that teaching collaborations encouraged by MOOCs are a stepping stone to research collaborations. This is all additional food for longitudinal studies of convergence and divergence cycles.

Blended Learning Management and Blended Learning with MOOCs

MOOCs and their descendants may be the way that learners cheaply sample topics that in an earlier time might have been sampled through publicly financed, high-quality education. In this light, the so-called high dropout rates of MOOCs may be a positive manifestation of being able to easily sample a topic. With so much variety too, campus instructors in some fields will exercise their discretion to allow some MOOCs to satisfy prerequisite requirements for more advanced courses. Note that even when a MOOC does not come with formal university credit, it can add bang for the buck to campus student education by enabling students to jump to advanced coursework. Topic sampling and prerequisite satisfaction may be nascent beginnings of a richer "cloud and campus" educational ecosystem, which would be a revolutionary convergence.

Increasingly, campus instructors are also adopting material (e.g., video lectures, assessments) and infrastructure (e.g., autograders) from MOOCs directly into their on-campus course offerings. The very first MOOCs saw the bottom-up creation of regionally local communities of learners who wanted to come together physically to help each other learn (Martin 2012). Thus, the idea that formal local cohorts, notably college courses led by instructors, would enter into global courses is an inverse dynamic. There are several models for instructor inclusion of MOOCs in campus courses.

Individual video lessons and exercises from a MOOC can be adopted for a campus course in a piecemeal manner, to supplement other course material, be it original to the campus instructor or material drawn from elsewhere on the Web. Thus, a MOOC is yet another collection of Web-based material from which instructors, serving as information aggregators, can draw from in designing their courses. It is potentially profitable to design a MOOC so that other instructors at other institutions can easily adopt pieces of it. Scholarship of educational practice with MOOCs will likely converge with existing practices with repositories of other forms of learning objects (Cohen et al. 2013), like Merlot's repository of multimedia educational resources for online education (Merlot 2014).

The proliferation of Web-based materials, particularly video lectures, have encouraged some instructors toward the so-called *flipped or inverted class* model, where students watch videos (or do reading or some other knowledge accretion exercises) prior to a class, then do active learning in the class to exercise newly acquired conceptual knowledge, under the (ideally) watchful eye and hand of an instructor. It is both the ability to revisit video lectures and reading as much as a student likes and active learning with an instructor playing a hands-on role, that are considered wins in the flipped classroom model (Brame 2013; Hollands and Tirtthali 2014). Though the flipped classroom model usually relieves the on-campus instructor of the need to lecture live, it does not relieve an on-campus instructor of the need to remain engaged with students – quite the opposite – in a successful flipped classroom, an instructor is likely to be more, not less, engaged.

Instructors are also using MOOCs in larger chunks and more systematically than piecemeal, even in their entirety, as the core of an on-campus course. Typically, this is done through what is called a *closed instance*, where the MOOC content is ported to a private site that only the students and staff of the campus course can access, together with administrators of the host platform. A closed instance is also known as a small, private, online course or SPOC (Fox 2013). The closed instance is distinguished by one-way "communication" – the campus course does not affect the MOOC content, or the activity within an ongoing MOOC.

In contrast to the closed instance is an *embedded instance*, where campus instructors or other-cohort leaders have students use content in an ongoing "live" MOOC (Bruff et al. 2013). In other words, campus students are also MOOC students. As with the closed instance, campus instructors can have students take the MOOC in part or whole. In the embedded case, there is the possibility of two-way communication, because campus students can contribute to discussion boards and peer assessments, as well as be represented in the data collected for enrollment and participation in the live MOOC.

In the case of embedded instances, in which campus students are participating as part of a global cohort, certain regulations (e.g., the US Family Educational Rights and Privacy Act or FERPA) protecting student privacy will influence the implementation. In general, insuring that graded material cannot be associated with personally identifiable information offsite or allowing optional involvement in an embedded instance, rather than required participation, may adequately address concerns. Ironically, while there will be no necessary implication that a MOOC student is also a campus student in an embedded instance, thus mitigating FERPA and other privacy concerns, there is the clear implication that a student in a closed instance is a campus student, and so a contractual agreement between students, institutions, and online content platforms to protect privacy may be the most desirable remedy to sufficiently ameliorate privacy concerns in both embedded and closed instances.

Why might a campus instructor want their students to take a course side by side with learners from outside their own institution, as in an embedded instance? The reasons are severalfold, and the potential benefits will likely vary with the discipline, the institution, the students, and the instructor. In theory, outside students will bring international perspectives to the campus course. There is nothing like participation in a MOOC to illustrate for campus students that "the world is flat" (Friedman 2005) and all the implications of that observation. Some MOOC students may also be professionals and alums of the institution and can be, in principle, a great source of mentorship and networking. This may be particularly so for underrepresented groups in certain fields, such as computing, with a paucity of women. The numbers of such mentors can be and probably will need to be encouraged by design and recruiting, rather than left to some accident. Inversely, learners who are unaffiliated with any institution may be incentivized to work through a MOOC if they can plug into established cohorts, such as students in university-embedded instances.

Whether a closed instance or an embedded instance, if the MOOC (content) is used in its near entirety in a campus course (i.e., the MOOC requirements are a subset of the campus course requirements), then the campus course is said to *wrap* around the MOOC, and the campus course is therefore called a *wrapper* (Bruff et al. 2013; Hollands and Tirtthali 2014; Fisher and Fox 2014). While blended learning with online and campus content has existed for a long time, it is typically the case that online content and in-class content have been created by the same instructor(s) or, in any case, that the online and on-campus materials were codesigned, considering the dependencies across components.

In a wrapper, the campus course instructor designs the in-class components with the online content fixed by another instructor. This introduces an important constraint into the course design space. Is it ideal that the campus instructor adapt completely to the substance, style, and naming conventions of the MOOC instructor? It may seem so, but some instructors might regard the students' adapting to the instructional differences, if handled appropriately, as an additional learning desideratum. In a graduate course, for example, it may be desirable that students see differences in what experts (i.e., online and on-campus instructors) think about certain materials (Bruff et al. 2013). In such a case, being conscious of the fixed online material would not translate into being perfectly compliant with it. Rather, overcompliance may bias most students toward convergent versus divergent thinking (Kuhn 1977), even more so than is the norm. Generally, the implications of using MOOCs for blended learning within a global student cohort and/or with a collection of (virtual and on-campus) instructors on divergence and convergence may be significant.

