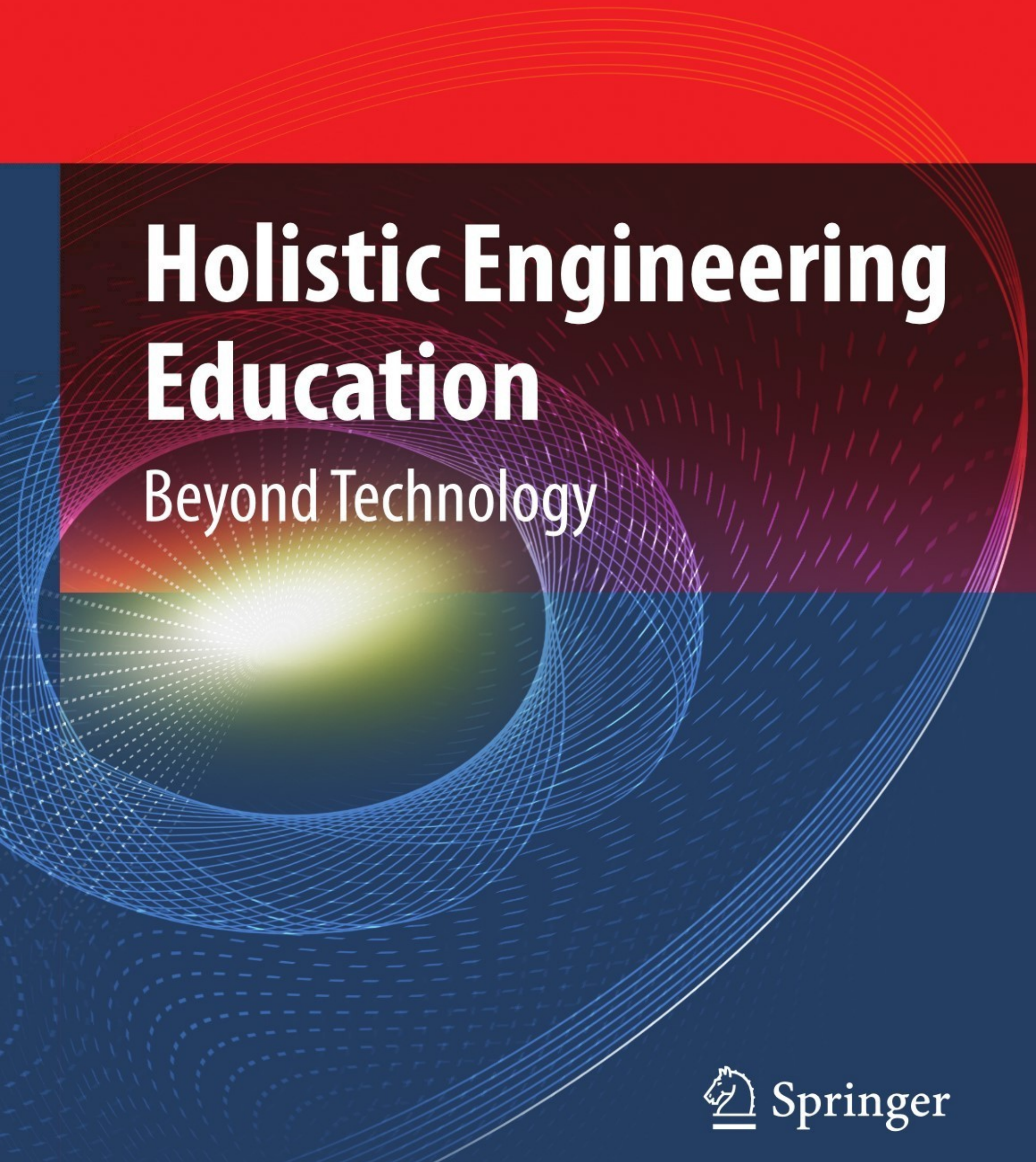
Domenico Grasso
Melody Brown Burkins
Editors



Holistic Engineering Education

Beyond Technology

Springer

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Forewords by C. Judson King, Richard K. Miller
and Maria Klawe

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For our spouses, Susan and Derek, and our children – Benjamin, Jacob, Elspeth, Caitlin, Riley, and Porter – who will inherit and live in the world we design today.

Whereof what's past is prologue; what to come,
In yours and my discharge.

The Tempest
William Shakespeare

Biographical Sketch

Domenico Grasso

Dr. Domenico Grasso is Vice President for Research and Dean of the Graduate College at the University of Vermont. Previously Dean of the College of Engineering and Mathematical at UVM, he holds a B.Sc. from Worcester Polytechnic Institute, an M.S. from Purdue University and a Ph.D. from The University of Michigan. He is a registered Professional Engineer in the states of Connecticut and Texas, and a Diplomate of the American Academy of Environmental Engineers. Prior to joining UVM, Dr. Grasso was Rosemary Bradford Hewlett Professor and Founding Director of the Picker Engineering Program at Smith College, the first engineering program at a women's college in the United States; and Professor and Head of Department in Civil & Environmental Engineering at the University of Connecticut. He has been a Visiting Scholar at UC-Berkeley, a NATO Fellow, and an Invited Technical Expert to the United Nations Industrial Development Organization in Vienna, Austria. He is currently Editor-in-Chief of *Environmental Engineering Science,* and has served as Vice-Chair of the United States Environmental Protection Agency Science Advisory Board, President of the Association of Environmental Engineering & Science Professors and Associate Editor of *Reviews in Environmental Science and Biotechnology*. He has authored more than 100 journal papers and reports, including four chapters and two books. Federal, state, and industrial organizations have supported his research work. He has served on advisory boards at Johns Hopkins, Notre Dame, WPI, and the National Academy of Engineering.

In 1998, Professor Grasso served on a World Bank funded international team of scholars that established the first environmental engineering program in Argentina. In 2000, *The Water Environment Federation* named him a "Pioneer in Disinfection." He chaired a US Congressional briefing entitled "Genomes & Nanotechnology: The Future of Environmental Research." Dean Grasso was co-founder along with Dr. Sally Ride, the first American women astronaut, of TOYChallenge, a national toy design challenge for 5th–8th graders to excite them about science, engineering, and the design process in a fun, creative, collaborative process, relevant to everyday life.

An environmental engineer who studies the ultimate fate of contaminants in the environment and develops new techniques to reduce the risks associated with these contaminants to human health or natural resources, Professor Grasso's research focuses on molecular scale processes that underlie nature and behavior of contaminants in environmental systems. He views engineering as a bridge between science and humanity, making it particularly well suited for incorporation into a liberal arts universities. His classes, although technically rigorous, also explore the societal and philosophical issues facing engineers and scientists.

Melody Brown Burkins

Dr. Melody Brown Burkins is the Senior Director for Research and Strategic Initiatives for the University of Vermont (UVM) in the Office of the Vice President for Research and Dean of the Graduate College. She also serves as Acting Director of the Vermont Advanced Computing Center, working to create opportunities for multidisciplinary programs throughout UVM as well as partnerships with diverse interests in academia, government, and business. Trained as an earth and ecosystems scientist with degrees from Dartmouth College (MS and PhD) and Yale University (BS), Burkins' interests in holistic approaches to science and engineering and 21st century questions in technology and policy stem from experience: as a science educator in the United States and overseas, as part of a multidisciplinary team in Antarctica's McMurdo Dry Valley Long Term Ecological Research (MCM-LTER) program, as an aide in the US Senate, first as the 1999–2000 USGS-GSA Congressional Science and Technology Fellow and then as the energy and environment advisor to US Senator Patrick Leahy.

Since arriving at UVM, Burkins has helped advance strategic priorities for the institution in multiple roles, including Associate Dean for the College of Engineering and Mathematical Sciences and Director of Federal Relations. In 2007, Dr. Burkins was appointed to the National Academy of Sciences' US National Committee to the International Union of Geological Sciences (USNC/IUGS) and became Vice Chair of the committee in 2009. She also serves on the UVM Institute for Global Sustainability Advisory Committee, the International Advisory Council, and the Center for an Agricultural Economy Steering Committee. She serves on the Town of Jericho Planning Commission and has given professional support to the Vermont Engineering and Environment Advisory Committee (VtEEAC). Burkins lives in Jericho, Vermont with her husband, Derek, and their two young sons.

Forewords

This book addresses a major issue of our times. As knowledge has inexorably grown over the years it has become ever more compartmentalized, and nowhere is this truer than in engineering. Engineering has for more than a century been divided into subfields such as electrical, civil, mechanical, and chemical, and now it has become specialized within those fields. Engineering education is nearly entirely scientific and technical. It leaves little room, if any, for learning other areas.

By contrast, actual engineering challenges are more and more multidimensional and are not solely technical in nature. Many engineering issues interact so closely with society and the public sector that they cannot be addressed without full recognition of the social and political dimensions. Examples abound, some of them being energy supply, conversion, and storage; clean water and water conservation; mitigation of pollution of air, land, and water; health care for the world's have-nots; global warming; and harvesting the potential of biotechnology for agriculture, food, and medicines. Many of these issues are so complex that they must be addressed by teams composed of persons versed in a variety of disciplines, with each member being cognizant of the concepts and approaches of the other team members. With globalization of business and society, engineering has become a worldwide profession, requiring good understanding of others' cultures and circumstances. The highly technical and narrow aspects of engineering education have served to limit the population to whom it is attractive. The need for major change in engineering education is urgent.

Domenico Grasso and Melody Brown Burkins have assembled an impressive array of authors from diverse backgrounds to explore the present-day circumstances and needs for engineering education and practice. The ideas and arguments put forward show that, while there is much agreement on the directions of change that are needed, there are still diverse opinions on the specifics. But it is clear that engineering education must be placed on a much wider base of knowledge, must integrate concepts of practice and social needs and impacts with the underlying scientific base, and must provide entry and exit points as education proceeds, rather that implicitly requiring a pre-college career decision. Koshland and Christ, in their essays, are convincing with regard to the value of an underlying liberal education for engineers.

With support and impetus from such leaders, why is change not happening faster? First of all, the traditional undergraduate engineering curriculum is chock full, in fact overstuffed. Thus broadening requires either taking technical material out or moving the professional degree to the graduate level, as is already the case for all other major professions. Therefore, in order to do the job right, not only must there be major broadening but there must also be an accompanying change in degree structure. There are, however, large sources of resistance and inertia. Although many corporate leaders appreciate the needs for broadening and some have explicitly urged movement of the professional degree to the graduate level, industrial recruiters by and large look toward the needs of the initial job function. They are largely satisfied with the present bachelor's engineering graduate and welcome not having to provide the higher salaries that are usually associated with further education. University faculty members have large and interacting burdens of teaching, research, and service. Changes in curriculum and degree structure are added burdens. Many faculty members concentrate upon the technical material that they know best and do not yet see the need for breadth. Professional societies reflect the interests of their industrial and academic members. Breadth serves the career interests of the students, but they are not yet well aware of that and are not much at the table anyhow for determining the curriculum. Breadth also promotes innovation and competitiveness, which are major public benefits, but the public is only very indirectly at the table. Of course, there are important islands where change is happening, but the large movements have yet to occur.

If readers of this volume are convinced that much broader, holistic engineering education must become the norm, what can they do to help it along? Change can and will happen when corporate leaders pass their own recognition of these needs down to the front line of the corporation. It will happen when professional societies and groups such as the National Academy of Engineering succeed in providing convincing arguments to university leaders and accreditors of universities. It will happen when would-be engineering students, their families, and donors of financial aid recognize that the additional expense of a broader education is both a sound investment and intellectually rewarding. It will happen when engineering faculty recognize that the multidimensionality of today's and tomorrow's challenges demand much more breadth than can be packed into the curriculum at the baccalaureate level. It will happen when engineering as a profession recognizes the wisdom that drove medicine, law, business, architecture, pharmacy, and other professions to build graduate-level professional education on the base of a liberal undergraduate education.

Berkeley, California

C. Judson King
Provost and Senior Vice President –
Academic Affairs, Emeritus
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Director, Center for Studies in Higher Education
Professor of Chemical Engineering, Emeritus
Berkeley Campus

A little more than 10 years ago I became the first employee of the Franklin W. Olin College of Engineering. Olin College was created specifically to address the need for systemic change in undergraduate engineering education. As a result, my colleagues and I have spent much of the last decade thinking almost exclusively about the subject of this book. This naturally involved thinking hard about the challenges of the future and also about the nature of engineering.

Taking a broad historical perspective, technology through the ages appears to serve as a form of “amplifier” of human intentions. It enables a smaller and smaller number of people in each succeeding generation to affect the lives of larger and larger numbers of others in society. These effects may be beneficial, or they may not. They may be intentional, or they may be unintentional.

Some years ago the National Academy of Engineering developed a list of the greatest technological achievements of the 20th century. The list included many things that we take for granted today, including electrification, the automobile, the airplane, clean drinking water, the telephone, computers, and the internet. The list is all about things-things that have transformed life on the planet. However, recently the Academy published a new list of 14 grand challenges for the 21st century. This new list is characteristic of a broad set of challenges that transcend time zones and political boundaries, including global climate change, sustainable energy, security in an age of terrorism, affordable quality health care. To a much greater extent than the achievements of the last century, these new challenges will require a holistic, systems approach to intentional engineering design that embraces the need to include human behavior on a global scale. It is clear that leaders for these new global challenges will require a much greater level of understanding of non-technical issues surrounding technological invention in order to avoid unintended consequences. The unintended consequences of previous technologies have, in some cases, contributed to the grand challenges we face today. These unintended consequences must be given substantially more attention now in order to achieve overall outcomes that are required, not just new technologies. These consequences often have to do with human behavior, and require primary consideration of economic, political, social, psychological, and even religious dimensions of the introduction of new products and systems.

The many distinguished authors in this important book provide many different perspectives on the challenges we face and the educational paradigms we are using today to produce the engineering leaders for the future. While each of them presents a different perspective, the theme of the book is clear: engineering leaders for the 21st century will need a much broader perspective and a holistic, systems-oriented education that is not common today. Change is needed, and the chorus of voices here makes a compelling case that the time has arrived. It will take a coordinated effort across many institutions to accomplish the change, and the change will undoubtedly take different forms in different institutions. But the basic compass direction for change is becoming clear. Deeper and deeper specialization in narrower and narrower engineering sciences is not the answer. We need a fresh approach, perhaps a new definition of engineering itself. Perhaps engineering has more to do with a way of looking at the world than with mastery of applied science and mathematics. Perhaps engineering is a method involving imagination, experimentation, and iterative improvement – a method that is not as common in our educational programs as it could be – a method that shares many of the basic principles of design or even fine arts. Perhaps engineering and entrepreneurship are so closely inter-related that they are at times indistinguishable, and involve seeing opportunities rather than problems, taking initiative and risk, and – through sustained effort – making a positive difference in the world. Perhaps engineering involves—as James Plummer of Stanford University has noted – the intersection of feasibility, viability, and desirability. It is not simply a matter of feasibility any more.

The ideas and opinions presented in this book provide a call for change, and also provide a clear direction for the change that is needed. I believe the message is important, timely, and compelling, and I am grateful to the authors for their vision, passion, and dedication to this important cause. The focus on developing holistic and systems approaches to the practice of engineering is exactly what is needed, in my opinion.

However, as we progress from here and the profession continues to evolve, I would like to suggest that we look beyond our peers in the field of engineering for models of change. There is an enormous amount of "low hanging fruit" to be obtained from close observation of the most effective innovations in business education and in medical education (and I am sure there are others). I would urge all readers of this volume to reach out to our peers in the other professions and in the arts and sciences and widen our observations and our conversations to build a truly holistic approach to change in the process of education. Changing the educational process may prove to be one of our grandest challenges and there is much to be learned from those in other fields.

Needham, Massachusetts

Richard K. Miller
President
Olin College

A holistic approach to engineering education is not a new concept at Harvey Mudd College. From its founding in 1955, HMC's approach to both engineering and science education has been one requiring breadth and depth across science, engineering, mathematics, social sciences and humanities, as well as cross-disciplinary integration via a systems approach. HMC's engineering degree has always been a general engineering degree, and HMC sees itself as a liberal arts college of science and engineering. Thus is a joy to see a book in which so many leaders from engineering education and practice endorse the ideas at the core of the Harvey Mudd College mission.

Even with more than 50 years of experience attempting to get holistic engineering right, together with the knowledge from our partners at other institutions with similar goals, e.g., Princeton, Smith, Swarthmore, Olin, and UVM, there is still much to learn. Moreover the rapid changes over the last decade in the global economy, the increasing concerns about energy and environmental issues, and the ongoing transformation of every aspect of society by information technology place new demands on engineering education. Today, every undergraduate engineering student should gain some international experience, understand the implications of energy generation and consumption and be highly proficient with computational tools. This is in addition to the superb skills we expect in leadership, communication, and teamwork as well as technical breadth and depth, and commitment to professional ethics.

Claremont, California

Maria Klawe
President
Harvey Mudd College

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Chapter 1
Beyond Technology: The Holistic Advantage

Domenico Grasso and Melody Brown Burkins

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> **ho·lis·tic***hō-∪lis-tik*\\ adj.
> **1:** *of or relating to holism.*
> **2:** *relating to or concerned with wholes or with complete systems rather than with the analysis of, treatment of, or dissection into part (Merriam-Webster Online Dictionary)*

> *Today's problems come from yesterday's solutions.*
> *– Peter Senge*

> *We cannot solve the problems of today by thinking the way we thought when we created them.*
> *–Albert Einstein*

As engineered technologies become woven into the fabric of our society, engineers ignore the need for integrating valuable, nontechnical skills into their educational paradigm at the profession's peril. The exciting future of engineering is beyond technological labels (e.g., mechanical engineer, electrical engineer, and chemical engineer) where isolated training falls to a more powerful profession of broadly educated "holistic engineers" – engineers who manage, lead, and understand complex, interdisciplinary systems that bring the power of engineering thought to issues spanning and connecting technology, law, public policy, sustainability, the arts, government, and industry. The end of technology as engineering's sole focus allows a future where the engineering profession actively grows and evolves, bringing the very best of science, technology, and innovation to serve the complex challenges of our 21st century lives.

What is the holistic approach to engineering education and practice? In simplest terms, it is a more cross-disciplinary, whole-systems approach to engineering that emphasizes contextualized problem formulation, the ability to lead team-centered

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projects, the skill to communicate across disciplines, and the desire for life-long learning of the engineering craft in a rapidly changing world.

It is an approach that recognizes that engineering's greatest and most immediate challenge for the 21st century is no longer solely how to train capable technical experts – the engineering leadership niche in the manufacturing economy – but how to cultivate professionals able to take on the most complex technological, social, environmental, and economic challenges facing today's societies. Many are unique challenges that did not exist even 20 years ago, ranging from mitigating climate change through smartgrid technologies to securing health records and financial markets in an increasingly inter-connected world.

The holistic approach is a clarion call to today's engineers to reform and reposition their profession, both in educational training and overall practice, to become more systems-focused and globally aware, in the true benefit of a complex, multidisciplinary, and multi-cultural 21st century. Should we fall short of this important goal, future practitioners risk being pigeonholed as highly-skilled experts who – though brilliant technologists – are without the requisite skills necessary for 21st century leadership in our global, fast-paced information, and innovation economy.

It is a testament to the timeliness, the urgency, and the power of this idea that this book has brought together many of the most distinguished minds in the engineering profession – both educators and practitioners – as contributors to this transformational message: the engineering discipline must become more holistic and collaborative if it is to continue to excel and succeed. Through the diversity and richness of our authors' voices, we hope to present a compelling, varied, and globally-informed argument for not only the immediate reform of traditional engineering curricula, but for a full embrace by practitioners of more systems-focused, interdisciplinary, and holistic approach to engineering projects.

We begin with education.

The term "holistic engineering" was likely first coined by University of Pennsylvania Professor Joseph Bordogna, former Deputy Director of the National Science Foundation and former IEEE President, as he was describing a more cross-disciplinary, whole-systems approach to engineering education. In 2007, a Chronicle of Higher Education essay entitled *Holistic Engineering* (reprinted as Chapter 2), by *Domenico Grasso*, an editor of this book and then-Dean of the University of Vermont College of Engineering and Mathematical Sciences, with co-author *David Martinelli*, Professor of Engineering at the University of West Virginia, laid out an overview of the core reasons so many in engineering leadership, from cutting-edge universities to multinational corporations, have been calling for change in the traditional approach to engineering education and practice. This essay also helps to lay the foundation for the many contributions found in this book. Examples in the essay illustrate the authors' clear theme: the future of the engineering profession will be most competitive for those adopting holistic approaches to their practice, marrying quantitative expertise with communication and teamwork skills, and creative thought to envision entirely new solutions than might not have been allowed under traditional, solely technologically-focused engineering approaches.

Following this opening and in a similar vein, the next essay, *Engineering for a Changing World: A Roadmap to the Future of American Engineering Practice, Research, and Education*, is penned by one of the foremost leaders and advocates for US engineering reform *James Duderstadt*. The President Emeritus of the University of Michigan and member of the National Academy of Engineering (NAE) Duderstadt is blunt and compelling with his arguments. The United States faces the very real prospect of losing its engineering dominance and competence, argues Duderstadt, in an era in which technological innovation is key to economic competitiveness, national security, and social well-being. Despite clear statistics showing the importance of engineering to a competitive and strong economy, studies show that US engineering professionals are still held in relatively low esteem in comparison to other professional disciplines and, sadly, this perception has translated into an inadequate national investment in engineering education as well as overall science and engineering research, ultimately rendering the field less attractive to the brightest young minds. Duderstadt's essay sounds the alarm for immediate change, and also presents a bold plan for transformative actions and investments – in universities, government, and the engineering profession itself – that, he reasons, will help to avert a national crisis.

Many claim that a deterioration of quantitative K-12 education is a primary cause of the challenges faced by engineering educators. In Chapter 4, *K-12 Engineering: The Missing Core Discipline*, *Iannous Miaoulis*, President and Director of the Museum of Science in Boston, home to the National Center for Technological Literacy calls for holistic engineering thought to reach even the youngest of our potential future engineering leaders. We live in a world, Miaoulis writes, created largely by human hands and thought – an engineered world. Yet as American youth navigate the classical K-12 curriculum of reading, writing, mathematics, biology, physics, and chemistry, they rarely learn about engineering as a globally transformative profession or its continuous impact on our daily lives. How can this be? Miaoulis explores both the etiology and remedies for this "missing core discipline." Acknowledging that bringing engineering ideas into the K-12 curriculum will not be easy, Dr. Miaoulis makes a compelling argument that an attempt to do so will help create a far more technologically literate populace.

Engineering education and practice occupies a complex space. One the one hand, it is a professional field of creative practice common to the liberal arts – architecture, painting, dance; and on the other hand, it is a field in which research is inspired by use. However, over the years a tension has developed between traditional liberal arts and engineering. In her essay, *Liberal Arts and Engineering, Catherine Koshland*, Vice Provost for Academic Planning and Facilities and Wood-Calvert Professor in Engineering at the University of California at Berkeley, examines engineering in the context of liberal arts colleges. The application of science through technology, she notes, can improve the welfare of many throughout society; but such technological interventions will not succeed if they are applied in the absence of cultural or social understanding, hence the need for a broader, more liberal engineering education.

Following in the liberal arts context is an essay by *Carol Christ*, President of Smith College – the first women's college, and one of the few liberal arts colleges in the United States to develop an undergraduate engineering program. In *What is Happening in Liberal Education?* Christ begins with an historical overview of the liberal arts curriculum and its own significant transformations over time. Christ specifically describes seven current key developments in the liberal arts that can be seen to parallel the challenges facing engineering today, including a movement away from subject matter to intellectual capacities as an organizing concept, interdisciplinarity, internationalization, an increasing emphasis on training for citizenship, environmental education, an increased focus on undergraduate research, and an increased focus on project-based learning. Christ's essay firmly establishes that, given the call to transform engineering education to a more holistic, 21st century approach, it is clear that engineering should be considered a liberal art.

A recurring theme for those interested in engineering education reform is that the complex challenges of the coming century will demand more creative, innovative, and holistic solutions – solutions that will require a new paradigm for pre-professional undergraduate preparation in our engineers. In their essay, *Holistic Engineering and Education Reform*, *Domenico Grasso* and *Joseph Helble*, Deans of the College of Engineering and Mathematical Sciences at the University of Vermont and the Thayer School of Engineering at Dartmouth College, respectively, summarize several programs with innovative engineering curricula designed to meet the challenge. Their essay explores the motivation to pursue engineering careers and calls into question the often cited and much-touted historical impetus of the 1950s and 1960 s, i.e., "Sputnik." They note that many engineers briefly or never practice in the field in which they receive their training and they point to the need for life-long learning. Grasso and Helble suggest that a first step in moving toward a curriculum that can better educate holistic engineers might be to work toward true multidisciplinarity at both ends of the undergraduate experience. By structuring a first year design course that brings together students of varied interests and backgrounds, the profession of engineering can be better contextualized within a societal framework in the students' earliest college experience, inspiring them to seek creative and impactful solutions as a core part of their engineering education. They also recommend that a unified senior design course be created to complement this first-year course – one that is truly interdisciplinary and involves engineering students of all disciplines working together, preferably in coordination with real-world business and marketing interests. Both, taken together, are an exciting first step in better preparing our engineering students to creatively design the integrated and holistic engineering solutions that will best serve society's complex needs.

The definition of holistic is that it is "relating to or concerned with wholes or with complete systems rather than with the analysis of, treatment of, or dissection into part." For engineering education this aligns ideally, of course, with the future of systems engineering. *Priscilla Guthrie*, the Chief Information Officer for the National Intelligence Community, challenges engineering educators with her chapter, entitled *Beyond Systems Engineering – Educational Approaches for the 21st Century*, where she posits that undergraduate engineering education has essentially walked away from the challenge of educating systems engineers, instead offering students an outdated, but growing, list of the “by-discipline” (electrical, mechanical, civil, environmental, and chemical) basics throughout their engineering program. Guthrie argues that this educational paradigm is neither sufficient, nor helpful, to modern engineering students or their future professions and identifies selected educational outcomes and reforms – including more holistic approaches to educating systems engineers – she believes should be pursued to better prepare student for modern engineering practice and study.

As US engineering leaders struggle with critical transformation of their engineering educational system, so do those on the international front. In the next two chapters, engineering education reform is explored by both *Hector Gallegos*, President of the Peruvian College of Engineering and Professor of the Universidad Nacional de Ingeniería, Pontificia Universidad Católica in Perú, and *Pan Yunhe*, President of the Chinese Academy of Engineering and President of Zheijang University in China.

