Chapter 8
Implications: People and Physical Infrastructure

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This chapter addresses two different issues: the complementary needs for an appropriately educated populace and for specific kinds of physical facilities to facilitate development of converging knowledge and technologies. Based on this dual focus, each of the major headings in this chapter has two sub-headings, one for education and one for physical infrastructure.

An "educated populace" must be further delineated to address the different educational needs as one grows older: (a) K–12, (b) community college/technical college (CC/TC) programs leading to associate degrees, (c) university/college programs leading to bachelor's and master's degrees, (d) research university programs leading to Ph.D. degrees, (e) informal education, and (f) continuing education. Since everyone should be in a position to make informed decisions on the benefits/risks of converging technologies, the K–12 and informal education efforts—efforts that potentially reach everyone—must confer that knowledge. Workers on the

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Table 8.1 University departments and their involvement in converging technologies

		Illustrative science departments				Illustrative engineering departments			
Converging tech.	Report chap.	Phys	Chem	Bio	Psych	ChE	EE	CSE	MSE
Nanotech		x	x	x		x	x	x	x
Biotech		x	x	x		x	x	x	x
Infotech		x	x	x	x	x	x	x	x
Adv Prosthetics	5	x	x	x	x	x	x	x	x
Cancer therapy	5	x	x	x	x	x	x	x	x
Cognition	6	x	x	x	x	x	x	x	x
Social networking	6				x		x	x	
Assistive robotics	7	x			x		x	x	x

Key: *Phys* Physics, *Chem* Chemistry, *Bio* Biological Sciences, *Psych* Psychology, *ChE* Chemical Engineering, *EE* Electrical Engineering, *CSE* Computer Science and Engineering, *MSE* Materials Science and Engineering

factory floor or in repair shops require specialized training beyond the traditional K–12 class work; CC/TC must address that need, as well as being a stepping-stone into bachelor's degree programs. At the bachelor's/master's degree level, a range of people such as engineers, business persons, politicians, and government regulators will need sufficient knowledge about converging technologies to expedite the transition of research discovery into innovative, socially benevolent products in the market. To ensure new ideas emanate from research discovery, it will be necessary to have Ph.D.s with sufficient breadth and flexibility to bridge the traditional disciplines. Finally, the growing pace in generating new knowledge and technical innovation will compel continuing education at all levels of the workforce.

The general theme of the NBIC2 workshop was converging technologies, i.e., convergence of knowledge from traditional academic science disciplines in order to engineer innovative technologies for the benefit of humanity. Table 8.1 itemizes some illustrative traditional academic disciplines (departments)—science focuses on the fundamental knowledge of natural things, whereas engineering focuses on the application of that fundamental knowledge. The rows show some selected technology goals that depend on the convergence of knowledge being developed in the disciplines (indicating, when pertinent, chapters in this book). The challenge for an educational system is to devise appropriate mechanisms such that the converging technology aspirations can be effectively and efficiently realized, in spite of any barriers imposed by the disciplinary silos (NRC 2012c; The Third Revolution 2011; Blackwell et al. 2009).

It should be noted that convergence is happening between the traditional disciplines. For instance, the subfields of "physical chemistry" in chemistry and "chemical physics" in physics highlight the fuzzy boundary between much of chemistry and physics. Much of modern biology—computational and molecular biology—draws heavily on mathematics, physics, chemistry, and computer science/engineering. It should also be noted that a converging technology can morph over time into an academic discipline of its own. Materials Science and Engineering began as a convergence of disciplinary topics in metallurgy, ceramics, chemistry (especially polymers), and physics. Starting in the 1960s, with Defense Advanced Research Projects Agency (DARPA) and the National Science Foundation (NSF) funding stimulus, it morphed into its own discipline, largely subsuming the older metallurgy and ceramics departments.[1] Computer Science and Engineering has a similar story; the progression from earlier mechanical inventions and mathematical theories towards the modern computational concepts and machines draws on contributions from physics, chemistry, mathematics, psychology, and several engineering disciplines.[2] The first Department of Computer Sciences in the United States was established in 1962. There are presently experiments at various universities to see if the continuing growth in nanoscale science and engineering (nanotechnology) might warrant a similar transition (Murday 2009).

8.1 Vision

8.1.1 Changes in the Vision Over the Past Decade

Education

Science, technology, engineering, and mathematics (STEM) education is now viewed as a key to the economic future of the United States (PCAST 2012a, b; Wladawsky-Berger 2012). While unemployment in the United States remained at ~8 % overall in 2012, jobs for skilled workers are going unfilled due to lack of qualified applicants (Engler 2012). That being said, we must also be attentive to changes in workforce needs so that an excess of any given skill set is not generated (Vastag 2012; ACS 2012; NIH 2012). The scope of the challenges mentioned in this chapter, and the potential cost to address them, is compelling partnerships among Federal/state/local governments, industry, and foundations (PCAST 2012a; NRC 2012c).

As one approach to remedy this situation, companies have recognized they must be more proactively involved to encourage STEM interests, influence the education system curricula, and project future employment needs (Schiavelli 2011). In 2010, Change the Equation was launched (http://changetheequation.org), a nonprofit that matches Federal and corporate funding to programs that promote science, technology, engineering, and math. State and foundation contributions to STEM programs are also growing (Holt et al. n.d.; http://stemgrants.com/).

The U.S. predominance in science and engineering (S&E) research is being challenged by dramatic improvements in other nations' programs (NRC 2012c). It is recognized that this will require attention to (a) the education of a native STEM workforce, (b) retention of those highly trained non-native students graduating from

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[1] http://en.wikipedia.org/wiki/Materials_science

[2] http://en.wikipedia.org/wiki/History_of_computer_science

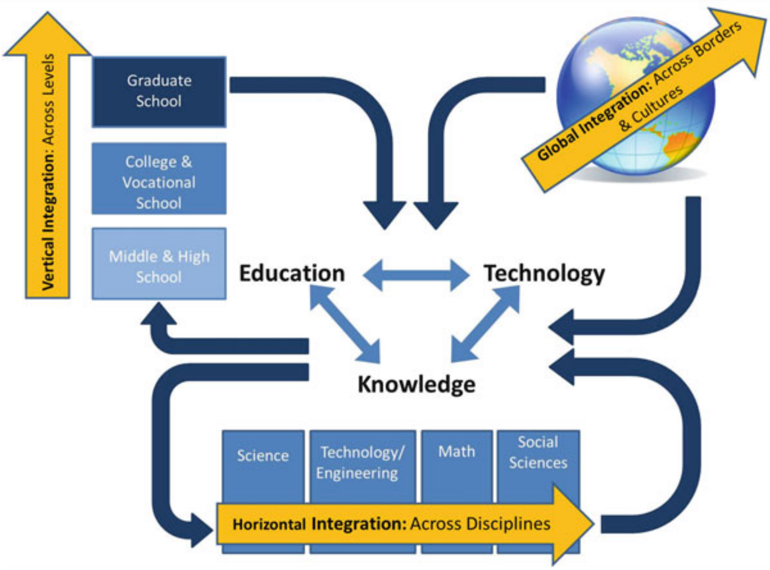

Fig. 8.1 Schematic highlighting the axes of integration required for maximal success in the convergence of technology and knowledge to further education (Courtesy of Robert Chang)

our universities, and (c) improved mechanisms to be aware of, and collaborate with, efforts in other nations.

Today the world is facing unprecedented global challenges that will take more than one country or region to solve. With population growth comes the need for more of the world's diminishing resources, which include energy, food, water, minerals, and many more. In addition, with large-scale transportation and growth in construction and industry, the environment and human health are under stress. Technology is helping, but it alone will not be able to solve these big problems. It will take the collective participation of all citizens to deliver the solutions. Everyone needs to have a big picture of the world and what is needed to build a sustainable future. This is where a cross-disciplinary approach is needed. An integrated education platform that includes STEM subjects and the social sciences is needed to teach and train the connectedness of STEM and society (see Fig. 8.1 and Case Study 8.8.1 that elaborate on this challenge and the approaches taken by several countries to address it). Both formal and informal education are needed in this regard.

Over the past decade, frontier scientific movements have occurred at the intersections of traditional disciplines, and that trend will certainly continue over the next decade. As an example from the National Nanotechnology Initiative (NNI), the National Cancer Institute-funded Cancer Centers for Nanotechnology Excellence (CCNEs) and the Physical Sciences Oncology Cancer Centers (PSOCs) have brought physical scientists and engineers into medical schools at an unprecedented level. Other programs also have played significant roles, for instance, the human genome project has brought together engineering, computer science, mathematics, biology, and social science. In another example, the convergence in the sciences and technologies over the last several decades has brought the social sciences to the brink of a transition from a phenomenological basis into disciplines based on chemical/physical laws underlying brain function, i.e., cognition.

Both educational deficiencies at the K–12 levels and the skyrocketing cost of university/college degrees (*push*), coupled with the revolutionary advances in digital information (*pull*), compel the introduction of new approaches to education (NSF 2011, 2007; Oblinger 2012; Molebash 1998; see also Chaps. 2 and 4 and Case Study 8.8.3). If the cost of digital capabilities can be lowered sufficiently, one can even entertain the possibility for personalized education (Evans 2012). It will be necessary for education, cognition, information technology, and subject matter experts to work together toward the most effective implementation of information technology in education. Further, one might argue that the communications skills traditionally embodied in reading and writing must now be supplemented by the development of digital communication skills, especially in post-secondary education (Adobe Education 2011).

K–12. There has been concern over the state of the U.S. K–12 education system for decades (NRC 2007a; NSB 2007; The Opportunity Equation 2009), including its lack of any instruction in engineering (NRC 2009). The importance of improvement in U.S. STEM education has been highlighted by an additional three recent reports (NRC 2007b; NSB 2010; PCAST 2010). A recent study, *Successful K–12 STEM Education*: *Identifying Effective Approaches*, focuses on means to achieve successful K–12 STEM outcomes (NRC 2011).

In the last decade the National Governor's Association has initiated a vision of common core standards for K–12, which seeks to identify up-to-date standards that can be adopted by all (or most) of the states. Given a mobile society, this vision is long overdue (Schmidt and McKnight 2012); students moving from one location to another should find essentially the same expectations. Common core K–12 standards for Mathematics and English Language Arts have been established (http://www.corestandards.org/). The present state science standards have been given a collective grade of "C" (Lerner et al. 2012). Common core standards for science, named Next Generation Science Standards (NGSS), are under development and are to be integrated, be progressive, and incorporate engineering and technology (http://nextgenscience.org/next-generation-science-standards/).

Community and Technical Colleges. The importance of community colleges/technical colleges as an approach toward a skilled workforce has been recognized (NRC 2012b). Manufacturing jobs requiring no more than a secondary education are declining at a rapid pace. Workers on the factory floor or in repair shops require specialized training beyond the traditional K–12 class work; CC/TC must address that need, as well as provide a stepping-stone into bachelor's degree programs. The CC/TC level of education is considered the "sweet spot" for reducing the skills gap in manufacturing; increased investment in this sector is recommended, following the best practices of leading innovators (NSTC 2012). In rapidly evolving, converging science/technology areas, community colleges/technical colleges will need faculty training, technical support, and access to advanced laboratory facilities to fully perform their critical role in today's education needs.

Colleges and Universities. There is growing recognition that the traditional academic departments at universities and colleges are: (a) losing too many students, (b) restrictive in their subject matter, (c) discouraging interdisciplinary collaboration, (d) not providing adequate knowledge about the skill sets required for innovation, and (e) not making effective use of the evolving information technologies (NRC 2002; Board on Science Education 2012; Young 2012). There are other indicators that the role of digital technology in education has also become more paramount (Center for Digital Education, http://www.centerdigitaled.com/; Oblinger 2012; Sacramento Bee 2012). Surveys of employers reveal that what they prize most in future managers are excellence in written and spoken communication, critical and creative thinking, an ability to collaborate across distances and cultural differences, breadth of knowledge and experience that takes students out of localism and provincialism, basic technical skills, quantitative literacy, and an ability to be flexible and take risks in changing environments (Davidson n.d.). In addition to breaking down barriers in the sciences/engineering disciplines, it's time to transform the focus, mission, and rhetoric of liberal arts by infusing a focus on cross-disciplinary critical thinking with real-world technological approaches to problem solving.

Research Universities. While acknowledged as among the best in the world, the U.S. research universities are facing serious challenges: (a) Federal/state funding for research has been unstable and is unlikely to grow significantly in the short term; (b) business and industry has not yet fully partnered to effectively translate, disseminate, and transfer into markets the new knowledge and ideas that emerge from research; and (c) cost efficiency must be improved (NRC 2012c).

Recent trends have led to increasingly blurred boundaries between academia and industry, including the demise of basic research in industrial laboratories and the subsequent reliance on universities for the new ideas that might transition into innovative technologies. NSF and other agencies have long encouraged academic–industrial collaborations, but the basic nature of those collaborations has changed over the past decade. For example, 15–20 years ago a typical university–industrial project might have been a collaboration between scientists from a large industrial lab (e.g., GE, IBM, or DuPont) and a university group to work on a project that, by its nature, would have been considered precompetitive. Thus, intellectual property issues and conflicts of interest were easily identified and resolved. Today, a typical collaboration is likely to be between a small startup company and the lab of the faculty member who started that company, perhaps fueled by Small Business Innovation and Technology Transfer Research (SBIR/STTR) resources, or perhaps fueled by the fact that the faculty member sees the company as an extension of his or her lab. This is a huge difference. The IBMs of the world didn't rely upon their university collaborators for success in the marketplace, but small startup companies often need the leverage provided through an academic partnership for both short-term survival and long-term success.

These trends are likely to accelerate over the next decade. How a given university positions itself within this changing world may end up making the difference in the types of science it supports, the faculty members it can recruit and retain, and the economic impact that the university has on its surrounding community.

Informal Education. Ten years ago, informal education was not explicitly in the vision for converging nano-, bio-, info-, cognitive (NBIC) and other technologies, nor were converging technologies explicitly in the vision for informal education. The subject of nanotechnology alone was just beginning to be on the radar screen for informal education, with several television and radio media projects including nanotechnology in their programming and a very small number of science museums either planning exhibits related to nanotechnology and/or doing live presentations on the topic (Flagg 2005).

In 2009, the National Research Council (NRC) published its report *Learning Science in Informal Environments*: *People*, *Places*, *and Pursuits* (Bell et al. 2009). The report identifies six strands of science learning that encompass a broad, interrelated network of knowledge and capabilities that learners can develop in these environments.

- *Strand 1*: Experience excitement, interest, and motivation to learn about phenomena in the natural and physical world
- *Strand 2*: 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 processes of learning about phenomena
- *Strand 5*: Participate in scientific activities and learning practices with others, using scientific language and tools
- *Strand 6*: Think about themselves as science learners and develop an identity as someone who knows about, uses, and sometimes contributes to science

The strands are distinct from, but necessarily overlap with, the science-specific knowledge, skills, attitudes, and dispositions that can be developed in schools. The strands are of special value in informal learning environments. The NRC report has helped the informal science education community to understand better the kinds of educational goals and impacts it should work toward in science learning. While much of this knowledge existed in the field prior to the report, it had not been pulled together into a coherent vision.

The Center for the Advancement of Informal Science Education (CAISE; http://caise.insci.org/) published its first inquiry group report early in 2009, *Many Experts*, *Many Audiences*: *Public Engagement with Science*, which focuses on the emergence of public engagement with science (PES) within the informal science education (ISE) field (McCallie et al. 2009). While the field uses the term “public engagement” quite broadly, the CAISE report focuses specifically on a paradigm for communication between scientists and the public that has developed in the science communication and public policy domains.

Over the past decade, many in the science communication and public policy arenas have argued that engaging the public in two-way dialogues about science-related public policy issues, in a way that allows scientists to learn from the public as well as the public to learn from the scientists, is a good strategy for strengthening communication and mutual support (McCallie et al. 2009; Leshner 2003; Yankelovich 2003). Today, public engagement with science in informal educational settings and as a formal component of policymaking is more prominent in Europe than in the United States. The approach gained momentum there as public opposition to genetically modified organisms and alarm at the BSE (mad cow disease) epidemic swelled in the late 1990s. Pointing to these public controversies about risk, scholars of "post-normal science" argue that the traditional decision-making model that relies on communicating the findings of scientific and technical research to receptive policymakers is inadequate in cases where "facts are uncertain, values in dispute, stakes high, and decisions urgent" (Turnpenny et al. 2011). These scholars assert that lively public engagement with science and technology across society is a strategy for managing long-term risks and realizing the benefits of new discoveries and technologies.

This "social technology," science and technology decision-making through public engagement focuses on quality as it stresses substance, process, and deliberation, as well as analysis (Jasanoff 2003). This approach introduces a "new organizing principle"—quality, rather than truth, as the value of scientific knowledge applied to problems in society (Luks 1999). Scholars in the United States have taken up and extended methodologies for post-normal science in the context of emerging technologies. David Guston at Arizona State University's Center for Nanotechnology in Society discusses the need for *anticipatory governance* (Barben et al. 2008, 992–993):

> … [It] comprises 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. Anticipatory governance evokes a distributed capacity for learning and interaction stimulated into present action by reflection on imagined present and future sociotechnical outcomes.

Public engagement with science as it has emerged in the field of ISE encompasses a range of activities and techniques that can help to address this need. Training science museum educators for dialogue and discussion rather than for making presentations is a current joint project of the Nanoscale Informal Science Education Network (NISE Net) and the Center for Nanotechnology in Society (CNS). This work is presenting a new vision for informal science education.

Newspapers and magazines retain high prestige among scientists, educators, and the general public, but now is a difficult time to use traditional print media to increase public awareness of converging technologies. Science journalism positions are being cut from newspaper and magazine staffs across the nation. The growing influence of social networking sites such as YouTube, Second Life, MySpace, and Facebook provide new opportunities to replace and/or supplement traditional media.

Continuing Education. Longer careers enabled by extended life spans and unfilled STEM-related jobs in a period of high unemployment are directing attention to continuing education as a retraining mechanism, including for military veterans

(Wetzel 2009). In 2012 at the University of Southern California, 4,800 graduate students were enrolled in accredited online master's degree programs spanning nine USC schools. Total annual revenues for online USC professional, graduate, and continuing education programs were expected to reach $114 million in 2012 (Balassone 2012).

Physical Infrastructure

With the proliferation of digital sensing and the subsequent growth in digital data has come the opportunity to use the revolutionary advances in information technologies in new and more effective ways (Atkins et al. 2003; NSF Cyberinfrastructure Council 2007), including the concept of networked science/citizen science (Wikipedia: *Reinventing Discovery*: *The New Era of Networked Science* (Nielsen 2011a); Cook 2011; CAISE 2012).

The success of the various user facilities hosted by NSF,[3] the Department of Energy (DOE),[4] and the National Institute of Standards and Technology (NIST),[5] along with the new national focus on advanced manufacturing, has led to efforts toward advanced manufacturing user facilities.[6] NSF is also introducing the National Ecological Observatory Network, the Ocean Observatory Initiative, and the Earth Cube Initiative.

8.1.2 The Vision for the Next Decade

A vision for converging technology education in the coming decade is building out the nation's human and technical infrastructure to better enable the rapid, effective creation and manufacturing of innovative, converging-technology-enabled products and processes that can address our shared social needs. To realize this vision it will be necessary:

1. For our education system to provide
    - Personalized education, customized to an individual's learning style, enabled by effective use of nanoscale information technologies, and informed by new cognition insights
    - The convergence of information technologies, coupled with deeper understanding of cognition, leading to highly effective, widespread, web-based education aids

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[3] Various centers and networks, such as the Nanoscale Science and Engineering Centers (NSEC), the National Nanotechnology Infrastructure Network (NNIN), and the Network for Computational Nanotechnology (NCN).

[4] NanoCenters at Argonne, Brookhaven, Berkeley, Sandia, and Oak Ridge National Labs.

[5] Center for Nanoscale Science and Technology (CNST) at NIST Gaithersburg.

[6] For example, manufacturers can find user facilities and assistance at the websites http://www.nist.gov/mep/ and http://www.ornl.gov/user-facilities/mdf).