Other Opportunities of Blended Learning with MOOCs

MOOCs can be embedded in wrappers in cases for which there is no existing campus expertise. Indeed, this is probably the most likely context for wrappers. There are fears about administration-imposed wrappers, motivated for their cost savings; turning campus education into a MOOC-centric, one-size-fits-all factory assembly line; a paragon for convergence; and enabling institutions to release their higher-paid, in-house expert faculty. These concerns are legitimate, even for optimists. Another perspective suggests the potential for faculty as *lead learners* within wrappers, illustrating lifelong learning for their students. In this setting, faculty embrace MOOCs for the additional expertise they bring to campus. For example, at many small colleges, a course like machine learning might never be offered, but it is content that faculty and students would both welcome. In this setting, a MOOC may be a godsend. Ideally, a faculty member is unafraid to learn side by side with students. Equally important is that students respect and enjoy a faculty member in the (lead) learning role, at least with respect to some of the very advanced and elective coursework.

A problem with embedded instances is that the desired MOOC offering must be synchronized with the campus offering. In most cases, campus instructors do not have the option of changing the time period in which their course is offered. How can there be any assurance that the MOOC will be offered at a convenient time? Fortunately, an answer to this lies in *self-paced courses*, which are rapidly gaining popularity on a number of MOOC hosting platforms.

A self-paced (open, online) course is intended to allow individuals to move through the course at their own pace. But the real significance of a self-paced course is that it also allows organized cohorts, such as a campus course, to move through at the cohort's "own" pace. MOOCs have been converted to the self-paced format, but self-paced courses are no longer MOOCs per se, since a massive number of students may not be enrolled at any one time. But imagine organized cohorts, like campus courses roughly synchronized to the same academic year schedules, harnessing self-paced courses. The self-paced course will also include other learners, perhaps by happenstance or better yet by design. Collectively, organized cohorts moving through a self-paced open online course and individuals that follow their draft will constitute an "anytime" MOOC, one that can be convened at any time, by any leader of an organized cohort.

An *anytime MOOC* is a special case of an ideal generalization – that we would like to enable a campus instructor to "flip a switch," thereby opening a campus course to the world, not for purposes of attracting massive numbers of students necessarily, but to benefit campus students by the sometimes divergent perspective and expertise of global students. If multiple cohorts are moving through the self-paced course in relative synchrony, there may be incentives by cohort instructors to collaborate on designing and sharing in-class active learning exercises, yet another example of across-institution teaching collaborations. A collaborative, anytime MOOC, as conceived here, may be one of many new descendants of MOOCs and perhaps a return to Siemens and Downes' original vision and more recent variants (e.g., Jaschik 2013).

The use of MOOCs in campus courses has caused some to view them as multimedia textbooks, a characterization that approximates the truth. The truth is that a textbook is usually a well-synthesized material – a product of convergence. In addition, a comprehensive textbook is a superset of any one course's content and therefore supports customization possibilities, whereas a MOOC, or any course for that matter, represents a single path through a subset of potential material. A MOOC, or any given course, is best thought of as an impoverished, deterministic, or over-constrained (multimedia) textbook.

At the opposite end of the spectrum from online over-constrained "texts" is the wild and wholly collection of online resources that have not been synthesized, whether organized into learning object repositories or not. These materials may collectively support almost unlimited choice and customization – these latter resources are under constrained. A good textbook, one might argue, is "optimally" constrained, providing enough choice for instructors to follow different trajectories, but also providing enough structure, constraints, and guidance so that the choice is not overwhelming! A critical step in convergence to an appropriate- and intermediate-constrained educational artifact, from the overabundance of online content, is in identifying common concepts across material, through crowdsourcing or a small group of editors. This idea of optimal tradeoffs is generalizable beyond the education domain.

It is likely too that MOOCs will merge with other online materials, to include video and active learning material created by MOOC participants, as well as with interactive digital textbooks, which are already being used in a self-paced manner by both cohorts and unaffiliated individuals. Several (descendants of) MOOCs may attach to the same online textbook, each representing different paths through the material.

Among the exciting possibilities with MOOCs in blended scenarios are some ethical considerations. Instructors, students, and administrators alike should attend to licensing. Even courses that are freely available for individuals to use may come with modest charges for academic use, as in campus wrappers (e.g., Open Learning 2014). In general, MOOC hosting platforms have terms of service, some of which might preclude tuition-bearing wrappers without explicit permission. Ideally, cost structures will allow individual faculty to experiment with new pedagogy, diverging from local campus practices to test new models.

Final Thoughts

There is much on MOOCs that has not been significantly addressed in this chapter, in part because "the present of MOOCs" is not nearly so interesting as "the future of MOOCs." What the chapter seeks to make clear is that descendants of MOOCs will likely be very different than current MOOCs. MOOCs of today emphasize large number of people freely coming together in rough synchrony. There is much to be learned and developed in this kind of environment (Fisher and Fox 2014; Hollands and Tirtthali 2014; Dillenbourg et al. 2014), but we are already seeing MOOCs evolving into asynchronous (e.g., self-paced) and (physically) distributed entities (e.g., closed and embedded instances), which promise to morph the characteristics of massive and open into a much-touted ideal of learning ubiquity, that bridges formal and informal education and individual and social learning; softens the boundary between learner and teacher; and extends across a lifetime of learning and teaching.

MOOCs, their descendants, and their creators and users are also central drivers and manifestations of many processes of convergence and divergence – in organizational structures and boundaries, in disciplinary boundaries, and culture – and they will ideally be studied as such, sooner rather than later.

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Precollege Convergence Education

R. P. H. Chang, Jennifer M. Shanahan, and Matthew Hsu

Contents

Abstract

Education is a long-term investment. If society is to reap the benefits of convergence technologies in decades to come, a convergence culture must be established at the precollege level. All students, regardless of their future careers, must have the opportunity to develop a strong foundation in systems thinking, grounded in a deep and flexible understanding of Science, Technology, Engineering, and Math (STEM), the social sciences, the arts and the humanities.

R.P.H. Chang (✉) • J.M. Shanahan • M. Hsu
Materials Research Institute, Materials Science and Engineering, Northwestern University, Evanston, IL, USA
e-mail: r-chang@northwestern.edu; j-shanahan@northwestern.edu; mhsu.northwestern@gmail.com

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This chapter describes a conceptual framework for convergence learning in the formal precollege education setting. It is based on the successful Materials World Modules program developed for precollege students over a 22-year period at Northwestern University.

Introduction

Teaching the convergence of science, technology, and society in a formal classroom setting is a great challenge, particularly at the precollege level. Yet, the economic security and global economic leadership of the USA depend heavily on how successfully it can prepare its students as convergence thinkers from an early age. The focus of this chapter is to present a conceptual framework on how this can be done in current classrooms without disruption to ongoing programs. This framework includes the following four fundamental constructs:

1. The full ***integration of the STEM curriculum***, essential for coherence, real-world relevance, depth of understanding, and the development of systems thinking
2. The hands-on practice of ***scientific inquiry and engineering design*** – the heart of the technology R&D cycle and a key conceptual shift of the Next Generation Science Standards (NGSS) released in 2013
3. The use of ***digital multimedia and interactive learning*** technologies to reach larger numbers of students and provide equal opportunity access and personalized learning support for all
4. A ***community-based approach*** that bridges gaps across sectors, disciplines, and grade levels and keeps new knowledge and perspective flowing into classrooms.