In the first of these essays, *The Education of an Engineer in a Holistic Age: A Latin American Perspective*, Professor Gallegos focuses his critique of the current engineering curriculum on the status quo he sees pervasive, and persistent, in Latin American engineering programs. Potential is being lost, he argues, to build the lasting infrastructure for engineering innovation and growth throughout Latin America. Gallegos goes further, with a detailed curriculum proposal for 21st century engineers including mathematics, basic science, and engineering science integrated seamlessly with core courses in culture, history, and importantly, design. He provides examples of how to prompt engineering students in this new, more integrative, reflective curriculum, requiring them to move away from purely technological and/or solo interests and work collaboratively across disciplines. He urges them to continuously ask questions, not once but multiple times, of themselves and their team as to the necessity, safety, benefit, and importance of an engineering project to society and the environment. Gallegos ends his essay with a special plea to engineering faculty – both in Latin America and globally – to recognize the importance of a more holistic, enlightened engineering education and to join in this much needed transformation, for future of both engineering and society.

The second international contribution, *On the Cultivation of Innovative Engineering Talent*, is a unique contribution from distinguished engineering colleagues in China. Complementing the ideas of Gallegos and contributors from throughout the United States, Yunhe argues that a more holistic approach to engineering – specifically with a focus of integrating more design, communication skills, and multidisciplinary thinking into the engineering curriculum – is of paramount importance to the cultivation of engineering excellence. Yunhe also gives new insight into how he expects China may accelerate the cultivation of highly talented 21st century engineers, with examples of programs and investments from his own Zheijang University, where there is active pursuit and aggressive selection of the best and brightest students, coupled with their enrollment in advanced, intensive engineering and innovation programs that are “foundation oriented, design oriented, and creation oriented.” In his essay, Yunhe expounds upon the importance of collaborative exchanges with industry, the need for international exchange of ideas, and the importance of a multidisciplinary perspective and innovative personality in the best 21st century engineer. With some aspects of the essay likely unique to the Chinese educational infrastructure and existing coordination with government and industry, the larger theme of the essay aligns with leading authors throughout this compilation: advocacy for an investment – as soon as possible – in a future of more holistic, globally-aware, and multidisciplinary approach to engineering.

A significant component of a holistic education is better understanding the world around us. This is especially true for engineers practicing in a global economy. In Chapter 11, *International Education and Holistic Thinking for Engineers*, *Dennis Berkey,* President of Worcester Polytechnic Institute (WPI), brings yet another critical yet under-utilized opportunity for engineering education reform to the table: the "purposeful" study abroad experience. While there has been a dramatic rise in popularity of study abroad programs for college-age students in the past 30 years, Berkey writes, less than 3% of all US study abroad students are engineering majors. At the same time, the inter-connectedness of today's economy – and the importance of technology in international commerce – suggests that an engineering education should require students to have a sense of the world beyond their campus or state. Berkey describes the development of a "purposeful" international experience for engineers that not only exposes students to new cultures, but also requires that the time spent abroad involve team-building and collaborative learning, interdisciplinary exposure, and new ways of communicating. Berkey argues that, in this way, a study abroad experience for engineers serves as the ideal platform for gaining holistic "21st century skills" and excelling in global innovation.

Engineers, with their technological expertise positioned ideally at the fertile intersection of both applied science and commercial business, are the prototypic creators of value in global economy. The next chapter, *Engineering Value Propositions: Professional and Personal Needs*, is a contribution from *Gary Wnek* and *Suzette Williamson*, both of The Institute for Management and Engineering (TiME) at Case Western Reserve University. The essay focuses on the rapidly changing, global innovation economy that requires a concomitant change in the engineering profession. If it is to maintain its positioning as a value creator, engineering must embrace a more integrated, interdisciplinary, and whole-systems approach. Referred to as the "Holistic Engineer" and "21st Century Engineer" in various complementary chapters in this collection, Wnek and Williamson propose yet another term for this new engineer, the "New Economy Engineer." They further use a simple metaphor for metabolic energy to engagingly suggest that it is "ATP" – or analysis, translation, and perception – that "fuels" the New Economy Engineer. Their hypothesis is that developing ATP in our undergraduate engineering students will be key to their competitive future as professionals.

David Goldberg is the Jerry S. Dubrovolny Distinguished Professor of Entrepreneurial Engineering at the University of Illinois at Urbana-Champaign, founder of the Illinois Genetic Algorithms Laboratory and author of "The Entrepreneurial Engineer." As an engineering educator fascinated by innovation and entrepreneurship, Goldberg wonders why, when engineering faculty colleagues talk about "the basics" of engineering education, he too often hears them refer solely to mathematics, science, and the engineering science disciplines. To be certain, mathematics, science, and engineering science are important, but are they really the most basic subjects critical to being an engineer? In his chapter entitled *The Missing Basics & Other Philosophical Reflections for the Transformation of Engineering Education*, Goldberg argues that this persistent definition of "the basics" is sadly inconsistent with the true needs of modern engineering practice and innovative ability. Goldberg further suggests seven critical thinking skills that should, he argues, become the new fundamentals of a 21st century, holistic undergraduate engineering education: asking questions, labeling technology and design challenges, modeling problems qualitatively, decomposing design problems, gathering data, visualizing solutions and generating ideas, and communicating solutions in written and oral form. He suggests that the failure of engineering education to address the missing basics is substantial – and that engineering education needs to change its thoughts, language, and practices to make the missing basics more central to the engineering canon.

It is in the context of this global "call to action" for education reform that *Domenico Grasso, Melody Brown Burkins, Joseph Helble*, and *David Martinelli*, furthers the compelling argument for 21st century engineering education transformation. *Dispelling the Myths of Holistic Engineering* was written as a response to skeptics in the traditional engineering education community who argue that any change to the status quo in curriculum and practice imperils the profession, the essay directly confronts five myths oft cited as reasons engineers, and engineering educators, should not alter their ways. Written at the request of the editor of *PE Magazine* and appeared in the August 2008 issue, this essay also buttresses arguments made by David Goldberg in exposing such educational myths not only as unhelpful to the profession, but seriously flawed, unsubstantiated, and illogical. The authors note that engineering educators who cling to 1950s models of teaching – e.g., adding more and more technologically specific classes to an already overwhelming engineering course load – are not preparing their students to succeed in today's rapidly evolving, information economy. Instead, the authors note, these educators stand in the way of a more holistic, and competitive, education paradigm for their students' best future, where young minds are trained in the fundamentals of engineering thought – how to "think like engineers" – and gain professional skill that will last their lifetime.

Just as the first chapters of this collection have focused on the potential for a transformation in engineering education to meet 21st century challenges, the next series of essays focus on new trends in engineering practice that are essential for corporate leadership.

These begin with an excellent analysis of the profession by *Wanda Austin*, President of the Aerospace Corporation, with her colleagues *Marilee Wheaton* (also an adjunct faculty member at the University of Southern California), *Charles Tang*, and *Mark Goodman*. The essay, *The Practice of Systems Engineering and Technological Leadership*, opens with the observation that failures in large-scale engineering projects, many resulting in multibillion-dollar cost overruns, are often blamed on the "complexity" of the project. Austin and her co-authors deconstruct this argument, offering a clear perspective on why "technical leadership" is so critical to the success of complex engineering projects, and how the practice of effective systems engineering enhances and enables that leadership. Using a diversity of examples to make their case, many from the aerospace industry, the authors aver that a holistic worldview in engineering is required as our knowledge-driven society increases its reliance on technology in order to enhance our daily quality of life. They further lobby strongly for the value of more holistic, systems engineering approaches to successfully tackle the increasing complexity of engineering projects and ensure outcomes beneficial to 21st century society.

The power of a more holistic, systems engineering approach to complexity – and the introduction of complex systems as an emerging and critical focus for the 21st century engineering enterprise – is the theme of the next essay from the President and CEO of the MITRE Corporation, *Alfred Grasso*, and his colleagues *Lou Metzger, Rich Byrne Steve Huffman, John Kreger,* and *Marie Francesca*. In Chapter 16, *Holistic Systems Integration*, the authors explain that today's engineers – no matter their specialty – can no longer expect to design and build single-purpose systems that operate flawlessly in isolation, but must recognize that their work will be part of a larger, heterogeneous system, with each component built for different businesses and users, that is constantly sharing information and interacting. Similar to Austin et al., the MITRE team suggests that to design systems that can perform as components of a large-scale, complex enterprise, engineers must expand the definition of the system and contextualize it within the enterprise in which it will function. Engineered systems must interoperate with, respond to, and – adopting Darwinian language – rapidly "co-evolve" with the real-time changes in technical, social, economic, and environmental surroundings. This increasingly dynamic nature of 21 st century engineering systems development – and the associated unpredictability of those systems as they become more and more complex – poses significant challenges to traditional engineers. However, this evolution also offers vast opportunities for creativity and innovation in design to the next generation of more holistically-trained, systems-focused engineering professionals who not only understand complexity, but embrace complex systems as a fascinating emerging market for the profession. [see Chapter 17]

The fact that IBM Corporation has been a leader in and trendsetter for emerging global markets in engineering is indisputable. In the 1970s, IBM urged universities in the United States and overseas to invest in the computer science major, recognizing the potential of information technology and information systems as the worldwide growth area of the future needing a talented workforce and career professionals. Since that time, IT has become an integral, if not a dominating, force in international commerce and innovation. In their essay for this collection, *Collaborative Innovation and Service Systems: Implications for Institutions and Disciplines*, National Academy of Engineering member and IBM Fellow and former Executive Vice President of Innovation and Technology, *Nicholas Donofrio*, with colleagues *Calline Sanchez*, Director of Systems Storage Development, and *James Spohrer*, Director of Global University Programs, advocate for the idea that system services are the next, exponential global growth area, calling for the immediate development of a “Services Science” that is grounded in a more holistic approach to engineering education. Their essay argues that investment in new global markets – all of which are expected to be largely multidisciplinary, collaborative, and rich with complexity – will require a workforce of professionals with the ability to understand complex systems and the services they bring to dynamic markets. They proffer that wherever people (and their determination of value) play an important role in the dynamics of complex systems, as in industrial and system engineering, financial engineering, software engineering, we will see an integrative force, working against specialization and toward more collaboration and cross-disciplinary skill sets. Service science and holistic engineering are both integrative disciplines – and while 21st century engineering professionals will always need expertise in a traditional or fundamental discipline, they will also need communication skills across a wide range of other disciplines and an ability to manage complex projects, people, and cultures. Fundamentally, the cultivation of more holistic engineers will serve to ensure a high-quality workforce and professionals leading collaborative innovation and services science programs.

The final chapter, *Technology and Policy*, of the book focuses on the knowledge, and study, of policy as one of the most powerful drivers of our global economy that will benefit from more holistic approaches to engineering education and practice. *M. Granger Morgan*, Head of Engineering and Public Policy at Carnegie Mellon University and Member of the National Academy of Sciences, notes that, in the 1960s and 1970s, and on some campuses even today, engineering education programs of the post-war period produced an environment in which many faculty belittled any activity – such as policy studies – not laden with partial differential equations. Today, however, many science and engineering educators are beginning to recognize the importance of preparing students with technical backgrounds who can address policy problems in which the technical details matter, both in terms of the way in which problems are framed and the analytical tools that are employed, but are not always paramount. This is part of increasingly complex engineering challenges, which marry societal, economic, environmental, media-related, and cultural differences around the world into beneficial solutions. Furthermore, techniques such as decision analysis, the systematic characterization and analysis of uncertainty, and methods in quantitative risk analysis, which were pioneered in engineering best serve the policy sector when holistic perspectives can be accommodated. Morgan is optimistic that, today, thousands of graduates of programs in technology and policy are beginning to approach their work in a more holistic way than their more conventionally educated engineering colleagues. For that, he suggests, they may well be the leaders of our global, technological future.

The book we have assembled, taken in its entirety, has many voices but one clear message: the current state of engineering education and practice which is designed largely for a manufacturing economy in the previous century must change – and change quickly – to meet the complex, global challenges of dynamic, 21st century information and innovation economy. In this new environment, investment in 20th century status quo engineering, adding more and more technological coursework to already overloaded engineering degree and shunning the complexity of modern engineering challenges, becomes a sadly Sisyphean task that is not only endless and ineffective, but has little benefit to the future of the engineering profession.

We have largely given the name "Holistic Engineer" and "Holistic Advantage" to this new thinking and investment for 21st century engineering and practice. Yet, by any other name – be it the 21st Century Engineer, Service Science Engineer, Systems Engineer, Global Engineer, New Economy Engineer, and Renaissance Engineer – the future of engineering is about reform.

It is also about competitiveness, life-long learning, and a true bridging of the engineering, scientific, and traditional liberal arts worlds that for too long have operated independently, even resentfully and without respect for each others' strengths. C.P. Snow once bemoaned the "Two Cultures" in his now-famous 1959 Rede lecture at the University of Cambridge (UK), believing the "science vs. liberal arts" dichotomies created by disciplines did little to benefit society. Instead, the division engendered mistrust and miscommunication, with both the engineering and liberal arts communities missing great opportunities to share strengths toward new discovery and enlightenment. We agree. The holistic approach presented in the essays throughout this book is not only about a long-overdue shift in outdated engineering education paradigms, but about positioning the engineering profession to reach its 21st century potential as a most competitive, cost-effective, and attractive profession in the global marketplace as well as a most respected, and sought-after, degree throughout academia.

> I can't understand why people are frightened of new ideas. I'm frightened of the old ones.
>
> – *John Cage*

Chapter 2
Holistic Engineering

Domenico Grasso and David Martinelli

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The Golden Gate Bridge, the longest suspension span in the world when it was completed, in 1937, is widely recognized as an engineering marvel and a symbol of technology in harmony with its surroundings. When the bridge opened to a ceremonial trickle of cars, it would have been hard to imagine that an estimated 100 million tons would eventually cross annually between San Francisco and Marin County. Even less foreseeable, however, were the nearly two suicides per month, on average, facilitated by this testament to the power of engineering thought. As we say in the profession, the bridge has exceeded its design specs.

‘The Golden Gate Bridge is a useful metaphor in considering the scope of the challenge faced by every engineer beginning a design project: how to design for a specific objective without creating unintended consequences. The need to avoid unintended consequences has never been more difficult or important than it is today, as population soars and technology, ever more complex, becomes increasingly embedded in human experience.

In this evolving world, a new kind of engineer is needed, one who can think broadly across disciplines and consider the human dimensions that are at the heart of every design challenge. In the new order, narrow engineering thinking will not be enough. American higher education is in an unusual position to create the 21st-century engineer.

Engineering and technical education are very much in the public eye now. For more than a year, Congress has debated how to best respond to the National Academy of Engineering’s report “Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.” The report is powerful in its statement that the “scientific and technical building blocks of our economic global leadership are eroding at a time when other nations are gathering strength.” Among the recommendations it proposes are increased investment in research

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and education in technical disciplines. In response to the report, President Bush announced, in his 2006 State of the Union address, the American Competitiveness Initiative, which Congress has been considering in various versions ever since.

But investing resources in simply encouraging a technical-education paradigm developed in, and best suited to, the 20th century would be shortsighted and ineffectual. Congress might be well advised to use the opportunity to encourage the major transformation that the new century demands – and that American engineering schools are distinctly positioned to supply.

In the global marketplace, engineers are proliferating at an astounding rate. The past decade and a half has seen the rapid economic development of half a dozen countries in Asia and Eastern Europe once mired in poverty or slow-growing controlled economies. Now millions more people are embracing capitalism, and with it the technological engine that drives it. A previously untapped global human resource is being extracted like oil from new wells, yielding first a manufacturing capability, and now a staggering number of new engineers and scientists. According to some estimates, Asia alone graduates more than ten times as many engineers annually as the United States does, many of them as qualified as our top graduates.

The emergence of a new global engineering work force and its threat to the US economy has been the topic du jour in engineering and business circles, but responses tend to focus on increasing the number of traditional engineering graduates so we can go head-to-head with other countries in the technological marketplace. Such a goal alone, however, would do little more than drive down the price and value of engineering services, leaving the United States no better equipped than other nations to solve the increasingly complex problems facing society.

The answers lie in the quality of the product rather than in the quantity of output. The crucial question facing academe is whether we are adequately preparing our future engineers and designers to practice in an era that requires integrated and holistic thinking or are needlessly limiting their solution spaces to those that contain only technological answers, with scant or passing consideration of the myriad of other influencing and dependent factors.

Where should educators turn in preparing high-quality engineers who are better equipped to serve in the changing global marketplace? As engineers are often taught, solutions to new problems are found in returning to first principles. In that context, “first principles” means examining the definition and role of the engineer in their purest forms.

For centuries, society’s problems have been sufficiently linear, mechanistic, and discrete to be served by engineers responsible for “solving problems through the application of math and science,” the classic definition of engineering that has served us well until now. By many accounts, 80% of our economy is now information-based. Yet if one were to pursue an undergraduate engineering degree from a typical state university, the result would be courses not significantly different from those offered during the middle of the past century, when we were largely a manufacturing-based economy.

Pursuing the holistic concept of the "unity of knowledge" will yield a definition of engineering more fitting for the times ahead. The unity of knowledge – first proposed by James Marsh, President of the University of Vermont in the early 1800s, and resurrected by the Harvard sociobiologist E.O. Wilson in his book *Consilience: The Unity of Knowledge* (Knopf, 1998) – is fundamentally about integrating knowledge across disciplines to deal with complex problems and better serve humanity. Many thoughtfully constructed versions of core curricula, sometimes referred to as general-education requirements, attempt to teach multiple modes of reasoning or ways of knowing. However, colleges rarely take the next step and encourage students to understand the connections among their courses and to integrate, or "unify," their learning.

In engineering, a discipline that purports to design for humanity and improve the quality of life, the unity of knowledge should be a sine quo non that asks engineers to look outward, beyond the fields of math and science, in search of solutions to entire problems. To better serve humanity, engineers must at least attempt to understand the human condition in all its complexity, which requires the study of literature, history, philosophy, psychology, religion, and economics, among other fields.

Such a perspective on engineering education need not be restricted to the undergraduate curriculum. The educational philosophy embodied in the unity-of-knowledge approach also has a research analog in one of the most promising areas of investigation today: complex-systems analysis (recently identified in the National Science Foundation draft strategic plan, "Investing in America's Futures" as an area of focus and investment). Typically, complex systems are those that change with time, do not vary in linear pattern, and demonstrate "emergence," that is, behavior that cannot be predicted in advance from constitutive parts. Complex systems are different from merely complicated ones, such as jumbo jets or fine Swiss watches, whose behavior, though characterized by the intricate interrelationship of many parts, is determined and reproducible. While advanced mathematics is a necessary tool for working in the field of complex systems, so too is an understanding of human nature. Complexity is especially evident when human decisions play a role in the system, for example, in the dynamic functioning of the electric-power grid.

Educating engineers more broadly will not only make them better designers but will also give them the tools to work productively alongside the other problem solvers they will be increasingly required to collaborate with: lawyers who resolve conflicts; economists who find the incentives and disincentives that promote positive change; historians who elucidate the present through knowledge of the past; artists who have an appreciation for form and function; and politicians who reach compromise. The ability to model and incorporate elements of economics, sociology, psychology, and business to identify possible solutions to pressing problems will be a major part of the future of engineering.

Consider a rather simple example: acid rain, which results in large part from burning coal. Environmental engineers and scientists worked hard on technologies to curb the pollution, but it was economists who developed the "cap and trade" permit program – which, through tradable pollution permits, has allowed market forces to create incentives for companies to cut pollution and reduce acid rain in the

Northeast. Were the mathematics in that economics program beyond the capabilities of engineers? Or did their preparation not allow them to consider all the possible solutions, which is to say, the ones that did not depend exclusively on technology?

When Stockholm was considering ways to transport more people into and out of the city, the concept of adding one more bridge to the 57 that already connect the 14 main islands that constitute the city would have been the natural engineering extension of past practices. Stockholm retained IBM – a company with a not-insignificant number of engineers. However, prompted by an economic realignment in the United States from manufacturing and industry to services and innovation management, IBM has already moved beyond traditional engineering thinking. Specifically, the company has embarked on a research-and-business model that applies technological and manufacturing models to the holistic delivery of services.

To solve Stockholm's traffic problem, IBM designed a "tax and drive" system, in which autos are fitted with transponders and drivers are charged a fee based on the time of day their cars are in the city. In the first month of operation, the system yielded a 25% reduction in traffic, removing 100,000 vehicles from the roads during peak business hours and increasing the use of mass transit by 40,000 riders a day. Stockholm needed no new bridge and gained the concomitant benefits of reducing pollution and conserving energy.

In a world where applied science and technology are available to practically anyone for a few rupees or yuan on the dollar, we have to ask ourselves, What will the US engineer have to offer that is not available in the global market for a fraction of the cost? If we decide to compete with other countries using the traditional definition of engineering, we will certainly succeed in converting engineers into a commodity.

A better response lies in changing the scope and significance of what engineering is, and, perhaps more important, who engineers are – namely, technically adept people who serve humanity through the application not simply of math and science, but of a wide array of disciplines. This new breed of engineer will be not only a truly comprehensive problem *solver,* but a problem *definer,* leading multidisciplinary teams of professionals in setting agendas and fostering innovation.

If, as many glossy college brochures say, engineers are problem solvers, we must open their eyes and minds to the range of problem-solving approaches that go beyond math and science. That is not to say that engineers must stay in school for 20 years to learn multiple disciplines in depth, but that they should experience the richness of a broad undergraduate education. It is not uncommon for only about 15% of the typical engineering curriculum in the United States to consist of electives. There is no question that our engineering graduates are well versed in the technical aspects of their profession. But it is equally clear that many of them graduate without the breadth they will need to think through the solutions we need.

Given that many rote engineering tasks can be easily outsourced, and that engineering organizations, including the National Academy of Engineering, are calling for the master's degree to be the first professional degree in engineering, it is time to consider a major overhaul of the undergraduate engineering curriculum. At the end of the 19th century, law schools concluded that they could no longer teach all of the vast number of laws that had accumulated over time and decided instead to teach students how to think like lawyers. So, too, at the beginning of the 21st century, should undergraduate engineering schools focus on teaching students how to think like engineers.

Building quantitative-reasoning skills should still be a top priority for American engineering education, but that rigor should be complemented with developing students' ability to think powerfully and critically in many other disciplines. To be sure, it will be a challenge, but a challenge with tremendous benefits.

Recently the Golden Gate Bridge, Highway and Transportation District selected an engineering firm to develop a plan to create barriers (physical or otherwise) to suicide attempts. With any luck, a well-considered and holistic solution to the human dimensions of the challenge will present itself, not one that creates unintended new problems born of the myopia of a purely technical approach.

Chapter 3
Engineering for a Changing World

A Roadmap to the Future of American Engineering Practice, Research, and Education

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We live in a time of great change, an increasingly global society, driven by the exponential growth of new knowledge and knitted together by rapidly evolving information and communication technologies. It is a time of challenge and contradiction, as an ever-increasing human population threatens global sustainability; a global, knowledge-driven economy places a new premium on technological workforce skills through phenomena such as outsourcing and offshoring; governments place increasing confidence in market forces to reflect public priorities, even as new paradigms such as open-source software and open-content knowledge and learning challenge conventional free-market philosophies; and shifting geopolitical tensions are driven by the great disparity in wealth and power about the globe, manifested in the current threat to homeland security by terrorism. Yet it is also a time of unusual opportunity and optimism as new technologies not only improve the human condition but also enable the creation and flourishing of new communities and social institutions more capable of addressing the needs of our society.

The Challenges to American Engineering

During the past several years such considerations have led numerous groups, including the National Academies, federal agencies, business organizations, and professional societies, to conclude that new paradigms in engineering practice, research, and education that better address the needs of a 21st-century nation in a rapidly changing world (e.g., see Augustine, 2005; Duderstadt, 2005; Clough, 2004, 2005; Grasso and Martinelli, 2007, Sheppard and William, 2008; NSB, 2003, 2007). Among the many concerns these studies have raised about American engineering are the following.

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Engineering Practice

The implications of a technology-driven global economy for engineering practice are particularly profound. The globalization of markets requires engineers capable of working with and among different cultures and knowledgeable about global markets. New perspectives are needed in building competitive enterprises as the distinction between competition and collaboration blurs. The rapid evolution of high-quality engineering services in developing nations with significantly lower labor costs, such as India, China, and Eastern Europe, raises serious questions about the global viability of the US engineer, who must now produce several times the value-added to justify wage differentials. Both new technologies (e.g., info–bio–nano) and the complex mega systems challenges arising in contemporary society (e.g., massive urban, transportation, and communications infrastructure) require highly interdisciplinary engineering teams characterized by broad intellectual span rather than focused practice within traditional disciplines. As technological innovation plays an ever more critical role in sustaining the nation's economic prosperity, security, and social well-being, engineering practice will be challenged to shift from traditional problem solving and design skills toward more innovative solutions imbedded in a complex array of social, environmental, cultural, and ethical issues.

Yet, despite the growing importance of engineering practice to society, the engineering profession still tends to be held in relatively low esteem in the United States compared to other learned professions such as law and medicine. Perhaps this is not surprising, both because of the undergraduate nature of its curriculum and because of the evolution of the profession from a trade (a "servile art" such as carpentry rather than a "liberal art" such as law, medicine, or theology). Yet today this is eroding prestige and influence is intensified by the tendency of many companies to view engineers as consumable commodities, discarding them when their skills become obsolete or replaceable by cheaper engineering services from abroad. Students sense the eroding status and security of engineering careers and increasingly opt for other more lucrative and secure professions such as business, law, and medicine. Today's engineers no longer hold the leadership positions in business and government that were once claimed by their predecessors in the 19th and 20th centuries, in part because neither the profession nor the educational system supporting it has kept pace with the changing nature of both our knowledge-intensive society and the global marketplace. In fact, the outsourcing of engineering services of increasing complexity and the offshoring of engineering jobs of increasing value threaten the erosion of the engineering profession in America and with it our nation's technological competence and capacity for technological innovation.

Engineering Research

There is increasing recognition throughout the world that leadership in technological innovation is key to a nation's prosperity and security in a hypercompetitive, global, knowledge-driven economy (Council on Competitiveness, 2005). While our American culture, based upon a highly diverse population, democratic values, free-market practices, and a stable legal and regulatory environment, provides an unusually fertile environment for technological innovation and entrepreneurial activity, history has shown that significant federal and private investments are necessary to produce the ingredients essential for innovation to flourish: new knowledge (research), human capital (education), infrastructure (e.g., physical, cyber), and policies (e.g., tax, property).

One of the most critical elements of the innovation process is the long-term research required to transform new knowledge generated by fundamental scientific discovery into the innovative new products, processes, and services required by society. In years past this applications-driven basic research was a primary concern of major corporate R&D laboratories, national laboratories, and the engineering schools associated with research universities. However, in today's world of quarterly earnings pressure and inadequate federal support of research in the physical sciences and engineering, this longer-term, applications-driven basic engineering research has largely disappeared from the corporate setting, remaining primarily in national laboratories and research universities constrained by inadequate federal support. This has put at considerable risk the discovery-innovation process in the United States.

Numerous recent studies (COSEPUP, 1998–2003; Duderstadt, 2005; Clough, 2004, 2005, 2006; Vest, 2006; Augustine, 2005) have concluded that stagnant federal investments in basic engineering research, key to technical innovation, are no longer adequate to meet the challenge of an increasingly competitive global economy. There is further evidence that the serious imbalance between federally supported research, now amounting to less than 26% of national R&D, along with the imbalance that has resulted from the fivefold increase in federal support of biomedical research during a period when support of research in the physical sciences and engineering has remained stagnant, threatens the national capacity for innovation.