- A distributed converging knowledge and technology network with a multidomain database, education modules, and facilities, including regional centers capable of leading efforts to enable/foster converging technology education
- New science, engineering, and technology knowledge incorporated more quickly into the standards/curriculum for K–20
- A working sustainable partnership structure within and between universities (including facilities, equipment, and expertise) and community/technical colleges to enable effective and efficient delivery of a broad education in converging technology areas
- A skilled workforce for converging-technology-enabled jobs with specific attention to the roles for community colleges and technical colleges
- Foundational courses in the college freshman year for non-science/engineering students that introduce the broader concepts of science and technology, including the expected impacts of converging knowledge and technologies
- Joint curricula developed by education colleges and science departments working in tandem and tied to a system of outcome metrics
- Restructuring of colleges away from traditional disciplines towards transdisciplinary approaches to the solution of societal needs, allowing focus on apprenticeship/mentoring in interactive workspaces while retaining rigorous student skill sets
- Awareness and understanding of societal implications of research in areas of converging technologies, and enhancement of science communication skills, both as key components of formal training for science and engineering graduate and undergraduate students
- Industrial participation in determining the graduate/undergraduate education experience to better prepare students for workforce needs
- Shift of graduate education programs from traditional departments into interdisciplinary programs, administered centrally with cross-departmental chairing of committees; removal of institutional barriers to interdisciplinary research
- Students given exposure to business and information technology (IT) best practices, in environments that encourage entrepreneurship
- Science museums and other venues of informal education interested in and capable of engaging public audiences in the areas and developments of current research, including converging technologies
- Convergence between physical/engineering sciences, the social/political sciences, and the science of science communication, leading to more effective public outreach and engagement efforts in informal learning environments

2. For our physical facilities to provide

- An infrastructure that enables rapid access to converging technology fabrication facilities (“advanced machine shops”) implemented at research universities, with distributed special user facilities for the most expensive items
- Expanded geographically distributed user facilities such as the National Nanotechnology Infrastructure Network (NNIN) and Network for Computational Nanoscience (NCN) but focused more broadly on converging technologies

- Advanced manufacturing facilities with the diverse capabilities necessary to accelerate transition of converging technologies into products
- Utilization of distance technology to give teachers and, more importantly, students direct access to, and control of, expensive university-based instrumentation within K–14 classrooms

3. For the social sciences to be more fully integrated with physical and information sciences, and to be based more on fundamental laws rather than phenomenological observation.

8.2 Advances in the Last Decade and Current Status

The social sciences today are roughly where the biology and geology disciplines were 50 years ago, on the cusp of becoming sciences based on fundamental chemical/physical laws rather than phenomenological observations. The social sciences are now largely based on statistical inferences based on human behaviors but are beginning to migrate toward statistical inferences based on understanding cognition/emotion processes in the brain. The increasing availability of large digital data sets and computational analysis (i.e., data analytics) is helping to accelerate this progress, as it already has in areas such as climate and land-use in geography and some sub-fields of economics.

8.2.1 Education

Numerous examples illustrate the introduction in the last decade of new educational materials addressing the remarkable advances in individual converging technologies, especially those represented by the nano-, bio-, and info- topics. There are fewer examples that address the boundaries between any two converging knowledge/technology areas (see Fig. 8.2).

The cost of public elementary, secondary, and college education in the United States is high—estimated at ~$900 billion for the 2004–2005 school year (DOD 2005). Figure 8.3 illustrates the relative funding provided by state, local, and Federal sources for K–12 in 2009.

The U.S. Department of Education has about $70 billion annually to support education (not including loan programs). But recent documents show only ~$3 billion across the entire Federal government is devoted to STEM education (OSTP 2012a, b). Foundations provide additional support for education of about $2–3 billion, with examples in Table 8.2; some of that funding addresses STEM education. Industry also provides some monies for STEM education. A challenge is to make the most effective use of the limited STEM development funds, which are distributed across diverse sources. Open Education Resources (OER) and other digital education aides are viewed as a key mechanism to bring down the cost of education (Wiley et al. 2012).

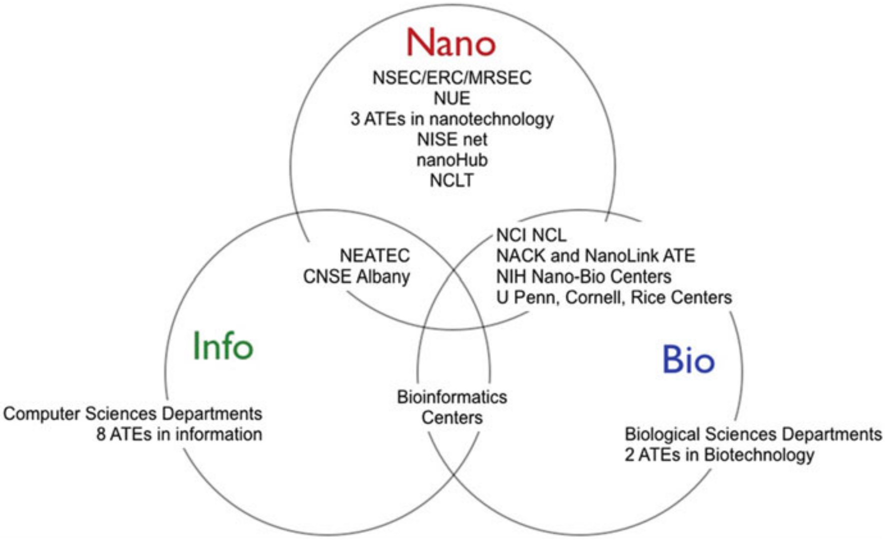

Fig. 8.2 Venn diagram illustrating education infrastructure components added in the last decade that address nano-, bio-, and info- needs, and those that provide capabilities at the intersections (Courtesy of James Murday)
Key: *NSEC* Nanoscale Science and Engineering Center, *ERC* Engineering Research Center, *MRSEC* Materials Research Science & Engineering Research Center, *NUE* Nanotechnology Undergraduate Education, *NCLT* National Center for Teaching and Learning, *NEATEC* Northeast Advanced Technological Education Center, *CNSE* College of Nanoscale Science and Engineering, *NCI* National Cancer Inst., *NCL* Nanotechnology Characterization Lab, *NACK* Nanotechnology Applications and Career Knowledge network, *ATE* Advanced Technology Education centers

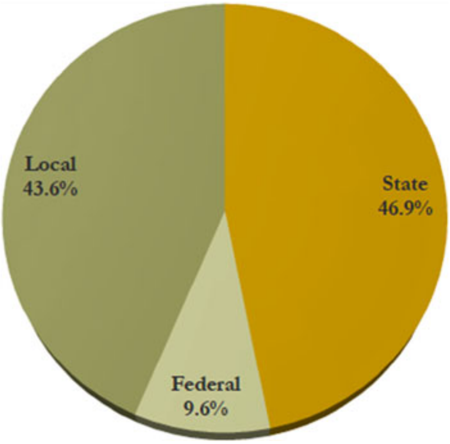

Fig. 8.3 Revenue sources for public-supported K–12 education in 2009, $590 billion total (Gai and Dadayan 2012; http://www.rockinst.org/government_finance/; ©Nelson A. Rockefeller Institute of Government, used by permission)

Table 8.2 Examples of foundation grants for education circa 2010

Foundation	Total awarded ($M)	No. of grants
Bill & Melinda Gates	357	314
Walton Family	223	289
W.K. Kellogg	137	101
Silicon Valley Community	80	630
Andrew W. Mellon	72	174
Michael and Susan Dell	63	191
Carnegie Corp. of NY	58	76
Ford	49	127
William and Flora Hewlett	49	116
Susan Thompson Buffett	47	103
Starr	45	84

Source: The Foundation Center (2012)

K–12

In 2010 the National Academy of Sciences released a report *A Framework for K–12 Science Education*: *Practices*, *Crosscutting Concepts*, *and Core Ideas* that identifies the key scientific ideas and practices all students should learn by the end of high school (NRC 2012a). This document provides the basis for the Next Generation Science Standards (NGSS)[7] that is currently under development by Achieve, Inc. The NGSSs are distinct from prior science standards in that they integrate three dimensions (Science and Engineering Practices, Disciplinary Core Ideas, and Crosscutting Concepts) within each standard and have intentional connections across standards.

In the last decade, NSF funded about a dozen projects that focused on nanotechnology education for K–12 and public audiences. These included K–12 formal education projects like *NanoTeach*: *Professional Development in Nanoscale Science* (DRL award #0822128), *Nanosense*: *The Basic Sense Behind NanoScience* (DRL award #0426319), *Probing the Nanoworld* (DRL award #0426401), and *NCTL*: *A Center to Develop Nanoscale Science and Engineering Educators with Leadership Capabilities* (DRL award #0426328). The projects in this portfolio of awards created innovative educational resources that were used and yielded evidence of learning in their target audiences of more than 10,000 students and teachers, but there is limited evidence of impact beyond those who directly accessed the resources produced by these projects (Nielsen 2011b).

With the growing cost of printed textbooks, there is now experimentation with electronic media to supplement or replace traditional textbooks.[8, 9] There are

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[7] http://www.nextgenscience.org/next-generation-science-standards/

[8] http://www.ck12.org/flexbook/

[9] http://theeducationcafe.wordpress.com/2010/02/03/online-textbooks-for-middle-school-and-high-school/

programs that are fully adaptive and data-driven, such as Pearson's SuccessMaker for K–8 reading and math.[10] In January 2012, Pearson, McGraw-Hill Education, and Houghton Mifflin Harcourt announced partnerships with Apple to produce exclusive content through the new iBooks 2 platform.

The digital format has an advantage for the topic of converging technologies in that changes to paper textbooks requires more than a decade, but e-books can be updated at lower cost and can be made available far more quickly. To assist teachers, there is software that focuses on unifying public cloud, private cloud, and local device applications into a single, secure solution.[11]

New information-technology-based instruction is being introduced beyond e-books. There are experiments with a "flipped classroom" whereby information technology is used to present content (lectures) at home and the classroom is used to do problem-solving activities with the teacher as personal coach rather than lecturer.[12] The National STEM Video Game Challenge is a multi-year competition whose goal is to motivate interest in STEM learning among America's youth by tapping into students' natural passion for playing and making video games.[13] The World Wide Workshop has developed a game design curriculum being used in five states.[14] There are fully accredited online private schools.[15] (See also Chap. 4.)

Community and Technical Colleges

NSF has funded a number of Advanced Technology Education Centers (http://atecenters.org/) addressing nano-, bio-, info- and advanced manufacturing technologies (see Table 8.3). The Nanotechnology Applications and Career Knowledge network (NACK Network; see the case study in Sect. 8.8.2, which illustrates how convergence at the nanoscale is being addressed in education) and the Midwest Regional Center for Nanotechnology Education (Nano-Link), emphasize the importance of teaching the cross-disciplinary aspects of nanoscience and nanotechnology. For example, the NACK courses available for free downloading at http://www.nano4me.org stress the converging knowledge/technology reality of today's world and are designed for students coming from very diverse science and technology disciplines (including biology, biotechnology, chemical technology, manufacturing/industrial technology, physics, chemistry, electronics, etc.). The approach is to add a nanotechnology skill set to students' educational backgrounds, no matter what

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[10] http://www.forbes.com/sites/jamesmarshallcrotty/2012/08/21/the-tech-driven-classroom-is-here-but-grades-are-mixed/

[11] For example, see https://customer.stone-ware.com/site/solutions/education/index.html, and https://getclever.com/about/

[12] htpps://sites.google.com/a/cloud.stillwater.k12.mn.us/flipped-classroom/about

[13] http://www.stemchallenge.org/about/Default.aspx

[14] http://www.worldwideworkshop.org/

[15] Examples include K12 International Academy, http://www.k12.com/int, and CalPac http://calpacschools.rtrk.com/?scid=2506134&kw=12030127&pub_cr_id=8435962594

Table 8.3 NSF-funded advanced technology centers addressing NBIC topics

Program name	Institution	Location
Nano		
Maricopa Advanced Technology Education Center	Maricopa Community Colleges	Phoenix, AZ
Northeast Advanced Technological Education Center	Hudson Valley Community College	Troy, NY
Midwest Regional Center for Nanotechnology Education (Nano-Link)	Dakota County Technical College	Rosemount, MN
Nanotechnology Applications and Career Knowledge (NACK)	Pennsylvania State University	University Park, PA
Bio		
Bio-Link National Center	City College of San Francisco	San Francisco, CA
Northeast Biomanufacturing Center and Collaborative	Montgomery County Community College	Blue Bell, PA
Info		
Boston Area Advanced Technological Education Connections	University of Massachusetts	Boston, MA
Cyber Security Education Consortium	University of Tulsa	Tulsa, OK
Center for Systems Security and Information Assurance	Moraine Valley Community College	Palos Hill, IL
Convergence Technology Center	Collin College	Frisco, TX
Creating the Next Generation of Cybersecurity Professionals	Prince George's Community College	Largo, MD
Information and Communications Technologies Center	Springfield Technical Community College	Springfield, MA
Mid-Pacific ICT Center	City College of San Francisco	San Francisco, CA
Advanced Manufacturing		
Florida Advanced Technological Education Center	Hillsborough Community College	Tampa, FL
National Center for Manufacturing Education	Sinclair Community College	Dayton, OH
National Center for Rapid Technologies	Saddleback College	Mission Viejo, CA
Regional Center for Next-Generation Manufacturing	CT Community Colleges' College of Technology	Hartford, CT
Technology and Innovation in Manufacturing and Engineering	Community College of Baltimore County	Baltimore, MD

field they come from. The students acquire, for their educational toolboxes, the ability to understand nanoscale concepts and to use them in other knowledge areas, as well as acquire invaluable "hands-on" ability to work at the nanoscale.

Colleges and Universities

The traditional lecture format is outdated and unscalable; there is need for standardized online delivery platforms. A growing number of experiments in the utilization of digital information technologies in college education (Brooks 2012; Sitzmann et al. 2006; Katsouleas 2012) includes web-based scaled-up courses offered by edX (Harvard, Massachusetts Institute of Technology, University of California–Berkeley, and University of Texas; https://www.edx.org/), Coursera (http://coursera.org), nanoHUB (http://nanohub.org/resources/), and the Kahn academy (http://khanacademy.org). To make the web-based approaches most effective, the nanoscale will be essential for information technology miniaturization and affordability, while cognitive studies will provide insight into the best way to implement the new technologies. Case study 8.8.3 provides some interesting ideas regarding the potential implications of e-learning for universities.

In 2004 the University of Albany, State University of New York (SUNY), created a College of Nanoscale Science and Engineering, an aggressive experiment in university nanoscale education with BS, MS, and Ph.D. degree programs. By leveraging its resources in partnership with business and government, CNSE supports accelerated high-technology education and commercialization and seeks to create jobs and economic growth for nanotechnology-related industries. (See the CNSE Case Study in Sect. 8.8.4.)

Engendered in part by converging technologies, there is growing experimentation in the engineering curricula to address the different demands on engineering graduates in the modern marketplace. For instance in 2010, select departments in the MIT School of Engineering launched a degree option that responds to the evolving desires of undergraduate students and to emerging changes in the engineering professions. Students satisfy department-based core requirements and declare an additional concentration, which can be broad and interdisciplinary in nature (energy, transportation, or the environment), or focused on areas that can be applied to multiple fields such as robotics and controls, computational engineering, or engineering management (http://engineering.mit.edu/education/engineeringdegree.php). Another example is the Franklin W. Olin College of Engineering in Needham, MA (http://www.olin.edu/), initiated in 2002, that has no academic departments and a commitment at all levels to active learning and interdisciplinary courses built around hands-on projects.

Research Universities

As a partnership paradigm, in 2005 the Semiconductor Industries Association (SIA) entered into a partnership with NSF and NIST in the Nanoelectronics Research Initiative (NRI; http://www.src.org/program/nri/). Industry monies funded four university centers: Southwest Academy for Nanoelectronics led by University of Texas–Austin, Institute for Nanoelectronics Discovery and Exploration led by University at Albany, Midwest Institute for Nanoelectronics Discovery led by Notre Dame, and Western Institute for Nanoelectronics led by University of California–Los Angeles. The Semiconductor Research Corporation (SRC) has also teamed up with NSF to fund research projects at existing NSF nanoscience centers and networks at universities across the country. In addition, there are six center research programs (STARnet, which supercedes the older Focused Center Research Program) jointly funded by SRC, industry, and DARPA. (See the SRC case study, Sect. 10.8.3 in Chap. 10.) Another partnership paradigm, reflecting medicine/health, is presented in Case Study 8.8.5.

NSF has implemented a variety of programs to encourage the development of new approaches to converging technology (e.g., solicitations 12-549 Computationally & Data Enabled Science & Engineering; 12-509 Science, Technology and Society; and 12-515 Advanced Health Services through System Modeling as recent examples), and other programs to foster innovation (e.g., solicitations 12-586, Innovation Corps–Regional Node Program, and 12-012, Creative Research Awards for Transformative Interdisciplinary Ventures [CREATIV]).

Informal Education

In 2005 with NSF funding, the Museum of Science in Boston, in partnership with the Exploratorium in San Francisco and the Science Museum of Minnesota in St. Paul, assembled a group of museums and nanoscale research centers to establish NISE Net (http://www.nisenet.org/). The focus of NISE Net's work has been to build the capacity of science museums and research centers to raise public awareness, understanding, and engagement with nanoscale science, engineering, and technology. (See the NISE Net Case Study, Sect. 8.8.6.) However, over the last 10 years there have been few advances in informal education and public engagement explicitly addressing converging technologies and their potential impacts, except for the work that has been done in connection specifically with nanotechnology.

In the last decade NSF funded several projects that focused on nanotechnology education for public audiences, including media projects like Earth and Sky's *Nanoscale Science and Engineering Radio Shows* (DRL award #0426417), Oregon Public Television's *Nanotechnology*: *The Convergence of Science and Society* (DRL award # 0452371), and Twin Cities Public Television's *Dragonfly TV GPS*: *Investigating the Nanoworld* (DRL award #0741749); exhibit projects like Cornell's *Too Small to See* (DRL award #0426378), Sciencenter's *It's a Nano World* (ECCS award #9876771), and the Materials Research Society's *Strange Matter* (DRL award #0000586); and NISE Net (DRL awards #0532536 and #0940143).

The Centers for Nanotechnology in Society (CNS) at Arizona State University (http://cns.asu.edu/) and at the University of California at Santa Barbara (http://cns.ucsb.edu/) have provided research on public perceptions of nanotechnology and ideas about the implementation of anticipatory governance. These organizations and the NISE Net have explored, both independently and collaboratively, how formal and informal education might include content related to the societal implications of emerging technologies. In 2009, a newly formed Society for the Study of Nanoscience and Emerging Technologies (http://www.thesnet.net/Welcome.html), dedicated to open intellectual exchange that is aimed at the advancement of knowledge and understanding of nanotechnologies in society, held its first professional conference in Seattle and has alternated between European and U.S. conference sites annually.

The Center for Nanotechnology in Society at Arizona State University and its collaborators at North Carolina State University conducted the nation's first National Citizens' Technology Forum on the topic of nanotechnology and human enhancement in 2008. Groups of citizens at six sites across the United States expressed concerns about the effectiveness of regulations, equitable distribution, and monitoring; expressed greater preference for therapeutic over enhancement research; and identified the need to provide public information, including more public deliberative activities and K–12 education, about nanotechnologies (Hamlett et al. 2008).

The same group also conducted a national survey about nanotechnology and human enhancement. The data showed that the public differentiates between different applications of converging technologies, giving strong support for some and opposing others (Hays et al. 2013).

Collaborations between informal science educators and researchers in science communication and the social and political sciences have led to growing capacities for public engagement on topics of societal and ethical implications of emerging technologies (Bell 2008; Bell et al. 2009; Reich et al. 2006, 2007; McCallie et al. 2009; Flagg and Knight-Williams 2008). Collaborations between CNS social and political scientists and NISE Net educators have led to the development of a series of professional development workshops aimed at helping informal educators incorporate dialogue about the societal and ethical implications of nanotechnologies into their ongoing program activities.

Another collaboration between CNS social and political scientists, NISE Net educators, and others concerned with science, technology, and public policy has led to the establishment of the ECAST Network (Expert and Citizen Assessment of Science and Technology; http://ecastnetwork.org/). While ECAST's mission is fundamentally a governance mission "to support better-informed governmental and societal decisions on complex issues involving science and technology," one of its methodologies involves broad public engagement aimed at helping the public learn about new technologies and their societal and ethical implications.

While the developments described here are not specifically about converging technologies, they describe newly developed capacities, structures, and convergence within academic and informal educational institutions that can be valuable contributors to informal education and public engagement about converging technologies in the decade ahead.

Research in science communication is another discipline that could support better public outreach and engagement. On May 21–22, 2012, the National Academies of Science held a colloquium on the Science of Science Communication.[16] The meeting surveyed the state of the art of empirical social science research in science communication and focused on research in psychology, decision science, mass communication, risk communication, health communication, political science,

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[16] http://www.nasonline.org/programs/sackler-colloquia/completed_colloquia/science-communication.html

sociology, and related fields on the communication dynamics surrounding issues in science, engineering, technology, and medicine. There were five distinct goals:

- To improve understanding of relations between the scientific community and the public
- To assess the scientific basis for effective communication about science
- To strengthen ties among and between communication scientists
- To promote greater integration of the disciplines and approaches pertaining to effective communication
- To foster an institutional commitment to evidence-based communication science

Speakers at the colloquium said that research suggests that scientists are highly trusted by the public) and that credibility is bestowed by the audience and is based on perceived common interest and perceived relative expertise. Despite a science goal of objectivity, personal ideologies also affect scientists' decisions and attitudes, but these may not be immediately visible to the public. Furthermore, psychological research suggests that we make decisions using one system of the mind and explain them using another. This suggests that our explanations may not be effective in influencing the decisions of others, especially if personal ideologies differ.