Each element of the abovementioned framework is discussed below in the context of the Materials World Modules – a well-established STEM education program that offers concrete examples, illustrations and statistical analyses of its practices based on large data sets from classrooms across the country and around the world.

What is MWM? The Materials World Modules (MWM) is an integrated STEM program based on crosscutting topics from the interdisciplinary field of Materials Science and Engineering (MSE) and the hands-on practice of scientific inquiry and engineering design. MWM was established at Northwestern University in 1993 with funding from the National Science Foundation (NSF) and further developed under the National Nanotechnology Initiative (NNI) and via subsequent grants from NSF, the US Department of Defense and industry. It has reached more than 200,000 students in the USA, Mexico, China, Qatar, and Singapore and been used to educate thousands of precollege teachers in integrated STEM. The National Research Council has recognized MWM for its efforts to bring engineering into the U.S. curriculum (Committee on K-12 Engineering Education 2009).

Table 1 Published MWM modules and their areas of relevance

1. Biosensors	Applications to medical diagnostics and environmental monitoring
2. Concrete	A ubiquitous infrastructure material with a large environmental impact
3. Ceramics	A material with applications in electronics, optics, and communication devices
4. Composite materials	An ancient technique for developing new materials
5. Polymers	Plastics, food, carpet, films and coatings, medical prosthetics and much more
6. Smart sensors	Intelligent sensing for energy and security devices
7. Sports materials	How the science of sports materials affect athletic performance
8. Food packaging	Materials for everyday use with a large environmental impact
9. Biodegradable materials	Applications to medicine, pharmaceuticals and the environment
10. Introduction to the nanoscale	How size and shape affect the properties of a material at the nanoscale
11. Nanotechnology	How nanostructured materials are made, detected and applied
12. Manipulation of light at the nanoscale	How light interacts with materials at the nanoscale
13. Dye-sensitized solar cells (nanoscale)	Using nanoparticles and natural dyes to make solar cells
14. Environmental catalysis: (nanoscale)	Use nanocatalysts to combat environmental pollutants
15. Nano-patterning	Use nano-imprint lithography to pattern materials at the nanoscale
16. Drug delivery at the nanoscale	Make a prototype, time-release nanomedicine

MWM consists of 16 classroom modules describing materials, their properties and their many applications to real life (Table 1).

Each module includes printed student booklets and experimental supplies for an average class of 25 students (Fig. 1) and a teacher's guide with linkages to standards, STEM courses, and assessments.

In 2006, Northwestern Researchers worked with STEM teachers and materials researchers at the Centro de Investigación en Materiales Avanzados (CIMAV) – a national laboratory in Chihuahua, Mexico to launch MWM-Mexico, a Spanish language version of MWM fully adapted for use in Mexican classrooms (Fig. 2).

In 2013, the program launched an introductory nanoscience module for use on mobile devices. The new format, called "i-MWM," combines digital multimedia and interactive learning tools with real-time assessments to support personalized learning and teaching inside and outside the classroom, as illustrated in Fig. 3.

Fig. 1 (**a**) Printed MWM student booklets (© 2000 R.P.H. Chang, Northwestern University) (**b**) Prepackaged MWM supply kits include materials not readily available in classrooms (© 2000 R.P.H. Chang, Northwestern University)

Fig. 2 Mexican MWM Program (© R.P.H. Chang, Northwestern University, 2012)

Fig. 3 Interactive i-MWM platform for anywhere, anytime learning (© R.P.H. Chang, Northwestern University)

Integration of the STEM Curriculum

There are many voices calling for the integration of the US STEM curriculum, which has been characterized as fragmented, crowded, and lacking in depth and coherence (Committee on K-12 Engineering Education 2009; National Governors Association Center for Best Practices 2010; Schmidt et al. 2005). The chapter "► Reconceptualization of Education" defines many of its specific deficiencies and the resulting lack of competitiveness among US students compared to their peers abroad. Given that the classroom is where most students spend the majority of their time and where their learning can be assessed regularly over time, the formal curriculum must be an area of primary focus and concern.

Convergence learning requires the full integration of STEM, not only among the four STEM components but also between STEM and the social sciences, arts and humanities. A close integration of these fields is necessary to:

- Demonstrate the relevance of STEM concepts to societal, economic, and environmental concerns (NGSS Lead States 2013)
- Motivate and engage students according to their personal interests (NGSS Lead States 2013)
- Deepen learning through curricular coherence (Schmidt et al. 2005)
- Spark innovation and guide user-centered product design (Brady 2014)
- Develop systems thinking, i.e., the ability to integrate functional parts into a system with optimal performance.

One of the most significant barriers to STEM integration has been the rigidity of the precollege curriculum, which is based primarily on state and local learning standards, together with the diversity of these standards, which vary significantly from state to state and region to region. Therefore, a critical development has been the recent release of new national learning standards – the Common Core State Standards in Mathematics (CCSSM) and in Language Arts (CCSSL) both issued in 2010 and the Next Generation Science Standards (NGSS) issued in 2013. Although the majority of US states have not yet adopted the new standards, there is a movement toward a unified US curriculum that is more coherent and better suited to international benchmarking.

The new standards call for the full integration of STEM learning, most notably the "interdependence" of science, engineering, and math, a focus on fundamental concepts that cut across STEM disciplines, and a new emphasis on the relevance of STEM to society, the economy and the personal interests of students (NGSS Lead States 2013). Implementing the new standards will require the erosion of the well-established disciplinary silos that separate disciplines in most US schools (Schmidt et al. 2005) and the preparation of teachers to collaborate across disciplines.

MWM and STEM Integration

The integration of the U.S. STEM curriculum has been an overarching goal of MWM since its inception. Three elements have been central to this effort:

A Focus on Materials: MWM is based on crosscutting topics from Materials Science and Engineering (MSE). With fundamental concepts that span physics, chemistry, biology, earth science, math, and nearly every field of engineering, MSE integrates, reinforces, and deepens STEM learning. Meanwhile, the "concrete" nature of materials makes abstract concepts more accessible, memorable, and intuitive for students. Learners of all ages can readily grasp that making a better tool – one that is cheaper, lighter, stronger, faster, or safer for the environment – often means using a different material to make that tool.

Designing for the Middle Band: MWM is not designed for gifted or exceptional students nor does it specifically target any one group of students. Rather, by targeting the middle band i.e., majority of students, it aims to reach all students equally and thereby produce the broadest impact on the U.S. curriculum as a whole. The result of this approach has been a methodology – described in section "MWM's Inquiry and Design Methodology" of this chapter – that is equally effective in classrooms of all kinds – rich and poor, urban and rural – regardless of teacher experience or student gender or socioeconomic background. For this reason, MWM has demonstrated the potential to narrow many of the persistent skills and achievement gaps that exist across US society (National Science Board 2014).