Engineering Education

In view of these changes occurring in engineering practice and research, it is easy to understand why some raise concerns that we are attempting to educate 21st-century engineers with a 20th-century curriculum taught in 19th-century institutions. The requirements of 21st-century engineering are considerable: engineers must be technically competent, globally sophisticated, culturally aware, innovative and entrepreneurial, and nimble, flexible, and mobile (Continental, 2006). Clearly, new paradigms for engineering education are demanded to (i) respond to the incredible pace of intellectual change (e.g., from reductionism to complexity, from analysis to synthesis, from disciplinary to multidisciplinary); (ii) develop and implement new technologies (e.g., from the microscopic level of info–bio–nano to the macroscopic level of global systems); (iii) accommodate a far more holistic approach to addressing social needs and priorities, linking social, economic, environmental, legal, and political considerations with technological design and innovation; and (iv) reflect in its diversity, quality, and rigor the characteristics necessary to serve a 21st-century nation and world (Sheppard and William, 2008).

The issue is not so much *reforming* engineering education within old paradigms but instead *transforming* it into new paradigms necessary to meet the new challenges such as globalization, demographic change, and disruptive new technologies. As recent National Science Board workshops involving representatives of industry, government, professional societies, and higher education concluded, the status quo in engineering education in the United States is no longer sufficient to sustain the nation's technological leadership (NSB, 2007).

The critical role of our engineering schools in providing human capital necessary to meet national needs faces particular challenges (Clough, 2004, 2006; Duderstadt, 2005). Student interest in science and engineering careers is at a low ebb – not surprising in view of the all-too-frequent headlines announcing yet another round of layoffs of American engineers as companies turn to offshoring engineering services from low-wage nations. Cumbersome immigration policies in the wake of 9/11, along with negative international reaction to US foreign policy, are threatening the pipeline of talented international science and engineering students into our universities and engineering workforce. Furthermore, it is increasingly clear that a far bolder and more effective strategy is necessary if we are to tap the talents of all segments of our increasingly diverse society, with particular attention to the participation of women and underrepresented minorities in the engineering workforce.

The current paradigm for engineering education, e.g., an undergraduate degree in a particular engineering discipline, occasionally augmented with workplace training through internships or co-op experiences and perhaps further graduate or professional studies, seems increasingly suspect in an era in which the shelf life of taught knowledge has declined to a few years. There have long been calls for engineering to take a more formal approach to lifelong learning, much as have other professions such as medicine in which the rapid expansion of the knowledge base has overwhelmed the traditional educational process. Yet such a shift to graduate-level requirements for entry into the engineering profession has also long been resisted by both students and employers. Moreover, it has long been apparent that current engineering science-dominated curricula need to be broadened considerably if students are to have the opportunity to learn the innovation and entrepreneurial skills so essential for our nation's economic welfare and security, yet this too has been resisted, this time by engineering educators.

Here part of the challenge – and key to our objectives – must be an appreciation for the extraordinary diversity in engineering and training to meet the ever more diverse technological needs of our nation. Different types of institutions and programs are clearly necessary to prepare students for highly diverse roles: from system engineers capable of understanding and designing complex systems from the atomic to the global level; master engineers capable of the innovative design necessary to develop products, processes, and services competitive in a global economy; engineering scientists capable of conducting the fundamental research necessary to address compelling global challenges such as energy sustainability; and engineering managers capable of leading global enterprises. And all of these institutions, programs, and roles must strive to provide exciting, creative, and adventurous educational experiences capable of attracting the most talented of tomorrow's students.

From a broader perspective, one might argue that as technology becomes an ever more dominant aspect of social issues, perhaps the discipline of engineering should evolve more along the lines of other academic disciplines such as physics and biology that have become cornerstones of the liberal arts canon. Perhaps the most urgent need of our society is a deeper understanding and appreciation for technology on the part of all college graduates rather than only those seeking engineering degrees. These, too, should be concerns of engineering educators.

A Framework for Change

So what should our nation seek as both the nature and objectives of engineering in the 21st century, recognizing that these must change significantly to address rapidly changing needs and priorities? Here we need to consider the implications for American engineering from several perspectives: (i) as a *discipline* (similar to physics or mathematics), possibly taking its place among the "liberal arts" characterizing a 21st-century technology-driven society; (ii) as a *profession,* addressing both the urgent needs and grand challenges facing our society; (iii) as a *knowledge base* supporting innovation, entrepreneurship, and value creation in a knowledge economy; and (iv) as a diverse *educational system* characterized by the quality, rigor, and diversity necessary to produce the engineers and engineering research critical to prosperity, security, and social well-being.

Here we begin with several premises:

- In a global, knowledge-driven economy, technological innovation – the transformation of knowledge into products, processes, and services – is critical to competitiveness, long-term productivity growth, and the generation of wealth. Preeminence in technological innovation requires leadership in all aspects of engineering: engineering research to bridge scientific discovery and practical applications; engineering education to give engineers and technologists the skills to create and exploit knowledge and technological innovation; and the engineering profession and practice to translate knowledge into innovative, competitive products, and services.
- To compete with talented engineers in other nations with far greater numbers and with far lower wage structures, American engineers must be able to add significantly more value than their counterparts abroad through their greater intellectual span, their capacity to innovate, their entrepreneurial zeal, and their ability to address the grand challenges facing our world.

- It is similarly essential to elevate the status of the engineering profession, providing it with the prestige and influence to play the role it must in an increasingly technology-driven world while creating sufficiently flexible and satisfying career paths to attract a diverse population of outstanding students. Of particular importance is greatly enhancing the role of engineers both in influencing policy and popular perceptions and as participants in leadership roles in government and business.
- From this perspective the key to producing such world-class engineers is to take advantage of the fact that the comprehensive nature of American universities provides the opportunity for significantly broadening the educational experience of engineering students, provided that engineering schools, accreditation agencies such as ABET, the profession, and the marketplace are willing to embrace such an objective. Essentially all other learned professions have long ago moved in this direction (law, medicine, business, and architecture), requiring a broad liberal arts baccalaureate education as a prerequisite for professional education at the graduate level.

In summary, we believe that to meet the needs of the nation, the engineering profession must achieve the status and influence of other learned professions such as law and medicine. Engineering practice in our rapidly changing world will require an ever-expanding knowledge base requiring new paradigms for engineering research that better link scientific discovery with innovation. The complex challenges facing our nation will require American engineers with a much higher level of education, particularly in professional skills such as innovation, entrepreneurship, and global engineering practice. To this end, we set the following objectives for engineering practice, research, and education:

1. To establish engineering practice as a true learned profession, similar in rigor, intellectual breadth, preparation, stature, and influence to law and medicine, with extensive post-graduate education and a culture more characteristic of professional guilds than corporate employees.
2. To redefine the nature of basic and applied engineering research, developing new research paradigms that better address compelling social priorities than those methods characterizing scientific research.
3. To adopt a systemic, research-based approach to innovation and continuous improvement of engineering education, recognizing the importance of diverse approaches – albeit characterized by quality and rigor – to serve the highly diverse technology needs of our society.
4. To establish engineering as a true liberal arts discipline, similar to the natural sciences, social sciences, and humanities, by imbedding it in the general education requirements of a college graduate for an increasingly technology-driven and technology-dependent society of the century ahead.

To achieve these objectives for American engineering, this study recommends the following actions.

Transforming the Profession

When physicians are asked about their activities, they generally respond with their professional specialty, e.g., “I’m a cardiologist” or “I’m a neurosurgeon.” So too, lawyers are likely to respond with a specialty such as corporate law or litigation. In sharp contrast, when asked about their profession, most engineers will respond with their employer: “I work for Ford” or Boeing or whomever. Hence the first goal is to transform engineering from an occupation or a career to a true *learned profession*, where professional identity with the unique character of engineering practice is more prevalent than identification with employment.

Part of the challenge here is that there are so many types of and roles for engineers, from low-level technicians or draftsmen to master design engineers to engineering scientists to technology managers. Hence as we explore possible futures for the engineering profession, it may be necessary to consider defining more formally through statute or regulation the requirements for various engineering roles. For example, one might distinguish these by degree levels, e.g., routine engineering services (sales, management) might require only a baccalaureate degree (B.S.) perhaps augmented by an M.B.A.; design engineers would require training at the masters level (M.S.); engineering scientists engaged in research would require a Ph.D.; and so forth, with the definition of role and degree requirements established by statute, as they are in medicine and law. As we will suggest later in this chapter, the changing nature of engineering and its increasing importance in an ever more technology-driven world may require even more senior engineering roles requiring advanced, practice-based engineering degrees.

Of course there will be strong resistance by many employers to elevating the education level required for the engineering profession, since many companies will prefer to continue to hire baccalaureate-level engineering graduates at lower cost, although such graduates are usually less capable of high value-added activities such as radical technological innovation. So too, many students and parents will question whether the extension of engineering education beyond the baccalaureate level will add sufficient personal return to justify the additional time and expense requirements. Hence key in any effort to elevate the educational requirements and thereby the value, prestige, and influence of the engineering profession will be a coordinated effort by engineering professional and disciplinary societies to raise public awareness of the intensifying educational demands of engineering practice. Furthermore, as other learned professions have demonstrated, it will also be important for the engineering profession to become more influential in both defining and controlling the marketplace for engineers and engineering services if they are to break through the current resistance of employers, clients, and students to more advanced educational requirements for engineering practice.

Hence attaining the necessary prestige and influence will almost certainly require a major transformation of the culture of engineering practice and the engineering profession itself. To this end, the following proposal is offered.

Proposal 1: Engineering professional and disciplinary societies, working with engineering leadership groups such as the National Academy of Engineering, the National Society for Professional Engineers, the American Association of Engineering Societies, ABET, and the American Society for Engineering Education, should strive to create a "guild-like" culture in the engineering profession, similar to those characterizing other learned professions such as medicine and law, that aims to shape rather than simply react to market pressures.

The initial goal should be to create (actually, recreate) a guild culture for engineering, where engineers identify more with their profession than their employers, taking pride in being members of a true profession whose services are highly valued by both clients and society. While engineering does have some elements of these modern guilds, the great diversity of engineering roles, professional organizations, and clients (employers) prevents engineering from exerting the influence or control over the marketplace enjoyed by many other contemporary guilds. Hence our proposal is for a more concerted effort on the part of engineering organizations – professional and disciplinary societies, engineering education, and those engineers with influence in public policy and politics – to exert a more coordinated and strategic effort to establish a strong guild structure for the engineering profession. The necessary transformation is suggested by a transition in both language and perspective. Engineers would increasingly define themselves as *professionals* rather than employees. Their primary markets would be *clients* rather than employers. And society would view engineering as a *profession* rather than an occupation.

Expanding the Engineering Knowledge Base

For over 50 years, the United States has benefited from a remarkable discovery-innovation engine that has powered our economic prosperity while providing for our national security and social well-being. As Charles Vest suggests, for America to prosper and achieve security, it must do two things: (1) discover new scientific knowledge and technological potential through research and (2) drive high-end, sophisticated technology faster and better than anyone else. We must make new discoveries, innovate continually, and support the most sophisticated industries (Vest, 2006).

Two federal actions at mid-century, the G.I. Bill and the government–university research partnership, provided the human capital and new knowledge necessary for the innovation that drove America's emergence as the world's leading economic power. Both federal actions also stimulated the evolution of the American research university to serve the nation by providing these assets critical to a discovery-innovation-driven economy. Today it has become apparent that the nation's discovery-innovation engine needs a tune-up in the face of the profound changes driven by a hypercompetitive, knowledge-driven global economy. Further, federal action is necessary to generate the new knowledge, build the necessary infrastructure, and educate the innovators – entrepreneurs necessary for global leadership in innovation.

In 2005 the National Academy of Engineering completed a comprehensive study of the challenges facing engineering research in America and recommended a series of actions at the federal level to respond to the imperatives of a flattening world (Duderstadt, 2005). Among the more important recommendations contained in this report are the following:

> *Proposal 2: The federal government should adopt a more strategic approach to research priorities and R&D funding. In particular a more balanced investment is needed among the biomedical sciences, physical sciences, and engineering is necessary to sustain our leadership in technological innovation. Long-term basic engineering research should again become a priority for American industry. The nation should secure an adequate flow of next-generation scientists and engineers through major federal fellowship–traineeships program in key strategic areas (e.g., energy, info–nano–bio, knowledge services), similar to that created by the National Defense Education Act. Immigration policies and practices should be streamlined (without compromising homeland security) to restore the flow of talented students, engineers, and scientists from around the world into American universities and industry. The federal government in close collaboration with industry, universities, and the states should explore new research paradigms that better link fundamental scientific discoveries with technological innovation to build the knowledge base essential for new products, process, and services to meet the needs of society.*

Similar concerns raised by leaders of industry, higher education, and the scientific community, culminating in the National Academies' *Rising Above the Gathering Storm* study, have stimulated the federal government to launch two major efforts aimed at sustaining US capacity for innovation and entrepreneurial activities: the administration's *American Competitiveness Initiative* and Congress's *America COMPETES Act* (the latter being including an awkward acronym for "Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science"). If fully implemented, over the next decade these efforts will involve doubling federal investment in basic research in physical science and engineering; major investments in science and engineering education; tax policies designed to stimulate private sector in R&D; streamlining intellectual property policies; immigration policies that attract the best and brightest scientific minds from around the world; and building a business environment that stimulates and encourages entrepreneurship through free and flexible labor, capital, and product markets that rapidly diffuse new productive technologies.

Transforming Engineering Education

Many nations are investing heavily in developing their engineering workforce within cultures in which science and engineering are regarded as exciting, respected fields by young people and as routes to leadership roles in business and government, in contrast to the relatively low popularity and influence of these fields in American society. But the United States does have one very significant advantage: the comprehensive nature of the universities in which most engineering education occurs, spanning the range of academic disciplines and professions from the liberal arts to law, medicine, and other learned professions. American universities have the capacity to augment education in science and engineering with the broader exposure to the humanities, arts, and social sciences that are absolutely essential to building both the creative skills and cultural awareness necessary to compete in a globally integrated society. Furthermore, their integration of education, research, and service – that is, learning, discovery, and engagement – provides a formidable environment for educating 21st-century engineers. By building a new paradigm for engineering education that takes full advantage of the comprehensive nature and unusually broad intellectual span of the American university, we can create a new breed of engineer, capable of adding much higher value in a global, knowledge-driven economy.

To take advantage of this unique character of American higher education, its capacity to integrate learning across the academic and professional disciplines, it will be necessary to separate the concept of engineering as an *academic discipline* from engineering as a *learned profession*. To this end, consider five specific proposals: (1) to establish graduate professional schools of engineering that would offer practice-based degrees at the post-baccalaureate level; (2) to restructure undergraduate engineering programs as a “liberal arts” discipline; (3) to develop a structured approach to lifelong learning for engineering professionals; (4) to include the academic discipline of engineering (or more broadly technology) in a 21st-century liberal arts canon suitable for all undergraduate students; and (5) to challenge the engineering community to commit itself to reflecting among its members the great diversity characterizing both our nation and the world. Let us consider each proposal in turn:

> *Proposal 3: Working closely with industry and professional societies, higher education should establish graduate professional schools of engineering that would offer practice-based degrees at the post-baccalaureate level as the entry degree into the engineering profession.*

Perhaps the most effective way to raise the value, prestige, and influence of the engineering profession is to create true post-baccalaureate professional schools similar to medicine and law, which are staffed with practice-experienced faculty and provide clinical practice experience. More specifically, the goal would be the transformation of engineering into a true learned profession, comparable in rigor, prestige, and influence to medicine and law, by shifting the professional education and training of engineers to post-baccalaureate professional schools offering 2 or 3 year, practice-focused degree programs in contrast to research-focused graduate degrees such as the M.S. and Ph.D. The faculty of these schools would have strong backgrounds in engineering practice with scholarly interests in the key elements of engineering, e.g., design, innovation, entrepreneurial activities, technology management, systems integration, and global networking, rather than research in engineering sciences. Students would be drawn from a broad array of possible undergraduate degrees with strong science and mathematics backgrounds, e.g., from the sciences or mathematics or perhaps a broader engineering discipline similar to the pre-med programs preparing students for further study in medicine.

The MEng degree programs developed for practicing engineers by many engineering schools might be a first step toward such professional schools, much as the M.B.A. suffices for the business profession. However, more extended programs akin to law and medical education would have greater impact on both student capabilities and the prestige of the profession. While a more extended post-graduate professional degree program would encounter the usual resistance from employers and students, if designed properly, the value-added education provided by a graduate professional degree in engineering would likely outweigh any loss of income from a similar time period spent while employed following a baccalaureate engineering degree.

Clearly, the educational content would be quite different from the engineering science curriculum characterizing most undergraduate engineering programs today. At the professional level, a practice-oriented and experienced faculty could develop topics such as design and synthesis, innovation, project and technology management, systems analysis, entrepreneurship and business development, and global engineering systems, as well as more abstract topics such as leadership and professional ethics. Additional electives could be offered in areas such as business (particularly management, strategic planning, and finance), policy (science, technology, and public policy), and other fields of particular student interest (e.g., biomedical and health, international relations, defense and security).

If the professional elements of an engineering education were shifted to a post-graduate professional school, this might provide a very significant opportunity to address many of the challenges that various studies have concluded face engineering education today at the undergraduate level. In particular, removing the burdens of professional accreditation from undergraduate engineering degree programs would allow them to be reconfigured along the lines of other academic disciplines in the sciences, arts, and humanities, thereby providing students majoring (or concentrating) in engineering with more flexibility to benefit from the broader educational opportunities offered by the comprehensive university.

> *Proposal 4: Undergraduate engineering should be restructured as an academic discipline, similar to other liberal arts disciplines in the sciences, arts, and humanities, thereby providing students with more flexibility to benefit from the broader educational opportunities offered by the comprehensive American university, with the goal of preparing them for a lifetime of further learning rather than simply near-term employment as an engineer.*

Here, we propose that the discipline of engineering would be taught by existing engineering schools through both degree programs at the undergraduate and graduate levels, including courses provided to all undergraduates as a component of a new 21st-century liberal arts core curriculum. Of course, part of the challenge is the basic codification of the engineering discipline, still a subject of some uncertainty and requiring further study (e.g., see Vincenti, 1990). Furthermore, because of the strong research interests and background of most current engineering faculty, the curriculum and degrees offered in the discipline of engineering would initially have more of an applied science character and would not necessarily require ABET certification, thereby allowing more opportunity for a broader liberal education on the part of undergraduates.

The current pedagogies used in engineering education also need to be reconsidered. Although the science and engineering curriculum includes laboratory experiences, most instruction is heavily based on classroom lectures coupled with problem-solving exercises. Contemporary engineering education stresses the analytic approach to solving well-defined problems familiar from science and mathematics – not surprising, since so many engineering faculty members received their basic training in science rather than engineering. To be sure, design projects required for accreditation of engineering degree programs are introduced into advanced courses at the upper-class level. Yet design and synthesis are relatively minor components of most engineering programs. Clearly those intellectual activities associated with engineering design – problem formulation, synthesis, creativity, and innovation – should be infused throughout the curriculum. This will require a sharp departure from conventional classroom pedagogy and solitary learning methods. Beyond team design projects, engineering educators should make more use of the case method approaches characterizing business and law education. More use might also be made of internships as a formal part of the engineering curriculum, whether in industry or perhaps even in the research laboratories of engineering faculty where engineering design is a common task.

An equally serious challenge to engineering education arises from the ever narrower specialization among engineering majors, more characteristic of the reductionist approach of scientific analysis rather than the highly integrative character of engineering synthesis. While this may be appropriate for careers in basic research, it is certainly not conducive to the education of contemporary engineers nor to engineering practice. Although students may be stereotyped by faculty and academic programs – and perhaps even campus recruiters – as electrical engineers, aerospace engineers, etc., they rapidly lose this distinction in engineering practice. Today's contemporary engineer must span an array of fields, just as modern technology, systems, and processes do.

There is yet another concern about engineering education that arises from the fundamental purposes of a college education and its foundation upon the concept of a liberal education. Two centuries ago, Thomas Jefferson stated the purpose of a liberal education: "To develop the reasoning faculties of our youth, enlarge their minds, cultivate their morals, and instill into them the precepts of virtue and order." Note how appropriate the concept of a liberal education seems today as preparation for the profession of engineering. And note as well that most of the concerns that have been raised about today's engineering education could be addressed by simply accepting the broader objectives of a liberal education for our engineering students.

It is proposed that one views engineering education at the undergraduate level as a discipline suitable both for engineering majors and for other students interested in particular aspects of engineering, e.g., technology management and public policy. Engineering schools would continue to offer multiple degrees as they do now, e.g., ABET-accredited B.S. degrees in engineering, broader B.S. or B.A. degrees in engineering science, and of course an array of graduate degrees (M.S. and Ph.D.). Students seeking an engineering background as preparation for further study in fields such as medicine, business, or law would continue to enroll in specific engineering majors, much as they do now. Many students would continue to enroll in ABET-accredited engineering degree programs to prepare them for entry into technology-based careers, although as we have noted earlier, these would require further professional education and training at the graduate level to enter the engineering profession. Students interested in research careers would major in either ABET-accredited or engineering science degree programs in preparation for further graduate study in engineering science (M.S. and Ph.D.).

However, of most interest here is the possibility that those students intending to enter the profession of engineering would no longer be subject to the overburdened curriculum characterizing ABET-accredited undergraduate degree programs. Instead they could earn more general liberal arts degrees in science, mathematics, engineering science, or even the arts, humanities, or social sciences with an appropriate pre-engineering foundation in science and mathematics, as preparation for further study in an engineering professional school. In this way, they would have the opportunity for a true liberal education as the preparation for further study and practice in an engineering profession characterized by continual change, challenge, and ever-increasing importance.

Here one must always keep in mind that while engineering educators certainly have a responsibility to address the needs of industry, government, and society, their most fundamental commitment must be to the welfare of their students. There is an old saying that the purpose of a college education should not be to prepare a student for their first job but instead prepare them for their last job. This will sometimes require turning aside from the demands that engineering graduates be capable of immediate impact and instead stressing the far greater long-term value to the student – and our society more broadly – of a truly liberal education.

In recent years, even science-intensive professions such as medicine have accepted the wisdom of broadening their admissions requirements to allow the enrollment of students from undergraduate majors in the social sciences and humanities. They seek more well-rounded students who can be molded into caring and compassionate physicians, who understand better the broader context of medical decisions and patient treatment. Although recent surveys have highlighted the difficulties that students currently have in transferring from other majors into engineering programs, the creation of graduate professional schools in engineering would provide the opportunity to broaden substantially the undergraduate requirements for engineering careers. Furthermore, the recent development of multiple course sequences to provide a concentration or minor in engineering for students in liberal arts colleges provides yet another route for broadly educated undergraduates to consider engineering careers after further graduate study, just as they can through the science sequences offered for pre-med students.

Broadening the undergraduate experience of engineering students would also provide a more sound foundation for lifelong learning. Today the United States faces a crossroads, as a global knowledge economy demands a new level of knowledge, skills, and abilities on the part of all of our citizens. To address this, the Secretary of Education's Commission on the Future of Higher Education in America has recently recommended, "America must ensure that our citizens have access to high-quality and affordable educational, learning, and training opportunities throughout their lives. We recommend the development of a national strategy for lifelong learning that helps all citizens understand the importance of preparing for and participating in higher education throughout their lives" (Miller, 2006). The commission believed it is time for the United States to take bold action, completing in a sense the series of these earlier federal education initiatives, by providing all American citizens with universal access to lifelong learning opportunities, thereby enabling participation in the world's most advanced knowledge society. The nation would accept its responsibility as a democratic society in an ever more competitive global, knowledge-driven economy to provide all of its citizens with the educational, learning, and training opportunities they need, throughout their lives, whenever, wherever, and however they need it, at high quality and affordable costs, thereby enabling both individuals and the nation itself to prosper.

This recommendation has particular implication for professions such as engineering where the knowledge base is continuing to increase at an ever-accelerating pace. The shelf life of education acquired early in one's life, whether K-12 or higher education, is shrinking rapidly. Today's students and tomorrow's graduates are likely to value access to lifelong learning opportunities more highly than job security, which will be elusive in any event. They understand that in the turbulent world of a knowledge economy, characterized by outsourcing and offshoring to a global workforce, employees are only one paycheck away from the unemployment line unless they commit to continuous learning and re-skilling to adapt to every changing work requirements. Furthermore, longer life expectancies and lengthening working careers create additional needs to refresh one's knowledge and skills on a continuous basis. Even today's college graduates expect to change not simply jobs but entire careers many times throughout their lives, and at each transition point, further education will be required – additional training, short courses, degree programs, or even new professions. And, just as students increasingly understand that in a knowledge economy there is no wiser personal investment than education, many nations now accept that the development of their human capital through education must become a higher priority than other social priorities, since this is the only sure path toward prosperity, security, and social well-being in a global knowledge economy.

Hence one of the important challenges to engineering educators is to design their educational programs not as preparation for a particular disciplinary career but rather as the foundation for a lifetime of continuous learning. Put another way, the stress must shift from the mastery of knowledge content to a mastery of the learning process itself. Moreover, this will require a far more structured approach to continuing engineering education, more comparable to those provided for other learned professions such as medicine characterized by a rapidly evolving knowledge base and profound changes in professional practice. It seems clear that continuing education can no longer be regarded as simply a voluntary activity on the part of engineers, performed primarily on their own time and supported by their own resources. Rather it will require a major commitment by employers – both in industry and in government – to provide the opportunity and support, and by engineering schools and professional societies to develop and offer the necessary instructional programs. It likely will also require some level of mandatory participation through regulation and licensure, similar to the medical and legal professions.

> *Proposal 5: In a world characterized by rapidly accelerating technologies and increasing complexity, it is essential that the engineering profession develop a structured approach to lifelong learning for practicing engineers similar to those in medicine and law. This will require not only a significant commitment by educators, employers, and professional societies but possibly also additional licensing requirements in some fields.*

This brings us to a broader proposal for a 21st-century college education. The liberal arts is an ancient concept that has come to mean studies that are intended to provide general knowledge and intellectual skills, rather than more specialized occupational or professional skills. The term liberal in liberal arts is from the Latin word *liberalis*, meaning "appropriate for free men" (social and political elites), and they were contrasted with the servile arts. The liberal arts thus initially represented the kinds of skills and general knowledge needed by the elite echelon of society, whereas the servile arts represented specialized tradesman skills and knowledge needed by persons who were employed by the elite. The scope of the liberal arts has changed with an evolving civilization. It once emphasized the education of elites in the classics, but with the rise of science and humanities and a more pragmatic view of the purpose of higher education, the scope and meaning of "liberal arts" expanded during the 19th century. Still excluded from the liberal arts are topics that are specific to particular occupations, such as agriculture, business, dentistry, engineering, medicine, pedagogy (school teaching), and pharmacy.