One intriguing and confounding idea in science communication comes from the work of the Cultural Cognition Project at the Yale Law School. One of its researchers in cultural cognition, Dan Kahan, says that it "causes people to interpret new evidence in a biased way that reinforces their predispositions. As a result, groups with opposing values often become more polarized, not less, when exposed to scientifically sound information" (Kahan 2010, 296). This leads him to conclude that, "we need to learn more about how to present information in forms that are agreeable to culturally diverse groups, and how to structure debate so that it avoids cultural polarization" (Kahan 2010, 297).

Public engagement efforts about converging technologies could benefit from designs that are grounded in this evidence-based communication science. They would also benefit from science communication training for science communicators and scientists. Collaborations between informal science educators and nanoscale research centers and professional scientist organizations has led to a number of activities that foster science communication training, especially for early career scientists and graduate and undergraduate students in science and engineering. The Materials Research Society in collaboration with NISE Net has offered a growing number of workshops at its two conferences each year. These include sessions such as *Mastering Public Presentations*, *Technical Poster Design*, and *Making the Most of Broadcast Media*.

The Boston Museum of Science developed materials for dissemination of two professional development activities on science communication for early career scientists and posted them in the NISE Net catalog in September 2011. The *Research Experience for Undergraduates* [REU] *Science Communication Workshop* provides REU students with training in how to communicate their research to the other students in their programs with skills also useful for communicating with the public. The *Sharing Science Graduate Student Workshop and Practicum* provides similar training for graduate students but is tied to participating in public presentations during NanoDays activities. In June and July 2012, the Museum of Science conducted a Dissemination Workshop for Education and Outreach Faculty and REU Directors at NNIN and other nano-research centers. Eight institutions attended and learned how to implement these science communication workshops for their own students.

Beginning in 2007, the Pacific Science Center developed Portal to the Public "…to assist informal science education 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." The Portal to the Public *Implementation Manual* includes the *Catalog of Professional Development Elements*, a practical guide to creating and facilitating professional development experiences for scientists" (http://pacificsciencecenter.org/Portal-to-the-Public/).

Continuing Education

Continuing education has always been important, but the rapid growth in fundamental knowledge and the resultant new technologies, coupled with their multidisciplinary aspects (convergence) combine to exacerbate this need. There has been a notable increase over the past decade in the availability of web-based remote learning. A variety of courses, certificate programs, and even graduate degree programs can be accessed either completely online or in a blended combination of online and classroom instruction. Examples of providers include the University of Washington (http://pce.uw.edu/online-learning/), the University of Illinois (http://oce.illinois.edu/), the University of Massachusetts–Lowell (http://continuinged.uml.edu/online/), the University of Southern California (http://continuingeducation.usc.edu/), and the e-Learning Center (http://e-learningcenter.com/). The online approach provides two critical advantages for people in the workforce: (1) material is available in time frames that fit their personal schedules, and (2) at least theoretically one can gain access to the best instruction, independent of geographical location.

Professional science and engineering societies also play a role in continuing education. For example, the American Chemical Society has introduced Sci-MIND (http://proed.acs.org/products-services/sci-mind/), an innovative and interactive training product designed to challenge chemists to continuously invest in their professional scientific development.

8.2.2 Physical Infrastructure

Over the last decade there has been significant growth in physical infrastructure in each of the individual NBIC disciplines, with some of that growth addressing convergence between at least two disciplines (see Fig. 8.4 and Table 8.4).

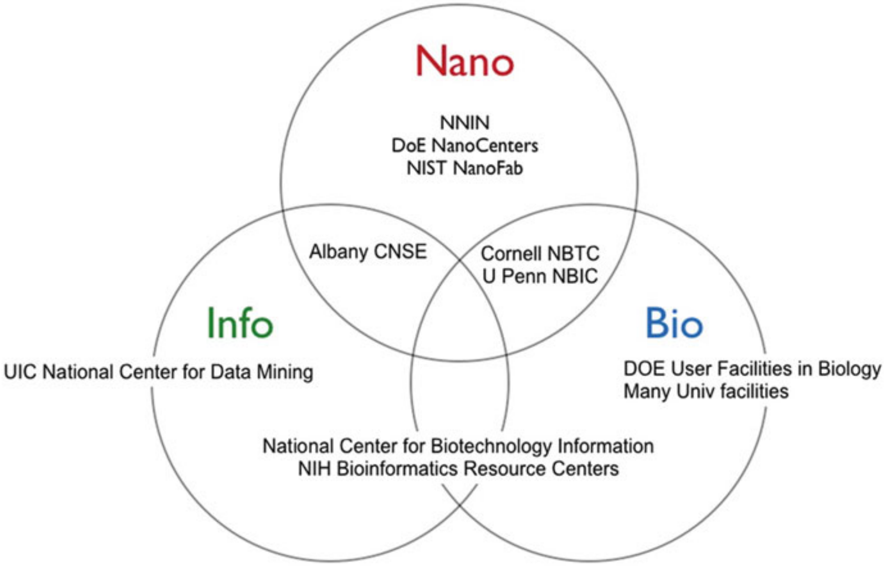

Fig. 8.4 Venn diagram illustrating facility infrastructure added in the last decade that addresses nano-, bio-, and info- needs, along with those that provide capabilities at the intersections (Courtesy of James Murday)
Key: *NNIN* National Nanotechnology Infrastructure Network, *CNSE* Center for Nanoscale Science and Engineering, *NBTC* Nanobiotechnology Center, *NBIC* Nano/Bio Interface Center, *UIC* University of Illinois Chicago

The NISE Net community of researchers and informal science educators is dedicated to fostering public awareness, engagement, and understanding of nanoscale science, engineering, and technology. With that goal, it has created and implemented exhibits and programs in a number of science museums (see the NISE Net case study, Sect. 8.8.6).

Innovative research depends on the infrastructure necessary to fabricate and characterize new devices and systems. In the past, university machine shops provided the wherewithal to do those tasks locally, with a minimum of time, effort, and expense needed to access the shop. The converging technologies frequently require highly sophisticated machines, too expensive to house within each university's "machine shop." While the existing user facilities illustrated above do provide the needed capability, for most researchers they require considerable travel time and delays waiting for facility permission.

The Network for Computational Nanotechnology is an "Infrastructure and Research Network" that strives to broaden researchers' access to sophisticated modeling and simulation tools and collaborations in the advancement of nanoscience and nanotechnology. It engages in research in the areas of (nano) electronics, mechanics, biology, photonics, and materials, primarily through leveraged funding and deployment of web-based research software tools on nanoHUB (http://nanohub.org/). (See the nanoHUB case study, Sect. 8.8.7).

Table 8.4 Sampling of center-scale projects with integrated capability for two or more NBIC fields

Affiliated agency	Program type	Member institution	Program title
Nano–Bio			
NSF	NSEC	Univ. Pennsylvania	Nano/Bio Interface Center
	NSEC	Rice Univ.	Center for Biological and Environmental Nanotechnology
	NSEC	Northwestern	Integrated Nanopatterning and Detection Technologies
AFOSR	MURI	Northwestern	Bioprogrammable 1-2-and 3-Dimensional Materials
	MURI	Harvard Univ.	Bio-Inspired Optics
NIH	NCI Alliance	Natl. Cancer Inst.	Nanotechnology Characterization Laboratory
	CCNE	Cal Tech	Nanosystems Biology Cancer Center
	CCNE	Dartmouth Col.	Dartmouth Center for Nanotechnology Excellence
	CCNE	UTexas Health Sci.	Texas Center for Cancer Nanomedicine
	CCNE	Harvard/MIT	Center of Cancer Nanotechnology Excellence
	CCNE	Northwestern	Nanomaterials for Cancer Diagnostics and Therapeutics
	CCNE	Stanford Univ.	Center for Cancer Nanotechnology Excellence and Translation
	CCNE	Johns Hopkins	Center for Nanotechnology Excellence at Johns Hopkins
	CCNE	Univ. N. Carolina	Carolina Center of Cancer Nanotechnology Excellence
	CCNE	Northeastern	Center for Translational Cancer Nanomedicine
	CNPP	Northeastern	Combinatorial-designed Nano-platforms to Overcome Tumor Resistance
	CNPP	Univ. Nebraska	High-capacity Nanocarriers for Cancer Therapeutics
	CNPP	Univ. Utah	Magnetoresistive Sensor Platform for Parallel Cancer Marker Detection
	CNPP	Cedar Sinai Med	Nanobioconjugate Based on Polymalic Acid for Brain Tumor Treatment
	CNPP	UNC Chapel Hill	Nanoscale Organic Frameworks for Imaging and Therapy of Pancreatic Cancer
	CNPP	Univ. New Mexico	Peptide-directed Protocells and Virus-like Particles: new Nanoparticle Platforms for Targeted Cellular Delivery of Multicomponent Cargo
	CNPP	Rice Univ.	Preclinical Platform for Theranostic Nanoparticles in Pancreatic Cancer

	CNPP	Univ. Cincinnati	RNA Nanotechnology in Cancer Therapy
	CNPP	Univ. S. Calif.	Targeting SKY Kinase in B-Lineage ALL with CD-19 Specific C-61 Nanoparticle
	CNPP	Emory Univ.	Theranostic Nanoparticles for Targeted Treatment of Pancreatic Cancer
	CNPP	Emory Univ.	Toxicity & Efficacy of Gold Nanoparticle Photothermal Therapy in Cancer
	CNPP	Northwestern	Tumor Targeted Nanobins for the Treatment of Metastatic Breast and Ovarian Cancer
	NHLBI-PEN	Burnham Institute	Nanotherapy for Vulnerable Plaque
	NHLBI-PEN	Georgia Tech.	Nanotechnology: Detection & Analysis of Plaque Formation
	NHLBI-PEN	Mass General Hosp.	Translational Program of Excellence in Nanotechnology
	NHLBI-PEN	Washington Univ.	Integrated Nanosystems for Diagnosis and Therapy
	NDC	Baylor Col. Med.	Center for Protein Folding Machinery
	NDC	NYU Med	Nanomedicine Center for Mechanobiology Directing the Immune Response
	NDC	Georgia Tech	Nanomedicine Center for Nucleoprotein Machines
	NDC	UC Berkeley	NDC for the Optical Control of Biological Function
	NDC	UCLA	Center of Cell Control
	NDC	UC San Francisco	Engineering Cellular Control: Synthetic Signaling and Motility Systems
	NDC	Univ. Cincinnati	Phi29 DNA-Packaging Motor for Nanomedicine
	NDC	Univ. Illinois-Urbana-Champagne	Biomimetic Nanoconductors
Nano–Info			
NIST	NRI	UTexas Austin	Southwest Academy of Nanoelectronics
	NRI	UCLA	Western Institute of Nanoelectronics
	NRI	Notre Dame	Midwest Institute for Nanoelectronics Discovery
	NRI	SUNY/Albany	Institute for Nanoelectronics Discovery and Invention
NSF	NSEC	Columbia Univ.	Center for Electron Transport in Molecular Nanostructures
	NSEC	Harvard Univ.	Science for Nanoscale Systems and their Device Applications
	NNIN	Stanford Univ.	Stanford Nanofabrication Facility
	nanoHUB	Purdue Univ.	Network for Computational Nanotechnology

(continued)

Table 8.4 (continued)

Affiliated agency	Program type	Member institution	Program title
DARPA	STARnet	UCLA	Function Accelerated Nanomaterial Engineering Center
	STARnet	Univ. Minn.	Center for Spintronic Materials, Interfaces and novel Architectures
	STARnet	UIUC	Systems on Nanoscale Information Fabrics Center
AFOSR	MURI	UC Santa Barbara	Investigation of 3D Hybrid Integration of CMOS/Nanoelectronic Circuits
	MURI	Stanford Univ.	Integrated Hybrid Nanophotonic Circuits
	MURI	Stanford Univ.	Robust and Complex On-Chip Nanophotonics
	MURI	Columbia Univ.	New Materials Approaches for Future Graphene-Based Devices
	MURI	U. Wisc. Madison	Adaptive Intelligent Photonic/Electronic Systems Based on Silicon Nanomembranes
	MURI	UTexas Austin	Three Dimensionally Interconnected Silicon Nanomembranes for Optical Phased Array (OPA) and Optical True Time Delay
ONR	MURI	UC Berkeley	Functionalized Nanoscale Graphene: A Platform for Integrated Nanodevices
	MURI	Univ. MD	Tailoring Electronic Properties of Graphene at the Nanoscale
	MURI	MIT	Graphene Approaches to Terahertz Electronics
Bio–Info			
NIH			PubMed Central
			PubChem
			National Center for Biotechnology Information
–	University centers	Univ. Washington	Department of Biomedical Informatics and Medical Education
–		Columbia Univ.	Department of Biomedical Informatics
–		Univ. Michigan	Department of Computational Medicine and Bioinformatics
–		Univ. Pittsburgh	Department of Biomedical Informatics
ARO	MURI	UTexas Arlington	Revolutionizing High-Dimensional Microbial Data Integration
	MURI	Albany Medical Col	A Brain-Based Communication and Orientation System

ONR	MURI	Northwestern	Conductive DNA Systems and Molecular Devices
	MURI	Univ. Minnesota	Roll-to-Roll High-Speed Printing of Multifunctional Distributed Sensor Networks for Enhancing Brain– Machine Interface
Cogno–Info			
DOE		PNNL	Cognitive Informatics
–		UTexas Health Sci UCenter	National Center for Cognitive Informatics and Decision Making

Key (*in order of use*): *NSEC* Nanoscale Science and Engineering Center, *AFOSR* Air Force Office of Scientific Research, *MURI* Multidisciplinary University Research Initiative, *CCNE* Centers of Cancer Nanotechnology Excellence, *CNPP* Cancer Nano Platform Partnership, *NHBLI-PEN* National Heart, Lung & Blood Institute Programs of Excellence in Nanotechnology, *NDC* Nanomedicine Development Centers, *NRI* Nanoelectronics Research Initiative, *STARnet* Semiconductor Technology Advanced Research Network, *NNIN* National Nanotechnology Infrastructure Network, *ONR* Office of Naval Research, *ARO* Army Research Office, *PNNL* Pacific Northwest National Laboratory

It is not only the physical/chemical/biological science facilities that are being affected by converging technologies; the earth sciences are in an analogous revolution, with a number of new facilities under development. In 2012 the National Center for Atmospheric Research (NCAR) opened on a new data center in Cheyenne, Wyoming. Scientists will use the supercomputing center to accelerate research into climate change, examining how it might impact agriculture, water resources, energy use, sea levels, and extreme weather events, including hurricanes. In 2013 the National Ecological Observatory Network (NEON) will open; it is a continental-scale research instrument consisting of geographically distributed infrastructure, networked via cybertechnology into an integrated research platform for regional- to continental-scale ecological research. Also in 2013, the Ocean Observatory Initiative will open; it is a program to provide sustained ocean measurements to study climate variability, ocean circulation and ecosystem dynamics, air–sea exchange, seafloor processes, and plate-scale geodynamics. To manage the data emanating from these new facilities, NSF is developing the Earth Cube concept (http://www.nsf.gov/geo/earthcube/), seeking transformative concepts and approaches to create integrated, convergent data management infrastructures across the geosciences.

8.3 Goals for the Next Decade

8.3.1 Education

It will be important to create a coordinated partnership of Federal/state/local governments, industry, and foundations addressing the challenges of STEM education in general and converging technologies specifically. This partnership must address an effective, affordable program to foster student interest in STEM careers, new approaches to STEM education, and accelerated transition of research discovery into technology innovation.

Converging technologies can certainly benefit from diverse perspectives. The United States is implementing efforts to entice underrepresented groups into STEM fields (e.g., see NRC 2012c and NSF programs such as BRIGE[17]). Converging technologies will benefit and may also assist in the recruitment, because they are expected to play major roles in ameliorating societal problems, a feature of interest to underrepresented groups (Sjoberg and Schreiner 2010; see also http://www.ils.uio.no/english/rose/).

Utilizing the vast capabilities of the Internet, a portal-like converging-technology website for educational research should be created to broadcast the latest innovative research news, to provide access to converging technology resources, to expand

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[17] Broadening Participation Research Initiation Grants in Engineering, http://nsf.gov/pubs/2007/nsf07589/nsf07589.htm

public interest in converging trends, to guide the introduction of converging technology into education, to showcase works in converging technology, and to introduce availability of converging technology-related programs (e.g., workshops and training events).

K–12

More timely, cost-effective approaches to including progress in science, engineering, and convergent technologies should be integrated into K–12 education. Teachers must be provided the materials and professional development needed to implement effective, hands-on activities on this topic. Experience with K–12 nanotechnology educational efforts (e.g., see Murday 2011) underscores the challenge to widely disseminate the outputs of innovative educational research on topics like converging technologies throughout local U.S. school systems nationwide.

There must be mechanisms for professional development of existing teachers. But it is also essential to improve the training of new STEM teachers. University/college education departments (education-process-oriented) and science/engineering departments (content-oriented) must work in tandem to develop joint curricula, with appropriate metrics to monitor and ensure their effectiveness.

A consortium effort should be established, enabled by Federal incentives and guidance, to provide teachers with training and materials they can use to enrich curriculum units with hands-on activities, media, and other resources to illustrate the potential future outcomes of converging technologies. The consortium should include such stakeholders as the National Science Teachers Association (NSTA), universities, science museums, and other community organizations.

Affordable, interactive, personalized digital education aides should be developed and disseminated as a means to improve the rate and extent of learning.

Community and Technical Colleges

Enabling and fostering a partnership approach to converging knowledge and technology (CKT) education programs at community and technical colleges across the United States is vital to meeting the growing converging technology workforce needs. The approach of forming partnerships in CKT areas between research universities, small colleges and universities, and community/technical colleges appears to be a very viable methodology for the future. It should address the issues of community/technical college access to the latest developments and directions, availability of a state-of–the art equipment base, and availability of staff expertise. The infrastructure and human capital efficiencies gained through this approach are substantial. This education partnership approach will help ensure the availability of a broad converging technology education (synthesis, fabrication, characterization, and applications) at 2-year community and technical colleges in every region of the United States.

Converging technology concepts also must be integrated into classical science and technology classrooms so that the students become aware of the many career opportunities available to them in these exciting fields. In order to do this, we need to continue to make significant investments in the professional development of current and future educators and administrators, and create activities and lessons that enable them to easily bring converging technology awareness into their classrooms.

Web-accessible high-cost equipment resources must become an integral element of all partnership programs across the nation. Interconnecting converging technology programs with local CC/TC feeder K–12 schools will enable students to explore converging knowledge/technology areas via hands-on distance technology. Web access is also envisaged to be a cost-effective and efficient method to bring twenty-first century tools as well as scientists and engineers into classrooms all across the country. The ideal outcome would be to spark interest in a larger number of students to explore education and careers (at all levels of study) in STEM fields in general and CKT areas in particular.

Universities and Colleges

There is a general consensus that degree programs providing a fundamental and thorough education in a core scientific discipline are highly effective at training students for cross-disciplinary research. That being said, a rigorous course of education does not need to be confined to an existing academic discipline. As any converging technology gains momentum and impact (as did materials and computing in earlier generations), there should be experiments in developing transdisciplinary curricula focused on the educational needs for that technology.

Widespread use of information-technology-based courses, underpinned by cognitive understanding, will enable the best instruction at lower cost to all students, independent of the matriculation school.

Research Universities

Within universities, effective organizational structures should be implemented that permit effective cross-disciplinary research to support graduate student/mentor relationships based purely upon scientific interests, regardless of the departmental affiliation of either person. Graduate training should be administered centrally with cross-departmental chairing. Many universities have significant barriers to these types of structures (Blackwell et al. 2009), typically because of financial boundaries, that can prevent graduate students from crossing departments or schools. For example, a department may recruit a graduate student and put that individual on a 1-year fellowship during the coursework period. This is viewed as an investment. If that graduate student moves to a different department, the investment is viewed as lost. This view is shortsighted. Universities want to position themselves to more effectively compete for research resources, and they also want to serve their mission of training students who can successfully enter an increasingly competitive workforce. Any barrier to cross-disciplinary research is going to ultimately prove to be a disservice to these key mission areas. Departmental and divisional structures provide useful frameworks for recruiting faculty, assigning teaching loads, and recruiting graduate students. However, they should not provide restrictive barriers to science and graduate education.

The social sciences, by virtue of continued progress in converging sciences and technologies, should be integrated more fully with the physical/engineering sciences and become disciplines founded in the fundamental chemical/physical laws governing brain function.

Informal Education

Effective public education about converging technologies should be widespread, informed by evidence-based communication science, include societal perspectives, and also include professional science communicators, informal educators, scientists, and engineers. The knowledge and skills needed to achieve this goal are dispersed across different fields, and a form of convergence is needed for success. In this case the fields are not only those directly engaged in physical sciences and engineering research, but also social and political science, educational psychology, and both formal and informal education. At present, converging NBIC technologies are not on the radar screens of either informal educators or the public. So there is a challenge, as there was for nanotechnology, to capture people's interest and attention.

Work on nanotechnology over the last decade has paved the way for public outreach and engagement about converging technologies. In addition, it will be important to bring social and political science researchers doing research on the societal implications of converging technologies together with (a) social scientists and psychologists doing research on science communication, and (b) practitioners in informal science education, science communication, and educational outreach.