A Nondisruptive Approach: MWM has never set out to replace the existing curriculum but rather to enhance it by reinforcing core concepts that were already being taught in the classroom. To this end, it created flexible, easy-to-use modules for insertion into existing courses, with an emphasis on standards alignment. Over the past 22 years, this approach has helped to produce a *gradual shift* towards STEM integration, which is evidenced by an evolution in how the modules are used in classrooms. At first, individual modules were inserted into an occasional science course, then in other STEM courses like Algebra and Chemistry in the Community. Later, groups of STEM teachers began creating and coteaching new integrated STEM courses on topics such as Chemistry-Physics and Science, Technology & Society. In 2006, MWM's nanotechnology modules were used to create a "small learning community" funded by the State of California Department of Education linking courses in science, math, social studies, art, and language arts. MWM has also been used in vocational settings and has become the basis for a national workforce initiative in Mexico.

One of the oldest R&D fields known to man, MSE offers outstanding societal and economic relevance. For centuries, materials and their properties have been the basis for most new technology, from farming implements to housing and transportation systems. Today, materials systems drive everything from mobile phones to medical diagnostics, and advanced bio- and nanoscale materials are pushing the frontiers of science and technology in renewable energy, environmental protection, health care, high-speed communications and global security. Because materials affect every aspect of the technology R&D cycle – from basic research to product design, manufacture, distribution, installation, and deployment – they are an ideal focus for STEM workforce development.

Scientific Inquiry and Engineering Design

An important construct of the MWM program is the use of scientific inquiry and engineering design. *Since 1993, MWM modules have taught specific STEM concepts through student-directed inquiry, and then challenged students to demonstrate their understanding of these concepts by using them to design functional products*. Today, the combined hands-on practice of scientific inquiry and engineering design is a key emphasis of the NGSS (NGSS Lead States 2013) and essential for STEM integration. It demonstrates the interdependence of science and engineering, affords students the opportunity to apply math principles to science and engineering problems (National Governors Association Center for Best Practices 2010), and as the heart of the technology R&D cycle, helps students better understand the role of science and engineering in society and the economy. The practice of engineering design is described as especially important for increasing diversity in STEM because it is "inclusive of students who may have traditionally been marginalized in the science classroom or experienced science as not being relevant to their lives or future" (NGSS Lead States 2013).

MWM's Inquiry and Design Methodology: Each module begins with a "hook" activity that captivates students' interest and encourages them to ask questions – the essence of scientific inquiry (Llewellyn 2002). The students work together to perform experiments, collect and analyze data, and apply their findings to design a product that addresses a socially relevant engineering problem. They test and redesign their prototypes to optimize their performance, which allows them to learn from what doesn't work, as well as from what does. Students write reports and make presentations to communicate the benefits of their designs. The process is illustrated in Fig. 4.

Developed in 1993, this methodology incorporates the benefits of three important movements in STEM education and predates their development:

"Backwards" Curriculum Design: This approach (Wiggins and McTighe 1998) begins by considering what students should know, understand, and be able to do, then determines acceptable evidence of these outcomes, and finally plans effective learning experiences that will achieve the desired results. MWM adopted this method in 1993, designing inquiry activities that would systematically equip students with the knowledge, understanding, and skills they would need to successfully carry out the culminating engineering design project at the end of each module.

Project-based Learning (PBL): MWM incorporates all of the major elements of the standard PBL model (Boss et al. 2013), which has been shown to deepen learning and retention, motivate students and their teachers, foster twenty-first century skills like critical thinking, collaboration, communication, and serve as the basis for learning partnerships that extend beyond the classroom. However, *MWM goes beyond the standard PBL practices by incorporating the iterative engineering design process shown in* Fig. 5 *and by emphasizing fundamental concepts that undergird science [and engineering] and provide insight into natural [and manmade] systems* (Schmidt et al. 2011).

Next Generation Science Standards (NGSS): Issued in 2013, the NGSS strongly emphasize the interdependence of science and engineering and define eight essential practices that students should master at the precollege level (NGSS Lead States 2013). Each MWM module teaches all eight of these practices, which include:

1. Asking Questions (for science) and Defining Problems (for engineering)
2. Developing and Using Models
3. Planning and Carrying out Investigations
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking
6. Constructing Explanations (for science) and Designing Solutions (for engineering)
7. Engaging in Argument from Evidence
8. Obtaining, Evaluating, and Communicating Information

MWM's methodology also implements the *iterative engineering design process* outlined in the NGSS (Fig. 5). For example, design projects challenge students to address "*problems of societal and global significance*" (e.g., designing a drug to

Fig. 4 (**a**) **The Hook.** Students in Xian, China, test how a motion sensor works in the Smart Sensors Module's Hook Activity and hypothesize how the sensor is stimulated (© 2012 R.P.H. Chang, Matthew Hsu, Northwestern University) (**b**) **Inquiry activities.** Students in Evanston, Illinois, investigate the decomposition of methyl acetate by acid catalysts in the Environmental Catalysis Module. They will analyze these data to determine how catalysts enhance reaction rates (© 2011 R.P.H. Chang, Matthew Hsu, Northwestern University) (**c**) **Engineering design project:** Students in Doha, Qatar design a smart coin counting detector in the Smart Sensors Module. They must optimize the detection mechanism to accomplish simultaneous counting and detecting the denomination of each coin (© 2012 R.P.H. Chang, Matthew Hsu, Northwestern University) (d) **Testing and redesign:** Students test the performance of their dye-sensitized solar cell (DSSC) designs in the DSSC Module and vary the fruit dyes to produce maximum current and voltage output to power a digital clock (© 2012 R.P.H. Chang, Matthew Hsu, Northwestern University) (**e**) **Communication:** Students present their design of a UV sunscreen in a school-wide symposium (© 2011 R.P.H. Chang, Matthew Hsu, Northwestern University) (**f**) **Teacher as Facilitator:** A high school teacher demonstrates how to set up an apparatus to study the decomposition of toxic pollutants (© 2009, R.P.H. Chang and Matthew Hsu, Northwestern University)

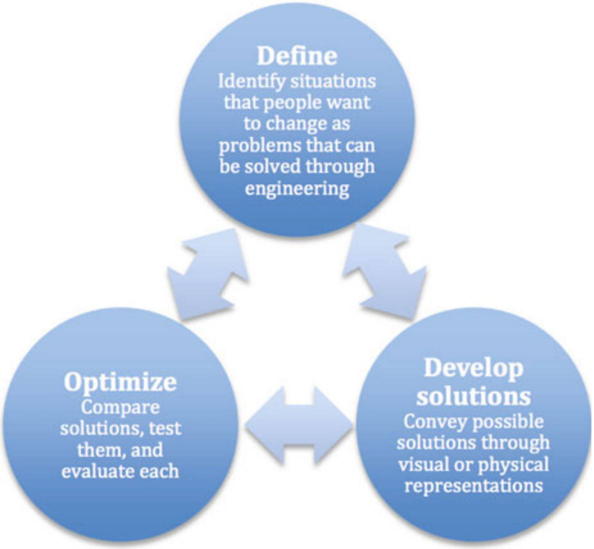

Fig. 5 The three core ideas of engineering design process presented in the NGSS for grades 9–12 (© Copyright 2013 Achieve, Inc. All rights reserved)

target cancer cells or an environmental catalyst to improve water quality) and *"attend to a broad range of considerations"* as they refine and optimize their designs, including the feasibility of manufacture and implementation, the needs of the end user (e.g., cost, ease of use), and the needs of society (e.g., safety, environmental impact).