Yet here, William Wulf reminds us of another important belief of Thomas Jefferson: one cannot have a democracy without informed citizens. Today we have a society profoundly dependent upon technology, profoundly dependent on engineers who produce that technology, and profoundly ignorant of technology. As Wulf observes, "I see this up close and personal almost every day. I deal with members of our government who are very smart, but who don't even understand when they need to ask questions about the impact of science and technology on public policy" (Wulf, 2003). He goes on to suggest that the concept of a liberal education for 21st-century society must include technological literacy as a component. Here he contrasts technological literacy with scientific and quantitative literacy, noting that everyone needs to know something about the process by which the knowledge of science is used to find solutions to human problems. But everyone also needs an understanding of the larger innovation engine that applies technology to create the wealth from which everyone benefits.

From this perspective, one could make a strong case that today engineering – or better yet technology – should be added to the set of liberal arts disciplines, much as the natural sciences were added a century ago. Here we are not referring to the foundation of science, mathematics, and engineering sciences for the engineering disciplines, but rather those unique tools that engineers master to develop and apply technology to serve society, e.g., structured problem solving, synthesis and design, innovation and entrepreneurship, technology development and management, risk–benefit analysis, and knowledge integration across horizontal and vertical intellectual spans.

> *Proposal 6: The academic discipline of engineering (or, perhaps more broadly, technology) should be included in the liberal arts canon undergirding a 21st-century college education for all students.*

The final proposal addresses the challenge of building an engineering workforce with sufficient diversity to tap the full talents of an increasingly diverse American population and address the needs and opportunities of an increasingly diverse and competitive global society. Here the objectives have been forcefully stated in a recent National Academy of Engineering study, “All participants and stakeholders in the engineering community (industry, government, institutions of higher education, professional societies et al.) should place a high priority on encouraging women and underrepresented minorities to pursue careers in engineering. Increasing diversity will not only increase the size and quality of the engineering workforce, but it will also introduce diverse ideas and experiences that can stimulate creative approaches to solving difficult challenges. Although this is likely to require a significant increase in investment from both public and private sources, increasing diversity is clearly essential to sustaining the capacity and quality of the United States scientific and engineering workforce” (Duderstadt, 2005; Marburger, 2004).

To this end, it is appropriate to conclude with the following proposal:

> *Proposal 7: All participants and stakeholders in the engineering community (industry, government, institutions of higher education, professional societies et al.) should commit the resources, programs, and leadership necessary to enable participation in engineering to achieve a racial, ethnic, and gender diversity consistent with the American population.*

Concluding Remarks

America’s leadership in engineering will require both commitment to change and investment of time, energy, and resources by the private sector, federal and state governments, and colleges and universities. Bold, transformative initiatives are necessary to reshape engineering research, education, and practice to respond to challenges in global markets, national security, energy sustainability, and public health. The proposals suggested in this chapter involve not only technological but also cultural issues that will require the collective commitment of the engineering profession and engineering educators and the support of industry, federal and state governments, and foundations.

Sometimes a crisis is necessary to dislodge an organization from the complacency that arises from past success. The same holds for a nation – and a profession, in fact. It could be that the emergence of a hypercompetitive, global, knowledge-driven economy is just what the United States and the profession of engineering need. The key to America’s global competitiveness is technological innovation. And the keys to innovation are new knowledge, human capital, infrastructure, and enlightened policies. Not only must the United States match investments made by other nations in education, R&D, and infrastructure, but it must recognize the inevitability of new innovative, technology-driven industries replacing old obsolete and dying industries as a natural process of "creative destruction" (a la Schumpeter) that characterizes a hypercompetitive global economy.

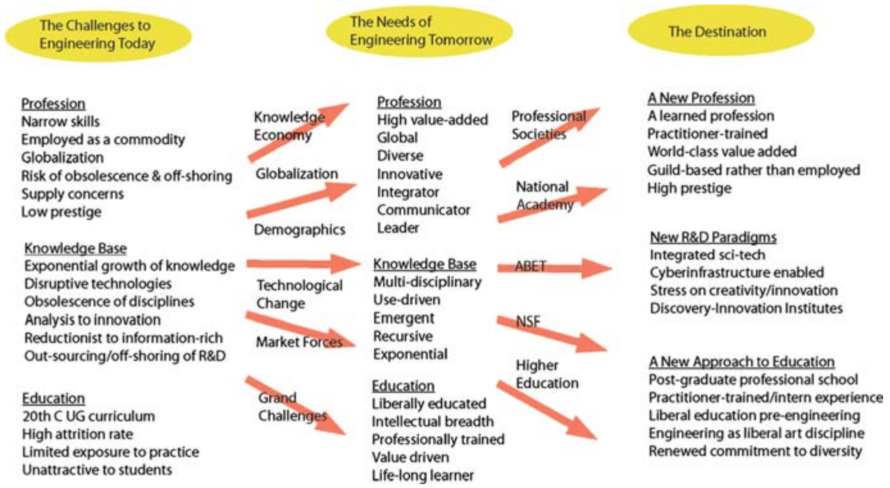
The same challenge faces the engineering profession. The growing tendency of American industry to outsource engineering services and offshore engineering jobs should serve as a wakeup call in our times similar to that provided to industry by the outsourcing of manufacturing in the 1980s. The global knowledge economy is merciless in demanding that companies seek quality services at minimal cost. When engineers in Bangalore, Shanghai, and Budapest produce high-quality results at one-fifth the cost of similar efforts in the United States, America's engineering profession simply must recognize that our engineering core competency is no longer particular technical skills or narrowly tailored engineering careers. It requires new paradigms for engineering practice, research, and education. The magnitude of the challenges and opportunities facing our nation, the changing demands of achieving prosperity and security in an ever more competitive, global, knowledge-driven world, and the consequences of failing to sustain our engineering leadership demand bold new initiatives.

Yet we also acknowledge that the resistance to the bold actions proposed in this chapter will be considerable. Many companies will continue to seek low-cost engineering talent, utilized as commodities similar to assembly-line workers, with narrow roles, capable of being laid off and replaced by offshored engineering services at the slight threat of financial pressure. Many educators will defend the status quo, as they tend to do in most academic fields. And unlike the professional guilds that captured control of the marketplace through licensing and regulations on practice in other fields such as medicine and law, the great diversity of engineering disciplines and roles continues to generate a cacophony of conflicting objectives that inhibits change.

Yet the stakes are very high. During the latter half of the 20th century, the economic leadership of the United States was largely due to its capacity to apply new knowledge to the development of new technologies. With just 5% of the world's population, the United States employed almost one-third of the world's scientists and engineers, accounted for 40% of its R&D spending, and published 35% of its scientific articles. Today storm clouds are gathering as inadequate investment in the necessary elements of innovation – education, research, infrastructure, and supportive public policies – threatens this nation's technological leadership. The inadequacy of current government and industry investment in the long-term engineering research necessary to provide the knowledge base for innovation has been revealed in numerous recent reports. Furthermore, the growing compensation gap between engineering and other knowledge-intensive professions such as medicine, law, and business administration coupled with the risks of downsizing, outsourcing, and offshoring of domestic engineering jobs has eroded the attractiveness of engineering careers and precipitated a declining interest on the part of the best

US students. Current immigration policies combined with global skepticism about US foreign policy continue to threaten our capacity to attract outstanding students, scientists, and engineers from abroad.

If one extrapolates these trends, it becomes clear that our nation faces the very real prospect of losing its engineering competence in an era in which technological innovation is key to economic competitiveness, national security, and social well-being. Bold and concerted action is necessary to sustain and enhance the profession of engineering in America – its practice, research, and education. It is the goal of this report both to sound the alarm and to suggest a roadmap to the future of American engineering. While it is important to acknowledge the progress that has been made in better aligning engineering education to the imperatives of a rapidly changing world and to commend those from the profession, industry, and higher education who have pushed hard for change, it is also important to recognize that we still have many more miles to travel toward the goal of better positioning American engineering to serve a rapidly changing world.



A roadmap to the future of American engineering

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Chapter 4
K-12 Engineering – the Missing Core Discipline

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The Missing Core Discipline

We live in a human-made world. From the moment we wake up until we lie down to sleep, we are immersed in technologies. The faucet we use to wash our face, the toothbrush we use to clean our teeth, the clothes we wear, the car we drive, our office or school, our home, and even the mattress we sleep on are all the results of engineering processes. The water we drink has undergone an engineered purification process. The food we eat is the result of countless engineering technologies. If you are reading this inside a building, take a moment to look around. Imagine how your environment would look without any human-made things. Almost nothing you see or experience would be present – no electricity, no chair, no walls, no book, and maybe no YOU. Without human-made pharmaceuticals and sanitation processes, the life expectancy would be 27 years.

We live in an engineered world. Engineering design creates the technologies that support our health, convenience, communication, transportation, living environments, and entertainment – our entire day-to-day life. We school our children so they can live a healthy, productive, and happy life. Our curriculum includes disciplines that prepare students to understand the physical and social world around them so they can be informed users, producers, and citizens. Social studies prepare students to understand human relations and dynamics. Mathematics prepares them to think in quantitative manners to model processes and to calculate. Language arts prepare them to communicate effectively and provide them with tools to learn other disciplines. Science prepares them to analyze and understand the physical world around them. Beginning in preschool, students learn about rocks, bugs, the water cycle, dinosaurs, rain forests, the human body, animals, stars and planets, chemical reactions, and physics principles. These are all important topics, but they only address a minute part of our everyday life.

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The science curriculum focuses exclusively on the natural world, which arguably, occupies less than 5% of our day-to-day activities. The classical K-12 curriculum essentially ignores the other 95%, the human made world. Technology is not part of the mainstream curriculum. In most academic environments the term technology is used to describe electronic devices. Most people do not understand that everything human made, other than some forms of art, are technologies. Although students spend years in school learning about the scientific inquiry process, the process scientists use to discover the natural world, they never learn the engineering design process, which is responsible for most of the things that support their day-to-day lives.

When I first realized this blatant omission, I was shocked. There are so many brilliant people working in K-12 education fields, so many higher education institutions that prepare educators and curricula, and many committed government leaders that care about education. How, then, have we reached the ridiculous point where one may be considered illiterate if she does not know how many legs a grasshopper has, yet is considered perfectly fine in not understanding how the water comes out of a faucet? Students in middle school can spend weeks learning how a volcano works, and no time understanding how a car works. How often will they find themselves in a volcano?

Understanding the natural world around us is essential, but ignoring the other 95% is simply wrong. I was curious to learn the reason that the human-made world is not part of the curriculum. I discovered that one of the most significant moments in American education was the publication of the report of the "Committee of Ten" in 1893. Charles Elliott, the president of Harvard University at the time, led this impressive group of education leaders. They used a quite rational approach to determine which disciplines students should be taught in K-12 schools in order to be prepared for productive work or college entrance. First, they decided what students need to know by high school graduation, then they looked at the things that typical students learn at home, and by subtraction, they decided what should be taught in schools to cover the difference. Fields such as biology, chemistry, physics, and earth science are typically not covered at home and they made the list. Yet technology was left out. Think of the state of technology in 1893. Not only was it quite basic and simple, but most of it focused on farming. And since the majority of school children were living in agrarian areas, they were learning "technology" at home. So the committee determined that it was not necessary to include technology in the regular curriculum. In addition, the committee was likely influenced by the bias of its leader. President Elliott was not a friend of "applied knowledge." He closed Harvard's Engineering school because he deemed Engineering to be too mundane for Harvard. The "Committee of Ten" report was used as a template to create textbooks and curricula and thus technology and engineering were omitted. As technology advanced to become a major influence on our lives, the core curricula and textbooks never caught up.

There was a parallel, yet not as successful movement to create "manual schools," led by the C.M. Woodward, the Dean of Engineering at the Washington University in St. Louis. This movement focused more on vocational education versus basic technological literacy for all. Industrial arts emerged as an elective discipline in some schools in the early 1900s, but also focused on the vocational side of technology. Industrial arts' aim was to train students to become technicians, such as builders and plumbers. Industrial arts gradually evolved to technology education (Tech Ed) which leans closer to engineering, but in most cases it was still viewed as "shop." Tech Ed teachers are not high in the prestige hierarchy in the K-12 academic world. Although in the beginning of the 1900s, Tech Ed programs were developed by engineering schools, schools of education gradually took over the discipline. Many Tech Ed programs are now in colleges and universities which have no engineering programs. This trend inhibited growth in the field that would parallel the explosion of engineering and technology, with a resulting focus on the vocational, rather than the academic. At present, technology education is either a small part of the student's education or simply an elective. In tough economic times, these are the first areas to be cut from the budget. As a result only a small number of students are afforded an opportunity to learn even that limited part of the human made world.

Why Should Engineering Be Part of the Core Curriculum?

Technological Literacy is Basic Literacy

How can one claim to be literate if she does not understand how 95% of her environment works, or how it was made? Technological literacy is simply *basic* literacy. It is no less important than understanding US history or trigonometry. Understanding how an engineer designs is just as important as understanding how a scientist thinks.

Engineering Promotes Problem Solving and Project-Based Learning

The engineering design process starts by identifying a need or a problem. It follows an organized path to arrive at one or more solutions that satisfy the need or solve the problem. Problem solving skills are far more valuable than many of the other skills that are the focus of our K-12 educational systems. I use my engineering training constantly to solve problems far removed from engineering, such as dealing with personnel issues or fundraising. Engineering provides a life skill that can be used in everyday life and in any occupation.

Engineering pulls other disciplines together, enabling students to work as a team to solve a problem they are passionate about. Imagine a second-grade engineering team trying to solve the problem of how to keep their classroom pet bunny rabbit at the school, even though one of their classmates is allergic to it. This problem presents a welcome opportunity for the students to apply the skills they have gained from other disciplines to solve a problem they personally care about. In order to build an outdoor habitat for their rabbit, students have to use their math to figure out the measurements of the hutch so the bunny can comfortably live in it and enter and exit, while not allowing the neighborhood raccoon to move in. They have to use their science knowledge, including the fact that heat flows from hot to cold, while insulating the habitat so the bunny can be comfortable during the cold winter months. They even have to use their art skills to make the habitat appealing. While doing this, they sharpen their team and collaborative learning abilities.

Engineering Makes Math and Science Relevant

Why do students lose interest in math and science in the middle school years? Some blame teacher quality and preparation. That may be a factor; however, I believe it is primarily because curriculum content is disconnected from the content of the students' daily lives and interests. In elementary school years, students love science because they learn about rocks, bugs, dinosaurs, and rain forests. These topics are exciting in elementary school, but quickly lose their appeal as the students reach puberty. In middle school, science begins to become more abstract, rocks become earth science, bugs become life science, and physical science deals with forces, energy, and other things that are "invisible" to students. These "natural world" topics are not so natural for children that live in inner-city, urban environments with few opportunities to travel and enjoy the natural world.

The "lack of relevance syndrome" continues at the college level. About half of the students that enter engineering school quit or transfer to liberal arts. Granted, some of these students are not adequately prepared in math and science and are challenged to the point where exit is the only solution, but many of them do quite well in math and science, yet they decide to switch. All colleges and universities, even the elite ones, lose a large portion of their first-year engineering class to liberal arts. When I became Dean of the School of Engineering at Tufts University in 1994, I learned that 22% of the first-year engineering students transferred to liberal arts. What I found even more disturbing than the shear number of transfers was the grade point average of these students was a B+, with average math plus verbal SAT scores was close to 1400! Lack of preparation was not the reason.

Why, then, were students switching at such great rates? I held a number of focus groups in order to understand the reasons. The number one response was "I did not find Engineering interesting." What I found interesting was that they had not yet taken any engineering. The first-year curriculum was filled with math and science, along with some computer programming and perhaps a basic design course. The magic and excitement of engineering was just not part of their experience. As a result, we changed the curriculum to not only include engineering earlier, but also to include it in an engaging way. We introduced engineering courses for first-year students that stemmed out of faculty's personal hobbies and interests and we opened the courses to liberal arts students as well. There were courses in Acoustics and Chemical Engineering under the titles "Design and Performance of Musical Instruments" and "Microbrewery Engineering." I developed two courses stemming out of my fishing and cooking hobbies. My fishing-related course was called "Life in Moving Fluids." It was an introductory fluid mechanics course, but from the point of view of a fish or a tree. The laboratory looked more like a biology lab than an engineering lab with live fish, sea anemones, and plants, along side liquid and air tunnels. The other course was called "Gourmet Engineering" where transient heat conduction-related differential equations would come alive in a state-of-the-art kitchen laboratory. Finite cylinders took the form of meat roasts, instrumented with thermocouples that would monitor the temperature to show if the math really worked. All these courses were designed in a way that made math and science relevant. The experiment worked. Within a year, Tufts became, and still is, the only school in the country where in some years more students transfer from liberal arts into engineering versus engineering to liberal arts.

Engineering makes math and science relevant which is critical in the middle school and high school years. Relevance is particularly important for retention of girls in science fields. Girls gravitate toward science disciplines that have an evident benefit to society. Half of the medical school students are women, and women comprise the majority of students in the life sciences. In some highly competitive veterinary schools, more than 80% of the students are female. Ability is clearly not the limiting factor. Engineering in K-12 can make science relevant and improve student interest, especially among girls.

Engineering as a Career

There has been considerable discussion and expressed panic for the prospective lack of engineers in the United States. Some skeptics argue that the gap between demand and supply of domestic engineers could be covered by outsourcing work to foreign engineers for less money and, in some cases, better work quality. While there are some engineering jobs that could, and probably should be outsourced, there are others that must remain domestic. If these jobs were outsourced, the security and culture in the United States would suffer.

Engineering jobs related to local infrastructure are prime examples. The design, construction, and maintenance of buildings, roads, power plants, airports, electric grid systems, etc., are best accomplished by engineers who are familiar with local conditions. Engineering jobs related to our national defense systems also cannot be outsourced. Would you be comfortable being protected by weapon systems imported from another country?

The United States has always been the center of innovation. Innovation, driven by US engineers, has made this country special and has attracted some of the best minds to immigrate here. This innovation has created the products, services, and wealth that still make living in the United States better than most countries. If this innovation culture gets eroded or outsourced, the entire character and culture of our nation will be affected dramatically.

In order to preserve the innovation culture in the United States, numerous committees have issued reports calling for an increase in support of K-12 mathematics and science education. What these reports have missed is that the connector between math, science, and innovation is engineering. Unless this connection is made in school, the number of future engineers will continue to fall short of the current and future demands.

The United States would have a lot more engineers if young people knew what engineers do. Approximately seven out of ten engineers in this country have had a relative that was an engineer. There are few other non-trade professions that are connected like this to family. Unfortunately, school career guidance counselors are typically uninformed about engineering. The general public is similarly uninformed and confused about what engineering is and what engineers do. In China, Europe, and India the engineering profession is better understood, and Engineering is considered a very prestigious career choice. Some of the most competitive admissions to European universities are for engineering majors. Almost half of the members of China's politburo have an engineering background.

As the demographics of our country change, and the percentage of Caucasians decreases, so, too, will the number of engineers. In African-American communities, most young adults that attend college focus on education, medicine, and law, largely because these were culturally considered respectable professions. These are the professions that their community has encouraged them to enter and thrive in – since African-Americans have historically been shut out of many professions including engineering. Given that the engineering profession is overwhelmingly comprised of Caucasians, and given the strong link between the engineering career choice and relatives in the profession, the numbers are bound to decrease.

Here in the United States there is confusion about the term "engineer." We call train drivers, radio station sound technicians, and janitors engineers, along with the traditional college educated engineers. It is not uncommon to see the doors of high school janitor closets lettered with signs saying "ENGINEERING." Even the janitor's closet at the National Academy of Engineering's old building had a sign saying "ENGINEERING." If you have a problem with your toilet in a hotel and you call the front desk for help, they may tell you "we are sending the *engineer* up right away."

The role of engineers could be better understood if public media represented the profession more prominently and accurately. Engineers are largely absent from mass-market television, where both kids and adults get their information. News programs could be encouraged to solicit input from engineers on topics such as cutting-edge technologies, port designs, earthquake prevention, and heart stents. Newspapers could include more statements from engineers when new designs succeed (vs. during failures). The nation has missed great opportunities to celebrate engineering achievements and to excite young people to pursue engineering careers. When NASA's Rover made it to Mars, the press called it a "science miracle." When something went wrong with it, the press called the event an "engineering error." There are no prime time TV shows with engineering heroes or main characters.

Unless the United States makes an effort to teach students about engineering early and to present the engineering profession in a realistic light, there is little chance of improving the career-choice statistics.

Navigating in a Three-Dimensional World

We live in a three-dimensional world and we should be able to conceptualize it as such. At times we all have to imagine and sometimes sketch things in three dimensions for considering optimal designs, for example when we redesign a kitchen or set up a warehouse.

Most engineering schools have a course on engineering design which is required for all first-year students. A significant component of this course focuses on 3D visualization skills. A surprising phenomenon that schools throughout the country once noted was that young men entering the engineering school were more capable tackling 3D challenges than their female counterparts. Both men and women had comparable college entrance test scores, high school grades, and in some cases, were from the same family. The phenomenon could not be attributed to some genetic factor, since after the design course, the 3D gap would close and both men and women could tackle these challenges with similar abilities and skills.

Researchers in Michigan studied the phenomenon and came to the conclusion that the reason for the differential performance between young men and women in 3D skills was attributed to the toys that they played with during their growing years. I was fascinated by the study and wanted to take a personal look at the different toy availability for boys and girls. I went to a large chain toy store and spent a few hours with the gender bias in mind. I was fascinated! There was an abundance of toys for boys that sharpened 3D visualization skills such as LEGOs, Lincoln Logs, construction sets, and lathes. The availability of such toys for girls was a different story. Most girl toys focused on nurturing and fantasy. Barbie's aisle was loaded with toys such as "Teen Talk Barbie" which once said "Will I ever have enough clothes?" and "Math class is Tough!" "My Little Pony" was another top seller which featured a plastic little horse with a fuzzy tail and a plastic comb. I quickly understood the validity of the Michigan study and realized that toys stemmed this inequity.

Currently, I am more worried that what used to be a boy versus girl issue has become a boy *and* girl issue. Children now spend most of their discretionary time in front of 2D screens, televisions, video games, laptops, MP3 players, and mobile phones. Building, tinkering, and other activities that primarily engage boys are no longer the preferred pastime. We have started creating generations of people that will not be able to visualize and design in three dimensions. This will not only affect the abilities of future engineers, designers, and architects, but also deprive people from a basic life skill. By introducing engineering in K-12 schools we will remediate this issue for both boys and girls.

These are the five driving issues that created the "call for action" to introduce engineering as a new discipline in the K-12 curriculum. This discipline should be parallel and equal to language arts, mathematics, science, and social studies. I recall someone once saying, "Introducing a new discipline in K-12 education is as challenging as moving a graveyard." I am beginning to see the truth in that statement.

The Transformational Moment

A small number of K-12 engineering curricula were developed in the early to mid-1990s; however, their purpose was to motivate students to pursue careers in engineering. Most focused on a specific engineering area such as electronics or automotive engineering. “Project Lead the Way” offered the first sequence of high school engineering courses aimed toward students that planned to attend engineering schools. Many engineering colleges also started K-12 education outreach programs. Recruiting and community service were the main motivators. The first effort to introduce engineering to all children, starting in kindergarten, was undertaken by the School of Engineering at Tufts University in 1994. The Center for Engineering Education Outreach was established and it created curricula and professional development programs for educators spanning all grade levels. The center also partnered with LEGO and created Robolab, the software that enabled the LEGO Mindstorm robotic kit to be used in classrooms.

While these breakthrough programs were very good, they only reached a small number of schools and students. There was clearly a need for a systemic change in order for the K-12 engineering movement to gain momentum. The opportunity was created in 1998, when the Board of Education in Massachusetts appointed a committee to re-write the Massachusetts curriculum framework and learning standards. I was appointed to the committee that would re-write the technology education component of the science standards. I worked with a team of K-12 educators, primarily K-12 Technology Education teachers and introduced the first engineering curriculum frameworks and standards in the United States. The senior staff in the Massachusetts Department of Education did not have much appreciation for Technology Education standards at the time and they saw the transformation of Technology Education standards to Technology/Engineering standards as a move in the right direction. The Technology Education teachers in the group also saw it as yet another evolution of their field and an opportunity for their professional position in the K-12 educator hierarchy to be upgraded and become more secure. On December 20, 2000 the Massachusetts Board of Education voted unanimously to adopt the new technology/engineering standards and to make them part of the state’s assessment. Assessments at the elementary and middle school levels were revised so that science and technology/engineering comprised 20%. At the high school level, technology/engineering became one of the four end-of-course assessment options for graduation, the other three being biology, chemistry, and physics.

At the elementary level, the engineering standards focused on distinguishing between the natural and human made world, such as comparing tools with animal body parts, e.g., scissors vs. lobster claws and dog paws vs. rakes. Material properties and the basics of the engineering design process were also included. They are intended to be covered by the mainstream classroom teacher, who also covers all other core subjects. At the middle school level, the standards focus again on the engineering design process and also on five technology areas: construction, manufacturing, communication, transportation, and bio-related technologies.

The middle school curriculum is intended to be covered primarily by technology education teachers and science teachers, if technology education teachers are not on staff. At the high school level the standards include more advanced content, including topics such as fluid mechanics and heat transfer.

Although the vote of the board was unanimous, the new standards were not received enthusiastically by all members of the academic community. Many superintendents were against them because their districts did not have the necessary resources to implement them, and many technology education teachers were ambivalent because they saw the inclusion of engineering as a challenge to the traditional instruction. Fortunately, the commissioner of education was strongly behind the new standards and they survived. As a result, Massachusetts became the first state to have engineering standards and assess them at all levels.

Expanding to the National Level

Massachusetts' bold move attracted the attention of the National Science Foundation and it began to fund K-12 engineering education curriculum development and programs. The relevant activities in Massachusetts schools increased in scope and in number; however, no other state followed suit. It became clear that if the initiative were to spread nationally, it would need a focused champion organization. Such an organization could not be in competition with the partners needed to expand it to the national level. Universities tend to be very competitive and so they would not be an ideal home for the lead organization.

In 2004, a year after I joined the Museum of Science in Boston, it became home to the new National Center for Technological Literacy (NCTL). NCTL's mission is to introduce engineering in both schools and museums. Its philosophy is that in order to accomplish a fundamental change in attitude toward engineering, school curriculum must change, in conjunction with the attitudes and understanding of those responsible to implement the change. In order for any program to succeed with this philosophy, it must focus on three areas: advocacy, curriculum development, and professional development. NCTL chose to take on those areas in the following ways.

Advocacy and Support

Although learning standards are centrally controlled in the vast majority of countries around the world, in the United States, they are controlled at the state level. State standards are influenced by standards developed by national groups, such as the National Research Council and the International Technology Education Association. NCTL advocates for the inclusion of engineering in these national standards, in state standards nation wide and in all relevant federal legislation and assessments. It also provides support for states that decide to include engineering standards in their curriculum frameworks such as standards and assessment tool development.