Continuing Education

By the end of the next decade, there should be viable, web-based converging technology programs in place. With extended human lifetimes, it is projected that people will be more mobile in their careers, changing directions several times. That and the rapid changes in disciplinary knowledge and technological capabilities will make effective approaches in continuing education more important in the next decade. There should be a growing availability of web-based instruction, an education approach that is "friendly" to employed individuals in that there is flexibility as to when course work is accomplished and no travel time and lower costs required to "get to school."

8.3.2 *Physical Infrastructure*

Manufacturing demonstration facilities need to be created that provide the capability for facility users to experiment with different approaches to the affordable, large-scale manufacturing of new convergent technologies.[18] A range of such facilities will be needed to reflect the different approaches to manufacturing,[19] e.g., additive manufacturing or bottom-up assembly rather than stamping or machining. There should be a geographical distribution of these facilities to minimize travel time. It will also be important to develop appropriate intellectual property agreements and access arrangements that are conducive to small and medium enterprises (SMEs).

It will not be affordable for every university to have every machine, so there needs to be a mechanism established to determine (a) the best distribution of those machines, and (b) appropriate routes for virtual access to them. Funds will be necessary to implement the findings.

8.4 Infrastructure Needs

Facilities that support modern biological, physical, and engineering research are expensive to build, support, and maintain at the state-of-the-art level. They are also critical resources if research university faculty members are going to compete effectively for grants. A microchip fabrication facility may be utilized as much by chemistry and bioengineering faculties as it is by electrical engineering faculty; it now plays the role that machine shops played a generation ago. Similarly, microscopy facilities and molecular characterization facilities can also serve as centers that bring disparate disciplines together. In addition, these facilities can provide valuable resources for companies that are spun out of university research programs. Most of these facilities can operate only partially on user fees; they require additional commitments from other sources.

There is a huge need for standardized online education delivery platforms, yet to date no provider makes an interactive and fully integrated delivery–testing–management learning platform using tested best practices. While it is clear that digital education will grow to be mainstream, it is not clear what the best solutions will be. Support will be needed for infrastructure that experiments with a variety of approaches and provides means to expand the most successful approaches to full-scale use. A government competition to provide such a platform could be effective.

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[18] As an example see http://engineering.mit.edu/research/labs_centers_programs/novartis.php

[19] On August 15, 2012, the White House announced the launch of a new public–private institute for manufacturing innovation in Youngstown, Ohio. the National Additive Manufacturing Innovation Institute (NAMII), including manufacturing firms, universities, community colleges, and nonprofit organizations from the Ohio-Pennsylvania-West Virginia “Tech Belt.” In his State of the Union address on 12 February 2013, the President announced the launch of three more of these manufacturing hubs, aiming for a network of 15 of such hubs.

8.5 R&D Strategies

8.5.1 Education

There must be improved mechanisms for the transition of NSF education discovery projects into full-scale usage. There are many stakeholder organizations involved, including professional education societies, parent–teacher associations, the U.S. Department of Education, state/local education bureaucracies, the Business-Higher Education Forum, Educate to Innovate, and various foundations. Attention must be paid to coordinating these organizations and to making their efforts collectively more effective.

The recommendations made in the 2012 PCAST report, *Engage to Excel*: *Producing one Million Additional College Graduates with Degrees in Science*, *Technology*, *Engineering*, *and Mathematics*, should be implemented. The report has five overarching recommendations to transform undergraduate STEM education during the transition from high school to college and during the first 2 years of undergraduate STEM education:

1. Catalyze widespread adoption of empirically validated teaching practices
2. Advocate and provide support for replacing standard laboratory courses with discovery-based research courses
3. Launch a national experiment in postsecondary mathematics education to address the math preparation gap
4. Encourage partnerships among stakeholders to diversify pathways to STEM careers
5. Create a Presidential Council on STEM Education with leadership from the academic and business communities to provide strategic leadership for transformative and sustainable change in STEM undergraduate education (Blumenstyk 2012)

A network of regional hubsites should be established—the "Converging Technologies Education Hub Network"—as a sustainable national infrastructure for accelerating converging technology education. Just as the National Nanotechnology Infrastructure Network has been critical for shared access to leading-edge equipment in the early days of the NNI, shared converging technology resources, expertise, and training are imperative to preparing a skilled workforce and well-educated innovation leaders of the future. Each hubsite would connect and serve a number of research universities, 2-year and 4-year colleges, public school districts, and government and industrial laboratories. Each hubsite would focus on activities most pertinent to its locale. The hubsites would host teams of visiting professors, school teachers, and researchers from around the country to carry out (a) integrated content development for K–16 from the R&D stage through publication and dissemination; (b) related professional development, assessment and evaluation, learning research, and networking for teachers, faculty, and other stakeholders; (c) work on the science of science communication; and (d) effective implementation of digital education technologies using new insights stemming from the cognition sciences. These hubsites should focus on bigger issues, with a goal to nurture research, energize teaching, and build partnerships. For example, the Arizona State University Origins Project is a transdisciplinary initiative offering new possibilities for exploring the most fundamental of questions.

Even a decade into the NNI, nanotechnology is only marginally noticeable by the general public; it is likely other converging technologies will suffer the same fate. A prime goal for the next decade's infrastructure is to unfold the "secret magic" behind the converging technology, transmitting the knowledge to educators from middle school and beyond, and providing media for access to this knowledge. This could be done by boosting innovative technology in the rankings of popular search engines such as Google, Microsoft Bing, and Yahoo! and by facilitating dynamic information exchanges via social networks such as Twitter, Second Life, and Facebook.

Investment should be focused by NSF, the Department of Education (an "ARPA-ED" would be a logical entity), and foundations to enable effective, affordable e-teaching aides and better use of information technologies such as mobile devices and web applications. There are a number of extant efforts, but no overarching leadership. The 2012 U.S. Department of Education Race to the Top district competition has "Personalized Learning Environment" as priority one. DARPA has an Education Dominance program[20] focused on several key approaches:

- Replicating expert tutor behavior using knowledge engineering techniques
- Modeling intrinsic motivation and memory to optimize learning and consolidation
- Building student/tutor models based on abstractions of a wide range of student behaviors with live tutors
- Incorporating remediation strategies to enable the digital tutor to provide targeted reinforcement

The Innosight Institute has developed "A Guide to Personalizing Learning"[21] with guidance toward the blending of information technology and traditional learning modes (Evans 2012). Gooru (http://www.goorulearning.org/) and Silverback Learning (http://silverbacklearning.com/) have announced a partnership to enable educators to pinpoint the exact educational areas where students individually excel or struggle, to identify student needs, and to immediately suggest the most appropriate and high-quality learning materials available.

K–12

The National Governor's Association has been proactive in establishing common core standards for K–12 curricula (http://nga.org/cms/center/edu). That effort should expand to develop programs and partnerships (involving state and

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[20] http://www.darpa.mil/Our_Work/DSO/Programs/Education_Dominance.aspx

[21] http://www.innosightinstitute.org/innosight/wp-content/uploads/2012/09/A-guide-to-personalizing-learning.pdf

local jurisdictions, Federal efforts, industry, and foundations) that will smoothly transition the continually evolving converging technology information seamlessly into the K–12 education system. The STEMx effort to transform STEM education and workforce development in the states, by the states, is an example (http://www.stemx.us/).

U.S. programs such as the Department of Education's Race to the Top (http://www2.ed.gov/programs/racetothetop/) should focus on the innovative capabilities inherent in the development of digital education, but with careful attention to its appropriate role(s) in learning.

Educators play an important role in introducing the reality of converging technology to younger generations and can encourage their interests to pursue higher education in converging technology fields. Government should support middle school educators' professional development opportunities by creating converging technology training programs and workshops, and encouraging the participation of the educators. Funding for innovative tools to assist converging technology teaching at middle schools should be increased. There is a huge gap between middle school skills and the skills needed in higher education research, such as the common analysis and visualization techniques used in graduate research. These analysis and visualization skills could be easily learned and used by middle school students with the support of new innovative visualization tools such as the Science of Science tool (http://sci2.cns.iu.edu) and Gephi (http://gephi.org).

A central website should be created to provide a registry for converging technology education materials; the Gooru/Silverback Learning Solutions partnership provides a step in this direction. The NSTA might serve as the evaluator for quality control to ensure website materials are of high quality, are in a format readily utilized by K–12 teachers, are carefully indexed to the common core standards (or the various state learning standards), and can be readily accessed from the NSTA website. Teachers must be made aware of the registry, find it useful, and find it easy to use.

There is a proposed STEM teacher core program to establish an elite corps of master teachers to boost U.S. students' achievement in science, technology, engineering, and mathematics.[22] It should explicitly incorporate converging technology, and it would benefit from a joint curricula developed by interaction between education and science/engineering departments.

Education partnerships such as the Triangle Coalition (http://trianglecoalition.org/), Business/Education Partnership Forum (http://biz4ed.org/), and Education Partnerships (http://educationpartnerships.org/) need to be fostered and better coordinated.

To attract underrepresented groups into STEM careers, it has been suggested that linking curricula directly with societal impact can be a motivator. Converging technologies will be at the heart of many, if not most, of the technological contributions toward the solution of societal challenges. This feature can be exploited to help remedy the underrepresentation. In addition, students, including minority

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[22] http://www.whitehouse.gov/blog/2012/07/18/white-house-office-hours-stem-master-teacher-corps

students, should be made aware of the financial benefits that may be realized from a STEM education (Langdon et al. 2011; Melguizo and Wolniak 2012).

Community and Technical Colleges

A consortium of regional CC/TC and associated industries should be instituted to frame converging technology curricula around industry skill requirements and link these to the proposed network of regional hubsites. In addition, national core skill education standards based upon national industry requirements need to be developed to ensure that students graduating from converging technology programs are familiar with key core concepts and can easily move from region to region of technology, as well as from region to region of the country, armed with practical skill sets.

Colleges and Universities

As noted in the section on advances in the past decade, advances in information technology are leading to many new and promising approaches to effective education. There should be an effort to partner Federal agencies toward developing plans and/or processes for sharing the most effective and efficient means to educate undergraduate and graduate students regarding converging technologies. There will not be a standard model. There is a need for flexibility and adaptability to respond to the variety of educational contexts in the United States. The NSF Integrative Graduate Education and Research Traineeship (IGERT) program, explicitly tasked to address converging technology opportunities, is one approach to watch (see the IGERT case study, Sect. 8.8.8).

The several massive open online course (MOOC) experiments now in progress should be closely watched by NSF and the U.S. Department of Education, with funding for new experimentation and then attention to large-scale utilization of the more successful efforts.

Research Universities

A center should be established to address the societal and ethical implications of converging technologies. The center should conduct expert assessment in anticipation of potential future applications. It could be focused on human health and physical potential (although other converging themes are important as well). The public consistently expresses interest in new medical advances, so this may be effective subject matter for gaining the attention of educators and the public. Such a center could play an important role in the governance of converging technologies, but it could also provide information and perspectives valuable both in formal K–12 education and in informal public outreach and engagement.

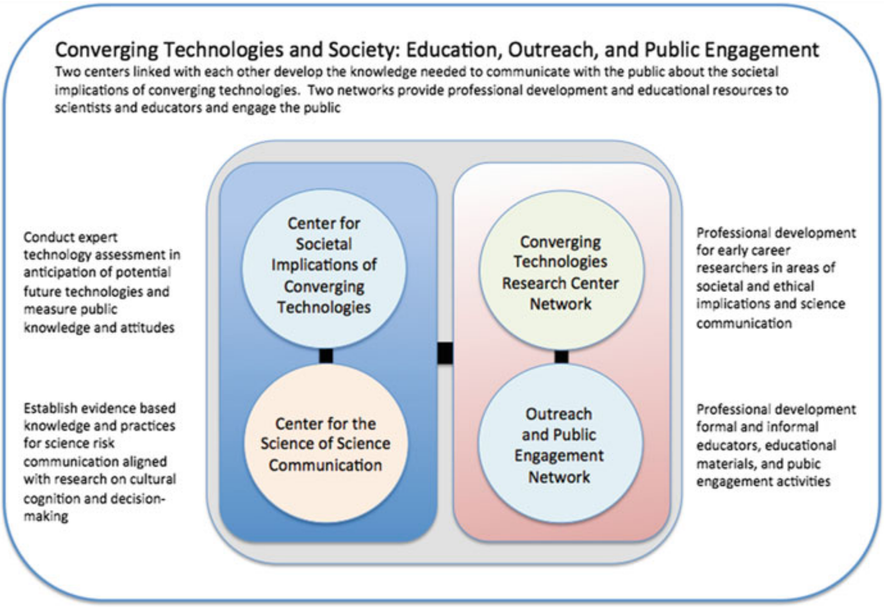

Fig. 8.5 Converging technologies and society: education, outreach, and public engagement (©Boston Museum of Science; courtesy of Larry Bell)

A center should also be established to address the science of science communication. This center should develop evidence-based knowledge and practices for science communication aligned with research on cultural cognition and science-informed decision-making. Such a center will be able to provide valuable scientific knowledge and also knowledge that can be useful to science communicators, educators, and scientists as they interact with lay audiences in their communities.

The treatment of tax-free bond-funded facilities at universities should be refocused to enable greater and stronger interactions between universities and industry (PCAST 2012a).

Informal Education

Industries can play a part in educating the public by increasing the appearance of the "converging technology" phrase in their advertisements. Leading converging technology IT companies are encouraged to include converging technology portals on their company websites.

An outreach and public engagement network, building on the experience of the NISE Net, should be created to establish a network of informal educators, science communicators, and university-based educational outreach coordinators (see Fig. 8.5).

They should be tasked with creating and disseminating professional development activities and materials to support educational enrichment experiences at all grade levels in both formal and informal education. This will provide students and the public with knowledge and experience with citizens' civic roles in connection with science and technology development in a democracy, as well as supporting general interest in science and science-related careers, all centered on converging technologies. This network would also create mechanisms to support widespread public engagement in policy considerations related to converging science and technology development, working with the center for societal and ethical implications and the center for science communication, to advance public participation in governance of converging knowledge and technologies.

Training in science communication and in the societal and ethical implications of technology must be incorporated into graduate and undergraduate science curricula and into sessions and workshops at meetings of professional societies. The initial focus should be on university centers that are conducting research in areas of converging NBIC technologies. The network should connect the educational outreach coordinators or other appropriate individuals who can implement student professional development activities that are built upon the work of the two centers and the outreach and public engagement network. The network would also disseminate information about established university-based courses in science communication for scientists as well as workshop activities designed for professional meetings.

Continuing Education

Partnering with the Business-Higher Education Forum and similar organizations will help to define the needs for continuing education focused on converging technologies.

Over the next 5 years, there will be up to a million military personnel returning to civilian life and getting into the U.S. civilian workforce. Juxtapose this with the 600,000 jobs currently open in advanced manufacturing and the anticipated need for ten million skilled workers by 2020. Programs, such as the Society of Manufacturing Engineers and U.S. Army example,[23] are needed to provide certifications to validate existing military personnel skills for civilian manufacturing jobs.

Portability and modularity of the credentialing process in advanced manufacturing is critical to allow coordinated action of organizations that feed the talent pipeline (PCAST 2012a).

8.5.2 *Infrastructure*

Two eminent programs that might be utilized to establish converging technologies manufacturing facilities are NIST's National Network for Manufacturing Innovation

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[23] http://www.sme.org/MEMagazine/Article.aspx?id=66817&terms=Army%20veteran%20training

(NNMI) and the Clean Energy Manufacturing Initiative (CEMI) of DOE's Energy Efficiency and Renewable Energy program.

8.6 Conclusions and Priorities

8.6.1 Education

New information-technology-based instruction must be fully exploited as means to (a) make high-quality education available via access to proven, effective digital education tools; (b) provide personalized, interactive education aides for faster, more comprehensive learning enabled by using all the learning modes (audio, text, video, tactile, motion); (c) provide competitions to excite STEM interest in youth; (d) level the access to quality education, especially for underrepresented minorities; (e) reduce the cost of introducing the new knowledge emanating from converging technologies; and (f) reduce the cost per person at all levels of education.

U.S. demographics clearly show that underrepresented categories of students in STEM must be addressed, but with attention to where the job openings will likely be (e.g., see Vastag 2012; ACS 2012; NIH 2012). Since a key driver for education is employment, it will be important for industry to participate in defining appropriate areas of concentration for K–14/undergraduate/postgraduate STEM education.

The United States must establish an integrated, progressive STEM education in K–20. The imminent K–12 Next Generation Science standards are only a first step that must be followed by curricula development, assessments, teaching aides, and teacher training. Further, those standards are clearly deficient in the area of information/computing technology. That deficiency reflects in part the problems of incorporating new information into an education system already struggling with triage—what topics must be deleted to provide room for newer topics.

Education must address the ways in which converging technologies are responding to urgent societal challenges such as the need for alternative energy sources and adaptation/mitigation for climate change (these are only two examples; many more could be added). Embedding converging technology education in important public policy debates could facilitate its introduction to a wide range of educational levels and disciplinary foci.

Along with the present emphasis on creation of new jobs, there should be emphasis on entrepreneurship as part of the education process.

A portal-like website for educational research related to converging technologies should be created to broadcast the latest news about innovative science and technology research and to provide access to converging technology resources, expand public interest, showcase work in converging technology, and advertize availability of converging technology-related programs and events. Social networking also should be exploited in this endeavor.

The behavioral sciences, as represented by cognitive science and psychology, are evolving toward the status of sciences based upon fundamental or nomothetic laws. This evolutionary trend will influence other areas of social science, especially those that interact strongly with information and computational sciences. Converging technologies will provide an opportunity to accelerate this evolution of the social sciences toward the advances that have been made by the hard sciences.

8.6.2 Facilities

Without affordable, reliable approaches to manufacturing, many converging technologies will never enter the marketplace. Building a range of user facilities that provide opportunities to explore manufacturing approaches is important to accelerating innovation.

Ready access to a wide range of converging technology characterization and fabrication capabilities should be implemented at each major research university, with user centers providing open access to those instruments too expensive (to build and operate) for wide dissemination.

Cyber infrastructure will require continual investment, both to keep it current and to extend the capacities to more people and institutions.

8.6.3 Visionary Priorities

- Using new insights into cognition, utilize new, inexpensive, nano-enabled digital education assets toward more effective, interactive approaches to personalized education with:
  - Sensing of the environment and the student to ascertain learning readiness
  - Interactive modalities—3D video/text display, oral (including interactive dialog), motion (haptic and large motor), virtual reality—all tailored to personal learning modes and motivations
  - Awareness of the learner's present state of knowledge and comprehension
  - Constant assessment of comprehension to ensure an efficient rate of progress
  - Downloadable new materials from a central storage site into a local memory for real-time accessibility
  - Web-basing to enable access to worldwide information
  - Affordability
- Create a distributed international "converging knowledge and technology network" with a multidomain database, education modules, and facilities
- Expand the concepts of geographically distributed user facilities, such as NNIN and NCN, to create converging technologies clusters, and introduce test bed/manufacturing user facilities to accelerate the translation of the research discoveries into innovative technologies.

8.7 R&D Impact on Society

Without the necessary infrastructure, especially the educated manpower, the promises and expectations in the rest of this report are doomed to slow progress if not to outright failure. Success in the education endeavors will provide the skilled workforce at all levels of the innovation chain, including the factory floor (CC/TC education), business professionals/public officials, including regulators (BA/MA education), implementers (BS/MS education), and research discovery (Ph.D. education). Access to facilities will provide the tools to accelerate transition of research discovery into innovative technology, thereby improving people's quality of life.

Converging technologies have the potential to produce revolutionary innovations that could have profound impacts on individuals and society. Yet we must more deliberately address the benefits and issues attendant to such changes, whether individual or collective. The National Academies report *Technically Speaking* observes that,

> Americans are poorly equipped to recognize, let along ponder or address, the challenges technology poses or the problems it could solve …. Although our use of technology is increasing apace, there is no sign of a corresponding improvement in our ability to deal with issues related to technology. (Pearson and Young 2002, 1–2)

Technically Speaking identifies five benefits to society of technological literacy, which are supported by the kinds of K–12 enrichment and public outreach and engagement activities proposed here and which address the three overarching themes of this report:

1. Improve economic competitiveness
    - Increase the economic benefit from a workforce interested in and prepared for work that emerges from research in converging technologies
2. Develop human capacity
    - Improve decision-making as consumers who are able to make more critical assessments of new technologies
    - Increase citizen participation in a democratic society in ways that are well informed
    - Narrow the technological divide by making knowledge about the opportunities provided by emerging technologies known to everyone
3. Increase society's sense of security about change
    - Enhance people's sense of social well-being as they are empowered by acquiring the tools to make sense of the world even as it changes around them

These benefits would apply for science and innovation broadly, but also specifically for converging technologies, through implementation of the educational and public outreach and engagement activities outlined above.

Converging technologies, of which NBIC is only one important example, will pose benefit/risk challenges for society. A better-informed public debate and decisions based on more quantitative appreciation of the balance of benefit/risk in new technologies will be important to attain the best while minimizing the worst.