MWM Learning Outcomes: Students have responded to MWM design challenges with enthusiasm and ingenuity. The best designs incorporate aesthetic and cultural values in addressing societal concerns. For example, a team of girls studying the Concrete module designed a glow-in-the-dark sidewalk to conserve streetlight energy. Chinese students studying the same module designed culturally relevant trash receptacles based on traditional Chinese figures to reduce litter in public parks.

The inquiry and design methodology produces statistically significant gains in content knowledge, process, and design skills and esteem for STEM study and STEM careers. A national study (Pellegrini 2010) measuring the impact of a single 10-h module on student learning found an average content knowledge gain of 2.5 standard deviations regardless of classroom setting, length of teacher experience, student background knowledge, or student socioeconomic background (Fig. 6). Girls slightly outperformed boys.

The student-led, teacher-guided approach has been motivating for students and teachers alike. In the words of one teacher, "No matter how many times I explain, I always have an 'I don't get it' response. After these activities, everybody had some knowledge they wanted to share. I would say again how much difference there is in "teaching" and "allowing the students to learn." I was amazed at the way all of the students, even the ones I had little hope for, got involved and retained what they studied. It was the retention that was perhaps most impressive. I can often engage

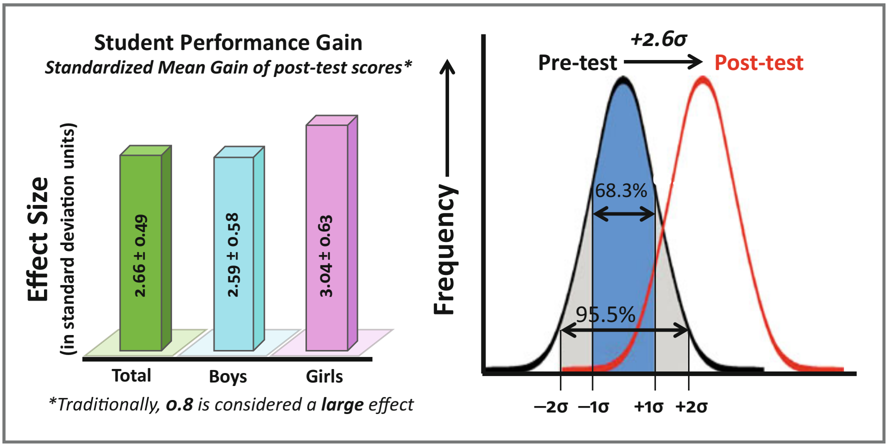

Fig. 6 Results from national field test data show an average student achievement gain of 2–3 standard deviations from a 2-week module implementation (© 2014 R.P.H. Chang, Northwestern University)

them by entertaining, but in this instance, they entertained themselves and actually remembered the material." A high school senior remarked, "Most of all, this [program] makes you think. It ties in everything from math and science and shows how they relate to life."

Digital Multimedia and Interactive Learning

Rapid advances of information technology have resulted in the exponential growth in the adoption of mobile devices in the last decade. Internet access and social networking on wireless devices is bringing instant access to information without spatial barriers. This new mode of communication is already demonstrating many important benefits to learning. For example:

The "flipped" classroom model (Strayer 2007) replaces traditional classroom lectures with online instructional content, allowing teachers and students to make better use of classroom time. This approach is especially conducive to convergence learning, which requires substantial knowledge transfer and collaborative hands-on work.

Delivering instructional content on mobile devices allows students take greater responsibility for their own learning (Cheung and Hew 2009) and makes content more widely available, particularly to students from low-income schools that struggle to afford up-to-date content. According to a recent study, three in four teens use mobile devices to go online; one in four uses a mobile device as a primary point of internet access. Girls, African Americans and low-income teens are more likely than other teens to be "cell-mostly" internet users (Madden et al. 2013).