Curriculum Development

Because engineering in K-12 is a new concept, there is a lack of relevant curriculum at all levels. NCTL develops K-12 engineering curriculum at all educational levels where it has identified gaps in existing curricula.

Professional Development

NCTL provides professional development programs for in-service teachers and administrators. Using a "train the trainer" model, NCTL partners with states, so that the professional development capacity can meet the demands according to the level of need in each state. In addition, NCTL works with universities to assist them in curriculum and program development for pre-service teachers.

At the national level, significant progress has been made. The National Assessment for Educational Progress (NAEP) science assessment now includes standards in "technological design." It is unfortunate that it is not called what it is: "engineering design," but still there is progress. The K-12 grant program from the National Governors Association explicitly encourages applicants to include K-12 engineering in their proposals and plans. There is now explicit language in many bills about technology and engineering education. The majority of states now include engineering standards of one form or another, most of them still calling them technology standards. Thousands of schools throughout the country have adopted some form of engineering curriculum. The curriculum produced by NCTL alone is used by over 1,000,000 students in all 50 states.

Challenges

Changing curriculum on a national scale is not easy, particularly when it must be accomplished one state at a time. Over time, NCTL and other advocates have made significant progress. However, we continue to be faced with significant challenges.

Current K-12 curriculum is packed with traditional material, some of it necessary and some not. Turf issues inhibit serious revisiting of what, and to what extent, students need to learn. The turf issues extend beyond the local level. When learning standards development committees are formed at the state level, each member advocates for more standards in their specialty area. Engineering is the newcomer and threatens the each member's "piece of the pie." Similar turf issues occur when developing educational standards at the national level.

Fear is always a consideration when implementing change and the thought of teaching a new topic has proven to be intimidating to many teachers, especially at the elementary levels. Some educators are intimidated by science alone. If teachers have a background in a discipline, or have ready access to professional development courses in that area, they have the ability to increase their knowledge, thus reducing their fear and minimizing their resistance. Unfortunately, colleges of education do not currently prepare prospective teachers for engineering and design. In addition, state-level certification programs do not require content knowledge in engineering for elementary teachers, so few teachers have even the slightest background in engineering education.

When properly presented, most educators react positively to the idea of introducing engineering in K-12 schools. Areas of STEM (science, technology, engineering, and mathematics) education are enjoying widespread support amongst school administrators, federal department of education officials, and National Research Council appointed committee members. However, when implementation and funding opportunities arise, all the attention is focused on the S and the M part of STEM. Many reports advocate for supporting math and science in schools in order to foster innovation in our economy. What they do not realize is that the connector between math, science, and innovation is engineering. The vast majority of school administrators misunderstand the term technology and they assume that technology means computers. Computers are just a small part of technology. Some school districts feel that they offer technology to their students simply because they teach them word processing and spreadsheet skills.

Education is a cyclical process. Students learn, and then some grow to be teachers and teach what they know. When a new discipline is introduced, in-service teachers must learn something new during their busy, professional lives. For this reason, there are few qualified to teach engineering at the middle and high school levels. The teachers that graduate from technology education programs are qualified to teach the technology components of the curriculum, but in many cases are under-prepared in mathematics and science, which provide the basis for engineering. Engineering schools have not stepped up in encouraging their graduates to pursue teaching careers, and certification requirements have made the process of switching from engineering to teaching cumbersome.

College admission requirements have also presented a challenge to the effort of early engineering education. It is ironic that most engineering colleges do not accept a high school engineering course as equivalent to science. They typically look more favorably at an applicant who has taken an advanced placement course in a science area that may have nothing to do with engineering, than a candidate who has taken an engineering course. This discourages students from taking engineering in high school and schools from offering it.

The final hurdle for the introduction of K-12 engineering exists due to the applied nature of the discipline. Engineering education requires new facilities and equipment. When school budgets are tight, administrators are hesitant, if not unable, to open new budget line items.

Moving Forward

In order to maintain the momentum, we should focus our attention on six key areas.

Standard Development and Assessment

The most significant step toward inclusion of engineering in the curriculum is to introduce engineering learning standards at the state and federal level, along with regular assessments of student performance. Technology education teachers, engineering professional societies, and industry members should be strong advocates for the creation of such standards and assessments.

Funding

As mentioned above, funding has focused on the science and mathematics part of STEM, but employment opportunities are predominantly in engineering and technology. For instance, the ratio of engineers to scientists on the NASA payroll is 12:1. NASA's mandate is to educate and motivate young people to enter professions relevant to NASA's mission, yet most of the education funds flow toward science. It is time to directly fund the engineering and technology portions, so they can come up to speed with, and help enforce the others. Funding initiatives that encompass engineering education are not likely to succeed without the aforementioned changes to the learning standards.

Teacher Preparation

Engineering must be inserted into the education cycle, so that teachers are prepared and excited about including the engineering discipline in their curriculum. In order to accomplish this, college programs must be modified. Technology Education teacher training should include more mathematics and science, as well as the engineering design process. Additionally, engineering schools should offer a new track-major that focuses on engineering education. Graduates of such programs would have a broad understanding of engineering, as well a good hands-on project building background. The curriculum should include teaching methods courses. A partnership between the college of engineering and the college of education, at the same or neighboring schools, would facilitate this. Graduates would be prepared to teach both science and technology/engineering courses. Certification requirements should be updated to better reflect the new engineering standards, and also make the career transition from engineer to teacher easier. Elementary school teacher preparation programs should include at least one course in design and understanding the human-made world.

Facilities

The lack of facilities can be overcome if state programs that fund school renovation and construction require schools to have facilities dedicated to technology and engineering. At the elementary school level the facilities may be "take apart" tables with simple tools. Middle and high schools should have design and building facilities, including power tools for prototype development.

Textbooks

Science textbook publishers should include engineering content and activities in their new editions, connecting the traditional science to technology. Engineering is by nature "hands on." This blends well with science textbooks that focus on inquiry. It is more challenging to integrate engineering in traditional science texts. However, more and more publishers now include engineering components. The technology education textbooks should also be modified to emphasize the engineering design process and to include contemporary technologies such as bio-related technologies and nano-technologies.

Changing the Culture

Informal education channels such as museums and science centers, as well as popular media should include more programs on engineering, technology, and relevant careers. Such changes would not only create a more technologically literate population, but would also inspire children to pursue relevant studies, and motivate parents to encourage their children as well.

Conclusion

Understanding how the human made world works, and how it is developed, is an essential component of contemporary basic literacy. Although the value of this understanding was largely ignored in K-12 schools until the mid-1990s, significant progress has been made. Engineering and technology standards are being included in many state curriculum frameworks. Federal legislation and national assessments now also include technology and engineering, and thousands of schools in all 50 states are using engineering curricula. This is a long road, but at the end we will have a nation of technologically literate citizens. This vision continues to fuel the momentum to ensure that K-12 Engineering will emerge as the essential new core discipline.

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Chapter 5
Liberal Arts and Engineering

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Introduction

Much has been written about liberal arts education over the past two centuries (or perhaps even two millennia). And what constitutes the liberal arts has changed over time. Why have so few liberal arts colleges adopted engineering as one of the liberal arts that its students may pursue and its faculty engage in their scholarship? Is engineering a liberal art? Can it be studied as a liberal art?

The Yale Report of 1828 (Hofstader and Smith, 1961, 278–279) expresses that "the scholar must form himself, by his own exertions" and that "we doubt whether the powers of the mind can be developed, in the fairest proportions, by studying language alone, or mathematics alone, or natural or political science alone." The transformation of American colleges into research universities in which the elective system developed at Harvard was adopted in the 19th century meant that disciplines and fields of study were no longer limited to the classics, religion, and mathematics. To be liberally educated meant engaging many fields of study.

Some scholars note that many institutions that saw themselves as guardians of the liberal arts, viewed engineering or technology as antithetical to their mission, as engineering "emphasized things rather than ideas" (Hawkins, 1999, 4).

At the same time, a distinction (and in some cases a perceived hierarchy) arose between basic science and applied science and technology. American higher education evolved as a place for "original research and teaching in pure science" (Stokes, 1997, 41). The separation between basic and applied science created in the minds of many in the liberal arts, a separation between science and engineering. Academe viewed the latter as applied and vocational, and hence determined that such fields had no place in a liberal arts institution.

Yet as Smith's President Carol Christ (Personal Communication, November 11, 2008) explains, "there is nothing stable about the definition of what might be a liberal art." Thus the limited universe of disciplines available to students of the

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liberal arts in 1800 is quite different from that offered in 2009. Each liberal arts institution offers a spectrum of disciplines or areas of study that the faculty agree are appropriate but none offer precisely the same scholarly areas. What defines an area worthy of scholarship and thus appropriate for study has evolved over time. One of the challenges facing the academy has been to define standards for scholarship in fields where the making of work or the practice "of the profession" is an integral part of the intellectual experience.

Engineering occupies a complex space. In one dimension, it is a practice field. It holds a place alongside painting, dance, theatre, the writing of fiction and poetry, architecture, music composition, and performance as a field where the making of the work is an important, if not the central element of the field. The theoretical frames, the quantitative analysis or critical assessments that underpin or explain, inform the making of the work but do not in themselves create although they are essential tools in that creation.

Practice fields have had an uneasy existence in the academy where the printed word (or equation) is valued above all other forms of communication. Thus creative work that can be easily described in text is more easily understood, and evaluation of scholarship more easily assessed. But performance and practice are more challenging to assess, and to narrate. Yet the process of design and the making of work are what drive many students and faculty. The chance to examine, interrogate, and experience what it means to create is central to their research and scholarship.

In another dimension, engineering occupies Pasteur's quadrant as a field in which research is inspired by use. In American higher education, particularly in the research universities, a place was created for the practice or applied fields. "The applied fields, while they seemed to repeat the separation of basic from applied science, have in fact provided an institutional home for research that is driven by the goals of understanding *and* use .... The distinction between basic and applied science was simple drawn within universities" (Stokes, 1997, 45). The research university tent was large enough to provide space for the liberal arts and for those fields inspired by use or practice.

What further complicates the story of liberal arts education and engineering education is the tension between a liberal arts education and a vocational or professional education, for engineering is one of the few professions that students can pursue at the undergraduate level in elite academic institutions. For many institutions with a focus on undergraduates, the emphasis is on liberally educating the student so that she is ready to pursue a complex career path and a rich post-graduate life with skills in critical thinking, analysis, and an appreciation for the complexity of the society in which she lives. Engaging in practice is seen as somehow in conflict with an engagement with ideas.

That engagement with practice, however, is consonant with another theme that runs through the concepts of liberal arts education, that of being educated for a democratic society: "The philosophy of the liberal arts is the philosophy of a democratic society in which citizenship, social responsibility and community are inseparable" (Lang, 1999, 138). Lang argues that often the liberal arts colleges have became disengaged from their communities. Would that have happened had there been greater engagement with engineering as a liberal art? Does the study of engineering as a liberal art provide students and faculty a means of engagement with the community?

In this essay, I will engage these topics, first with a personal story and then by examining engineering in the context of liberal arts colleges, and then with the broader issue of applied studies and their role in academe. Two themes run through this assessment: the power of the making of work, and the role that engineering has played as a bridge between society and science.

Personal Story

In my case, I had an unusual chance to pursue my education twice, in both instances at exceptional institutions. When I went off to college, I went with an intense desire to engage my teachers and classmates intellectually, to delve deeply into questions about life, about how and why we think and behave as we do. I went with a very open mind about possible majors and took full advantage of the opportunity to explore a wide variety of courses. I had no idea in what I would major, but I was fairly determined that it would not be math or science, fields in which I had little confidence that I could master, and frankly were fields that I had studied because my mother said they were good for me, a little like eating canned Brussels sprouts.

As an undergraduate, I studied at Smith College (and took some great classes at Amherst) and then transferred to Haverford College (and took some amazing classes at Bryn Mawr College). My eyes were opened by Smith's famous Art 100; it was illuminating to leave lecture and head for the museum to view works that were of the era or school or medium that had just been discussed. It was challenging to read great works of literature, in English and in French, to study psychology, religion, philosophy, history, and anthropology. Discussions began in class, migrated out of class, spilled into the dining center or the sidelines during field hockey practice. But the questions that could not be addressed in reading or discussions or in a research paper were ones of how the creative process emerged, what it meant to actually make a work. While I loved learning about the works in art history, I became increasingly frustrated by writing about objects that were visual and tactile. I wanted to get my hands involved.

An introductory course in materials allowed me to explore different media. A first course in figure drawing drew me into the process of analysis – what it meant to translate three dimensions into two, to begin to explore translation and representation. Sculpture and painting soon followed. The process was both one of personal discovery and creativity as well as a more objective one of examining the world and one's experience in it through visual means. At each stage, the development of work was informed and influenced by the study of history, psychology, women's history, the history of art, religion, and philosophy. It was affected by critiques, both formal and informal. The critique is that process whereby one's work is formally and verbally assessed by one's teacher, outside artists, and fellow classmates. It is a revelatory process, since one is very much in the public eye, explaining and defending the work, receiving and responding to praise and criticism alike. The process was intellectually demanding and rewarding.

When I finished the first phase of my studies, I knew that I wanted to return to school at some stage, but I needed to be economically self-sufficient which meant finding a job. I intended to work and keep painting. In 1974, the opportunities in Washington DC were in areas related to energy. I landed a position at the Office of Coal Research, a somewhat obscure office within the Department of Interior. It afforded me the opportunity to explore a whole new set of ideas and issues – that is our national energy situation, our policies, ideas about energy independence, and the role of coal in that picture. The office was flush with resources, ideas abounded, and because there was so much work, and too few bodies, I was given responsibility and opportunities that normally did not come to someone with just an undergraduate degree, and a non-technical one at that. I drew on every bit of high school math and science that I had learned.

A year and a half later, I found myself transplanted to California with my husband who would be attending Stanford Law School. His parents suggested that I think about school, asking whether I wanted to study art or engineering. Actually, I intended to get a master's degree in policy, with an emphasis on energy policy. But Professor William Reynolds, who was interested in engaging students with strong liberal arts backgrounds to study engineering, persuaded me to do so. He encouraged me to take the prerequisite courses in math and science and engineering fundamentals. He also employed me to write the newsletter for the Stanford Energy Institute which allowed me to stay focused on the policy issues that drove my interest in science and engineering, and kept me from becoming discouraged. He acknowledged my training in art as parallel to that in design in engineering and encouraged me to pursue experimental work. He was masterful teacher and mentor. I completed my master's degree and was admitted to the PhD program where I studied with Tom Bowman, another risk taker in that I was his first PhD student and an unconventional one. (I would note also that I had my first two children while I was a graduate student; the department and my advisors in particular were supportive and flexible – I took a little longer to finish my degree but it was worth it!)

What I loved about the study of engineering was that, like the practice of art, it gave me a structure and approach to solving problems. Engineering like art is a lens through which to analyze and view the world. Through its various forms it asks us to consider and reconsider how we view the world. As engineers, we have a rich set of tools and methods that give us approaches to the problems that engage us. We can lay out the problem, define its boundaries and initial conditions, and apply to those problems a variety of analyses and solutions defined by the character of the problem itself. Those tools when applied well allow us to construct buildings and vehicles, design artificial limbs and other devices to improve health, develop new energy delivery systems or enable us to harness the sun's energy in new and less environmentally damaging ways. These tools enable data to be analyzed, communications to be encrypted, libraries to be digitized, and new forms of art to be produced.

Engineering gave me a very different lens through which to consider policy. It has allowed me to frame the questions I ask experimentally or in the field. I would argue, however, that these engineering tools are insufficient both to grapple with the challenges of the 21st century and to understand the impacts of our actions. And that is why it is important to embrace engineering as a liberal art.

Let me illustrate. Roughly one-third of the world's population burns fuel indoors for cooking, for heat, and illumination. Exposure to air pollution indoors and out accounts for up to 10% of ill health, ill health that leads to death or to a great loss of productivity or quality of life. Various technological strategies are being employed to reduce these exposures. The use of improved stoves as a technological intervention has been one of mixed success: improved stoves were not adopted by the intended users because the design failed to provide the user with the expected performance or required them to adapt cooking practices in ways that they were unable or unwilling to change.

The full import of the limits to technical solutions was driven home for me over the last several years through a research project to evaluate a demonstration rural energy project in northeast China (Fischer et al., 2005, 51–60). We were asked to evaluate not only the environmental health impacts, and the economic ones but the social impacts. My graduate student and I both trained in engineering and environmental health science collaborated with an anthropologist. We used our combined skills, and in particular by using an ethnographic approach we were able to identify local circumstances, perspectives, priorities, and power structures that influenced and help to explain project outcomes. In its original design, this village-scale energy project was expected to use locally available corn stalks to generate household cooking and heating gas, and electricity, in a configuration financially attractive both to potential investors and household consumers. During the course of the project's development, we made several visits to conduct interviews with and on-site observations of village residents, factory workers, project representatives, village leaders, and other key informants. We also made in-door air quality measurements of households burning coal, straw, and the producer gas (Fischer and Koshland, 2007a,b 141–150). The sponsoring agencies, both international and Chinese, deemed the project successful when it produced the gas. In our on-site visits, in contrast, we discovered an essentially failed project – although the plant produced gas, it produced insufficient quantities, and its distribution to the village was flawed. And because in the few cases when it was used, it simply added to the fuel mix, it actually increased air pollution in those homes because it did not substitute for the coal. Because of the interdisciplinary approach we had taken, we could assess the root causes of the project failures, and thus can offer lessons for future village-scale modern biomass energy projects in rural China. Many of the technical, administrative, and logistical problems encountered by this project were rooted in cultural misunderstandings, which led to poor communication and inappropriate implementation. Including an ethnographic perspective alongside technical and economic analyses can help avert or resolve cultural misunderstandings (Young et al., 2007, 3121–3126; Fischer et al., 2008, 78–81). Had the initial approach of this project included far greater needs analysis, cultural assessment, and partnering at the local level, the technology could have been adapted to better much the available fuel stocks, the system better designed to meet the actual needs, and the business model tailored for the reality of rural agricultural China – instead a western business model was imposed, and all along the way, differences in cultural practices and expectations created a path to failure.

Science, and its application through technology, can provide many avenues for improving the welfare of peoples but such technological interventions will not succeed if they are applied in the absence of cultural or social understanding. Thus I would argue that the multiple lenses that combine and intersect need to go beyond science and engineering. Engineering and the liberal arts each need to engage the other in a more compatible relationship.

So why has the kind of liberal learning not emerged in engineering? And why have the liberal arts been slow to embrace engineering as one of its own?

Engineering and the Liberal Arts Colleges

Remarkably few liberal arts colleges incorporated engineering studies into their curricula over the last 150 or so years. In many ways this is not surprising, given the aversion to vocational or professional education articulated by so many faculties over that time frame. Formal training for most professions did not exist, and in many cases arose separately in technical schools or colleges. The development of land-grant colleges and universities and the development of professional standards began to change the types of programs that students could pursue as undergraduates.

A handful of liberal arts colleges adopted engineering majors: Haverford and Swarthmore Colleges developed engineering majors in the late 1800s with Swarthmore graduating its first major in 1874; Union College was the first with a major in 1845. Smith College is one of the newest entrants with its Picker Engineering program that began in 1999.

In a survey conducted in 1963 by Haverford College of other programs (Haverford College archives), only a handful of colleges had departments or divisions of engineering: Swarthmore, Union, and Haverford. Washington and Lee offered a physics-engineering major. Six other liberal arts colleges offered courses but did not offer a major. Twenty institutions offered a 3–2 plan (including Amherst, Carleton, Colby, Davidson, Williams, and Reed). Denison offered engineering until 1953 and then converted to a 3–2 plan. Pomona had a department before WWII; after that time they suggested physics and mathematics to students interested in engineering. At the time of this 1963 survey, no colleges indicated an interest in adding the major, and those who offered the major had few takers, on the order of two or three per year. And nearly 50 years later, the landscape is remarkably similar.

In the 1960s, both Haverford and Swarthmore engaged in a discussion about the place and future of engineering within a liberal arts college, and came to opposite conclusions. Haverford faced with an aging faculty, growing student interest in other areas such as fine arts, and limited resources, felt it had to make choices. At the time, neither the board nor the faculty leadership could envision an engineering science curriculum that would not involve costly investments.

In the early 1960s, a study committee was constituted at Haverford and recommended: (1) The phase out the Engineering program as then constituted by 1972 and (2) to begin a study of the feasibility of an alternative program in applied science. "The discussion emphasized the impracticality, for a small college like Haverford, of providing the equipment necessary for an adequate modern program in Engineering: the aim of the report to continue in ways appropriate for the future the purpose of the program that was appropriate in the past," suggesting a 3–2 option with Penn or taking appropriate math, science, and humanities courses in preparation for engaging engineering study at the graduate level.

The last active faculty member, Ted Hertzel, eloquently expressed his frustration with the alternatives proposed by his colleagues:

"I think there is the mistaken belief that the needs of Haverford students with engineering interest can be met by courses in physics. A considerable number of our engineering majors in recent years had thought so too, but learned otherwise and transferred out of physics." Yale has recently made a study of their engineering program. The following is quoted from their report. "…engineering is distinct from science, and this fact must not be obscured by the frequent similarity of basic subject matter. …. What distinguishes the engineer from the scientist? Clearly it is the end product of his work. The engineer seeks a socially useful device or process: he is trying, with scientific techniques, to solve a problem which is initially presented to him in terms of a social objective. The scientist, on the other hand, is interested in knowledge per se, and knowledge which is ultimately expressed in the most compact and aesthetically satisfying way. The ultimate goal of the engineer is a specific accomplishment, while that of the scientist is a contribution to general understanding" (Hertzel personal papers, Haverford College archives).

He goes on to note that while the scientist and engineer must have rigorous training in the same basic principles, "The engineer is, in a sense, the middleman between the sciences and society, and as such he must, to an increasing degree, know both society and science. He operates within a framework of values, even though he may often be dealing with much the same subject matter as the pure scientist."

Hertzel proposed a program in keeping with Haverford's liberal arts tradition that would have incorporated greater inter-departmental cooperation, a goal which then was favored by the college. He noted the trends in greater specialization and concentration in other fields (in preparation for professional education) and argued that such specialization was inappropriate for engineering in the liberal arts context:

"The engineer needs breadth and versatility, in social and in natural sciences. And obviously, those interested in engineering would not come to Haverford if they wanted the most concentrated, specialized, technical preparation."

What Hertzel envisioned but never realized is very much embodied in the program that Smith College would develop almost 30 years later.

At the same time that Haverford was questioning the wisdom of continuing engineering as a major, Swarthmore engaged in an overall critique of the college. In the section on engineering, it asks "how can one educate for the latter 20th century without a serious exposure to these matters" (Critique of a College, 1967, 169).

Swarthmore too recognized that "engineering is a profession that mediates between knowledge and society" ... that "As the profession that links the values of the humanists, the discoveries of the scientists and the analyses of the social scientists, engineering plays a central role" (Critique of a College, 1967, 170).

The consequence is that Swarthmore has retained engineering as a major, one that its provost (C. Hungerford, Personal Communication, December 4, 2008) says is an "integral part of its identity... that fits into community based learning." Community-based learning is a natural outcome of the Quaker-based commitment to social responsibility that permeates much of Swarthmore's educational mission. Engineering provides one important place where theory and practice intersect.

At Swarthmore, engineering is a department within the division of natural sciences and engineering. It offers an ABET-accredited general engineering degree with emphases in civil and environmental, electrical, mechanical, or computer engineering. The required courses and prerequisites are comparable to other science majors and have substantial room for students to engage in the study of other non-science or engineering subjects. Forty-one percent of engineering majors are double majors and 29% have minors in fields ranging from economics to English. Students participate in a culminating senior design experience and students have the opportunity to engage with the faculty in their research. Students express a preference for the lecture format for classes (they see this as efficient) combined with intensive problem sessions. Group work is encouraged in labs, and homework can be done "collaboratively." Swarthmore's program survived and thrived in part due to more resources with nine tenure lines versus the two that Haverford had devoted to this area.

A major thrust in the department is providing student support to retain students in the physical sciences. The focus is on each individual student; each has a faculty advisor beginning their first semester. Resources are devoted to provide direct support for students in their first 2 years with a team of "wizards," consisting of upper-level engineering students who will help any student studying in the sciences. Swarthmore's Lynn Molter called such students cross-pollinators. The engineering building is active at all hours and classes for non-majors are popular.

So why did two Quaker Colleges embrace engineering as a liberal art when few of its sister institutions did so. In its assessment of engineering at Haverford, the study committee asked "Does engineering belong"?

> We have asked ourselves, first of all, whether engineering belongs in a Quaker educational institution. On this, our answer is clear. The religious approach of the Society of Friends concentrates on individual experience of the inward light but it is always tempered by experimental evidence and check through a search for common ground with other seekers. This way of testing insights against reality has led friends from the beginning toward a very practical concern for earthy matters. Friends were prominent among the early manufacturers, scientists, and social reformers in both England and the Untied States. A modern Quaker education institution can continue this tradition through providing broad training for pioneering technicians, problem-solving unifiers, and men of practical vision.

> We next asked ourselves whether engineering belongs in a liberal arts institution. Here it seems clear that vocation or trades school engineering, principally because it is so specific and subject to rapid obsolescence, is not likely to serve the goals of a liberal education. Vocational engineering training fits awkwardly in a modern liberal arts program. However, advances in the physical sciences and social sciences have opened up a number of new areas that provide intellectually challenging topics for inclusion in a liberal arts curriculum, and several of them fall within the engineering domain.

So the college concluded as did Swarthmore, that engineering was compatible with Quaker values, with social and civic responsibility and that indeed there were dimensions of engineering that could "contribute very effectively to a liberal arts curriculum." Both these institutions recognized the value associated with the making of work, and with the role that engineering can play in linking across the disciplines to address critical human social issues.

While Haverford never followed through on an assessment of applied science, it did embrace computer science and it developed a department of fine arts that embraced visual learning and the making of work, albeit through a lens qualitatively distinct from the engineering lens.

Smith and Union Colleges

Union College, the first college chartered by the Regents in New York in 1795, was the first to introduce engineering into an undergraduate curriculum, establishing its program in civil engineering in 1845; its alumni playing a central role in the construction of New York City. Benefiting by its proximity to the headquarters for General Electric Co, Union added electrical engineering in 1895. For over a century, the programs in engineering and the rest of the liberal arts institution existed side by side, compatible but not really engaged with each other. As President Stephen Ainlay indicated, the curricula existed in parallel. It was left to the individual student to find linkages.

In the 1990s, the curriculum was reevaluated. An effort was made to ensure that the engineering students experienced the same general education program as the other liberal arts students, and a commitment was made to send a large majority of Union's students abroad. Efforts were made to have engineering students develop the capacity to see the big picture, not be merely technically efficient. But what was missing was having engineering be a meaningful part of the education of all students.

A strategic planning process in 2005 was a transformative experience. It exposed the tension between CP Snow's two cultures. Union embraced this tension and sought ways to make intellectual connections through the strategic planning process. As Cliff Brown, former Chair of the Faculty stated, "if there was to be true integration, then it must be grounded in serious philosophical principles" on which the community of scholars could agree. The questions they raised were similar to those raised three decades earlier by Haverford and Swarthmore: what were liberal arts? Was engineering merely vocational? How could it be a liberal art?