The convergence of NBIC technologies holds the promise of transformative, personalized education and entertainment based on information systems interacting with humans. The science of communication, honed by the challenges of CKT and a growing hard science basis for social sciences, will provide insights that accelerate the learning process. This will be even more important in the future as the pace of new knowledge accelerates.

8.8 Examples of Achievements and Convergence Paradigm Shifts

8.8.1 Vision for Changing Education Through Integration of Knowledge and Technology: A Vertical, Horizontal, and Global Approach

Contact person: *R. P. H. Chang*, *Northwestern University*[24]

Introduction

Throughout human history it has been shown over and over that information is "king." Better information or data has helped to improve all aspects of life, including economic forecasts, business management, health, and security. Starting with the invention of the transistor, integrated circuit, laser, and nanotechnology-based discoveries, the volume of information gathered, stored, and processed has been increasing exponentially. In particular, the cost of information has also come down dramatically, with 87 % of the world's population now having cell phones (ITU 2011) that also can provide entertainment and business transactions.

The ability to process tens of gigabits of information on a personal computer or tablet has dramatically changed the way of life for most citizens. In particular, information-based knowledge can be quickly gathered and processed for learning and training. Interactive digital information in the form of video, 3D simulation, and virtual reality has greatly enabled everyone to learn through visualization and real-time experience. As our knowledge of processes in the world grows, it pushes at the boundaries of what can be taught from textbooks and classic educational paradigms, demanding that we apply that knowledge and use our technology to create better educational tools. Examples include cockpit simulation for flight training and the study of nanoscience through interactive digital games and large-scale simulation of nanoparticle interaction dynamics.

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[24] This work was supported by NSF (DMR award #0843962). The author thanks Jennifer Shanahan and Kathleen Cosgrove for their help in preparing this case study.

A concrete example of how technology and human knowledge are strongly coupled, reinforcing one another, can be found in understanding how the human brain learns and perceives. Consider the case of surgical residents learning to perform complex surgeries for the first time. Many classic learning paradigms have followed the practice of "see one, do one." Basic neuroscience research (knowledge) in some ways bears this out as an effective mechanism. *Watching* someone perform a task activates parts of the brain that will later *do* the task—a literal mental rehearsal (Rizzolatti et al. 2001). Thus, when asked to physically do the task after seeing it, the initial learning pathways have been forged; the parts of the brain that will have to cooperate to enable this task have at least introduced themselves. When learning a surgery, however, there are limited resources to allow for a safe first practice, and limited opportunities to "see one." Though residents watch videos, study diagrams, and attend lectures, it is likely that these 2D representations do not fully engage their learning circuits. Newer virtual surgery (technology-based) 3D training systems allow interaction and even provide haptic feedback, and allow for better learning and better-prepared surgeons who can learn more and be more precise in their practice—creating new knowledge (Hart and Karthigasu 2007; Wong and Matsumoto 2008).

These findings, that full simulations and virtual learning environments enhance learning, highlight an important aspect of the integration of technology, neuroscience, and education: that is, to be most effective and best utilize natural learning circuits, the learning must engage the student not just with sounds or images, but with responsive, reciprocal interaction. As our technology improves to allow for better human subject testing in more natural environments, we will begin to understand and target our educational technologies to ensure that we are tapping in to these full learning circuits, which will prepare the next generation to make their technological advances. This in turn can help make good brains great!

Importance of Convergence for Economic Development; The Infrastructure of Translating Education into a Technology Workforce

It is interesting to observe how countries have developed their economic growth over the past 50 years. While not all leading economists agree that education, science, and technology are the engines behind all economic growth, a few successful examples are given below to demonstrate how the use of the concept and implementation of the principle of convergence of education, knowledge, and technology have brought economic success.

Example 1: *Japan*. Japan is a country without many natural resources and whose economic success depends heavily on its skills to turn imported resources into technology-driven products. Soon after the Second World War, with the help of the United States, it started to rebuild itself by hard work and a strong emphasis on STEM education. Over the decades, it relied on perfecting foreign technology and innovation of its products for export. In order to accelerate this development and with limited financial resources, the Japanese government took the lead in the 1970s to apply the principle of convergence and set up integrated hubsites throughout Japan to boost economic development. Each of these hubsites had at least one nearby national research lab, industrial lab, and university. This was an effective, efficient way to streamline high-tech product development from concept to manufacture. Professors and their students perform research in the nearby labs, and this also serves as a model of workforce development. These initial hubsite models proved to be very successful and, as a consequence, Japan further established science cities, one of which is Tsukuba, a leading location for advanced research and technology development in Japan today.[25]

Example 2: *Taiwan*. Taiwan is an island much smaller than Japan. In many ways it is very similar to Japan in its economic development strategy. Over the past 50 years through a focused industrial development plan led by its government, Taiwan has become a leader in high-tech electronic products. With initial government subsidies, Taiwan built Hsinchu as its first convergence city with a science and technology park,[26] along with a powerful Industrial Technology Research Institute (ITRI; http://www.itri.org.tw/) surrounded by several leading national universities. Again, the main route to success has been high-level and in-depth education at universities coupled with training in the local industries for the strong workforce that is needed. Many of the researchers from ITRI, and university professors and their students, have launched start-up companies. Taking the knowledge gained from their economic success, large manufacturing plants have been launched in China by Taiwanese business leaders.

Example 3: *China*. In the early 1990s China took the above convergence models to another level of sophistication and grandeur. A partnership between the Singapore and Chinese governments was established in 1994 to launch a China–Singapore Suzhou Industrial Park (CS-SIP) with area of 288 km^2.[27] In addition to government-sponsored research labs and industrial labs, there are many satellite campuses of top universities from other parts of China. In May of 2006, the SIP was the first location for the joint China–UK university known as the Xi'an Jiaotong–Liverpool University (http://www.xjtlu.edu.cn/en/), which offers degree courses in Architecture, Electronics, Computer Science, Communications, and Management. Today, similar models have been used throughout China to establish regional and sometimes international high-tech convergence hubsites.

Example 4: *Mexico*. The Governor of Nuevo Leon, Mexico, in 2003 led the way to reposition the city of Monterrey as the "Monterrey International City of Knowledge" with goals to establish a model for Mexico and increase its per-capita GDP from

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[25] For example, see *Tsukuba*, *Ibaraki*. http://en.wikipedia.org/wiki/Tsukuba,_Ibaraki and University of Tsukuba. *Prospectus*, http://www.tsukuba.ac.jp/english/about/index.html

[26] *Hsinchu Science and Industrial Park*: http://en.wikipedia.org/wiki/Hsinchu_Science_and_Industrial_Park

[27] See *China-Singapore Suzhou Industrial Park*: http://www.sipac.gov.cn/english/ and *Suzhou Industrial Park*: http://en.wikipedia.org/wiki/Suzhou_Industrial_Park

$10,000 to $35,000 by 2030. To do so, the Research & Innovation Technology Park was established with a spread of 172 acres and a phase-one investment of $145 million (Engardio 2009). Many U.S. and Mexican companies and national labs have already established their presence in the park. In addition, park leaders have made sure that they are in close collaboration with local universities to help provide the future workforce that is needed for the growth of local industry. They are also collaborating with the University of Texas in research and education, and using Northwestern University's Material World Modules Program for STEM course development and training for precollege students. This is an excellent model of technology, knowledge, and education convergence.

Example 5: *The United States*. The College of Nanoscale Science and Engineering (CNSE) at SUNY-Albany is perfect example of how to have a focused approach in the integration of education and training with research and development in the area of nanoscience and technology all under a single roof. With a total projected investment of $14 billion and 800,000 square feet of premier research space including Class 1 cleanrooms and fabrication facilities, this is a very large focused investment. The CNSE has over 300 global corporate partners and nearly 3,000 R&D jobs on-site, making it one of a kind in the world for nano education, technology, and knowledge generation.[28] This is also an example of double convergence, with nanoscale science and engineering already being a focused integration of the STEM field (see also the CNSE case study, Sect. 8.8.4).

Example 6: *Germany*. All of the earlier examples of development have started from ground-zero and with large investments. This is an example where existing successful components of education, knowledge, and technology were successfully integrated based on the principle of convergence. Karlsruhe Institute of Technology (KIT) was established in 2009 as a result of a merger between the 187 year-old University of Karlsruhe and the 181 year-old *Forschungszentrum Karlsruhe* (a federal research lab).[29] With such a merger, KIT instantly became a powerhouse of integrated education and technology development in Germany and Europe. It allows the continued training of a STEM workforce along with the advancement of discovery, innovation, and entrepreneurship. This is a unique example for others to emulate.

Vision for Change

As alluded to earlier, the world needs leaders with a global perspective and knowledge of how to implement an integrated approach to produce solutions to the

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[28] See *College of Nanoscale Science & Engineering*. http://www.cnse.albany.edu/Home.aspx and Center for Economic Growth. *College of Nanoscale Science & Engineering*: http://www.ceg.org/economic_development/sites/the-college-of-nanoscale-science-and-engineering/

[29] See *Karlsruhe Institute of Technology*: http://en.wikipedia.org/wiki/Karlsruhe_Institute_of_Technology

impending global issues in energy, environment, health, security, and resource management. The fundamental building blocks are education, knowledge, and technology. These building blocks need to be mixed in a synergistic way to establish a basis for global sustainability.

In considering the results of these examples, successful implementation of convergence has already started to a certain degree with the consideration of both vertical and horizontal, and even bilateral integration between countries, as seen in the example of China. Mexico shows us that a vertical, ground-up effort in the education system to engage pre-college students in an integrated STEM curriculum has a positive impact on students' preparedness for college and their ability to innovate in industry. In the United States we have been working hard at the university level to break down departmental barriers to provide a horizontally integrated approach to education and research. NSF has been taking the lead in establishing cross-disciplinary centers for research and education.

Moving forward by combining different methods of vertical, horizontal, and global integration will allow us to conserve resources and maximize the development of a stronger, science-literate, global citizenship. I would argue that the potential of our knowledge and technology is not fully reached until citizens can learn how to use it and improve upon it. This requires a new push to revolutionize education, increasing its accessibility and using our technology know-how to improve learning and teaching. The technological advances in cyber infrastructure and pervasive access of digital media create an opportunity to implement near-free and massive formal and informal education to all citizens. This creates a science-literate global citizenry who can best use a variety of networks to share practices in solving global issues, starting from such simple practices of recycling and conservation of materials use, or disseminating information about transmittable disease. Similarly, collaboration will not be as dependent on physical proximity, creating opportunities for countries to have virtual collaboration centers, shared technology and resources, and access to specialized knowledge. By starting at the bottom with innovative, freely accessible education, we can find ways to integrate education, technology, and knowledge and fully reach our potential as a global community to tackle global challenges. Thus the vision for the future requires a changed education practice that utilizes the integration of knowledge and technology in multiple directions: vertical, horizontal, and global.

8.8.2 Pennsylvania State University Center for Nanotechnology Education and Utilization—NACK Network (http://www.nano4me.org)

***Contact person**: Stephen J. Fonash, Pennsylvania State University*

With the support of the National Science Foundation's Advanced Technology Education (ATE) program, Penn State has developed a nationwide partnership of research universities and community colleges with the goal of bringing meaningful core-skills nanotechnology workforce education to technical and community colleges

Fig. 8.6 NACK's laboratory practice is part of the Nanofabrication Manufacturing Technology Capstone Semester (Courtesy of S. Fonash)

across the United States, This partnership, the NSF National Nanotechnology Applications and Career Knowledge (NACK) Network, is focused on (1) resource sharing among community colleges and research universities for nanotechnology workforce development, (2) the availability of course materials, for web or in-class use, covering a core set of industry-recommended nanotechnology skills, (3) student awareness of converging knowledge and technologies, and (4) broad student preparation for careers in the wide spectrum of industries utilizing micro- or nanotechnology (Fig. 8.6).

In addressing the widespread need for a workforce possessing strong nano- and microtechnology 2-year degrees (Fonash 2009), NACK has created and offers continually updated, free-of-charge core-skills course lecture and lab materials, web-accessible equipment capability, and faculty development workshop curricula. Since the inception of the nationwide effort in 2008, NACK research university–community college partnership hubs have been set up and are functioning in Puerto Rico, New York, Indiana, Minnesota, Texas, and Arizona. Others are underway. These are in addition to the Pennsylvania hub comprised of 30 Pennsylvania schools and funded by the State of Pennsylvania since 1998.

The Penn State nanotechnology workforce development programs began as a Pennsylvania focused activity with the founding of Pennsylvania Nanofabrication Manufacturing Technology (NMT) Partnership funded by the State of Pennsylvania in 1998. The Pennsylvania NMT program encompasses 29 academic institutions in Pennsylvania, which offer a total of 53 2-year and 4-year nanotechnology degrees (Hallacher et al. 2002). In 2003 the additional component of a National Science Foundation (NSF) ATE regional center for nanotechnology workforce education was added. In 2008 this NSF ATE activity evolved into the NACK Network nationwide workforce development partnership. By creating education pathways from high school to skilled manufacturing careers across the country, the NACK Network is working to train the U.S. nanotechnology manufacturing workforce.

The NACK Network has introduced a number of paradigm shifts designed to give the United States a well-trained nano- and microtechnology workforce. These shifts address four key issues faced by many community and technical colleges as they consider developing courses for converging knowledge/technology areas. Specifically, in the case of the converging knowledge/technology area of nanotechnology, NACK has addressed the following:

- *Economic pressures*. To alleviate the economic burden of each institution creating and sustaining four semesters of new courses, NACK has designed a suite of standard courses to give students from a variety of science and technical fields a meaningful immersion in the converging knowledge/technology area of nanotechnology. This suite, which may be offered at a regional research university center or at a community college, taken online, or used in any combination of modes, gives students from biology, engineering, technology, chemistry, physics, and other programs a broad, meaningful experience in nanotechnology. There is a skill set requirement rather than a course set requirement for entry into these courses. The skill set requirements can be met by traditional biology, chemistry, engineering technology, math, materials science, and/or physics courses available at most 2-year institutions. Institutions thus do not need to develop four semesters of new courses. Students emerge from this suite with an exit skill set developed by the NACK Industry Advisory Council.
- *Student enrollment pressures*. The nanoscience/nanotechnology course suite approach eliminates the pressure to maintain a baseline student enrollment in a high-tech program. Students move from traditional programs into the nanotechnology immersion suite which, as noted, may be taken at a community college, at a university, online, or in any combination. The critical mass of students needed to economically maintain a nanotechnology education experience must be attained only for the course suite.
- *Pressures on faculty, staff, and facilities resources*. The NACK approach to the faculty, staff, and facilities issues faced by 2-year degree-granting institutions is one based on resource sharing. It entails several components: (1) sharing facilities and (2) sharing courses. Sharing facilities means 2-year-degree students using the facilities at a research university to obtain hands-on nanotechnology exposure, or it means community colleges themselves setting up a teaching cleanroom facility to be shared among institutions in a given area. In the NACK approach, sharing courses has the following possible implementations: a research university assuming responsibility for teaching the capstone semester for students attending from community colleges, community college students using web-accessible courses provided by NACK, and community college faculty using units from NACK's web-accessible courses.
- *Geographic isolation of some 2-year degree institutions*. The NACK approach to overcoming the drawbacks of geographic isolation in teaching students interested in nanotechnology is twofold: offering the nanotechnology suite of courses online for downloading, and providing web-based access to equipment. The NACK philosophy is that it is best to operate a tool (e.g., field-emission scanning electron microscope, scanning probe microscope, etc.) using a computer right

next to it, but second-best is to operate the tool with a computer via the web—even if the tool and computer are separated by thousands of miles.

8.8.3 Brave New University: How Convergence Might Transform Academia

Contact persons: *Michael E. Gorman, University of Virginia; Erwin P. Gianchandani, Computing Research Association; James C. Spohrer, Director, IBM University Programs*

The path from the transformation of institutions (online academe) to the transformation of individuals (connected and collective intelligence) has been politically charged. When the rector of the Board of Visitors at the University of Virginia recently decided to force the resignation of the University's president, one of her reasons was that the university was not on the leading edge of the recent online education movement. The politics surrounding the resignation, then restoration, of the president illustrate the high-stakes politics involved in the adaptation of universities to socio-technological change.

Online and distance education represent important challenges to the 1,000-year-old university model, but their potentially disruptive impact pales in comparison to other promising developments in convergent technologies, which could transform human bodies, brains, and social systems at a pace faster than anything experienced in human history.

Education Anywhere

Mr. Jefferson's goal in founding the University of Virginia was to create "an academical village" in which students and faculty could be part of a learning community, living right next to one another on Jefferson's historic Lawn, an architectural marvel that itself would be a constant source of inspiration. For Jefferson, having students and faculty together in the right surroundings was essential to intellectual growth.

Nearly 200 years later, technologies permit students to take courses—taught by world-class experts—from their laptops anywhere in the world with good Internet access. Students can even participate in discussion groups and joint projects online. Can this online experience replicate the kind of special bond created between students and a university—an experience that is part of a university's "brand" and ensures long-term loyalty and connection with alumni? Which aspects of a village are captured online, and which are not captured? What new affordances going beyond "an academical village" does online offer?

Inspired by "World of Warcraft," a gaming environment in which teams of 40 or more participants from all around the world work together to solve problems like defeating tough resilient monsters, the first author developed a simulation of the NNI for a recent course. Through this, students engaged in role-playing representing

Congress, funding agencies, selected Federal agencies, laboratories (both industrial and academic), nongovernmental organizations (NGOs), and a newspaper (Gorman et al. 2013). Readings and class discussions prepared the students to develop their own goals for the NNI and even a branching tree diagram of the technologies they had to develop to reach these goals. The laboratories competed or cooperated to develop and own technologies, writing proposals to funding agencies, navigating regulatory agencies and NGOs, etc.

Simple software was implemented to scaffold this experience, keeping track of the technology tree, budgets, intellectual property, patent owners, all proposals to the funding agencies, etc. The scaffolding, when combined with software to manage online groups, made it easier to offer this simulation over the Internet.

An alternative would be to capture this environment on an "island" on Second Life, in which students would have avatars and virtual buildings for their labs, agencies, etc. The first author recently had the opportunity to serve on an NSF review panel on Second Life and thought it worked nearly as well as being together physically. (NSF specially designed its island for this sort of work and put considerable effort into making it practicable—partly because this collaboration mode is much less expensive than having all panelists come to NSF.)

Convergent Technologies

Distance learning and Second Life are simply the beginning; there are technologies emerging with even greater transformative potential. Consider the ubiquity of smart phones and tablet PCs—indeed, the increasing dependence of today's youth upon these devices—as capable of enabling an entirely new learning modality. What sorts of "apps for learning" could we engineer? How might they improve students' perception and understanding? How might they catalyze changes in students' behaviors, perhaps by piquing interest and enhancing motivation at the right time in the learning process? These devices still require looking down at a screen, often while walking (or driving or biking)—but perhaps not for much longer: Google is pioneering modalities that would provide this information hands-free, and implants and neural interfaces are on the horizon. Indeed, these and other learning platforms envisioned just a decade ago are becoming realities more rapidly than many anticipated (Spohrer 2002).

Crowdsourcing—the process of engaging a distributed group of agents (humans and/or computers) to complete complex tasks—similarly offers the potential to engage active learners in solving actual problems. Researchers at the University of Washington recently developed a collaborative, web-based video game called Foldit that allows players to manipulate virtual molecular structures following real chemical rules. The more elegant the structure created, the higher the score attained. In the fall of 2011, players identified the structure of an enzyme critical for reproduction of the AIDS virus within weeks of the game's launch, a challenge that had stumped scientists for decades. Similarly, the search for Genghis Khan's tomb demonstrates the power of crowdsourcing to leverage advanced visualization technologies to pinpoint, in this case, interesting archeological sites in Mongolia. To be part of a university education, these crowdsourcing experiences would have to incorporate reflecting on the learning experience, and learning about the relevant fields, e.g., biochemistry and archeology. Here Dewey's vision of learning by doing could potentially become learning by solving. How many unsolved problems are a small number of inferences away from a properly prepared learner's mind?

And how about acquiring and transferring hands-on tacit knowledge (Gorman 2002)? Haptic interfaces could one day allow students to do a laboratory experiment together over a distance, moving the appropriate instruments and getting better at skills like creating a scanning tunnel microscope (STM) tip or dissecting a (virtual) frog or participating in an archeological dig.

Convergent technologies promise a day when prospective students might have neural interfaces and other enhancements that would allow them to experience a virtual environment as if it were real (Roco and Bainbridge 2003; Robinett 2003).

Similar technologies could be used to enhance "NNIsim" by turning it into an augmented reality, with virtual offices and equipment, and the ability to visit laboratories and foundations. Representatives from government or NGOs or actual labs could provide input on how to design avatars representing roles not actually played by simulation members—like the President. One could use crowdsourcing to turn NNIsim into a tool for public engagement. Imagine multiple NNIsims mixing scientists, policymakers, public stakeholders, and university students, each simulation following its own course to a unique set of technologies and goals, with details of the arguments preserved.

University-quality education could be available round the clock, right when a user needs it to get background and current information. Instead of classrooms and courses, learning communities might evolve, centered on specific problems or issues.