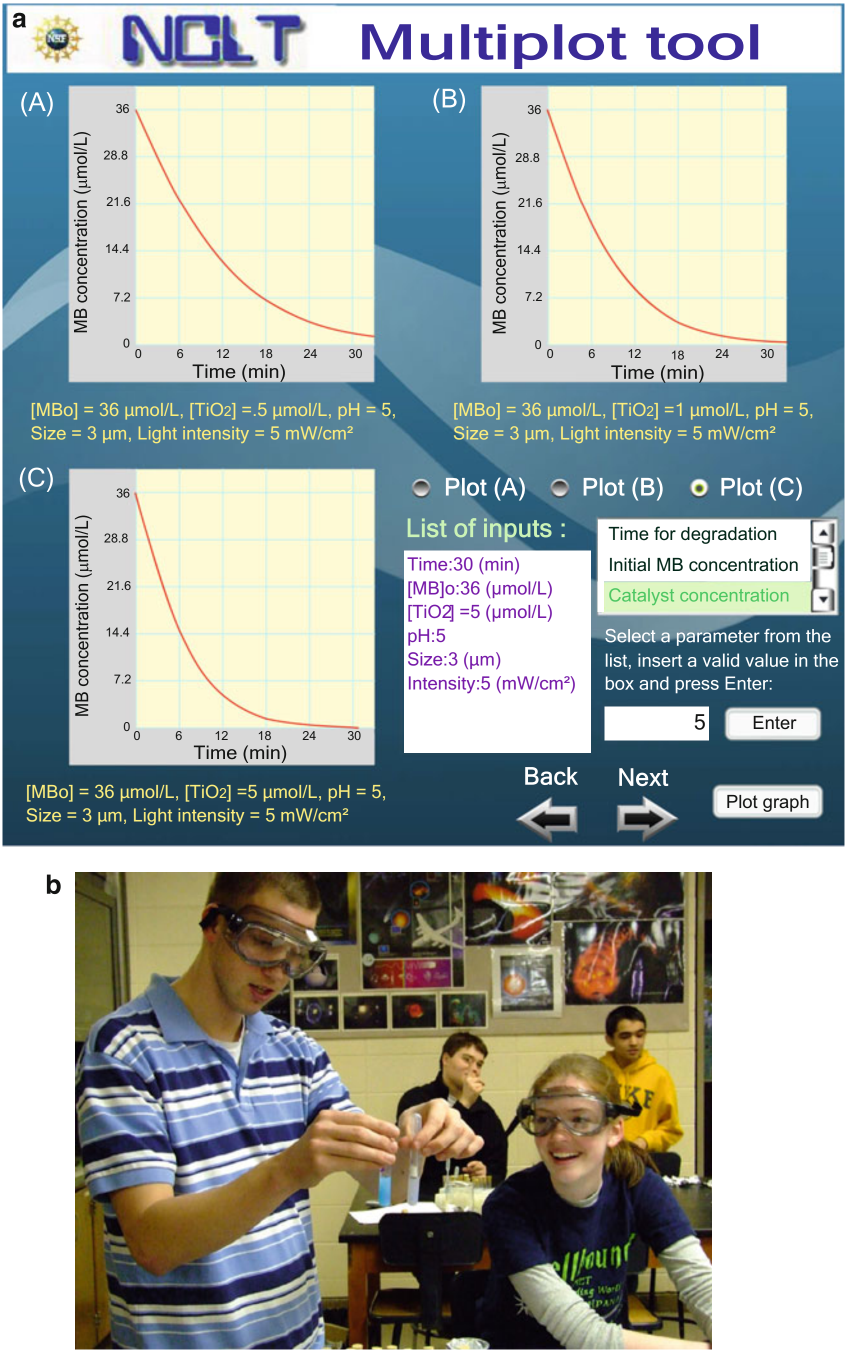

Fig. 7 (continued)

Interactive simulations and games have been shown to be more effective than traditional teaching methods for the study of advanced concepts that require a great deal of reinforcement (Vogel et al. 2006) and their effectiveness is increased when students are given autonomy over their use. They can be adapted to the pace of the user (Mayo 2009), capitalize on different learning styles by presenting information in different sensory modes (Gee 2003; Mayo 2009) and provide continuous immediate feedback that reinforces learning and self-efficacy (Mayo 2009).

MWM's Approach to Interactive Learning

In 2013, an interactive web-based MWM module (i-MWM) was developed entitled "Introduction to Nanoscience" based on content from several MWM print modules. This new digital version has been field tested in several New Jersey school districts, and is reaching selected schools around the country with promising results.

i-MWM uses a dual cyberspace (online) and real-space approach to "flip" the traditional classroom, encouraging online self-study outside the classroom and collaborative inquiry and design work (outlined in section "MWM's Inquiry and Design Methodology") inside the classroom. Interactive animations, simulations, and modeling tools illustrate 2D and 3D objects and complex time-dependent phenomena (Fig. 7a). These tools support the data analysis needed for classroom projects (Fig. 7b) and have the added benefit of enhancing spatial reasoning and reinforcing connections to math.

Games are used to give students an intuitive feel for nanoscale objects. Because they blend the formal and the informal, students enjoy them enough to use them outside of class. An undergraduate student with an interest in helping younger students understand nanotechnology created a series of fun, engaging games based on a character called "Sammy the Superscaler." (Fig. 8). One of these games supports the design and testing of a dye-sensitized solar cell. Players are hired by the Superscaler Manufacturing Company to design a high-efficency solar cell from nanoscale materials (Fig. 9). Their challenge is to create the best possible device from the materials and funds available. Like researchers in the real world, if they do well, they are given access to more funds and better materials.

i-MWM offers students a personalized learning experience. Multimedia tools appealing to different senses and learning styles expand students "voice and choice" about their own learning process (Boss et al. 2013; Vogel et al. 2006).

Fig. 7 (**a**) In the Environmental Catalysis Module, students use a simulation tool to predict how the concentration and particle size of a titanium dioxide (TiO_2) photocatalyst affects the breakdown of a blue dye, used to simulate a water pollutant (© 2008 R.P.H. Chang and Matthew Hsu, Northwestern University) (**b**) Students comparing the result of two samples of methylene blue solutions containing TiO_2 photocatalyst with and without catalytic activation via UV light. They will use this information to "design" a prototype catalytic system that removes polluted water from a popular tourist area (© 2008 R.P.H. Chang and Matthew Hsu, Northwestern University)

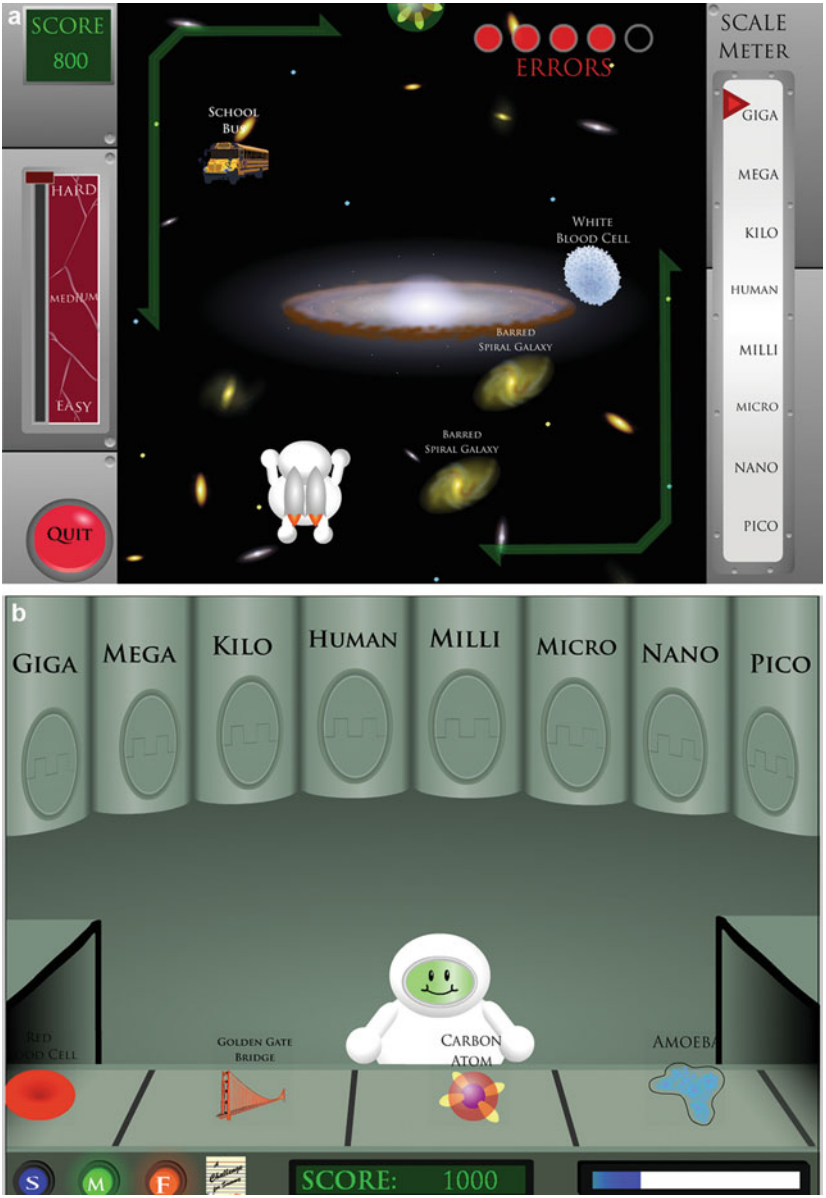

Fig. 8 (**a**) In "Sammy's Great Scale Adventure," Sammy the Superscaler invites players to explore environments at different scales (giga, macro, micro, nano, or pico) and identify objects that do not belong in them (© 2011 Ryan Reid and R.P.H. Chang, Northwestern University) (**b**) In the "Sammy and the Sorting Factory" game, Sammy invites players to help him sort objects according to these scales as they arrive on a conveyer belt and place each object in its proper category (© 2011 Ryan Reid and R.P.H. Chang, Northwestern University)