Through an effort to learn how the engineers think on fundamental philosophical levels, the case for integrating engineering methodologies and design approaches into the liberal arts curriculum was made. How engineers define systems and how those definitions relate to systems defined by chemists, historians, or economists were examined. Those engineers seek to find solutions that are elegant, defined both by simplicity and efficiency was illustrated. Faculty in other disciplines began to see avenues for collaboration in teaching and research. Aspects of the way engineering approaches curricular development and define learning goals began to permeate the rest of the campus, and vice versa. And it became clear that one could make the case that an educated person in the 21st century needed to understand science and technology and the intellectual process of discovery and design that is fundamental to engineering practice. One could equally make the case, that for engineering solutions to be successful in the 21st century, they must respond to social, cultural, and economic conditions of the communities that embrace the solutions.

Union adopted several goals. They sought to become a national leader in establishing the study of engineering as a liberal art. They identified emerging disciplines and converging technologies that arise at the intersections among the currently defined disciplines, and sought to develop research and curricula that engage these areas of convergence. And perhaps most important, they sought to use engineering as a resource for the rest of the campus so that students and faculty alike could develop an understanding of the design process, and expertise in its application.

As a result of these efforts, engineering faculty became engaged in the freshman precept, an intensive writing and critical thinking course, and in the sophomore research seminar, designed to engage all students in the process of scholarly research. They developed modules for team taught courses under the auspices of a Mellon grant. One such class sought to wed technology and literature assessing entrepreneurship in the ancient world; another taught the Odyssey and examined the technical challenges that Odysseus faced. Through paired courses where classes are separate but students do joint activities, students were able to collaborate and share their respective expertise, for example, pairing upper level electrical engineering and upper level neuroscience with collaborative labs.

Several introductory engineering classes carry no prerequisites and are available to any student to fulfill the campus requirements in science and technology.

What is remarkable about Union is the range of faculty from engineering and the arts and sciences engaged in the collaborative process in both research and teaching. They have sought and been successful in competing for NSF grants to support innovative teaching. They like Haverford and Swarthmore have competed successfully for HHMI grants that link biology across the disciplines and provide broad support for students in science and engineering. They have strong institutional commitment from the President, from the Dean of Engineering, and from the Chair of the Faculty who played an important role in the strategic planning process.

The introduction of an engineering major at Smith College in 1999 was historic. It embraced the commitment of the college to the STEM fields for women. The effort recognized the concerns expressed by the community about the impact of engineering on a liberal arts college: would it turn the college into a research institution? Would it over professionalize the education? These and many other concerns were confronted and addressed. In conversations with President Carol Christ, Provost Susan Bourque, and Picker Engineering Director Linda Jones, the impact of the program were revealed.

Critical to the integration of the engineering major into the liberal arts education was the requirement that students earning the B.S. in engineering must also complete the Latin Honors distribution (with courses in the seven general areas of knowledge literature, historical studies, social science, natural science, mathematics and analytic philosophy, the arts, and a foreign language).[1] It was critical to acceptance within the academy that the major not be seen as vocational, nor its students viewed as narrow technologists. Equally important was the effort by the faculty and the institution to seek ABET accreditation of the major, that becoming a practicing engineer was a legitimate and even necessary goal, although it was also expected that many if not the majority of students would use this major as a step toward professions such as medicine or law.

Smith graduated its first 4 year class of engineering majors in 2004 and achieved ABET accreditation shortly thereafter. To their delight, many are practicing engineers; about 40% of graduates attend graduate school and 60% are in industry or not-for-profits.

Engineering faculty and students are fully integrated into the culture and fabric of the campus. More than one senior faculty member who deeply opposed the move to develop engineering as a liberal art has admitted to the provost that their initial opposition was dead wrong. Engineering students themselves are ambassadors for the program with their seriousness and purposeful commitment remarked on by faculty in the humanities and social sciences who appreciate the different perspectives to problem solving that these students bring.

The engineering faculty were challenged to achieve their pedagogic goals while not succumbing to the tempting yet least productive effort to simply fill students with content. The pedagogic goals included critical thinking and learning through experience. The faculty has sought to teach engineering in context and to create a community of learners. They begin by asking students throughout the 4 years to reflect on their learning. They ask students to evaluate their goals in selecting this major and then assessing how engineering will fit into their lives. Students are expected to "own the materials." They take reflection as a serious endeavor and are responsive to it (L. Jones, Personal Communication, November 11, 2008).

Essential to the Smith experience has been the concept of "learner-centered education." This concept has several dimensions. First is the commitment to education as a shared responsibility of students and faculty. The concept that all participate in a community of learners encourages the faculty as well as the students to take intellectual risks: the faculty are "edgier" and willing to be put to the test. When they do

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[1] Smith College does not have a core curriculum.

not know the answer to a question posed by their students, they create a partnership with their students to arrive at the answer; the faculty guide the process of discovery.

The process of discovery involves an intimate relationship with the making of work, with the materiality of objects. The emphasis is on learning through a process where theory becomes tactile. The design process and discovery are emphasized in the entry-level design class that is open to any student on campus and carries through each class, culminating in the senior capstone design course. Thus a deep understanding of the making of work is a critical dimension of Smith's approach. The process of discovery, of analysis and of creation, is one in which students engage in teaching as well as learning.

The faculty developed their pedagogy through a best practice seminar for faculty that met weekly to share ideas, and included colleagues from education as well as visiting scholars. Two faculty members with a strong interest in educational approaches took the lead. The conversations centered on intentionality – the faculty challenged each other about what they were trying to accomplish in the classroom. These intellectual encounters with each other developed a better understanding of what they collectively expected from their students at each level in the curriculum. The faculty began to understand how they rely on their counterparts and to recognize how others rely on them in terms of material to be covered in the various courses. The seminar led to modifications in the original curriculum as well as consideration of a B.A. degree option that is currently making its way through the campus approval process. Linda Jones (Personal Communication, November 11, 2008) noted that these conversations forced everyone to move out of their comfort zone: "it was both a 'brutal and wonderful' experience to have one's colleagues challenge one's approach."

Both the president and the provost emphasized the powerful impact that the engineering major has had on the thinking throughout the college about liberal education. Four dimensions stand out.

Design is a unifying theme for engineering. The success of the design clinic has captivated the imagination of other department faculty and has many of departments considering capstone experiences, hands on experience, and team work. The discovery-based approach to education has motivated other departments to reconsider their pedagogical methods and approaches to the teaching of their disciplines. At Smith, the design process that emphases discovery and team work integrates well with other collaborative processes on campus.

The engineering faculty has brought a different culture for data and accountability for results through both their approach to pedagogy and through their research. They have sought evidence that their pedagogical approach is effective.

The appreciation of the practice fields, the fields that involve the making of work, has shifted the conversation about the ultimate vocational needs of students. No longer is such a focus viewed as compromising a liberal arts education. Incorporating practice and the making of work are viewed as legitimate approaches to inquiry, and compatible with developing an understanding of theory and concepts.

And finally, the importance of ethical accountability and social responsibility that is emphasized by the engineering faculty and embraced by their students has spilled over into discussions about the roles of transmitting values and ethics across the curriculum.

Engineering as a Liberal Art

These four institutions provide persuasive evidence that engineering can be embraced as a liberal art. So what has inhibited both its adoption in more liberal arts institutions, and even more strikingly, why have so few engineering schools integrated more meaningfully the other liberal arts in the education of their students?

Engineering took a different path than other professional disciplines. While medicine, law, the ministry, and much of business education devolved to the graduate level, engineering retained professional education at the undergraduate level. It is the observation of some that the change offer undergraduate engineering degrees that could be completed in 4 years rather than five sacrificed the inclusion of more humanities and social science in the curriculum. Others argue that with increased specialization within engineering, more technical courses were added, and few if any deleted. The ABET accreditation process while ensuring adherence to professional and technical standards, may also constrain and inhibit change particularly at the undergraduate level. In any case, the result has been a less rich, more technically focused education at the undergraduate level. Efforts such as ABET 2000 have provided some encouragement to faculties to change but powerful forces (even within ABET) continue to inhibit major transformation. Recent work by Sheri Sheppard (2009) of Stanford University and her colleagues at the Carnegie Institute as well as work by other authors in this volume address more completely the opportunities for rethinking the education of engineers, at least at elite research universities and liberal arts colleges.

Ana Lee Saxenian's analysis of Silicon Valley (Saxenian, 1996), and its success in comparison to Route 128 in Boston in the 1980s and early-mid-1990s, offers some insight into how we might rethink the relationship between engineering and the liberal arts, and engineering as a liberal art. Saxenian observed that the valley emphasized entrepreneurship combined with collective learning, and collaborative networks that were continuously reconstructed through interaction. There was a continuous regrouping of skills, knowledge, and (intellectual) capital. Teamwork, collaboration, interaction, fluidity – these are not words we generally associated with how our faculties function. Yet these attributes are among those embraced by Smith and Union Colleges in their efforts to conceptualize engineering as a liberal art. And the approach extends beyond the engineering departments to embrace the other liberal arts in a more dynamic and fluid relationship.

Conclusion

In crafting the education of our students, in rethinking the curriculums within a liberal arts context, we need conversations about what we want our students to gain in their four undergraduate years. How do we engage their minds, how do we instill in them the means to read critically and deeply, to ask penetrating questions, to uncover new forms of knowledge?

Our liberal arts traditions call for both the development of knowledge and expertise in a discipline or area of concentration, as well as exposure to and grounding in all the broad disciplinary areas. Each liberal arts discipline provides a scholar (a student or a teacher) with a lens or set of lenses through which to see the world and to provide a means to respond to what is observed. Each major consists of a framework, a set of concepts, methods, and approaches that provide a way of asking questions, gathering data, analyzing, and organizing the observations. In those fields where the making of work is central, the approach may be characterized by the process of design – central to engineering, to the visual arts and architecture and the planning fields, and shared by dance, music, and theatre. The discovery and design process yields the creation of a work.

Meeting the challenges posed by our increasingly complex and global society requires approaches to solutions that draw on both the arts and the sciences, on both theory and practice: they require advocacy and education, knowledge of peoples and cultures, and the engineering of prevention and control strategies, both technical and social. Our society will benefit from having a generation of leaders educated not only with the immensely powerful problem solving strategies of the engineer, and the profound understandings of the basic sciences but also with a deep understanding of human culture, values, and psychology and philosophy – this means developing an appreciation for the other lenses that provide insight into the nature of the problems we face and the solutions we seek to implement. It means using our curiosity and imagination to develop empathy, to develop the capacity to hear and to develop relationships that provide the basis for partnering to solve problems, both within the academy and without.

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Chapter 6
What Is Happening in Liberal Education?

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The very question – what is happening in liberal education, has a contemporaneity – something is happening – now – that represents, for better or worse, a departure from the past. We might lament this departure – *what* is happening in liberal education – or we might welcome it – what is *happening* in liberal education – but the question itself suggests a stable concept – liberal education – that is undergoing change.

The root meaning of the word liberal in the phrases liberal arts and liberal education. The derives from the Latin word *liberalis*, pertaining to a free man, as opposed to a slave. Hence liberal education was seen as education appropriate for a freeman, or a gentleman, as opposed to someone in a servile or menial class of society. It has come to mean study for the sake of general intellectual culture as opposed to education for a professional, vocational, or technical purpose. This dichotomy, between liberal and professional education, took on increasing prominence in the 19th century, especially in Victorian England, where there was at once a substantial expansion of scientific and technical education and an increase in the number of degree granting universities, ending the monopoly of Oxford and Cambridge. The debate, about the content and value of a liberal education, needs to be understood in this context, in which class, access, and the privileges of a gentleman are very much part of the subtext. John Henry Newman's classic work, *The Idea of a University*, which remains today the most comprehensive and influential definition and defense of liberal education, takes shape from this democratic context; Newman wrote the book to define the values and aspirations of the new Catholic college that the Pope had asked him to establish in Dublin. In the preface he writes, "Robbed, oppressed, and thrust aside, Catholics in these islands have not been in a condition for centuries to attempt the sort of education which is necessary for the man of the world, the statesman, the landholder, or the opulent gentleman" (xlii). Another Victorian writer, Thomas Henry Huxley has a different perspective. In "A Liberal Education;

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And Where To Find It," first delivered to the South London Working Man's College in 1868, and in "Science and Culture," delivered at the opening of Josiah Mason's Science College in Birmingham in 1880, he champions a new model of scientific education, in service of a new population, in opposition to the Oxbridge model. Matthew Arnold's essay "Literature and Science," is a direct response to Huxley. It was the lecture that Arnold delivered most frequently on his American tour, in 1883 and 1884, which included stops at many colleges and universities, among them, Dartmouth, Princeton, Brown, Yale, Wellesley, Vassar, Amherst, and Smith.

Recalling this historical background is instructive for several reasons. It reminds us that the dichotomy between liberal arts and professional education in which so much of the discussion of the liberal arts is still cast had a social and historical context. Embedded within it was a debate about class, privilege, and access. In a world today in which almost all students expect to enter the professional workplace, and in which we share a belief in equity of access, I wonder whether we are well served by an opposition between the goals of professional education and the liberal arts that is cast in terms remarkably similar to those of the 19th century. I myself believe that it does not, to the detriment of both professions and the liberal arts.

Those who studied this history of the liberal arts know that the liberal arts curriculum has never been stable. In 1845, when Union College added engineering to its curriculum, faculty, students, and alumnae surely asked, "What is happening in liberal education," in much the same way that some members of the Smith College community asked the question when Smith launched its engineering program in 1999. The phrase liberal arts suggests to many of us a historical stability, extending back several centuries. Yet any history of the American college curriculum shows that the idea of a stable central core constituting the liberal arts is a myth. In 1754 a prospectus for the new King's College, later to become Columbia University, announced that the course of study would include surveying, navigation, geography, history, husbandry, commerce, government, meteorology, natural history, and natural philosophy. In this list of subjects, perhaps half would be included among the traditional liberal arts today. When Thomas Jefferson reorganized the curriculum of the College of William and Mary in 1779, he abolished professorships of divinity and oriental languages and added professorships in public administration, modern languages, medical sciences, natural history, natural philosophy, national and international law, and fine arts (Rudolf, 41). These lists are instructive for several reasons. They show that disciplines that we now regard as essential components of a liberal arts education, like the modern languages and the fine arts, entered the curriculum in comparatively recent times as disruptive innovations. They also show that the question in defining a liberal arts curriculum has not been whether to mix the academic, the practical, and the professional, but how to do so.

In the curricular wars of the 19th century, much breath was expended and much ink was spilt about the required content of a liberal education, and particularly about the place of Greek and Latin within it. In the final decades of the century, both Ezra Cornell, after whom Cornell University was named, and Charles William Eliot, the legendary President of Harvard, introduced the elective system to their universities in order to defuse these fierce arguments about content. That system, which quickly spread throughout American higher education, introduced greater diversity into the curriculum and allowed students to choose the courses they would take. In a history of the Yale curriculum published in 1901, John C. Schwab described the result, "The history of the Yale curriculum is the story of a medieval workshop, with its limited range of simple tools, all of which the apprentice learned to master, developing into a modern factory, well-equipped with a large stock of tools and machinery, no two of them alike in their construction or use, many of them delicate and complicated, and few of them fully understood or manipulated by all the employees of the shop." Schwab's metaphors – drawn, interestingly, from the practice of engineering – provide a lens through which we can reflect on our current assumptions about curriculum. Schwab's medieval workshop suggests a simple confidence in a core curriculum that every student learns to master. Very few colleges in the 21st century embrace this model of a universal core, undiluted by elective choice. Schwab's metaphor of the modern university as a factory, in which each worker learns to use his or her set of tools in relative ignorance of those of others, is one that still has resonance today. We live in academic neighborhoods shaped by the assumptions, terms, and tools of our disciplines; travel between them can be arduous. Perhaps we need to imagine the curriculum in the 21st century in more electronic terms, as a worldwide web, in which links move us into different disciplines, different cultures, different areas of knowledge, with abruptness and with lightening speed.

So I will now turn to my question, what is happening in the liberal arts. In a nod to the seven liberal arts of the ancients, included in the trivium and the quadrivium, I will discuss seven critical developments. The first is a movement away from defining liberal education in terms of subject matter – a broad array of courses in a wide range of disciplines. Such a conception has shaped the general education requirements at many colleges and universities. To become a liberally educated person, the argument goes, you must take a course in the arts, in literature, in a foreign language, in philosophy or ethics, in the social sciences, in mathematics, in the natural sciences. Increasingly, however, those in higher education thinking and writing about liberal education have been defining its goals not through coverage of a range of subjects but through what I term capacities. Derek Bok's 2006 book, *Our Underachieving Colleges*, is both symptomatic of this development and has helped to influence it. The titles of Bok's chapters define what he believes to be the goals of a liberal education: learning to communicate, learning to think, building character, preparation for citizenship, living with diversity, preparing for a global society, acquiring broader interests, and preparing for a career. Note that Bok expresses these goals through verbs – learning, building, living, and preparing. To borrow from Matthew Arnold's definition of culture in *Culture and Anarchy*, education is not "a having and a resting but a growing and a becoming." At Smith College, we have defined the goals of a Smith education through the capacities that we want our students to acquire:

1. Develop the ability to think critically and analytically and to convey knowledge and understanding, which requires
    - writing clearly
    - speaking articulately

- reading closely
- evaluating and presenting evidence accurately
- knowing and using quantitative skills
- applying scientific reasoning
- engaging with artistic creation and expression
- working both independently and collaboratively

2. Develop a historical and comparative perspective, which requires
    - learning foreign languages
    - studying the historical development of societies, cultures, and philosophies
    - understanding multi- and inter-disciplinary approaches
3. Become an informed global citizen, which requires
    - engaging with communities beyond Smith
    - learning tolerance and understanding diversity
    - applying moral reasoning to ethical problems
    - understanding environmental challenges

The emphasis on capacities rather than on areas of knowledge in defining a liberal education reflects consciousness of a world in which new knowledge is increasing exponentially, in which disciplinary boundaries are shifting and dissolving, and in which students can expect to have not just multiple jobs but multiple careers. To return to Schwab's metaphor, students can no longer expect that mastery of a single set of tools will prepare them well for the world that they will enter. Very few will spend their lives at a single station in the world's factory.

Reflecting on the changes in the production of knowledge and the stability of disciplines and careers brings me to a second important development in liberal education – the increasing value that we place on interdisciplinarity. It is useful to take a brief look at the intellectual developments that have motivated this emphasis. Primary has been the reorientation, prominently in the social sciences but to some extent in the humanities, created by area studies. Scholars increasingly came to feel that to understand Latin America, or Africa, or the former Soviet Union, they needed the tools of multiple disciplines – history, political science, economics, and sociology. Departments, programs, and research centers were created that focused upon an area of the world rather than a single discipline. Parallel to this development and in some ways similar to its intellectual trajectory has been the emergence of fields of study focusing on populations – women's studies, Afro-American Studies, and ethnic studies. The perspectives that this new set of disciplines has brought to the ways in which social position shapes perception and experience has led humanities disciplines to use the tools of social science. Similarly, it has led social sciences to use and interpret texts and artifacts in ways that have been the province of the humanities. Meanwhile, in these same decades, disciplinary boundaries have become increasingly porous in the sciences. Researchers in many fields have come to believe that complex problems require interdisciplinary and cross-disciplinary analysis, and that we must consequently develop the ability in our students to move across disciplines and bodies of knowledge. This is more than taking a course in music, and a course in English, and a course in economics, and a course in biology. It involves understanding differences in methods of inquiry and argument and asking how the tools and materials of one discipline can illuminate the subjects of another. The problems we face today are complex and far-reaching; their solution requires various modes of inquiry and multiple frames of reference. How can biologists, geologists, and engineers work together to understand watersheds? What can the anthropologist teach us about literary texts and the literary scholar teach the anthropologist? How can the philosopher help us understand the new capabilities we have in genetic engineering?

The distinguished scientist Thomas Cech, formerly president of the Howard Hughes Medical Institute, calls interdisciplinary fluency "intellectual cross-training." Using the analogy of athletics, where athletes perform a variety of exercises not directly related to their main sport in order to improve their overall strength and conditioning, Cech recommends intellectual cross training for the scientist, in order to develop the ability to collect and organize facts and opinions, to analyze them and weigh their value, to articulate an argument. Cech argues that the humanities are important to the sciences not because they produce more cultured people, but because they produce better scientists.

> Just as mathematics is considered to be a good exercise for the brain even for those who will never use calculus in the future, so the study of great books, history, languages, music, and many other non-science fields is likely to hone a scientist's ability to perceive and interpret the natural world. More specifically, in history, literature, and the arts, one is presented with diverse, mutually contradictory 'data' – different points of view due to incomplete knowledge or the different backgrounds of those doing the viewing. One learns to distill the critical elements from the irrelevant, synthesize seemingly discordant observations, and develop a strong argument. While scientific data are commonly thought to exist on a different plane – absolute, precise, unambiguous, beyond reproach – such is rarely the case. Random error and systematic deviations must be taken into account. Choices of experimental design inevitably affect the results obtained. Interpretations are often heavily influenced by expectations, which in turn are heavily influenced by earlier conclusions, published in the research literature. Scientists need the same skills as humanists to cut through misleading observations and arrive at a defensible interpretation, and intellectual cross-training in the humanities exercises relevant portions of the brain. (210)

One could easily make the same argument as Cech does here so eloquently in reverse, that cross-training in the sciences produces better humanists.

Cech's concept of intellectual cross-training bears an interesting relationship to traditional ideas about the range of disciplines that constitute the university. In *The Idea of a University*, John Henry Newman argues that universities must include what he calls "the whole circle" of studies. For Newman, there is a totality to knowledge, and the aim of education is to teach comparison, discrimination, and judgment of relationship. Individual disciplines grow by completing, correcting, and balancing one another. Even though students cannot pursue all the subjects that are open to them, they profit by learning from a faculty who, "zealous for their own sciences, and rivals of each other, are brought, by familiar intercourse and for the sake of intellectual peace, to adjust together the claims and relations of their respective subjects of investigation" (76). Newman urges intellectual generosity, a live and let live attitude, for he feels the pursuit of knowledge needs "elbow room" (358). Newman's concept of the university contains an essential respect for the disciplines, which, like the citizens in a democracy, need to adjust their claims in service of the whole. Cech's idea, and the modern concept of interdisciplinarity, is somewhat different, for it assumes that you cannot adequately understand complex problems without the knowledge and tools of multiple disciplines. To return to Schwab's metaphor, he imagines the college or university not as a factory in which we learn to manipulate one set of tools without a great deal of concern about our ignorance of others, but as a worldwide web, in which you continually change your frame of reference. The young men and women entering today's workforce must be prepared to tackle multifaceted problems that require more than a single discipline for their solution – climate change, energy policy, and large-scale human migration. They must become skilled at understanding what different frames of intellectual reference, different methodologies, and different disciplinary tools have to contribute to the solution of complex problems. Most of the important challenges that we face do not come in neat disciplinary boxes. We need to become adept at stepping out of your particular frame of reference to understand what others might offer. The more intellectual tools we bring to our task, the more likely we are to succeed.

The third development important in liberal education also requires fluency in traveling across boundaries – internationalization. When Eleanor Roosevelt spoke at Smith in 1949, she described the world situation in words that apply today: "How well prepared are we to live in a world that has constantly grown smaller and where we must rub shoulders with people of different cultures, of completely different customs and habits and religions, who live under different legal systems, whose languages are different?" (9) I think we have to answer, 60 years later, that we are not as well prepared as we should be to live in this increasingly small and volatile world and that other countries may understand more about us than we do about them. Students need the kind of cultural sensitivity and fluency that enables them to work across different cultures, both within their own countries and around the globe. Most professions and businesses are no longer local, and the young men and women who enter them must understand the different cultures in which they work. There is a growing consensus that we must shape the curriculum in a way that provides students the skills, the knowledge, and the values that enable them to live and work in a global context. This has profound implications for our institutions, for it is a matter not just of language study and course work but of perspective and attitude. When Smith's third president, William Allen Neilson developed Smith College's junior year abroad programs in the 1920s and 1930s, he articulated three goals for them: fluency in another language, the capacity to adopt a European perspective, and commitment to international institutions and international understanding. Although we would no longer limit the perspective we would hope our students would acquire to a European one, Neilson's goals seem equally relevant today. Pursuing them may well include faculty development as well as structural change. We need to ask how our policies encourage or discourage study abroad, and how we make study abroad available to students from all financial circumstances and all majors.

The growing sense of the importance of global awareness brings me to the fourth development in liberal education that I would like to describe – training for citizenship. The idea that the goal of a liberal arts education trains good members of society is a classic one. Newman articulated it in *The Idea of a University*; I am sure that many of our founders claimed it as their purpose in endowing our colleges. Sophia Smith announced as her intention, "to increase women's power for good." I think that we are seeing today a renewed focus on education for citizenship, often realized through centers for community engagement, which bring our students and faculty into neighboring communities in collaborative projects that combine learning and service. New national and international organizations evidence this development. Campus Compact, whose goal is to educate college students to become active citizens, was founded in 1985 with four members; it now has 1100. The Talloires Network an international collective founded at Tufts University in 2005 to promote the civic roles and social responsibilities of higher education now has over 100 members.

The fifth development that I will identify is closely connected to this renewed emphasis on civic education – environmental education. In our growing awareness of the crisis of global warming, many educators are asking what its implications are for our concept of liberal education. David Orr's book, *Earth and Mind*, is the most comprehensive and passionate argument that we must reshape liberal education to assure a sustainable future. "[T]he worth of education must now be measured against the standards of decency and human survival – the issues now looming so large before us in the 21st century. It is not education, but education of a certain kind, that will save us" (8). Majors in environmental science and policy began to emerge about 30 years ago; now many institutions find that the study of the environment and the search for sustainable solutions provide a meaningful, unifying context for learning and research. Environmental literacy is increasingly seen as one of the basic literacies that higher education aspires to provide. The commitment to environmental education is necessarily interdisciplinary. The challenges we face would not be solved through science or economics or politics or engineering alone. Rather, we need to position students for learning at the points where each of these fields intersects – urgently and significantly – with another.

The final two developments that I will mention in thinking about liberal education both have to do with pedagogy rather than content or capacities. The first is an increased focus on undergraduate research. More schools are engaging students in undergraduate research, not just as the culminating project for those who do senior honors, but for larger numbers of students over the course of 4 years. We are trying increasingly to engage our students in the process of inquiry and discovery that is the central enterprise of our disciplines. We recognize that such engagement in research is a developmental process, in which students gain the necessary knowledge and tools as they progress through their undergraduate careers. We also recognize that engaging in independent research not only carries intellectual benefits but also develops qualities of character – independence, perseverance, ability to control a large and complex project, and decision making.