Steve Jobs designed the workspace at Pixar to maximize the possibility of chance encounters between employees at random times during the day, knowing that these encounters would lead to new ideas and collaborations (Isaacson 2011). Would a virtual community of this sort be as good as a real one? Virtual communities like Second Life can be designed to encourage random encounters. Empirical work needs to be done on the richness of these encounters, especially as the technology improves (Gorman and Spohrer 2010).

Perhaps most importantly, convergent technologies create the opportunity to capture more data on how students—and by extension, human beings more generally—learn. Recent and ongoing advances in recognition, tracking, and recording allow us to capture and pool data at low cost and make it available to an analytical pipeline. We can observe when a student pauses a video, what he/she reviews in his/her smart goggles, etc. We can notice when many students arrive at the same wrong answer, so that we can refine our teaching methodology accordingly. We can predict how well students will do before they even set foot in the classroom. And we can achieve the ultimate quest of personalized education.

So imagine a virtual University of Virginia, with a replica of some of Mr. Jefferson's historical buildings in an advanced equivalent of a Second Life island—perhaps goggles, retinal implants, or even a silicone interface linked with the brain and coupled with goggles to transmit the right stimuli to trigger the optic nerve and appropriate parts of the brain. Collectively these could be used to enter the Lawn from any location. Now students could, from afar, "stroll" the Lawn and discuss ideas as if they were there. Goggles or retinal implants could also be used while walking the actual Lawn to provide additional information on the social, intellectual, and architectural environment (Spohrer 1997). The University of Virginia runs a Semester-at-Sea Program to take students around the world. Convergent technologies create the possibility of sending a small number of students and linking a much larger number online through an immersive environment that allows them to share parts or all of the experience, interact with locals, and participate fully in lessons learned.

What Is Lost and What Is Gained?

In this way, convergent technologies could potentially save universities money on infrastructure: students would not have to fly or drive to a physical campus, stay in a residence, eat in dining halls, have health clinics, etc.; rather, their cost would be whatever technology is required to sign onto the courses. And in a world where goggles or retinal implants were readily available, much of the costs would be borne by the students—as is happening at universities where students are required to buy or bring their own computers. Like the students, the faculty could reside anywhere the appropriate technology was available—no longer incurring costs to relocate. Faculty could even be available asynchronously to share a learning experience with a student or a group of students.

But the cost savings from creating a virtual university of this sort may be less than one might expect, and may also create a divide between those students who can afford the best enhancements and those who cannot. Moreover, the primary focus should be on the quality of the university experience. Undergraduates are going through significant developmental changes within and outside of the classroom, learning a great deal from their peers and forming lifetime bonds (including marriages). They participate together in sports and clubs and service organizations. A virtual university cannot emulate all of this.

Laboratories and field research are not just places where students learn hands-on tacit knowledge: they are also places where they learn the collective tacit knowledge involved in becoming part of a disciplinary culture (Collins 2010), particularly when undergraduates and graduate students are engaged with faculty in making discoveries and creating new technologies. Would this kind of enculturation be as well developed in a virtual university?

Could virtual universities have unique "branded" experiences and co-evolve improvements with students? Or will the university as an institution disappear, with students simply selecting from a wide range of courses and experiences they can meld together into a degree? Universities are not just locations for knowledge transfer: they are places where knowledge is created, applied, and integrated across multiple fields. Students apprentice themselves to faculty to become members of the scientific community, build reputations, and sometimes even launch new entrepreneurial firms based on those newly found understandings of the world. Universities are also places of reflection on our society, our technologies, and ourselves. One advantage of convergent technologies is that they force us to examine the role of universities as institutions in society from many perspectives beyond knowledge transfer (teaching). By removing constraints and imposing new ones, convergent technologies allow deeper explorations of what are the essential characteristics of both institutions and individuals.

Equal Educational Opportunity for All?

At the same time, as tuition costs rise, it becomes harder and harder for those of modest means to complete college, which undermines the American ideal of a meritocracy in which anyone who works "hard enough" has an opportunity to succeed. The availability of education anywhere through online tools could theoretically reduce this gap, but only if the infrastructure were put in place and the convergent technologies were inexpensive or subsidized. Otherwise, students might have to pay more to link into a virtual university than to attend the real one.

What about equal access to convergent technologies like cochlear, retinal, and neural implants? Students who are blind, deaf, or have other sensory, motor, or cognitive issues that make learning more challenging will benefit from these and other convergent technologies. As these capability augmentations improve, it is possible that someone initially born blind, deaf, or with cognitive disorders may actually surpass the average capability levels of people born without those disabilities. It is also likely that these technologies will be adapted to augment the capabilities of learners not diagnosed with any special needs.

Ideally, such augmentations should be available for all students and faculty, but what if they cannot afford them? How would the presence or absence of enhancements affect the admissions process? Universities alone cannot be expected to guarantee universal access. To benefit from knowledge today you sometimes have to have the wealth to buy an iPhone or live somewhere with wireless Internet access. Amartya Sen (2000) describes development as freedom because those in poverty worldwide have few options compared with those of even modest means.

Today's capability divides (e.g., wealth, place of birth, etc.) exist in part due to the lack of governance systems that would ensure everyone has access to the applications of knowledge. Spohrer (2002) explores the meaning of learning in an age of rapid technological change, and concludes that new rules and regulations must co-evolve with new technologies brought about through convergence. Advanced civilizations must be as good at developing new governance systems (rules) as they are at developing technological systems (capability augmentations).

Universities are great places to discuss the ethics of equal access to these technologies, the governance systems required to create such access, and also the values issues that arise (for example, not all those born deaf want cochlear implants for themselves or for their children). Universities are also going to be deeply involved in creating the breakthroughs that lead to these technologies and have an interdisciplinary community that could conduct research on, and evolve solutions to, emergent problems.

Resiliency in Our Systems

Another challenge is resiliency. Anyone who uses distance education now knows that even well-known technologies have glitches. Two of the first author's classes were canceled one semester because of a failure of the University of Virginia's campus-wide online system for scaffolding student collaboration—it simply crashed. There were other failures caused by interactions among mutually dependent IT systems and human actors, to the point where as much time was spent troubleshooting the systems with support people as was spent teaching.

Imagine super-performing students whose tightly coupled convergent technologies crash, and who may no longer be able to operate without them. Then add the possibility of hacking into these systems—of hacking into neural-IT interfaces and stealing information, substituting memories, or just disrupting thought and action with viruses.

Resilient systems are critical—and part of this resilience depends on the ways in which our cognition, our minds, are distributed across a range of technologies and shared with other human beings (Gorman 1997). Can this kind of resilience be maintained or even enhanced by a more virtual university? If modern university campuses are turning from academic villages into mini-cities (including increasing numbers of student linked online), then how can innovativeness, equity (competitive parity), sustainability, and resilience of these nested, networked systems be enhanced (Spohrer and Giuiusa 2012)? As the amount of knowledge on which societies depend for a high quality of life grows, so, too, does the knowledge burden to maintain sustainability and resilience, thereby stressing the responsible individuals and institutions that must either carry more knowledge or communicate and interact with larger populations of entities across which the knowledge is distributed (Jones 2005).

Transcending the "Online" Debate

In the recent push toward online education, what's striking is what has been largely missing from the conversation. The online education debate up until this point has largely been one-dimensional, focused on the ability to put classes online. Certainly there are related issues: the significance of this movement upon higher education and the broader public, as well as the viability in terms of profit. But online education is about much more than simply transcending the boundaries associated with traditional universities—brick-and-mortar classrooms, large, lecture-based classes, increasingly rigorous enrollment requirements, etc. It is also about the wealth of convergent technologies that have transformative potential for augmenting and enhancing human performance and capabilities. Indeed, if we pause and think about the educational opportunities enabled by the mix of mobile devices, virtual reality goggles, neural interfaces, crowdsourcing platforms, haptic tools, and the like, we can start to see just how revolutionary this transformation can be. Not only institutions but also individuals will be transformed—their capabilities and their opportunities. In many ways, these are the questions that should be asked of university presidents and by which we should judge their tenures—not simply whether they are partnering with today's big-name online education providers, but how are they partnering with their local communities to enhance quality of life for everyone (Trani and Holsworth 2010). Convergent technologies will create additional opportunities for university–business partnerships, with universities providing breakthrough R&D and education not only in how to create new technologies (Lécuyer 2006) but also in how to study and manage their impacts. Universities will have to evolve policies for the conflict-of-interest and intellectual property disputes that can arise from these collaborations (Cole 2009).

Properly managed, the most likely impact of convergent technologies on universities is the potential to deliver a quality education off-campus to a much more diverse student population globally—but those students will have to be living somewhere, supported by local infrastructure and local institutions. Wise universities will begin to experiment with these new capabilities, just as they are now doing with online education, comparing this kind of education with the campus experience. Those who learn at a distance could be required to spend some time on-site, just as those on a campus are encouraged to go abroad. All of these experiments must be done with careful attention to social and ethical issues.

The university as an institution is over a thousand years old. Will it still exist in another thousand years? If we survive our own tendency to go to war with each other, human beings at that point may have diverged into what amounts to multiple species, based on the capabilities and choices available to people. We may be mining asteroids, settling other planets, and having at our disposal a "utility fog" that allows self-assembly of desired items (Spohrer and Engelbart 2004). Each generation will live longer, and the capability gap between generations may grow over time, depending on multiple nanotechnology, biotechnology, information technology, and cognitive science (NBIC) (and beyond) enhancements that interact in complex ways. There will be an increased need for institutions that study and teach this process of transformation, and encourage deep reflection on what sort of future we are evolving, and why. Universities should not simply react to these changes; they will be discovering and inventing many of the technologies that will produce transformations (including educational ones) and are therefore in a unique position to study and manage their impacts, reflecting on what kind of brave new worlds we want to create.

8.8.4 University at Albany, College of Nanoscale Science and Engineering (http://cnse.albany.edu/)

***Contact person**: Alain C. Diebold, University at Albany, State University of New York*

The College of Nanoscale Science and Engineering of the University at Albany, State University of New York (SUNY) is the first college in the world dedicated to education, research, development, and deployment in the emerging disciplines of nanoscience, nanoengineering, nanobioscience, and "nanoeconomics." At CNSE, academia, industry, and government have joined forces to advance atomic-scale knowledge, educate the next-generation workforce, and spearhead economic development. The result is an academic and corporate complex that's home to world-class intellectual capital, unmatched physical resources, and limitless opportunities.

CNSE has reshaped the traditional "silo"-type college departmental structure into four cross-disciplinary constellations of scholarly excellence in nanoscience, nanoengineering, nanobioscience, and nanoeconomics. Through this game-changing paradigm, students engage in unique hands-on education, research, and training in the design, fabrication, and integration of nanoscale devices, structures, and systems to enable a wide range of emerging nanotechnologies. Students are supported by internships, fellowships, and scholarships provided by CNSE and its array of global corporate partners. CNSE complements its groundbreaking bachelor's, master's and Ph.D. programs in nanoscale science and engineering with educational outreach to elementary, middle, and high schools; partnerships with community colleges and academic institutions around the world; and certificate-level technical training. This unprecedented effort is designed to educate the next generation of nanotechnology-savvy professionals and build the foundations of a skilled nanotechnology workforce at every level.

Buoyed by its unparalleled combination of intellectual know-how and leading-edge technological infrastructure, CNSE's Albany NanoTech Complex is the site of some of the world's most advanced nanoscale research, development, and commercialization activities. Here, academic and corporate scientists engage in innovative research in a variety of fields, including clean energy and advanced sensor and environmental technologies; advanced CMOS and post-CMOS nanoelectronics; 3D integrated circuits and advanced chip packaging; ultra-high-resolution optical, electron, and EUV lithography; and nanobioscience and nanomedicine.

CNSE has built the world's first "nano mall," known as CNSE's Albany NanoTech Complex (Fig. 8.7). With more than $14 billion in high-tech investments, it serves as the hub of the world's most advanced university-driven research enterprise, offering students a one-of-a kind academic experience and providing over 300 corporate partners with access to an unmatched ecosystem for leading-edge R&D and commercialization of nanoelectronics and nanotechnology innovations. CNSE's footprint spans upstate New York, including its Albany NanoTech Complex, an 800,000-sq-ft megaplex with the only fully integrated, 300 mm wafer, computer

Fig. 8.7 Photo of the CNSE Albany NanoTech Complex (Courtesy of S. Janack)

chip pilot prototyping and demonstration line, with 85,000 sq ft of Class-1-capable cleanrooms. More than 2,700 scientists, researchers, engineers, students, and faculty members work here, including representatives from such companies as IBM, Intel, GlobalFoundries, SEMATECH, Samsung, Taiwan Semiconductor Manufacturing Company (TSMC), Toshiba, Applied Materials, Tokyo Electron, ASML, and Novellus Systems.

In September 2011, New York Governor Andrew M. Cuomo announced a $4.8 billion investment to develop a new era of computer chip technology in New York, highlighted by creation of the world's first Global 450 Consortium (G450C), headquartered at and managed by CNSE, through which Intel, IBM, Samsung, GlobalFoundries, and TSMC will work collaboratively to lead the industry transition from 300 mm wafer to 450 mm wafer production. A concurrent expansion will add nearly 500,000 sq ft of next-generation infrastructure, an additional 50,000 sq ft of Class-1-capable cleanrooms, and more than 1,000 scientists, researchers, and engineers from CNSE and global corporations.

In addition, CNSE's Solar Energy Development Center in Halfmoon, New York, is an 18,000-sq-ft facility that features a state-of-the-art, 100 kW prototyping and demonstration line for next-generation copper indium gallium selenide (CIGS) thin-film solar cells. CNSE's Smart System Technology and Commercialization Center of Excellence (STC) in Rochester offers the largest array of world-class solutions in the industry related to microelectromechanical systems (MEMS), including a 140,000-sq-ft facility with over 50,000 sq ft of certified cleanroom space with 150 mm wafer production, complemented by a dedicated 8,000-sq-ft MEMS and optoelectronic packaging facility. CNSE also co-founded and manages operations at the Computer Chip Commercialization Center at SUNYIT in Utica and is a co-founder of the Nanotechnology Innovation and Commercialization Excelerator in Syracuse.

And, in partnership with SEMATECH, CNSE leads and serves as headquarters for the $400 million U.S. Photovoltaic Manufacturing Consortium (PVMC), an industry-led collaboration created through the U.S. Department of Energy's (DOE) SunShot initiative to accelerate next-generation photovoltaic (PV) technologies, with a goal of reducing the total installed cost of solar energy systems by 75 % over the next decade.

8.8.5 The David H. Koch Institute for Integrative Cancer Research at MIT (http://ki.mit.edu/)

***Contact person**: Amanda J. Arnold, MIT*

As noted throughout this study, convergence will be key to advances in many crucial areas. This case study describes how Massachusetts Institute of Technology (MIT) is literally internalizing the convergence approach and rebuilding itself to tackle the innately interactive challenges of cancer.

In 2007, MIT launched a partnership between the faculty of the former MIT Center for Cancer Research (CCR) and an equivalent number of distinguished engineers drawn from across MIT's science and engineering departments. By 2010, the David H. Koch Institute for Integrative Cancer Research was born in Building 76 (Fig. 8.8).

Infrastructure: The Importance of Physical Facilities

Building 76 or The Koch Institute (KI) was built specifically to foster the cross-disciplinary approach of convergence. The building features roughly 180,000 sq ft of state-of-the-art laboratory and work space. The floor plans are specially designed to foster interaction and collaboration among biologists and engineers—both in terms of dedicated lab space and in the common areas, where informal talks lead to new collaborations and spontaneous information-sharing.

Importantly, KI features 13 core facilities[30]—now being rededicated as the Swanson Biotechnology Center—to provide centralized technical services to faculty and students. From routine (though essential) support services to advanced technical and consulting services, these cores facilitate, support, and enhance KI research. Many of the facilities also offer training programs that enable Koch Institute staff, students, and postdoctoral fellows to acquire the additional technical and intellectual expertise needed to advance both their work and their careers.

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[30] The full list of 14 KI core facilities is available at http://ki.mit.edu/sbc

Fig. 8.8 MIT's Koch Institute (photograph from http://ki.mit.edu/approach/ki)

Examples of these core units include:

- *Applied Therapeutics & Whole Animal Imaging*: This provides assistance with design, approval, and execution of relevant preclinical trials, in addition to instrumentation for *in vivo* and whole animal imaging.
- *Bioinformatics & Computing*: This provides Koch Institute researchers with assistance with experimental design and subsequent analysis of next-generation sequencing (Illumina platform) and microarray experiments, genome annotation projects, and other sequence and phylogenetic analysis applications, in addition to critical data backup as well as desktop hardware installation and maintenance.
- *Biopolymers & Proteomics*: This provides integrated synthetic and analytical capabilities for biological materials, including DNA, proteins, and nanoparticles. Services include sequencing, mass-spectrometry-based proteomics approaches for identification, characterization, or quantitation of proteins from simple to complex mixtures, and high-pressure liquid chromatographic analysis and purification.
- *High-Throughput Screening*: This supports development of a wide range of experimental assays into high-throughput screening strategies and includes liquid-handling robotic systems, high-content imaging capabilities, and management of RNAi and small molecule libraries.
- *Histology*: This assists investigators in producing quality histological slides from frozen, paraffin-embedded, and resin-embedded tissues, thus enabling

investigators to better evaluate the pathologic consequences of various mutations or treatments.
- *Nanotechnology Materials*: This is one of the newest cores; it supports new materials discovery and optimization, enabling development of drug- and gene-delivery vehicles, imaging, nano- and microparticles, and devices.

The costs of these core services are partially defrayed by funds from a number of sources, most notably a Cancer Center Support Grant to KI from the National Cancer Institute (NCI) at the National Institutes of Health (NIH). To the extent capacity will allow, a number of the cores are available to the broader MIT community and other collaborators.

Workforce Preparation and Training

In addition to the unique combination of scientists, clinicians, and engineers utilizing shared core facilities, the faculty and trainees cross-collaborate via research focus areas that drive the convergence of life, physical, and engineering sciences at KI. The main research focus areas at KI are:

- Nano-based formulation
- Detection and monitoring
- Metastasis
- Analysis of pathways of sensitivity and resistance
- Cancer immunology

The educational philosophy of the convergence model at KI requires that a deep disciplinary background remains vital but that a robust cross-disciplinary education is essential. Trainees and faculty at KI learn a kind of “convergence culture” to help them communicate across disciplinary lines and to become fully “multilingual” among and between disciplines.

The Funding Model

Federal funding is a key component of KI sustainability. Specifically, KI efforts are propelled in many ways by innovative funding models offered by the National Cancer Institute (NCI), part of the National Institutes of Health (NIH).

KI benefits from its designation as 1 of 12 Physical Sciences in Oncology Centers (PS-OC) awarded by NCI. The MIT PS-OC is collaboration among MIT, Harvard University, University of California–San Francisco, Harvard Medical School, Boston University, Hubrecht Institute, and Brigham and Women’s Hospital. The overarching goal of this team is to use both theoretical and experimental approaches inspired by physics and engineering to attack important problems in cancer biology by developing novel technology and analytical and computational methods to track the dynamics of cancer at the single-cell level.[31]

KI is also a key component of the MIT-Harvard Center for Cancer Nanotechnology Excellence (CCNE). This is a collaborative effort among MIT, Harvard University, Harvard Medical School, Massachusetts General Hospital, and Brigham and Women's Hospital. It is one of eight Centers of Cancer Nanotechnology Excellence awarded by NCI and focuses on developing a diversified portfolio of nanoscale devices for targeted delivery of cancer therapies, diagnostics, noninvasive imaging, and molecular sensing. In addition to general oncology applications, the consortium focuses on prostate, brain, lung, ovarian, and colon cancer.[32]

A third and key component of Federal funding that is driving work at KI is MIT's participation in the NCI Integrative Cancer Biology Program (ICBP). MIT was first awarded this grant for the period September 2004–February 2010 to develop and effectively apply systems biology approaches to fundamental problems in cancer biology and therapy. Building on the cross-disciplinary success of the ICBP at MIT, KI received NCI funding to become a Center for Cancer Systems Biology (CCSB), a part of NCI's ICBP, in March 2010. The purpose of the NCI CCSB initiative is, "to stimulate the development and application of the integrative systems approaches and mathematical/computational modeling to cancer research … specifically in the areas of (a) cancer biology, (b) experimental therapeutics, (c) early interventions, and (d) cancer susceptibility."[33]

However, Federal funding does not make up the whole picture. Creative exploration at the leading edge of cancer research has often led to important, transformative new discoveries that themselves can lead to major improvements in patient care. Yet early-stage ideas often do not always qualify for funding from traditional government sources. To support ideas considered too risky for Federal research, the Koch Institute Frontier Research Program is a funding model that supports boldly conceived, highly innovative, and highly collaborative research proposals from faculty. Project areas funded in Koch's Frontier Program include:

- Inhaled nanoparticle formulations to deliver small interfering RNA (siRNA) molecules into the lungs of cancer patients
- Surgical tools that facilitate the real-time detection of residual cancer cells on surgical margins
- Methods to reactivate the tumor-specific immune cells in melanoma patients

There is no doubt that industry partnerships are also an important aspect of the KI funding model. For instance, TRANSCEND is a partnership between KI and

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[31] For more information about the MIT PS-OC, visit http://ki.mit.edu/approach/partnerships/psoc

[32] Additional information about the NCI Alliance for Nanotechnology in Cancer, MIT-Harvard CCNE is available online at http://nano.cancer.gov/action/programs/mit/

[33] For more information about KI and NCI's Integrative Cancer Biology Program see http://ki.mit.edu/approach/partnerships

Ortho-McNeil-Janssen Pharmaceuticals, Inc. The initial 5-year collaborative agreement fosters oncology research and technology development in the areas of cancer diagnostics, cancer biology premalignancies, genetic models of disease, and profiles of the tumor microenvironment. A Joint Scientific Steering Committee composed of MIT faculty members and Ortho-McNeil Janssen employees jointly reviews and selects proposals from MIT researchers for funding. In addition, there is a provision for visiting scientists from Ortho-McNeil Janssen to participate in projects within the investigators' laboratories at the Koch Institute.[34]

University Partners

At a national level, more institutions are developing courses and programs that prepare students, postdoctoral researchers, and fellows for convergence-driven research. These efforts should be supported with concentrated Federal funding. Emerging university efforts working at the frontier of converging technologies include (Sharp and Langer 2011):

- Stanford University: The Clark Center (2003) houses the Bio-X program
- Harvard University: The Wyss Institute (2009)
- Georgia Tech: The Petit Institute for Bioengineering and Bioscience (1995)
- University of Chicago: Molecular Engineering Institute (2011)
- University of Michigan: North Campus Research Complex (2009)

8.8.6 Informal Education: NISE Net and NanoDays (http://www.nisenet.org/nanodays)

***Contact person**: Larry Bell, Museum of Science, Boston*

The Nanoscale Informal Science Education Network (NISE Net) was launched in 2005 with National Science Foundation support to foster public awareness, knowledge, and engagement with nanoscale science, engineering, and technology through establishment of a network, a national infrastructure that links science museums and other informal education organizations with nanoscale science and engineering research organizations. As with converging technologies today, nanotechnology at that time was little known by the public or by educators and exhibit developers in informal educational institutions.