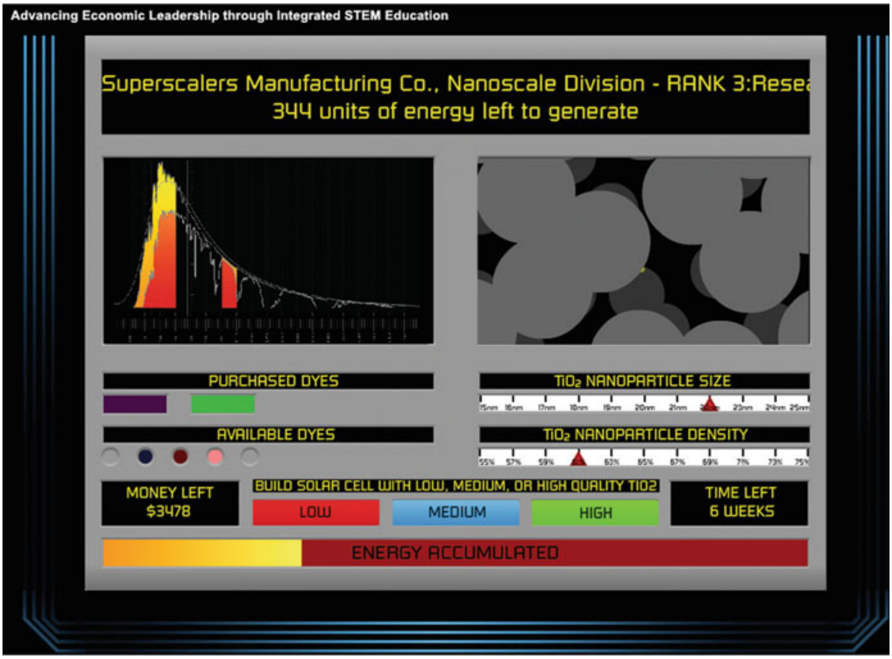

Fig. 9 Dye-sensitized solar cell game (© 2011 Ryan Reid and R.P.H. Chang, Northwestern University)

For example, students with reading challenges may find it easier to grasp a concept by listening to a narrated tutorial or viewing an animation. Students can personalize their learning experience by studying at their own pace using the tools they find most useful, following "multiple routes" to learn the same concept (Gee 2003). Figure 10 illustrates the diversity of tools available to study the nanoscience concept of Surface-Area-to-Volume Ratio (SAV.) Built-in periodic assessments – recently shown to improve retention (Roediger and Butler 2011) allow students monitor their own progress and review material as needed. Web-based analysis software help teachers intervene where and when they are most needed.

Community-Based Approach

The fourth construct in the framework is a community-based approach to program development that bridges gaps across sectors, disciplines, and grade levels and keeps new knowledge and perspective flowing into classrooms.

The goal of STEM integration is a lofty one that cannot be accomplished by any single sector, discipline, or initiative. Education is a huge national enterprise that is funded at more than $1 trillion annually and consists of 50 independent state units, each with its own standards, budgets, and practices. Although top-down,

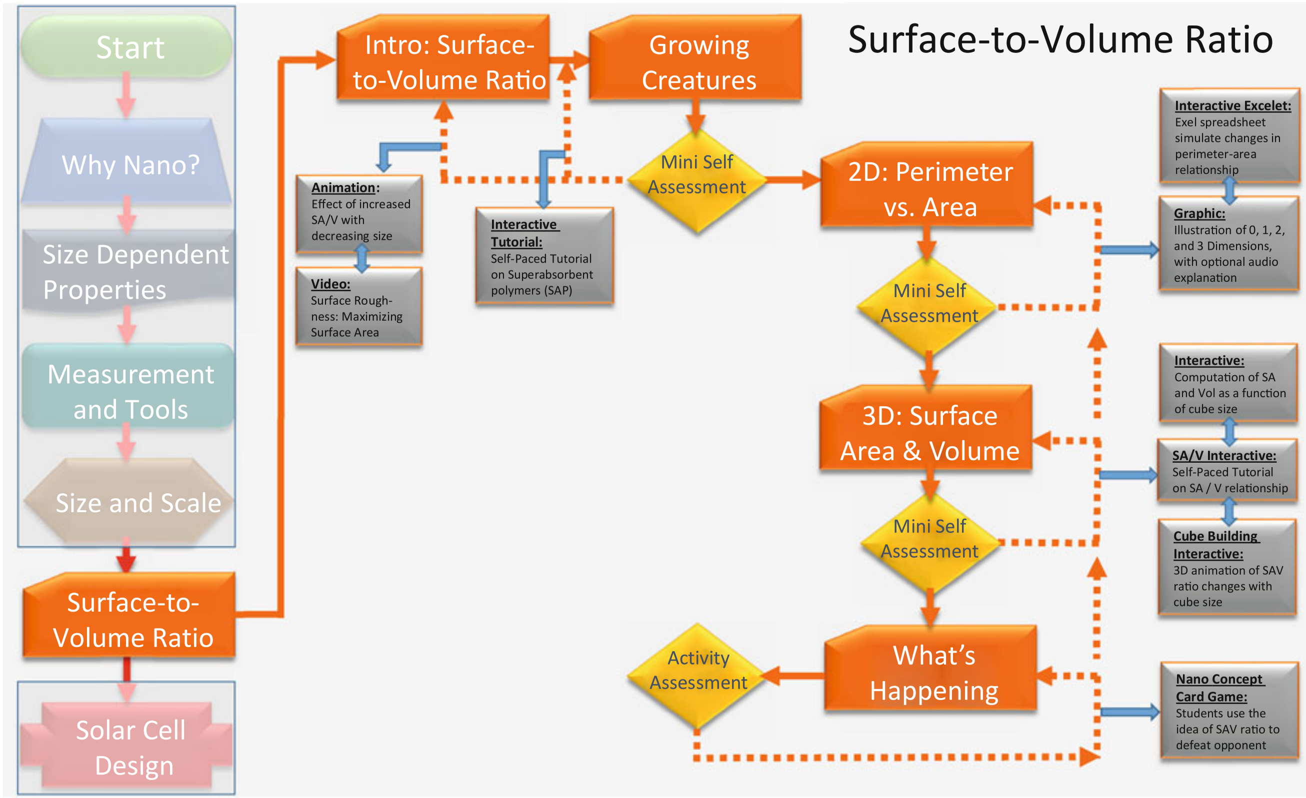

Fig. 10 Illustration of various immersive interactive tools embedded in the prototype i-MWM unit to support the study of SAV (© 2014 R.P.H. Chang and Matthew Hsu)