The final development that I will describe is connected to undergraduate research; it is an increased emphasis on project-based learning. There is an increasing interest, and sense of value, in engaging students in team-based projects with an immediate and practical application. Let me give a few examples, all from Smith: a sociology class studying a current attempt to locate a solid waste disposal site in a poor neighborhood in Holyoke, Massachusetts, including interviewing the principals involved and attending all the public hearings; a museum studies class preparing and mounting an exhibition, complete with catalogue, marketing literature, and educational programs; the development of an online encyclopedia of Smith history from materials in the college archives. Traditional definitions of the liberal arts often claim a dichotomy between general knowledge – knowledge that is appropriately the province of the liberal arts – and knowledge that is professional, technical, or useful, and therefore not the province of the liberal arts. As I argued at the beginning of this essay, I think that this dichotomy is a false one. College curricula have frequently included areas of study like architecture or meteorology that we would consider both liberal and professional, and most professional education has its roots in traditional liberal disciplines. There is today a growing sense of the artificiality of the division between professional and liberal arts education, a development reflected in the increasing interest in project-based learning. Such projects enable students to use the knowledge and methods of the liberal arts to address problems of praxis and to use practical problems to test the power and adequacy of our disciplinary paradigms. Furthermore, the development of such pedagogy supports the kind of civic education I described earlier – often bringing knowledge to bear on social problems.

The developments that I have described demonstrate that a lot is happening in liberal education. I will now turn to the subject of engineering to ask how these developments in the liberal arts are connected to it. I first want to challenge the formulation – engineering *and* the liberal arts, as if they were two distinct areas of knowledge and study. If we are to teach our students to move fluently among the disciplines, we cannot hold to a falsely stable sense of the liberal arts. As I have shown, the liberal arts curriculum has never been stable. The structure of the disciplines is a historical artifact, and it changes over the course of time. I have often been amused by the question whether Smith's development of the sciences, embodied in its new engineering program and its plan for a new science center, means that it will abandon the liberal arts. Citizens of 18th-century Virginia could have asked Thomas Jefferson the same question when he introduced medical science and natural history into the curriculum. The sciences are among the liberal arts – fields of study that contribute to general intellectual culture. We must make the same claim for engineering. Just as the modern languages and the natural sciences came to be regarded as liberal arts over the course of the 19th century, engineering and computer science must become part of a liberal education in the 21st century. We must determine not only how best to educate engineers in the traditional liberal arts but what role engineering might play in the education of musicians, economists, political scientists, and philosophers. Just as the study of literature and art enriches and deepens the education of scientists and engineers, so the study of science and engineering should enrich and deepen the education of historians and poets.

In his essay, “A Liberal Education; And Where To Find It,” Thomas Huxley asks us to imagine a world in which the life and fortune of each one of us depend upon winning or losing a game of chess. He asks, “Don’t you think we should all consider it to be a primary duty to learn at least the names and moves of the pieces; to have a notion of a gambit, and a keen eye for all the means of giving and getting out of check? Do you not think we should look with a disapprobation amounting to scorn, upon the father who allowed his son (I would insert the mother who allowed her daughter), the state which allowed its members, to grow up without knowing a pawn from a knight?” (208–209). Huxley goes on to argue that we are indeed in such a situation, in which the chess board is the world, the pieces are the phenomena of the universe, and the rules of the game are the laws of nature – what he calls later in the essay, “Erdkunde,” or knowledge of the earth. I would claim that engineering in the 20th century is an essential element of the game of chess we need to learn for our survival, a piece of earth knowledge, and that we must think of engineering as a liberal art.

Once we begin thinking of engineering as a liberal art, it follows that not only do we think of engineering education differently; we think of education differently in the classic liberal arts disciplines. When we developed our engineering program at Smith, we were careful to create a structure of requirements for engineering majors that assured substantial course work across the traditional liberal arts disciplines. Students are required to take courses in literature, the arts, historical studies, the social sciences, foreign languages, in addition to the natural sciences and mathematics or analytic philosophy. The program describes its philosophy in the following way: “Engineering is the application of math and science to serve humanity. For graduates to be prepared for practice, post-baccalaureate education, or for life in general, it is important that they be exposed to factors that define the human condition and appreciate the implications of the human record.” When the college approved the set of distribution requirements specifically for engineering majors, it embraced a model of engineering education in the context of the liberal arts, and the curriculum has achieved that goal. What has been unexpected is the influence that engineering has had on the rest of the curriculum. Let me give two examples. All of our engineers, like those at many schools, are required to do a senior design project – a year-long course in which a team of students collaborates on an actual project sponsored by an industry or government partner. The experience of doing such a project offers profound educational benefits – in learning teamwork, decision making, time management, discipline, presentation skills, as well as the fulfillment of solving a real and complex problem. Faculty in other areas of the college have looked at this model and have been discussing how to use it in disciplines very distant from engineering – art history, archival research. The second example of the impact of engineering upon other parts the curriculum I find even more surprising. Faculty have commented on the ethical seriousness that engineers bring to classes in history, or literature, or philosophy. Motivated by a code of ethical practice, they bring a sense of ethical consequence to getting the right answer in other disciplines.

It is a particularly appropriate time, I think, to broaden our concept of the liberal arts to include engineering because so many of the developments in the liberal arts that I have described characterize engineering education. It is inherently interdisciplinary, using a broad range of knowledge in science and mathematics to develop engineering solutions within a social, political, economic, and aesthetic context. It is both research and project based, providing multiple opportunities for students to solve new problems under the guidance of faculty and industry mentors. The practice of engineering is international; engineers work without borders. The goals of engineering are profoundly civic; engineers use their knowledge in service of society, addressing human needs and problems with technological solutions. It embraces sustainability as a core value; indeed, in a world of finite natural resources, we depend upon engineering solutions to conserve the resources that sustain us.

But perhaps most profound, engineering education is based on the idea of capacities. The goal of the Picker Engineering Program at Smith is to educate leaders for a sustainable world. Its three primary pedagogical objectives are leadership, adaptability, and integration. Among the defined outcomes that the program has defined as its goals are

- a conceptual understanding of engineering design fundamentals,
- the ability to transform fundamental engineering principles into socially informed design,
- the ability to solve problems in both a reductive and integrative fashion,
- an understanding of the scientific method as well as the ability to analyze and interpret the resulting data,
- competency in using engineering tools to solve problems,
- the ability to collaborate effectively with a team of diverse individuals,
- the ability to communicate effectively with diverse audiences,
- an understanding of professional responsibility and the ethical implications of their work,
- an understanding of the impact of their work on both a local and global level within the context of contemporary and historical events, and
- an appreciation for continual intellectual advancement.

This vision of engineering represents a pioneering change. There have been calls for such a change from the Millennium Project at the University of Michigan, “Engineering for a Changing World,” and the National Academy of Engineering, in its 2020 Project. Liberal arts colleges are in a particularly good position to offer leadership in this effort. It is far too easy to focus on the challenges that liberal arts colleges face in mounting engineering programs – their relatively small size, their lack of graduate students, and their lack of corporate and industry ties. But the very fact that engineering in liberal arts colleges is not a separate school with its own area of the campus, curriculum, and culture provides some important advantages. Engineering within a liberal arts college can more easily develop a curriculum that integrates the study of engineering with the traditional liberal arts disciplines. And in doing this, our colleges are in a unique position to give engineering a place among the liberal arts.

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Chapter 7
Holistic Engineering and Educational Reform

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Introduction

A recent report from the National Science Foundation projected that employment in science and engineering occupations will increase approximately 70% faster than the overall growth rate for all occupations between 2002 and 2012 (National Science Board, 2006). For engineers, this projection translates to the addition of 976,000 new jobs during this 10-year period. In 2006, US colleges and universities graduated approximately 74,000 new bachelor's level engineers (American Society of Engineering Education, 2006). Assuming that US domestic production of engineers stays relatively constant, as it has over the last 20 years (see Fig. 7.1 National Science Board, 2006; Task Force on the Future of American Innovation, 2006), by the year 2012, the United States will fall short of this projected need by more than 200,000 engineers. Over this same period, the global supply of engineers is expected to increase, due to increasing production in countries such as China (Fig. 7.1). This trend, coupled with increasing economic globalization and the comparatively low percentage of students studying engineering or science in the United States (Fig. 7.2), has led many to conclude that US-based industry will globalize much of its engineering work for reasons of both cost and limited resource availability within the United States.

Much has been made of the impetus to pursuing science and engineering careers that was generated by the launch of Sputnik in October 1957. And many have attempted to fashion a similar call to action based on our national economic security. However, when one looks at the production of bachelor's level engineers, on a population normalized basis, it appears that the Sputnik "phenomenon" had little impact on engineering study. As the data in Fig. 7.3 (National Science Board, 2006; U.S.

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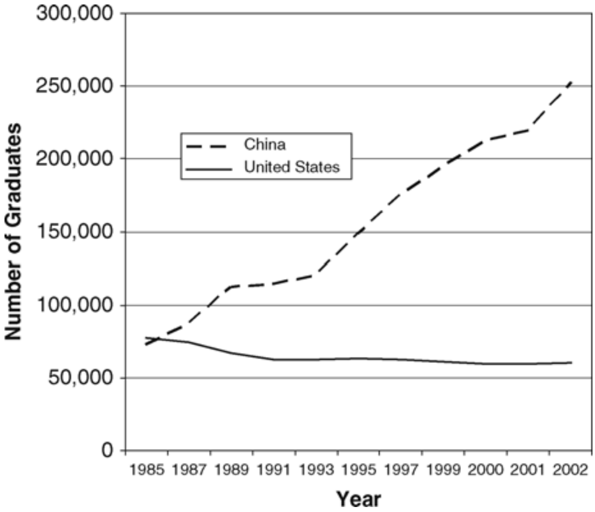

Fig. 7.1 Engineering college graduates in the United States and China (adapted from data in reference National Science Board, 2006). Missing United States 1999 data approximated by the average of 1997 and 2000 data

Department of Education, 2006; U.S. Census Bureau, 2006; Population Estimates taken from US Central Intelligence Agency World Factbook, specific country pages, indicated year) demonstrate, there was only a relatively modest increase in the production of bachelor's level engineers in the late 1960s and early 1970s as the Sputnik generation came of age. Rather, the more significant increase occurred in the late 1970s and early 1980s, most likely corresponding to the energy crisis and the nascent environmental movement, both still prominent and socially relevant topics of our times. Moreover, although data suggest rather static interest in engineering over the last 20 years (Fig. 7.1), 1985 saw the peak in interest in engineering careers, most likely a result of the early promise of biotechnology and information technology – areas associated with engineering and very closely tied to the human experience.

While national comparisons of numbers of engineering graduates can be useful in assessing gross trends, they fail to account for the varied capabilities of foreign-educated engineers and what a recent report (Gereffi and Wadhwa, 2005) identified as two distinct groups of engineering graduates: dynamic engineers and transactional engineers. Dynamic engineers were defined as individuals capable of abstract thinking and high-level problem solving using scientific knowledge. Dynamic engineers lead innovation and typically have a minimum of a 4-year engineering degree.[1] Transactional engineers, on the other hand, are typically responsible for rote and repetitive tasks in the workforce. Transactional engineers are commonly trained at the associate, technician, or diploma level in less than 4 years. Related to

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[1] Figure 7.1 reports the number of dynamic engineers.

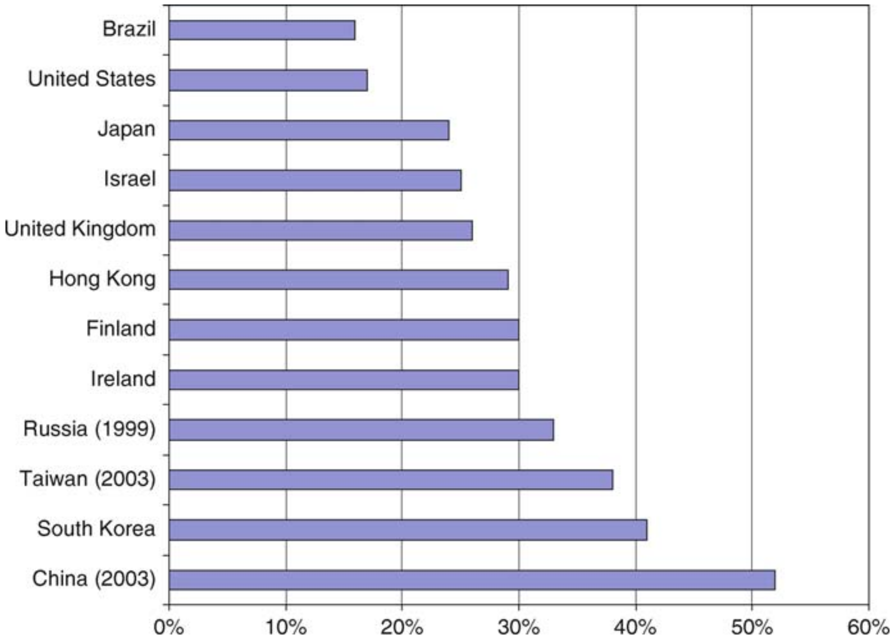

Fig. 7.2 Percentage of undergraduates receiving science[2] and engineering degrees[3] (adapted from reference Task Force on the Future of American Innovation, 2006)

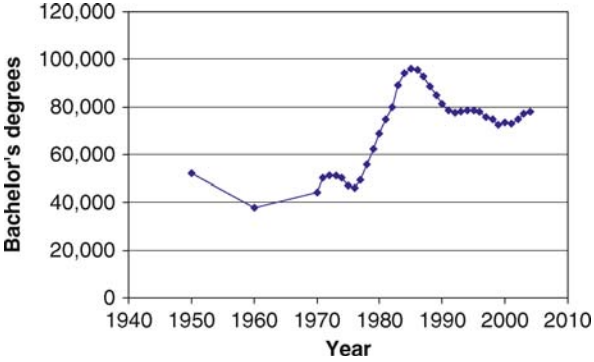

Fig. 7.3 US Bachelor's degrees in engineering by year. Data source: US Department of Education, National Center for Education Statistics (U.S. Department of Education, 2006)

this, such numbers also fail to account for the size of the engineering workforce *per capita*, a potentially useful metric when comparing the production of engineers among nations. Figures 7.3 and 7.4 are illustrative of this point. When one

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[2] Science includes physical, biological, earth, atmospheric, and ocean sciences, agriculture, computer science, and mathematics.

[3] Data are for 2002 or year stated.

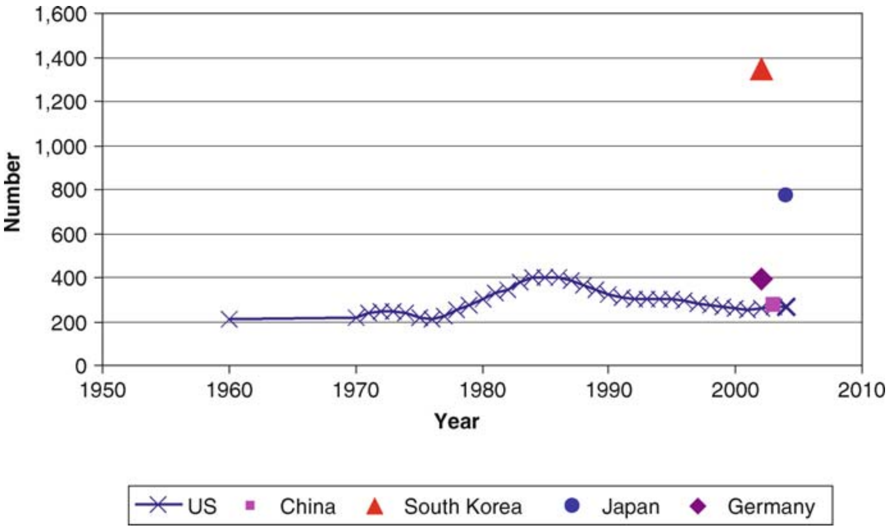

Fig. 7.4 Number of engineering Bachelor's degrees or equivalent per million population. Sources (National Science Board, 2006; U.S. Department of Education, 2006; U.S. Census Bureau, 2006; Population Estimates taken from US Central Intelligence Agency World Factbook, specific country pages, indicated year)

normalizes the production of engineering graduates to population, the US production is quite similar to that of China, but falls considerably short of other nations that have a stronger technological societal ethos, such as Germany and Japan.

Although the population of a country such as China translates into a significant engineering labor resource, the state of development of their infrastructure is far behind that of the United States. Their needs to modernize and grow this infrastructure will likely create a significant domestic demand for engineers reducing the availability of Chinese and Indian engineering graduates who might help reduce the shortfall in the United States.

It is therefore critically important that we increase the representation of engineering graduates in the United States. There are many aspects that must be addressed to close the gap between the US engineering workforce demand and the current or projected supply. One critical topic, that is the focus of this paper, is engineering college curriculum reform. In order to better approach the levels of engineering representation in society similar to counties such as Germany and Japan, we argue that educational reform to increase the perceived and actual social relevance of an engineering education and career is needed. This reform must be grounded in a broader more holistic education of engineers. Several institutions have already embraced this approach and have proven to be very successful. This paper will review some background information and then highlight some salient features of programs with a holistic philosophy.

Background

The stagnant numbers of US engineering graduates occurring at a time of record college and university enrollments have been attributed to (Teitelbaum, 2002)

1. The failings of the US K-12 education system, especially its inadequacies in science and mathematics (Fig. 7.5 Task Force on the Future of American Innovation, 2006).

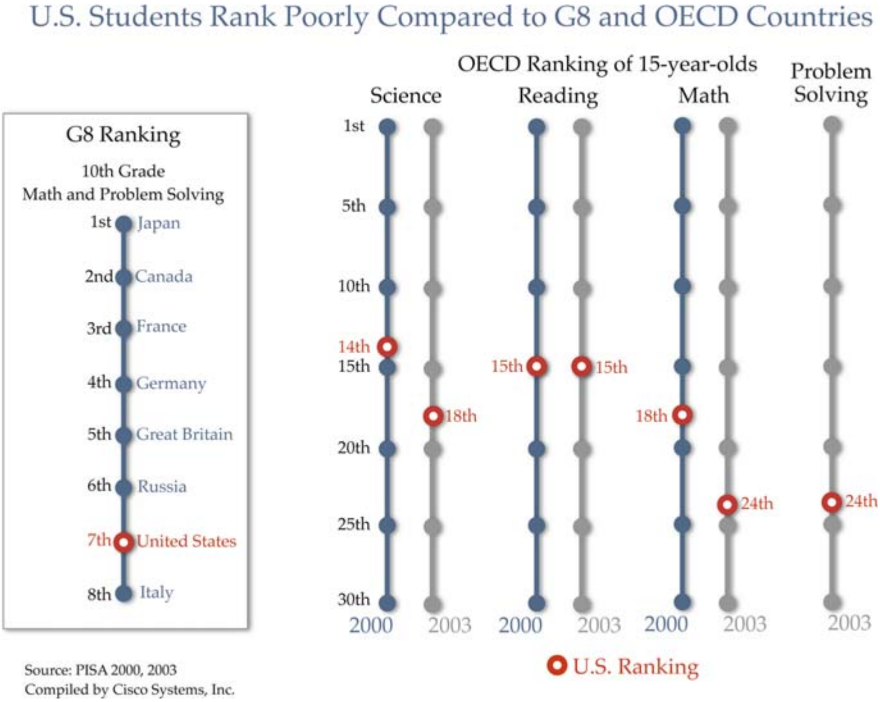

Fig. 7.5 Ranking of tenth grader (G8 nations) and 15 year old (OECD) performance in various standardized tests. (reprinted with permission from reference Task Force on the Future of American Innovation, 2006)

2. A declining level of interest in such fields among US students, especially among the "best and brightest," in part because of the relative difficulty of science and mathematics as fields of study.
3. Inadequate knowledge among younger US cohorts of science and engineering fields as careers, or in the alternative of the science and math prerequisites required to pursue them at university level.
4. For women and minorities, a lack of role models in these fields, suggesting to younger cohorts that such fields are "not for me."

It is argued here that an additional reason might be the nature and structure of the extant engineering curricula that are offered at universities around the nation. The transformation of the US labor force from one that was largely manufacturing-based in the middle of the 20th century to one that is more than 80% information-based today (Bureau of Labor Statistics, 2006) has created challenging opportunities for engineering programs. However, an investigation of university engineering curricula in chemical, electrical, and civil engineering from the 1950s, 1980s, and today suggests that in many cases, other than important but relatively focused modifications such as the addition of biology to meet science requirements and the elimination of military science, much in the engineering curricula has been essentially static over this period. Elements of all these factors combine to yield what one recent study of multiple engineering cohorts reported as graduation rates as low as 33% (Zhang et al., 2002).

ABET 2000 has allowed universities to become more creative in attempting to better educate future engineers to address the challenging problems of the 21st century. Capitalizing on this opportunity, the National Academy of Engineering report entitled *Educating the Engineer of 2020* (National Academy of Engineering, 2005) called for universities to revise their engineering curricula to better prepare engineers to solve problems that Peter Senge (Senge, 1994) describes as having derived from yesterday's solutions. Indeed, a recent article published in the Chronicle of Higher Education entitled "Holistic Engineering" (Grasso and Martinelli, 2007) argued for a new paradigm in engineering education; one focused more on engineering fundamentals and complemented with an array of broad topic courses. Consistent with the NAE report, the article suggested that this approach would enhance the engineers' ability to better contextualize their work within the greater needs of society and develop the creative, innovative, and holistic solutions to the problems and challenges of the 21st century. This broader educational philosophy would allow engineers to play a more prominent role in policy and decision making and attract more individuals to the profession to meet the demands of the coming century. Quoting directly from the NAE report, a university's goal should be to graduate "technically proficient engineers who are broadly educated, see themselves as global citizens, can be leaders in business and public service, and who are ethically grounded" where "learning disciplinary technical subjects to the exclusion of a selection of humanities, economics, political science, language, and/or interdisciplinary technical subjects is not in the best interest of producing engineers able to communicate with the public, able to engage in a global engineering marketplace, or trained to be lifelong learners."

Although it is well accepted that a sound math and science background is a necessary prerequisite for a successful engineering career, there is also the critical and complementary issue of motivation. Ask a physician why she selected a career in medicine and you rarely hear "I liked biology," rather the more common response is "I wanted to help people" (Grasso, 2002). This predilection is evident in the proportions of women who have entered other professions that have manifest social relevance (e.g., medicine, law, business). Figure 7.6 (U.S. Department of Education, 2006) shows that looking back to the 1960s, the penetration of women

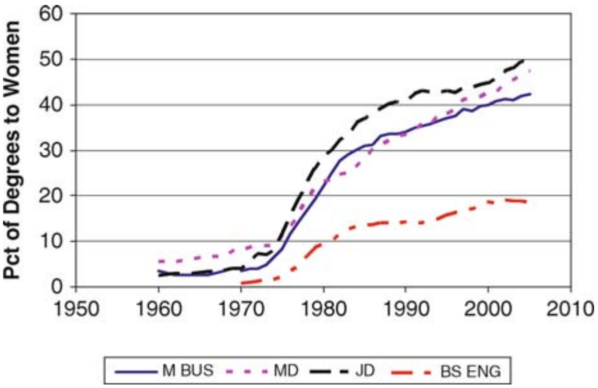

Fig. 7.6 Percentage of US degrees granted to women in business (all Master's degrees), medicine (Doctor of Medicine degrees), law (Juris Doctor degrees), and engineering (Bachelor's degrees), 1960–2005. Source: selected tables from US Department of Education, National Center for Education Statistics (U.S. Department of Education, 2006)

into all the professions was scant. However, as society demanded better gender representation and integration in all its professions, engineering alone has languished at about 20% while medicine, law, and business are approaching parity. Certainly the technical rigor required to enter medicine is comparable with that required to enter the profession of engineering. However, engineering has failed to make a sufficiently compelling case for social relevance. It is this sense of social relevance and context that must be the prime motivation for students to be successful in the negotiating the challenges of an engineering education.

Moreover, the creativity and innovation promise of careers in engineering are often not borne out during the undergraduate experience. The creative aspects of design are all too often reduced to choosing the correct beam, or determining the proper residence time for a reactor – and these aspects are commonly delayed until late in a student's education. The senior design experience, which is often open-ended and offers the reward for which many students enrolled, is only a portion of the educational experience. This lack of emphasis on nurturing the creative aspects of our profession has resulted in a mind set where students believe that the objective of their education is to follow specific protocols and just go out and "get a job" rather than go out, be innovative and "create jobs." But how does one teach creativity and innovation? These processes typically derive from considering problems from different perspectives. The art of discovery is not necessarily about visiting new lands but seeing with different eyes. The broader ones education and the more ways of thinking to which one is exposed, the more creative, holistic, and expansive is the solution space.

It is not surprising that when one looks at the percentage of engineers with their highest degree in engineering employed who are practicing in a field close to their discipline (Fig. 7.7 National Science Board, 2006), we find that that on average less than half (46%) of engineers are so employed after 35 years. As one might expect,

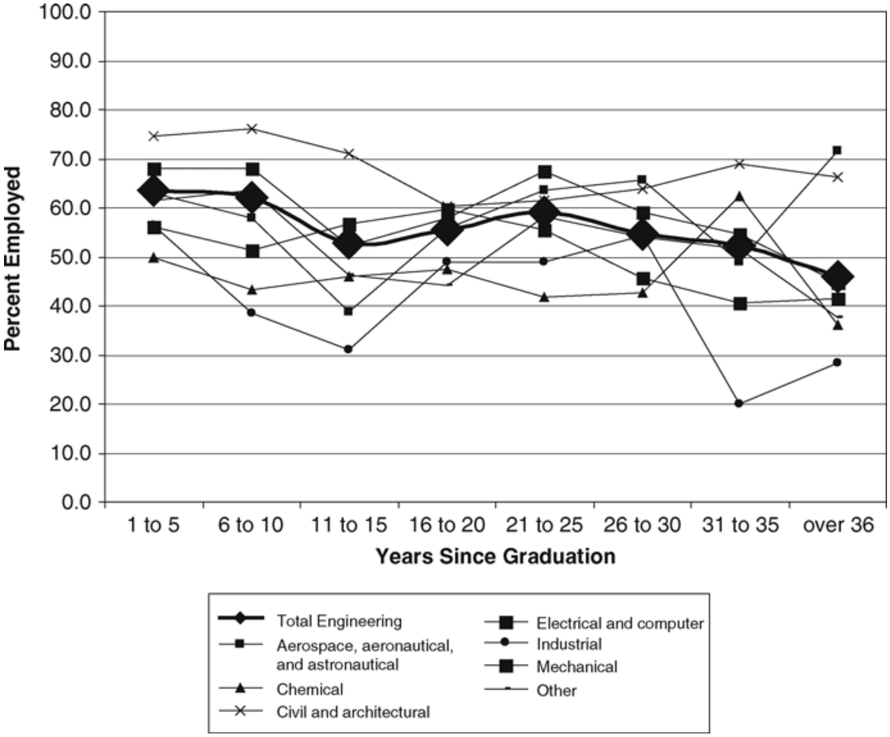

Fig. 7.7 Employed individuals with engineering highest degrees whose jobs are closely related to field of highest degree, by years since degree: 2003 (adapted from data in reference National Science Board, 2006)

the percentage of engineers practicing close to their discipline of education generally decreases with time. However, more remarkable is the large percentage of virtually all engineering graduates that do not work in an area close to their educational training. This is very strong justification for providing a broad education to engineering students so that they may effectively pursue varied career options.