Informal educational activities about nanoscale science and engineering were virtually nonexistent 10 years ago, and even fundamental ideas about the behavior of matter at the nanoscale were mostly absent from informal science education. For the most part, informal science educators felt that content of this sort was too

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[34] More information about partnerships at KI is available at http://ki.mit.edu/approach/partnerships

difficult for the public to understand, not really exhibitable, and of little interest. As a result, prior to 2005, nanotechnology was covered in only a small number of ISE institutions. Inverness Research Associates reported that at that time there was little expertise, experience, or incentive to provide nanoscale science education for the public (St. John et al. 2009). Neither science museums nor science research institutions had all the requisite capacities to carry out high-quality nanoscale science education, and they found little incentive to develop such capacity, as it was unclear that their audiences had a driving interest in the topic.

To address these challenges, NISE Net sought the convergence of expertise from the informal educational community and the nanoscale research center community, including not only scientists and engineers but also educational outreach specialists and experts from the social and political sciences and the arts. Subsets of this group worked together to create a catalog of accessible and engaging programs, activities, exhibits, forums, media, tools, and guides to support making informal education about topics related to nanotechnology openly available to all. By July 2012, the catalog included 236 entries, all downloadable from http://www.nisenet.org. Accompanying the downloadable activities are 118 evaluation and research reports that provide knowledge about what was learned in developing these educational materials and other activities of the NISE Net.

With the initial entries to this online resource in place by 2008, NISE Net launched a nationwide NanoDays festival of nanoscale informal education at 100 sites across the United States, with the distribution of a kit of educational material featuring several of the most accessible activities from the broader catalog and all of the supporting material an institution would need to host a NanoDays event. The NanoDays kit was designed to make it as easy as possible for a science museum or a research center to have an experience with nanoscale informal science education that is successful for the public participants, the researcher participants, and the informal educators. From 2009 to 2011, 200 physical kits were distributed each year, and in 2012 the total was increased to 225.

Inverness Research has found that national NISE Net efforts, in particular NanoDays, have been catalytic in engaging new informal science education institutions and scientists to enter into nanoscale science education (St. John et al. 2009):

> I think the NanoDays kit communicates that nano is do-able and that it's a shared initiative and the fact that you're doing the same thing that 200 other people around the country are all doing is kind of empowering. (Alexander et al. 2012)

Between 2008 and 2012, NanoDays Kits were distributed to 375 organizations, including nearly 200 science and children's museums, which represent 53 % of all such organizations listed in the database of the Association of Science-Technology Centers. Another 122 went to university research centers/departments, many of which collaborated with science museums and other informal educational organizations. Kits went to all 50 states, Washington, DC, Puerto Rico, and the Virgin Islands (Fig. 8.9).

NanoDays has not only introduced science museums to hands-on activities related to nanotechnology but also has created collaborations between science

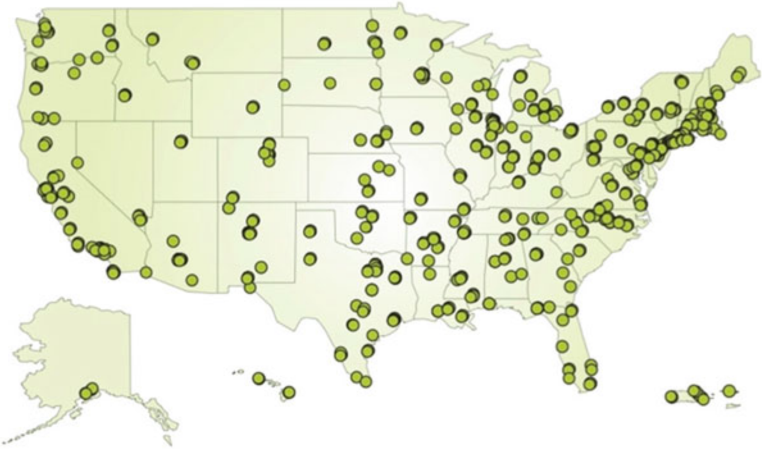

Fig. 8.9 NanoDays map showing the distribution of NanoDays kits to 375 sites in all 50 states, Washington, DC, Puerto Rico, and the Virgin Islands from 2008 to 2012 (http://nisenet.org/nanodays; ©NISE Net, used by permission)

Fig. 8.10 NanoDays teams from just a few of the 225 sites in 2012, comprised of informal educators and research center students (http://nisenet.org/nanodays; ©NISE Net, used by permission)

museums and nanoscale research centers as informal educators, scientists, and university students worked together to provide nano educational experiences for the public (Fig. 8.10). The public has benefited from the knowledge and expertise shared by researchers and graduate students, and the students have gained valuable experience in communicating with the public about their areas of research.

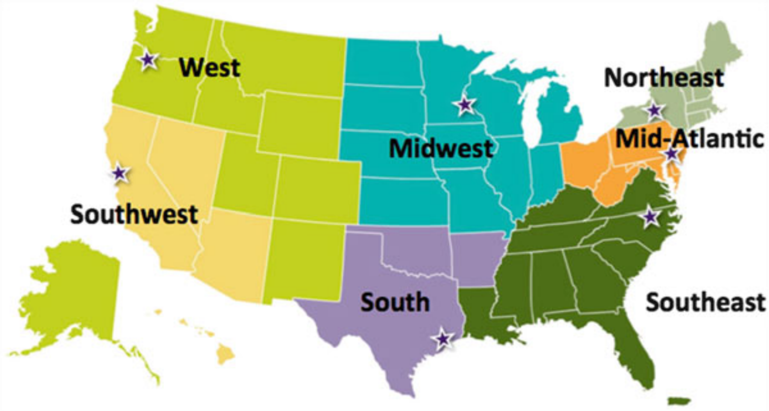

Fig. 8.11 NISE Net Regional Hub Structure (http://nisenet.org/nanodays; ©NISE Net, used by permission)

Like converging technologies—NBIC and beyond—today, nanotechnology was a new and unfamiliar topic to most science museums a decade ago, and creating a sense of a community with a common "cause" was key to getting widespread participation. The NISE Net created a hub structure with seven regional hubs to support the introduction of nanoscale science and engineering content to informal educational organizations nationwide and the deeper infusion of nanoscale content into ongoing programs, exhibits, and other educational activities (Fig. 8.11). This hub structure is a resource that could be used to disseminate other content, including content specifically focused on converging technologies.

Whereas the work of the NISE Net focused on nanotechnology, much of the underlying science is appropriate for a broad range of converging technologies, particularly those that involve work at the nanoscale. Many of the applications anticipated in educational programs about nanotechnology involve nano in convergence with other technologies such as biotechnology or information technology. Finally the NISE Network was made possible by the convergence of the fields of informal education, nanoscale science and engineering, and the social and political sciences. The convergence of these various players, development of the catalog of educational materials, development of the network itself, research and evaluation, and a wide range of activities carried out by the network has been supported by NSF by approximately $4 million/year in two- to five-year awards, beginning in October 2005 and expected to continue through September 2015.

The public has benefited by having educational activities and resources available at sites across the country where people can have a one-on-one, hands-on experience with engaging activities related to nanotechnology. Such work supports both the interest of students in a new field like nanotechnology or converging technologies more broadly, and provides the pubic with a trusted local resource for questions that may arise from current and future applications.

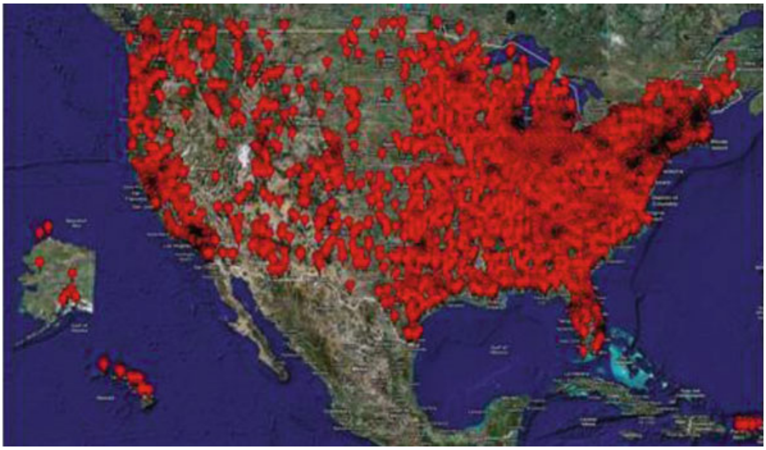

Fig. 8.12 nanoHUB.org users' locations in the United States (© nanoHUB.org, used by permission)

8.8.7 Network for Computational Nanotechnology (nanoHUB) (http://www.ncn.purdue.edu/home/; http://nanohub.org/)

***Contact person**: George B. Adams, Network for Computational Nanotechnology*

The Network for Computational Nanotechnology supports the National Nanotechnology Initiative by designing, constructing, deploying, and operating the nanoHUB.org national cyber-infrastructure for nanotechnology theory, modeling, and simulation. NCN was established in September 2002 and is funded by the National Science Foundation to support the NNI.

nanoHUB.org is a science gateway where users can run any of over 250 nanotechnology simulation programs using their web browsers with just the click of a button. In the 12 months ending June 2012, nanoHUB users ran 570,000 such simulations (see map of U.S. users, Fig. 8.12). They also learned about nanotechnology from 3,300 educational resources, including state-of-the-art seminars and complete courses authored by over 1,000 members of the nanotechnology research and education community.

Purdue University's open-source HUBzero® software platform powers the nanoHUB website, and the open-source Rappture Toolkit is used to build the browser-compatible, interactive, graphical user interfaces for software programs published on nanoHUB.

nanoHUB has already had a strong impact on U.S. nanoscale science and engineering (NSE) research. The simulations and resources of nanoHUB have directly supported 885 research papers in the nanotechnology literature to date. To assess the quality of these papers, the number of citations that each has accumulated was counted and the h-index for the 885-paper "nanoHUB collection" computed. Figure 8.13 presents the results, which show an impressive h-index rating.

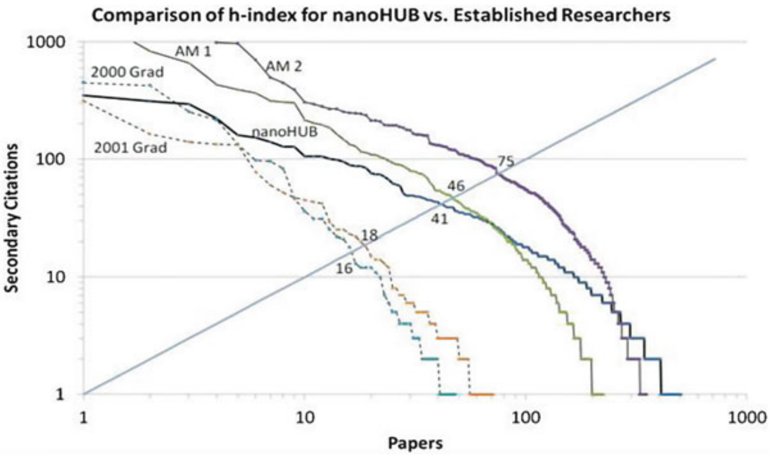

Fig. 8.13 nanoHUB.org h-index compared to two typical researchers earning their Ph.D. in 2000 (2000 Grad) and 2001 (2001 Grad) and two national academy of engineering members (AM 1 and AM 2). The abscissa coordinate is the number of papers that have citations greater than that number. There are 41 papers of the 885 that cite nanoHUB that are in turn cited in the literature at least 41 times. If 10-year-old nanoHUB.org were considered a co-author on these 885 papers, it would have an h-index of 41 (© nanoHUB.org, used by permission; https://nanohub.org/about/contact)

nanoHUB has also had a strong impact on U.S. NSE education. Faculty at 189 institutions have used nanoHUB in 761 classes totaling 14,521 students to date, including all top 50 U.S. engineering schools and 88 % of the top 33 physics and chemistry schools. It should be noted that nanoHUB is reaching students at all academic levels, and it has assumed a strong role in the science education of minority and nontraditional students. For the 449 Minority Institutions listed by the U.S. Department of Education, including 90 Historically Black Colleges and Universities (HBCU), and 215 High Hispanic Enrollment institutions, nanoHUB has been used by 18 %, 34 %, and 23 %, respectively. Bruce Barker, President of Chippewa Valley Technical College, Eau Claire, Wisconsin, has pointed to nanoHUB's value to his students, "We have a high percentage of non-traditional students, many of whom are older and starting new careers, or who are coming from disadvantaged families; nanoHUB provides them with a toehold to a wider academic world." (from telephone interview January 2010 with George B. Adams, Purdue).

nanoHUB is enabling a revolutionary convergence of U.S. NSE research and education. It moves newly published tools into the engineering classroom within months, even weeks, rather than years. Typically, research innovations take about 4 years to enter engineering course content through textbooks. Completely new concepts often take longer. However, simulation programs, primarily authored by researchers, that are published on nanoHUB, and that then reach a classroom do so with a median time of 174 days (5.7 months) (Fig. 8.14).

Fig. 8.14 Histogram of time from software program publication to classroom adoption via nanoHUB.org (© nanoHUB.org, used by permission; https://nanohub.org/about/contact)

NCN is leading an effort to rethink electronic devices from the nanoscale perspective. With support from Intel Foundation, NCN has created "Electronics from the Bottom Up," courseware that may reshape the teaching of nanoelectronic technology and will train a new generation of engineers to lead the Twenty-first Century semiconductor industry. Using these new concepts, NCN is building an electronic device simulation platform that powers several tools on nanoHUB and runs efficiently on the largest computers on the national grid. Dr. Dmitri E. Nikonov, Components Research, Technology, and Manufacturing Group, Intel Corporation, who is charged with using simulation to evaluate beyond-CMOS electronic devices (the next generation of transistors), asserts that, "nanoHUB tools are indispensible to the mission of my department."

NCN built the HUBzero and Rappture Toolkit not as special-purpose software but as infrastructure. Infrastructure is a general, fundamental service platform analogous to community water distribution systems that enable drinking, showering, and irrigation conveniently throughout the community; roadway pavement that provides heavy duty, all-weather pathways for a myriad of vehicles from bicycles to semis; and the electric power distribution system that delivers accurate timekeeping information to clocks and the energy to move elevators from floor to floor. The nanotechnology research and learning communities are using nanoHUB to publish, and thus share, their ideas and the fruit of their labor in ways not before possible. This sharing has brought the members of the community closer together than ever before. Infrastructure is empowering, reduces costs, and ultimately supports applications beyond the imaginings of its creators.

New communities are using HUBzero to carry out their missions, including cancer care engineering, healthcare delivery, pharmaceutical product development and manufacturing, environmental systems analysis, volcano research and risk mitigation, earthquake and tsunami research and risk mitigation, and energy from biomass. These and other communities in the years to come will leverage hub capabilities to help users carry out their missions more rapidly and effectively.

8.8.8 Integrative Graduate Education and Research Tr3aineeship (IGERT) (http://igert.org)

***Contact**: Mihail C. Roco and Melur K. Ramasubramanian, NSF*

NSF's Integrative Graduate Education and Research Traineeship aims to better address grand challenges in science and engineering that are inherently interdisciplinary and complex. It involves not just science and engineering, but also policy, government, and geopolitics. The IGERT program provides support to students to work with three or more advisors on an interdisciplinary topic. The program has been developed to advance the challenges of educating U.S. Ph.D. scientists and engineers with interdisciplinary backgrounds, deep knowledge in chosen disciplines, more holistic research themes, and technical, professional, and personal skills. The program has been intended to establish new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries. It is also intended to facilitate diversity in student participation and preparation, and to contribute to a world-class, broadly inclusive, and globally engaged science and engineering workforce.

IGERT creates opportunities to better tackle grand challenges. For this purpose, it includes systematic training for future scientists and engineers to take on these challenges and strategic support for research, thereby building an innovation ecosystem. Education needs to couple to policy, business, and law and must be student-focused, as well as enhance student interest in engineering, science, and technology entrepreneurship (http://summit-grand-challenges.pratt.duke.edu).

The IGERT program aims at developing career skills desired by both academic and nonacademic employers, catalyzing sustainable institutional change in graduate education for the training of future scientific research workforce, and broadening participation. It provides a framework wherein institutions, through principal investigators (PIs), can propose programs with enough flexibility to accommodate students' desires to design education plans to match their career goals.

The awards are made to institutions ($3–3.2 million for 5 years) with senior PIs who distribute the funds to Ph.D. students typically for 2–3 years. Since 1997, 278 awards were made to 122 different lead institutions in 43 states, Washington, DC, and Puerto Rico. There are about 25 trainees per award, typically supported for 2 years each. IGERT has supported 6,500 Ph.D. students. Examples of multidisciplinary themes supported are nanotechnology, smart sensors and integrated devices, biosphere-atmosphere research, molecularly designed materials, assistive technology, sequential decision-making, urban ecology, astrobiology, and alternate energy sources.

8.8.9 The Graduate School of Convergence Science and Technology (GSCST) at Seoul National University, Suwon, Korea (http://gscst.snu.ac.kr/eng/)

***Contact**: Dr. Y. Eugene Pak, Director Convergence Research Division, Seoul National University*

In the midst of rapid growth in a knowledge-based economy, demand is rising for field-oriented experts with interdisciplinary integration of knowledge in not only basic sciences such as physics, chemistry, and mathematics but also cultural, social, life, and medical sciences. Creative experts are sought in the fields of newly emerged convergence technology such as information technology (IT), biotechnology (BT), and nanotechnology (NT).

The Graduate School of Convergence Science and Technology at Seoul National University was founded in 2009 with the following missions: (1) act as a knowledge-producing base for global standards, (2) lead the development of new technologies for future industry, (3) cultivate creative experts with international competitive power, (4) develop new technologies for industries through the 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 experts in the new convergence technologies such as IT, BT and NT, thereby promoting the creation and development of new industries. GSCST will act as a role model for nourishing creative experts in convergence studies. In order to encourage interaction and convergence among different disciplines, traditionally separate academic departments are loosely divided into programs. GSCST currently consists of four programs—Nano Science and Technology, Digital Contents and Information Studies, Intelligent Systems, and Radiation Biomedical Sciences—and one department: Molecular Medicine and Biopharmaceutical Sciences (see Fig. 8.15).

In addition, all students are required to take an introductory course in Convergence Science and Technology. This course first deals with the definition and classification of convergence science and technology and then introduces the fundamentals of nano-convergence technology, digital contents convergence technology, and intelligent convergence systems technology. Students are assigned a term paper or a term project that is carried out in teams consisting of students with diverse backgrounds. The main point of this course is to learn to collaborate with people with different specialties in solving complex problems as a team effort. In its fourth year running, currently GSCST has about 217 graduate students in master's and Ph.D. programs. So far, 47 master's students have graduated, most of whom found jobs in high-tech industries such as Samsung, LG, KT, Hyundai, and some even in overseas companies. About a third continued on in a Ph.D. program.