government-led policy directives are useful in defining certain goals, they are insufficient to bring about real change. The chapter "▶ Reconceptualization of Education" introduced the vision of convergence learning communities made up of members from different sectors – academic, industrial, government, citizen groups, and community organizations – who share a commitment to convergence learning and pool their knowledge, resources, and perspectives to produce a strong "collective impact" (Kania and Kramer 2011). *In this model, all stakeholders, especially parents, have a vested interest in ensuring that precollege education produces a qualified national workforce and a responsible, well- informed citizenry and each local community participates in education as an integral part of its own economic strategy. For this reason, this fourth construct in the framework drives the successful practice of the first three.*

MWM's Community-Based Approach

Since its inception in 1993, MWM has taken a community-driven approach to content development, teacher development, funding support and product dissemination, and continually built on this practice as the backbone for its success.

Content and Teacher Development

One of MWM's unique strategies has been to combine the development of its content with the development of knowledgeable lead teachers who can ensure its effective implementation.

An international study comparing the US curriculum to those of nations that are most successful in science education (Schmidt et al. 2005) found that the US science curriculum lacks curricular coherence, introducing a mile-long "laundry list" of topics without giving students the background knowledge needed to master them in depth or the interdisciplinary connections needed to understand their broader relevance. As a result of this haphazard approach, national data show that the majority of US students are unprepared to succeed in college-level STEM and that many of its best-qualified students in science and engineering come from abroad (National Science Board 2014).

MWM's goals in content and professional development have been to:

1. Bridge the knowledge gap between secondary and tertiary education by continuously transferring leading-edge research and technology applications from university laboratories into precollege classrooms
2. Improve curricular coherence by introducing fundamental concepts in precollege and link them to a variety of applications to prepare students for college-level STEM study

3. Work directly with its end users (teachers) to ensure an affordable, effective, and easy-to-use product that would be appealing for students and well aligned with existing course content, learning standards, and the constraints of the classroom
4. Organize workshops (online and face-to-face) to prepare teachers in the "inquiry and design" methodology

Reaching these goals required the establishment of a meaningful, long-term collaboration between precollege STEM teachers and university researchers. At the outset, materials scientists and engineers from Northwestern University met with local middle and high school STEM teachers to discover how to work with them to design a curriculum supplement based on academic research. A corps of MWM "lead teachers" worked jointly with Northwestern faculty and students to design modules that would meet their needs and those of their students. Eventually, this core partnership was expanded to include teachers and researchers from other disciplines (e.g., History, Social Studies, Art, and Language Arts). The content development teams identified age-appropriate language for explaining the research and underlying concepts to precollege students, created curriculum linkages, and designed hands-on activities that would be safe and feasible for classroom use.

In 2004, under the US National Nanotechnology Initiative, the NSF established the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) at Northwestern and charged it with inserting nanotechnology concepts into the formal US STEM curriculum in grades 6–16. Under the NNI-NCLT, MWM's content development teams were expanded to include nanotechnology researchers, cognitive scientists, assessment experts, teaching faculty, and students from a broader range of institutions including a national laboratory, community colleges, and several Historically Black Colleges and Universities. *Together, these partners identified the fundamental concepts underlying nanotechnology* (Stevens et al. 2009) *created coherent learning progressions to guide their insertion into each grade level, and then used these progressions to develop a series of MWM modules on nanotechnology topics.*

The two most important outcomes of MWM's community-based development approach have been:

Coherence across Disciplines: MWM offers outstanding connections to STEM and non-STEM courses alike including examples pertaining to art, history, archeology, architecture, and the natural world. The communication and writing components required input from the language arts, while teaching nanotechnology concepts required strong math connections including logarithm and exponents, ratios, dimension, and proportions.

Coherence across Grade Levels: MWM modules are "stretchable" from grades 6–12, depending on the amount of scaffolding a teacher wishes to provide. Fundamental concepts are presented coherently to systematically build mastery from one grade to the next, thereby preparing students for college level study. The result of this approach is a deeper, more flexible understanding of science and its "underlying simplicity" (Schmidt et al. 2011).

Simultaneous teacher development and endorsement: Teachers appreciated being involved in the content development process, being able to test the modules in their classrooms, and having their feedback used. They also appreciated the opportunity to work alongside university research faculty in a collegial manner, to learn about new research findings, and to be connected to laboratory research. This *community-building process* generated confidence in the modules and trained a corps of lead teachers with a deep mastery MWM's methodology who could educate and inform others.

Community-Based Adoption and Dissemination

Although teachers and students are quite enthusiastic about using MWM in the classroom, its formal adoption as an integral part of the STEM curriculum has taken longer to implement. However, with mounting pressure from other community stakeholders, it is anticipated that changes will become more expedient, especially given the shortage of native technical workers and the need to implement the NGSS, the Common Core State Standards, and the Framework for 21st Century Skills.

The first step has been to use MWM modules as the basis for new elective courses that resemble those taught in universities. Workshops demonstrating the use of MWM for integrated STEM teaching – a particular focus of the NGSS - have led school districts in Maryland, South Carolina, Florida, California, and other parts of the country to adopt MWM content and practices.

Local and regional corporate support has also played an important role. Companies have been funding the adoption of MWM by their local schools and encouraging company representatives to join community workshops and student events. With the successful example of new content adoption in one community, news has spread quickly to other communities.

Networking Among Communities and Regions

While local government and industry are critical to the economy of a specific locale, the federal government plays a vital role in linking communities and regions through national initiatives. Such efforts can benefit the entire country by leveraging local and regional support and homogenizing STEM education across the US. For example, in 2006, the Department of Defense established an MWM Outreach Center for teacher professional development and module dissemination. This investment leveraged prior federal investments in MWM's development - including the establishment of the NNI-NCLT in 2004. The Center had a major impact on national networking: MWM workshops have been help across the 50 states, benefitting thousands of teachers. Different states and regions have been able to share experience and best practices. This, in turn, has strengthened workforce development and paved the way for economic growth. With the rapid expansion of information technology, such networking efforts will prove essential to the future education paradigm in content development, content sharing, and teacher training in particular.

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