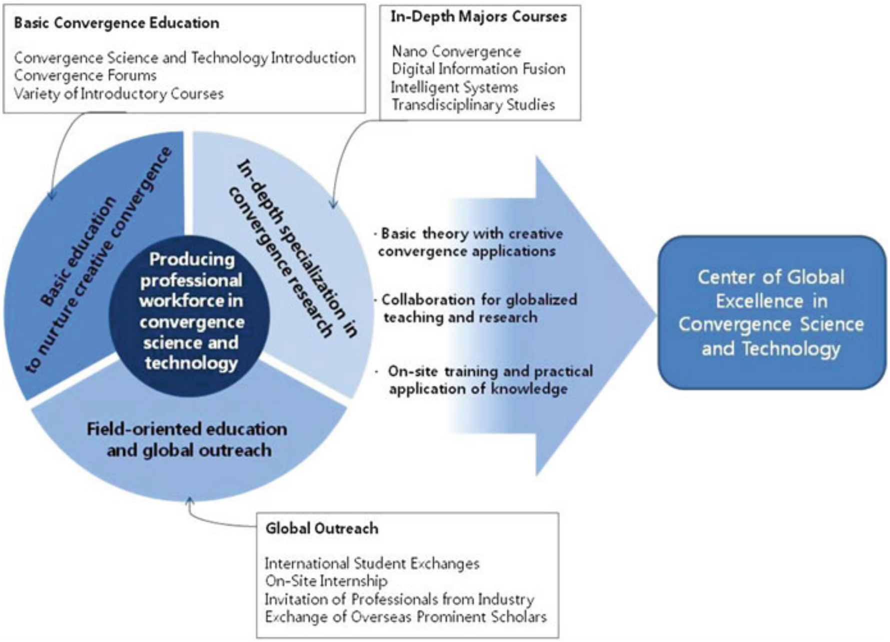

Fig. 8.15 Vision of the graduate school of convergence science and technology (Courtesy of Y. E. Pak)

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, materials science, and mechanical engineering. This wide scope of the emerging NSET presents both promises and challenges: NSET, via convergence, has the potential of providing novel solutions and technologies unavailable from the traditional scientific disciplines individually, thereby greatly improving the ways humans obtain and process information, diagnose and treat diseases, and address energy and environmental issues. The challenge is that we must have the intellectual foresight to identify potential convergence areas having the greatest academic and social impacts. We also must turn those opportunities of convergence into reality.

The mission of our NSET program is to educate next-generation engineers and scientists who possess a solid understanding of the principles of nanoscience and are capable of making real-world impact. The department offers interdisciplinary courses and research opportunities at master's and Ph.D. levels in the following three loosely defined areas: Nanophysics and Nanodevices, Nanomaterials and Nanochemistry, and Nanobiological Science.

Program in Digital Contents and Information Studies. This addresses the radical changes in the information-oriented society that have greatly affected and altered our behavior, our life, and the whole social structure. In order to prepare for such changes, we must take “information-convergent” approaches by converging what was once regarded as independent fields of study, including information science, computer science, communication studies, business administration, and so on. Such convergent approaches require education and research institutes that can train analysts, directors, designers, and managers who not only have a high understanding of human society and culture, but who also are familiar with information technology.

In many countries, an Information School or iSchool already exists, providing a program for “information-convergence”. These schools originate from library science and computer science; however, there are a number of factors in these programs that do not fit well with Korea’s reality. In order to meet Korea’s needs, Seoul National University launched its Information Convergence program as a collaborative effort between the Computer Science Department that provides education and research programs relating to information technology studies, and the Information Technology & Contents Technology (ITCT) Department that has capability for designing and analyzing the cultural contents with in-depth understanding of information technology. The goal is to understand people’s needs and usage of information, analyze the role of information within our society, and to construct the information infrastructure for cultural understanding. Throughout this, we intend to create a better environment where people can create and share knowledge more effectively. Furthermore, we plan to bridge the gap between academia and industry by taking reality-based approaches that will maximize the students’ potentials and research minds. We believe that such efforts will help train students to be creative and skilled enough to be able to work in the IT, knowledge-based, or cultural contents industries.

Program in Intelligent Systems. This combines mechanical engineering, computer engineering, human engineering, electrical and electronics engineering, intelligent systems engineering, business, and industrial design. One good example of intelligent systems is self-driving vehicles, which encompasses a synergistic combination of future smart cars with various information technology infrastructures such as cloud computing. The program seeks to establish intelligent systems that link humans, engineering, and markets together to foster experts who can apply the knowledge to reality, and to cultivate experts with professional knowledge who are capable of creating an innovative thought process.

Program in Radiation Biomedical Sciences. This utilizes a wide range of cutting-edge interdisciplinary academic study encompassing radiology, biophysics, radiopharmacology, radiochemistry, nanomolecular imaging, and imaging science, and it exploits the new biomedical science fields by converging a variety of traditional academic majors such as medicine, physics, pharmaceutics, chemistry, nuclear engineering, electrical engineering, materials science, and mechanical engineering. Recently, a part of the program (i.e., interdisciplinary program in Radiation Applied Life Science) became the world’s first accredited medical physics graduate course outside of North America. This program has been developed into world-class education and research par excellence.

The curriculum of Radiation Biomedical Sciences focuses on the training of creative interdisciplinary specialists based on the expert knowledge of radiation science and biomedical science. We provide the education and practice for these experts to become core human resources who would manage medical institutions and national laboratories. We are creating a talent pool who will eventually nurture the domestic industry of radiation and medical appliances. The graduate program in Radiation Biomedical Science has the educational purpose to foster world-class human resources who have the interdisciplinary expertise, capability for combining that knowledge, and creative research skills. They are expected to lead the future interdisciplinary studies-oriented convergence science and technology field of Radiation Biomedical Convergence.

The *Molecular Medicine and Biopharmaceutical Sciences Program*. This program belongs to the World Class University (WCU) project, is a newly established division of the Graduate School at Seoul National University. It aims to become the world's top-ranked program in molecular medicine and biopharmaceutical science through collaborative research with the greatest scholars in the world. It is a graduate program to train professionals for translational research, combining fundamental knowledge in medical life science with applied knowledge such as pathophysiology, preclinical and clinical trials, and clinical medicine.

Up to now, research in the biomedical field has had limitations with respect to immediate clinical application because previous studies concentrated only on basic research rather than considering clinical applications. However, the importance of translational research has recently gained interest as a means of forming a bridge between research results and clinical medicine and related industries. Basic research scientists propose new methods or materials to clinicians to treat patients. Clinicians deliver clinical information or results of illnesses to basic scientists so that they can induce more meaningful results from their basic studies. Therefore, the necessity of translational research is gaining strength as a means to implement new technology in clinical medicine and pharmacology, and to apply the results of basic life science to clinical fields and development of new drugs. Translational research can provide a better understanding of the cause and mechanisms of a certain disease through studies of clinical medicine at the molecular level.

One approach of clinical medicine is to treat illnesses through pharmaceuticals. In our current aging society, our dependency on medicines is deepening every day. In order to develop a new medicine, we first need to understand the etiology of the disease, discover target molecules, and validate the efficacy of the produced medicine. In order to develop a medicine with therapeutic efficacy, we need to find the active compound that acts on the target molecules. To discover such compounds, many have to be screened and their efficacy, toxicity, and bioavailability analyzed to find the leading compound. This process is a main area of pharmacology. If medicine and pharmacology are combined, discovery and validation of targets and deduction of active compounds are done in the same place, making the environment for developing new medicines optimal. Also, when pharmacology and medicine are combined, the clinical information of the efficacy of active compounds can be exchanged swiftly, definitely making it possible to efficiently procure leading compounds.

8.8.10 Building a Next-Generation Convergence Research Hub at the Advanced Institutes of Convergence Technology (AICT), Seoul National University (SNU), Suwon, Korea (http://aict.snu.ac.kr/eng/)

Contact: *Dr. Y. Eugene Pak, Director Convergence Research Division, Seoul National University*

Established in 2008 with investment from Gyeonggi Province, the AICT is located in the Gwanggyo Techno Valley (GTV) near Korea's capital Seoul. More than 50 % of Korea's population and much of its industry and intellectual infrastructure are located in the province. This recently established "mini cluster," which combines features of a research institute, business incubator, and learning institution, has chosen to specialize in the convergence of key technologies deemed crucial to the future of the competitiveness of the Korean economy. To this end, the Seoul National University has established the Advanced Institutes of Convergence Technology (AICT) and the Graduate School of Convergence Science and Technology (GSCST) on the GTV campus. AICT's mission is to combine cutting-edge research on convergence technology with the education of a new generation of innovators trained in interdisciplinary science and engineering—all with the purpose of creating a next-generation high-tech hub based on convergence technology applications. In addition, the Korea Advanced Nano Fab Center (KANC), the Gyeonggi Bio Center, and the Gyeonggi Small & Medium Business Center (GSBC) have also been located in the valley to provide a comprehensive infrastructure to conduct convergence technology research and business development. GTV is close to large multinational companies such as Samsung, Hyundai, SK, and KT, as well as many high-tech SMEs. With this strategic location, GTV can act as a "corridor" or "link pin" connecting other technology clusters situated near Seoul and in other parts of the country.

Locating the research institutes away from the main campus of SNU 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.

The four institutes organized around 17 research centers cover convergence technology areas such as nano, bio, IT, and transdisciplinary studies (see Fig. 8.16). Through the process of providing seed funding by the AICT and assistance with moving from early planning to the pilot stage, the Bio Convergence Institute was able to win a 10-year $100 million government grant to develop key technologies for fast and low-cost drug development (BioCon). This project brings together many researchers from diverse disciplines such as molecular biology, bioinformatics, micro and nano engineering, as well as robotics.

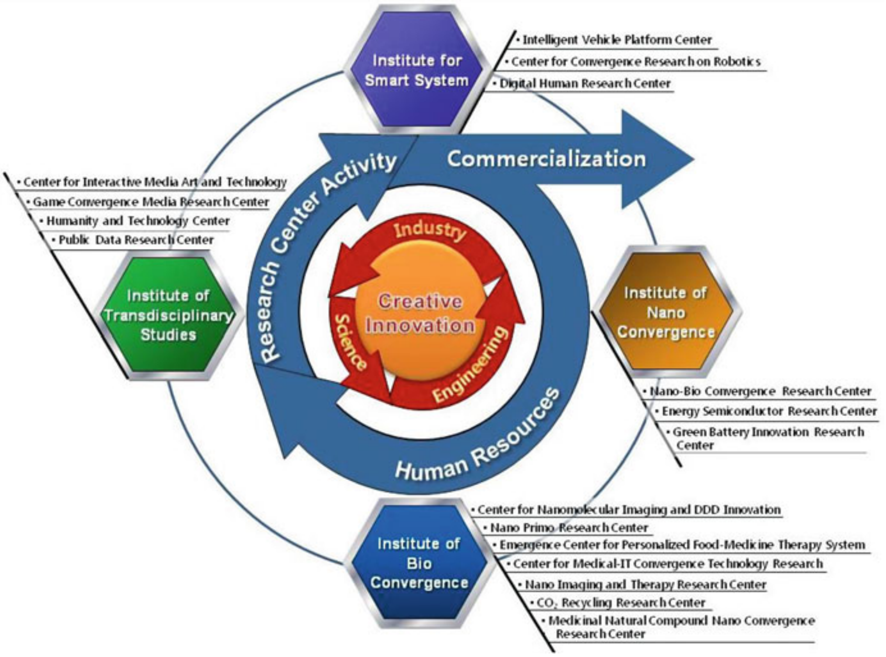

Fig. 8.16 Diagram illustrating the concept of AICT (Courtesy of Y. E. Pak)

In order to encourage this type of success, AICT provides seed funding and infrastructures for research projects that have high convergence content. Another area of high-impact research is the future intelligent vehicle platforms program based on electric power for clean environment and IT and cloud computing for convenience and safety. Companies can participate in this process and be partners in establishing centers of excellence whose members include researchers from the various participating organizations. Overseas institutes are also welcome to join or invest in these Technology Centers of Excellence. For example, the Energy Semiconductor Research Center was formed with the support from a global LED (light-emitting diode) company to work together on key technological issues as well as to identify new applications that require convergence of disciplines, including industrial design, psychology, and human sensory perception.

AICT managers believe that convergence technology is the key to successful future innovation, and they see large South Korean companies well suited for this new phase of global competition. In order to strengthen the budding SMEs to be more globally competitive, an executive education program called the World Class Convergence Program (WCCP) was created to train CEOs and

CTOs to utilize new convergence technologies so that new business opportunities can be created. To strengthen its alliance with the business sector, AICT is in close collaboration with the Korea National Industrial Convergence Center, whose charter is to make strategic plans for the successful incubation and application of convergence technologies in industry.

Key to successful convergence is learning to define a clear end goal and identifying critical constituent disciplines or technologies so that an appropriate team of experts can be brought together to meet the end goal. AICT has invited professionals from industry to join in this team-building effort with professors, researchers, and students. AICT also tries to create an environment to allow free exchange of ideas that encourage new and innovative concepts to develop from diverse backgrounds. To this end, a very flexible organizational structure is put in place so that new centers can readily be created and merged.

Technology convergence will continue to play an important role for innovation as technologies become more complex and diverse. Networking of innovation centers with the world-class production or manufacturing clusters will also be important in bringing up the speed to meet future market demands. AICT aims to play this important role in fostering international cooperation of Innovation Centers

8.9 International Perspectives

The following are summaries relevant to this chapter of discussions at the international regional WTEC NBIC2 workshops held in Leuven, Belgium, September 20–21, 2012; in Seoul, Korea, October 15–16, 2012; and in Beijing, China, October 18–19, 2012. Further details of those workshops are provided in Appendix A.

8.9.1 United States–European Union NIBIC2 Workshop (Leuven, Belgium)

The EU workshop on NBIC2 had three working groups: Human Development; Sustainable Development; and Co-evolution of Human Development and Technology. Each identified an important education component—personalized education, melding of STEM and social sciences/humanities in education, and life-long learning. Workshop participants are listed in Appendix B.

The Human Development Working Group discussed the opportunity for a paradigm shift by morphing formal and informal education toward adaptive life-long learning systems, a goal especially important as lifespan increases. Converging technologies will enable learning platforms that can be tailored to personal learning modes (print, video, oral, haptic, motion, interactive). To make these platforms successful, it will be necessary to better understand cognition and learning processes, and the human–machine relationship. Because of resistance to change by the existing education systems, there will be challenges to develop the market for personalized education. In addition to the new personalized education platforms, it will be necessary to promote the convergence of traditional disciplines, preferably by improving awareness among those disciplines of the benefits to such a change. At the university level, this will likely require changes to traditional academic organization and reward systems. There needs to be a vetted portal that can provide access to education assets, perhaps an Amazon.edu.

The Sustainable Development Working Group principally addressed sustainability. While converging technologies can provide some partial solutions to a sustainable future, the human factor in education will be critical to changing societal behavior. Better integration of social sciences and humanities with STEM education will be important to realizing that goal. Change will be necessary at all levels, with special attention to integrated, progressive content and to the use of information technology in innovative teaching aides.

The Co-evolution of Human Development and Technology Working Group explored the interplay between machine and human capacities to augment productivity while retaining jobs. Our present education structures are already outdated, and the pace of converging technological change will exacerbate the situation. Education will be key to jobs in the coming economy. To enable the opportunities enabled by converging technology, changes will be necessary at all levels, but especially for vocational, undergraduate, graduate, and continuing education. Converging technology implies innovation, and this must be explicitly incorporated in the educational process. Because of increased use of automation by all organizations, high school education needs to be rethought to include vocational training in the machine–human interface. At the Ph.D. level, converging technologies will require teaming and multidisciplinary perspectives; this will require a different approach than those presently used by most universities.

8.9.2 United States–Korea–Japan NBIC2 Workshop (Seoul, Korea)

***Panel members/discussants*:**

Kwyro Lee, National NanoFab Center (Korea)
James Murday, University of Southern California (U.S.)
Masahiro Takemura, National Institute for Materials Science (Japan)
Mark Lundstrom, Purdue University (U.S.)
Yoon-Hwae Hwang, Pusan University (Korea)
Chul Gi Ko, Korea Advanced Nano Fab Center (KANC, Korea)
Y. Eugene Pak, Seoul National University (Korea)

Physical Infrastructure

In the past 10 years, extensive nanoscale user facilities have been established and are being well used by academia. There remains the challenge to increase industrial usage and to adapt these facilities to converging technologies. For biology this poses a particular challenge since semiconductor-processing cleanrooms are over-pressured to reduce particulate contamination, while biology cleanrooms are under-pressured to reduce the risk of dissemination of any biological materials posing health risks. There is also the challenge to achieve self-sustainability by identifying sources of funding for continuing operation, maintenance, upgraded instrumentation, and availability of skilled operators. This challenge is exacerbated by the need for better coordination among the several government ministries involved in funding such operations.

As the science and engineering basis for converging technologies continues to mature, it will be important to transition into a technology and business development perspective, including test beds for manufacturing that are compatible with large-scale implementation.

The continuing installation of high-speed, real-time Internet linkages to individuals potentially enables the capability for them to gain access to center-based high-cost instruments, and to expand the application of citizen science beyond such topics as astronomy.

Education

The last decade saw increasing acceptance of interdisciplinarity as an essential component for advances in science and technology; this should evolve into a convergence of those disciplines into a transdisciplinary approach, reflected by new university organizational structures and faculty reward systems. As an example, Seoul National University opened its Graduate School of Convergence Science and Technology in March 2009 with the following missions: (1) act as a knowledge-producing base for global standards, (2) lead the development of new technologies in the future industry, (3) cultivate creative experts with international competitive power, (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 experts of the new convergence technology consisting of IT, BT, and NT, thereby promoting the creation and the development of new industries (see case studies, Sects. 8.8.9 and 8.8.10).

The maturation of digital information, including the development of three-dimensional displays and the replacement of desktop consoles with mobile devices, will instigate major changes in education. However, credentialing online courses is still a subject of concern; one approach could be the use of local testing centers for proctored exams.

Korea and Japan have government-funded programs providing world-class research capabilities:

1. In Korea, the World Class University (WCU) project is a higher education subsidy program of the Korean government, which invites international scholars who possess advanced research capacities to collaborate with Korean faculty members and establish new academic programs in key growth-generating fields. With a vision to enhance the competence of Korean universities and nurture high-quality human resources, the WCU project seeks to achieve two goals:
   - Enhance national, higher educational, and industrial competitiveness in interdisciplinary fields
   - Transform Korean universities into world-class research institutions
2. In Japan, the World Premier International Research Center Initiative (WPI) was launched in 2007 by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in a drive to build within Japan "globally visible" research centers that boast a very high research standard and outstanding research environment, sufficiently attractive to prompt frontline researchers from around the world to want to work in them. These centers are given a high degree of autonomy, allowing them to virtually revolutionize conventional modes of research operation and administration in Japan.

There is a need for a high-impact journal and a professional society addressing convergent technologies.

8.9.3 United States–China–Australia–India NBIC2 Workshop (Beijing, China)

Panel members/discussants:

James Murday, University of Southern California (U.S.)
Chennupati Jagadish, Australian National University (Australia)
Xiaomin Luo, BGI Healthcare (China)
Mark Lundsgtrom, Purdue University (U.S.)

Physical Infrastructure

The existing nanoscale user facilities need to be generalized to address converging technologies; these facilities are important in that they enable better communication between researchers as well as provide access to specialized instrumentation. While many modern electron microscopes can be remotely controlled, this capability needs to be instituted in other high-cost, user-facility equipment. Self-sustained funding for facilities is also a problem in this region of the world.

Both China and Australia have instituted efforts to facilitate the scale-up of nano-enabled technologies. The Cooperative Research Centres (CRC) program is an Australian Government Initiative administered by the Department of Industry, Innovation, Science, Research and Tertiary Education. The CRC program supports end-user-driven research collaborations to address major challenges facing Australia. CRCs pursue solutions to these challenges that are innovative, of high impact, and capable of being effectively deployed by the end users.

China's Suzhou Industrial Park held a joint groundbreaking and opening ceremony for 24 new projects in January 2011. Nanopolis, one of the industrial park's communities, has an estimated total investment of USD 1 billion. Its mission is to focus on micro-nano manufacturing engineering, especially the R&D of universal technologies and standard processes in the fields of nanomechanical-electrics and photo-electronics. By centering on pilot lines, the institute will offer support for technological commercialization and project incubation, as well as provide extensive services of talent training, quality control, safety assessment, and intellectual property rights protection. Suzhou Nanotech is a state-owned company under the Suzhou Industrial Park, which is home to the China International Nanotech Innovation Cluster jointly supported by the Ministry of National Science and Technology (MOST), the Ministry of Commerce, and Jiangsu Province.

Education

University programs for the nanoscale continue to evolve, presently mostly as concentrations within a traditional discipline. Some universities, such as Flinders University in Australia, are experimenting with full degrees.

With the maturation of digital information technology, the growing capability to biosense an individual's state of alertness, and growing insights into cognition, the vision of an digital tutor—a personal, lifelong educator—is in reach. This workshop affirmed the personalized digital education goals stated in the visionary priorities of Sect. 8.6. STEM education is the logical initial focus since it has lesser cultural ramifications.

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