Educational Innovation

Four engineering programs, two nascent and two historic (Smith College, Olin College, Dartmouth College, and the University of Vermont), have evolved unique approaches to the challenge of nurturing creativity and holistic thought and inspiring students to consider engineering careers. The two former programs started with blank slates and could create any form or structure of their choosing.

Olin College offers only three accredited engineering degrees: mechanical, electrical, and general engineering (Olin College, 2007). The curriculum is based on three major components: science and engineering fundamentals, entrepreneurship, and the liberal arts. To help students stay well-rounded and balanced, they are encouraged to pursue their personal artistic, humanistic, philanthropic, and technical interests through the college's Passionate Pursuit program. Students complete a final project at the end of each semester and receive non-degree credit for their efforts. Examples of recent Passionate Pursuits include The Art of Glassblowing, Jewelry Making, Russian Studies, Flute Performance, and Rock Climbing with Physics (Olin College, 2007).

Olin students are also required to complete a Foundations of Business and Entrepreneurship course and incorporate entrepreneurial components into design courses. There is a focus on active learning and interaction with minimal reliance on traditional lectures, on the use of student portfolios (purposeful collection of student work used to demonstrate mastery of the course measurable outcomes, and to provide a personal reflective tool for self-assessment), and on interdisciplinary courses. The Olin program's philosophy is to build connections among fundamental science, mathematics, and engineering; among different fields of engineering; among the arts, humanities and social sciences, and technical disciplines; and among business, entrepreneurship, and technology. As a result, the Olin curriculum is conceived and taught in a highly interdisciplinary way. The curriculum culminates in SCOPE (Senior Consulting Program for Engineering) a final year-long engineering project for an industrial or corporate client.

Smith College was the first women's college in the United States and one of the few liberal arts colleges to establish an engineering program. The Smith program has a continuous emphasis on the use of engineering science principles in design and culminates in a final design clinic based project that incorporates broad-based societal aspects for an industrial or governmental client. Unlike Olin College or traditional colleges of engineering, Smith offers only one accredited undergraduate degree, in Engineering Science, the broad study of the theoretical scientific underpinnings that govern the practice of all engineering disciplines. The Smith decision to offer only one degree in engineering science was based on the recognition of pitfalls of overspecialization in a world of rapidly changing technologies and increasingly complex multinational markets (Smith College, 2007).

Not surprisingly, Smith also pays significant attention to the liberal arts, requiring its entire engineering student body to take a "Latin Honors" set of courses. That is, at least one course in each of the seven general areas of knowledge must be taken: literature, historical studies, social science, natural science, mathematics and analytic philosophy, the arts, and a foreign language. This is particularly noteworthy for two reasons. Smith has no core curriculum and therefore the engineering students at Smith are the only majors required to have this curricular breadth. Secondly, 1 year of a foreign language is required of all engineering students, another unique feature of the program which helps prepare graduates to understand foreign cultures and practice in a global economy.

At Dartmouth College, where the Thayer School of Engineering is one of the oldest engineering programs in the country, the story is similar; undergraduate students are grounded in the liberal arts, rooted in the humanities, and learn engineering through an interdisciplinary systems-based engineering curriculum (Hansen, 2006).

Students pursuing engineering at Dartmouth meet general education requirements identical to those of all other liberal arts majors with emphasis on humanities, sciences, and writing. In the engineering courses, there is an emphasis on a systems approach to engineering throughout, and the incorporation of team-based design projects from the outset. For example, in the first sophomore-level engineering course, an interdisciplinary offering entitled "Introduction to Engineering," student teams are challenged to identify a practical problem in a general area addressing a contemporary problem (for example, "energy technology" has been chosen as one of the course themes for fall 2007), brainstorm to identify possible solutions, research the relevant patent literature, choose an approach, prototype, test, refine, conduct economic analysis, prepare a business case, and present and defend their results to a design review board – all in a single 10-week term. Through this course, students take a systems approach to problem definition and solution, rather than being restricted to the tools and language of a specific engineering discipline. Evidence for the success of this approach is provided by the nine student teams who have filed for patent protection on their term projects within the past five academic years, with one student team recently winning a national breakthrough award for their effort to develop an alternative to children's training wheels (Popular Mechanics, 2006).

The Dartmouth program described above typically culminates in the awarding of a Bachelor of Arts (A.B.) degree in Engineering Sciences as the students' first degree. Students may then choose to pursue an ABET-accredited Bachelor of Engineering (B.E.) degree, also in Engineering Sciences but with more disciplinary emphasis, an emphasis based upon student choice of electives. The B.E. is typically earned through a fifth year of study, although 20% of B.E. recipients earn the B.E. and A.B. concurrently in 4 years. This combination provides students with both the breadth characteristic of a liberal arts education and the depth desired as the foundation for graduate study in an engineering discipline.

Finally, the University of Vermont College of Engineering and Mathematical Sciences has long offered a traditional engineering program, with accredited degrees in civil, mechanical, electrical, and environmental engineering and an unaccredited degree in engineering management. However, it recently underwent organizational restructuring unifying historical engineering departments into a single School of Engineering. Consistent with and capitalizing on this transformation, the School of Engineering is also undergoing a major curriculum reform. Proposed curriculum changes are based on the vision of how to best prepare engineering graduates for the 21st century and lifelong careers. The student educational experience will stress innovation and creativity in design and will be personalized, multidisciplinary, liberal, systems-oriented, integrated, and interactive.

Some major curricular reform elements that have been recently instituted inclued that a Bachelor of Arts in Engineering program intended to serve as a bridge between engineering and the liberal arts and to provide opportunities for students who want to learn how to think like engineers but would like to pursue other careers (e.g., medicine, law, finance), and a Bachelor of Science in Engineering Science to allow students to pursue interdisciplinary studies in multiple engineering areas or in areas connecting engineering with mathematics, physical or life sciences, or business.

Interestingly, in all four cases[4] the programs elected to organize themselves in a structure that has no traditional academic departments or boundaries and stresses broad interdisciplinary education that is contextualized in a societal relevant framework and stress creativity. In all these programs, students are exposed to modes of reasoning beyond the science and engineering paradigms, allowing them the resources to consider more holistic approaches to solving what might otherwise have been considered narrow technical problems. If engineers are to move beyond a profession characterized by specific performance expected of the "sons of Martha" (Grasso, 2002; 2004) and move to a profession truly inspired by creativity and holistic systems thinking, we must move to a broader undergraduate preparation for our students.

Not surprisingly, the interest in these programs outpaces the national trends. For example, at the University of Vermont applications to the School of Engineering have increased by 64% since the announcement of the Curriculum 21 reform effort.

Summary

There are many traditional engineering programs in the United States and abroad. The dawn of a new century gives us pause to consider the strengths and weakness of these programs that have generally served us well in the past. The projected shortages of engineers in the United States are an indication that the profession's attractiveness has not kept pace with the profession's opportunities. Moreover, the challenges of the coming century will demand creative, innovative, and holistic solutions that will require broader pre-professional preparation. This paper summarized several programs that have model curricula designed to address these concerns.

Curriculum reform is not without challenges and it is not suggested that all traditional programs abandon a departmental structure and seek an integrated organization and curriculum. However, a first step in moving toward a curriculum that can better educate holistic engineers might be to work toward true interdisciplinarity at both ends of the undergraduate experience. By structuring a first-year design course that brings together students of varied interests and backgrounds, the profession of engineering can be contextualized within a societal framework inspiring students to seek creative solutions using the engineering method but unencumbered by traditional disciplinary protocols. This would serve to encourage students to continue with the rigors of an engineering education and concomitantly to seek a broad education to help them address the myriad of factors which the future will demand. Complementing the first-year course, a unified senior design course that is truly

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[4] It is also worth noting that UC-Merced's new School of Engineering is also devoid of traditional academic departments.

interdisciplinary and involves engineering students of all disciplines together would better prepare our students to design the holistic, creative, and integrated solutions that will serve society's needs.

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Chapter 8
Beyond Systems Engineering – Educational Approaches for the 21st Century

Priscilla Guthrie

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Engineering is about using technology to solve problems for society[1]; applying these changing technologies to meet the demands of the increasingly knowledgeable, interconnected, and interdependent human enterprise. For over half a century, engineering has played a key role in fueling US economic growth.[2] Products, construction, processes, and even organizations developed by engineers have significantly improved US productivity[3] and changed the way we live and work. With the extensive integration of technology into the fabric of society, engineering and science are likely to become increasingly important drivers for all economies. Given the potential for impacting our way of life and the lives of future generations, the topic of the future of engineering education is important enough to warrant gathering many ideas from diverse sources.[4]

Over time, the term "engineering" appears to have migrated from the primary definition,[5] "the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people" toward a secondary definition, "the design and manufacture of complex products," which focuses on the technical aspects of a solution. This migration has not helped the profession. It has separated designers and developers from users, created separate words

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[1] Ramo, Simon. An Interview Conducted by Frederik Nebeker, Center for the History of Electrical Engineering, February 27, 1995.

[2] Augustine, Norman (chair), *Committee on Prospering in the Global Economy of the 21st Century. Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. The National Academies Press, 2007.

[3] Augustine, Norman, America's Competitiveness, Statement before the Democratic Steering and Policy Committee, U.S. House of Representatives, January 7, 2009.

[4] The author has been engaged, albeit intermittently and unsuccessfully, for almost 40 years in attempting to increase the percentage of female engineers, and for almost 30 years in adapting systems engineering constructs to support development of human interactive environments.

[5] "engineering." Merriam-Webster Online Dictionary, http://www.merriam-webster.com, May 8, 2008.

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and language that hinder communications, and left many "product buyers" unable to articulate their requirements or to determine whether a product meets the need. All of these factors contribute to a lack of trust between the technical community and the general public – all of this at a time when more people depend on technology than ever before. This is a significant problem for our profession. Engineering endeavors should be holistic, with context taking precedence, setting the stage for, and playing a prominent role in the collaborative development of solutions.

Until the Industrial Age, requirements and uses for engineering products were relatively well understood. Engineers provided value in the creative application of science to meet a need. The products were mostly stand-alone or for use in small environments, and met relatively straightforward, well-understood needs.

During the Industrial Age, the environment itself became more complex. Industrial engineering as a profession was, in part, created to provide an interface between factory operators (humans) with their increasingly complex environments and requirements, and the other engineering disciplines, for example mechanical engineers and power engineers. This change increased the separation of the human, or contextual, side of the environment from the engineering activities and solutions.

During the mid-late 20th century, advances in technology allowed engineers to build significantly more complex products. Although some say that systems engineering started with industrial engineering, systems engineering as documented and practiced today is largely built on processes developed in the last quarter of the 20th century to support government space and defense programs. It focused on the secondary definition of engineering provided above, "the design and manufacture of complex products."

This approach to systems engineering started with requirements definition and allocation, and typically followed up with design, development, integration, and test. The significant early applications of systems engineering were for space and defense systems where the human interactions were focused and relatively limited, for example, missiles, satellites, and manned space flight, and where technology and technical complexity were drivers. The requirements were defined and documented, and the challenge was in functional allocation, design, development, integration, and test of the product.

As systems engineering was developing, it became obvious that engineering educators had work to do to equip students to add value in these large, technically complex environments. There were not enough hours available in the already four-plus-year degree program to allow students to learn all of the technical skills and to also gain an understanding of the systems engineering processes and lifecycles within which they would be required to work. Additionally, many of the educators themselves had not worked with or within these new constructs. Further, since engineering is really the application of science to *new* problems, figuring out how to teach these complex processes was non-trivial as the systems engineering processes often required tailoring for different problem sets. Instead, educators focused on providing sufficient technical rigor so that students entered the workplace with skills that provided enough value to overcome their lack of experience. And, increasingly, employers counted on new hires to have hands-on experience with current tools and technologies. Students graduated with the required technical skills, but without knowing how to work with users or document requirements in ways that would provide value throughout the product development lifecycle. In fact, they were graduating with little knowledge that a system lifecycle existed. Perhaps more importantly, engineering students were entering the workplace without knowing how to work collaboratively and across technical disciplines (e.g., disciplines such as hardware and software).

Engineering education at the undergraduate level essentially walked away from the problem of educating systems engineers, instead focusing on providing students with instruction on the growing list of the "by-discipline" basics including new tools and techniques. Employers tried, with varying levels of success, to (1) identify people with the aptitude to become systems engineers and (2) teach their new engineers how to work together on large, technically complex activities. And this turned out to be the easy part of educating engineers, as the focus was still primarily technical.

Today, technology has been integrated into, and even extends, our social structure. In many cases, technology cannot even be separated from the social environment (e.g., the Internet). We are increasingly networked and interdependent, technically and socially. Both the enabling technologies and the social enterprise learn and evolve rapidly. Engineers must apply increasingly complex science and technology to benefit users that learn and increase their expectations at an astonishing rate. As the defense community learned in the development of highly human interactive command and control systems, the systems engineering processes that were pioneered to address the large, technically complex activities turned out to not work as well in these human-driven environments. The engineering education community never successfully addressed the problem of educating systems engineers. The difficulty is compounded when the goal is to engineer solutions that meet the needs of the social enterprise.

A holistic approach to engineering is required to ensure that solutions add value on all levels within the context of the evolving social fabric. For example, agricultural engineers must consider among other things, the impact of the marketplace, weather, sustainability, and environmental and farm policy. This broad, networked, interdependent social/technical context is both the starting place and the operational environment for modern engineering solutions, and it is an environment that evolves rapidly. Engineers must be prepared to work collaboratively with others within and outside their area of expertise to understand the context for "what" is needed, and to develop solutions – the "how." Engineering endeavors should be holistic, with context taking precedence, setting the stage for, and playing a prominent role in the collaborative development of solutions.

To do this, the engineering education community should foster holistic engineering curricula that broaden students' understanding of, and ability to work within the social context. As was the case for systems engineering, there are clearly not enough available hours to simply add these requirements to existing programs. Trading one set of courses for another will also create issues, as employers count on colleges and universities to provide graduates with hands-on familiarity with newer tools and technologies; backing off on some of the current training (vice education) will require simultaneous investment by engineers and employers in updating the knowledge of the existing workforce to enable them to learn and leverage new capabilities.

It seems time to reconsider the engineering curriculum. The marketplace needs people that can successfully engage in the application of science to the needs of society. Given the rapid pace of change on both "sides" of engineering – technology and society – the educational system cannot be expected to teach new engineers everything they need to know, and indeed, it is unlikely that any single engineer has all of the knowledge required to work a typical effort. While it is not possible to teach students everything they need to know, it is also not acceptable to send students to the workplace unprepared. This leads to a few recommendations:

- Make students aware of the environment, or the context, for their work.
- Teach students the basic technical skills of their profession, including and especially approaches to solving problems.
- Require collaboration in a significant percentage of the coursework to prepare students to work with other engineers and with people from other disciplines in articulating the questions – the "what," and in defining and delivering solutions – the "how."
- Prepare engineering students to engage in lifelong learning.
- Instill a belief that creative, innovative, cross-discipline collaboration is a US value-add.

Developing the new curricula and proving that the changes increase the overall return is likely to take time, but sending students into the workplace with an understanding of how to solve problems and with the skills to collaborate with and among the widest possible range of subject matter experts on the "what" and the "how" is a good starting point. To make this possible will require fundamental changes within the engineering education community and stakeholders, including ABET, educators, educational institutions, students, parents, and employers.

ABET will need to consider the requirements of basic engineering education. Educators may need to consider whether existing engineering segmentation, for example, electrical, mechanical, industrial, is still useful. Educators will need to develop new and/or different topics and materials, and continually evolve the materials to meet the needs of our changing society. They will also need to introduce or mainstream new teaching methods, some of which may appear difficult to scale. Students will need to accept the requirement to learn skills that are considered nontechnical, e.g., collaboration, communication, interfacing with other disciplines. Employers will need to embrace new employees with less specific technical skills (e.g., ability to use certain tools), but who are better prepared to collaborate with others to solve problems in complex environments that go well beyond technology.

It is obvious that no approach to engineering education will send fully qualified students into the profession with their educations behind them for good. Both "sides" of engineering endeavors, science and the social environment, continue to change. Interestingly, the rate of change within society may outpace that of technology.[6] Therefore, rather than focusing primarily on technical skills, students must be taught about the environment, how to tackle complex problems, and how to collaborate with others to understand what is required in the design and implementation of innovative solutions. Students should be made aware of the need for dialog between policy makers and engineers as part of their education. It will also be important for students to understand that lifelong learning is a key tenet of their profession – so that they are prepared to work solutions within the current social context, able to understand the enabling sciences, and are prepared to embrace new ways of working.

While the changes recommended for engineering students are extensive, implementing the changes proposed in this chapter will require concerted, sustained effort by the entire engineering community. No segment will be more important to this quest for engineering excellence, or asked to make more change, than the educators. As noted in the prior section, they will be asked to

- Consider, and possibly revamp, existing engineering segmentation, for example electrical, mechanical, and industrial
- Develop and evolve new materials to teach the basics of the profession and approaches to problem solving, including understanding what is required and how the requirements might be met
- Introduce or mainstream teaching methods, including collaborative coursework that will be more difficult to develop, scale, sustain, and evaluate, and with which they may not have experience
- Provide a model for lifelong learning that students can review, analyze, and adopt.

While these changes are extensive and will take time, they appear to be essential to enhance and sustain the reputation of our profession. More importantly, they will leverage the innovative and creative capacities of US engineers as full partners in advancing our society.

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[6] Brown, John Seely. Storytelling, Passport to the 21st Century. http://www.creatingthe21st century.org/JSB2-pace-change.html, 2001.

Chapter 9
The Education of an Engineer in a Holistic Age: A Latin American Perspective

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A rich education has never been solely one of instruction in facts and processes. A truly rich education, in any field, must also include the opportunity for students to form values, develop critical thought, explore ethical arguments, and conduct service for the common good. In engineering, these rich educational traditions create not only excellent engineers but also potential leaders, capable of solving engineering problems with competence and imagination. This approach to a rich education – the holistic education approach – is what will best serve the future of Latin American engineering universities.

Today in Latin America, the rich and contextualized opportunity of the holistic approach to engineering education is – unfortunately – a privilege of study available in only a few university programs. Most programs do not reach the goal, focused too closely on technical skill, and some are not even aware there is a problem in focusing on technical facts and processes in the engineering curriculum. One of the main causes, at least in Latin America, may be the creation in recent years of innumerable for-profit institutions. Their goal, too often, is for bottom-line, short-term profit in teaching focused skills, not necessarily in creating the most broad-minded and creative engineering graduate. Another challenge is the lack of competent university professors with experience in the real-world complexities of engineering business, politics, and community outreach – professors who might otherwise bring the art and creativity of engineering practice back to the classroom.

This cannot continue. Latin American engineering education must rise to the challenge of incorporating more holistic approaches, if not simply for the betterment of our engineer minds, but also because the last three decades have shown significant changes in both our society and our economy– the driving forces framing the work of future Latin American engineers. Engineering education must keep up with those changes. For example,

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1. In the 1990s, the Industrial Era ended and the Information Era started. This new era in the United States was marked by the years in which overall national investment in computers and communication equipment began to exceed investments in industrial machines for mining, agriculture, construction, and exploration. This same era – and the change from an industrial economy to one centered around rapidly changing information – arrived in Latin America at the end of the 20th century.
2. The world has become a global marketplace, resulting from the massive introduction of new technologies that make it possible to immediately transmit and exchange a myriad of information at the touch of a button. Moreover, after the communist world collapsed, a single kind of economy – one with a strong neoliberal emphasis – has grown in its place. In this context, technological innovation and business skills have become essential and highly competitive. Even with, and perhaps especially because, uncontrolled capitalism has helped create a severe world economic crisis, high-level skills in innovation and business management remain highly desired.

We all live in a new and globally connected world that is changing rapidly and constantly. As such, we can state that the only permanent thing is change. And, to a great extent, engineers are the experts trained to be responsible for the process of change. Engineers are uniquely trained and sensitized to perceive that the many things that are designed, produced, and operated by humankind – communications, for example – both have an immediate impact on society and, by their existence, may also feed back into the complex engineering process itself. Constantly adapting to this permanent state of change, feedback, and complexity is a core challenge facing today's engineering practitioners. In the past years, there was a time to learn and a time to work. In our new, global era, learning and working have, by necessity, become one and the same.

To truly create a fundamental education program that allows engineers to adapt to change and be leaders in fields beyond any specific technical expertise, the objective of the majority of programs for engineering studies in Latin America must be substantially modified. The investment must not only be in major curriculum reform for undergraduate engineers but ensure engineering graduates continue to be life-long learners throughout their careers.

This new objective requires a renewal of educational techniques that strengthen interpersonal relationships, adding depth to the technically oriented and engineering information-specific curriculum that has prevailed to date.

This means, in the end, educating engineers who can "learn to learn" and who are ready to do so all along their professional lives. Twenty-first engineers will be, effectively, illiterate and noncompetitive if they have not "learned to learn."

The following are therefore indispensable actions as Latin America moves to more holistic approaches to engineering education:

(a) We must redefine how we teach – removing absurdities such as insisting in mastering the theory of sets in mathematics, or focusing on sciences relevant only to a single engineering specialty;

(b) We must avoid the simplistic idea of believing that engineering is only an applied science, without aspects of creativity and art;
(c) We must avoid saturating curricula with time-limited, specified technical knowledge that is essentially perishable in today's modern market of rapidly changing information and ideas;
(d) We must include a comprehensive cultural education in the traditional curriculum and the competence to effectively communicate; and
(e) We must make sure that we are graduating students with an education that trained them to solve diverse and complex engineering problems creatively, with final outcomes grounded both ethically and socially.

This curricular change must be carried out according to the too-often-forgotten idea that you cannot – and should not – teach students more than what they can truly retain as core knowledge. Understanding that there are core areas of intellectual, rhetorical, and social skills that a graduate of a university engineering program must possess beyond technical training is key to this change. Engineers' education requires a new balance between the indispensable cultural education (the university's fundamental mission) and the implementation of skills, abilities, and values that belong to engineering in our new era.

Models for Engineering Education in Latin America

Today, all over the world, and in spite of the fact that the "engineering" degree does not usually distinguish between them, university systems essentially graduate two distinctly different types of engineers: one who is competent to create, perfect, and operate technologically driven processes and another who is trained more broadly, with the ability to take on non-technological tasks of leadership and contribute to the future of engineering and scientific knowledge.

Undoubtedly, both types of graduates have clearly defined positions in the current exercise of engineering and both are therefore socially necessary. Societies – no matter their wealth, level of socio-economic development, and environmental awareness – require both types of engineers to create or maintain their built environment and thus accelerate their development process. Societies must also work to maintain an efficient proportion of each type of engineer in order to best meet the needs of their communities and state.

The challenge, however, lies in the fact that current university degrees in Latin America do not easily allow societies to distinguish between more technical, or more broadly trained, engineers. Nor can users of engineering services easily identify which kind of engineer they wish to hire from existing university programs.

In a study prepared in 1980 by the Engineering Professors' Conference in the United Kingdom, two different education models were proposed for engineering and, as a consequence, two different kinds of degrees offered. The first of these degrees was created specifically to ensure the engineering graduate was educated with confidence and competence to successfully tackle – and solve – new, unspecified, and complex problems whenever they are presented to him/her. This engineer's education emphasized transferable understanding and skills across multiple disciplines. The second degree, of a lesser class than the first one, resulted in an engineering graduate with core competence to successfully solve highly specified technical problems. This education track focused on engineering skills and specialized abilities.

The United Kingdom Civil Engineer Institution acknowledged the first degree with the title of Engineer (or "Designer Engineer") and the second simply as a "Technical Engineer."

Some engineering programs abroad, for example those of the Massachusetts Institute of Technology (MIT) in the United States or the Imperial College of Science and Technology in the United Kingdom, are clearly defined to produce the "Designer Engineer." Programs at these institutions are organized to educate a professional who is capable of facing unstructured problems, adopting strategies for multiple solutions, using creative thinking, working in teams, and communicating complex ideas effectively. All of these characteristics allow the professional to apply fundamental engineering thought to successfully carry out complex projects and designs.

Although Designer Engineer programs do not yet exist in Latin America, data show that they would likely have great potential. For example, the Escola Politecnica da Universidade de Sao Paulo in Brazil – which has been traditionally identified with a strong scientific approach to engineering and emphasis on technical specialization – recently discovered that they were not graduating competent engineers who could solve unstructured problems that included complex ethical and social components. They actively surveyed state authorities, entrepreneurs, engineers, professors, and students about the skills needed by 21st century engineers, and found that 80% of students strongly preferred the more holistic, "Designer Engineer" education model for their future. According to the students, their preference of this more holistic engineering education path included a belief that it would bring them better career prospects, greater adaptability to rapid technological change, and the possibility to reach high-level leadership positions in their engineering career.

Sao Paulo University has taken these recommendations to heart and is poised to become a leader in the transformation of engineering education to a more holistic model. And because the influence of Brazil is so great, there is no doubt that many other Latin American universities – the public Buenos Aires University of Argentina, the private Los Andes University of Colombia, and the private Catholic University of Chile – will likely follow Sao Paulo's more holistic engineering education investment for the future.

Creating the Holistic Engineer

The challenge for our modern world – and for Sao Paulo University engineering specifically – is now to ensure that future engineering students will be exposed to a curriculum in which they will develop the core characteristics of the holistic engineer. This will include an awareness of engineer's role in service to society, environmental sensitivity, the ability to comprehend complex problems spanning disciplines, a sensitivity to issues of societal culture, ethics, art, and history, and – of course – strong technical engineering skills as well.

Furthermore, the engineering student must learn, and appreciate, the impact of design and its connection to society and the environment. Design, done well, acknowledges that the political, psychological, economic, cultural, environmental, and social conditionings inherent to any engineering project are just as much a part of the solution challenge as mastery of science and technology. Yet how do we teach socially and environmentally aware design skills? How do we teach engineers the ways in which they must take human needs into account and ensure engineering design serves the needs of multiple lifestyles and cultures?

Ultimately, the new engineering education will need to address these questions with a new focus on creating a more "cultivated human being" as its core investment. This new engineering education recognizes that allowing time for students to experience the cultural, social, political, and economic realities in the world around them – or abroad – is essential. The new paradigm will also require that engineering education create new bridges between standard engineering curricula and courses in philosophy, art, music, and painting. And the paradigm will require that this new generation of engineering students, with their unique training, still continue to feel part of the worldwide community of engineers and value the rich historical traditions of the engineering practice.

This change will not be easy. Those inclined toward the engineering profession, as a group, are often eager to focus and specialize early in their undergraduate training in order to become experts in a field. Yet early specialization at the pre-graduate level too often leads to technical proficiency without professional insight and vision. In the worst cases, specialization too early can prevent excellent engineers from reaching their true leadership potential by limiting their options to excel. Finally, specialization too soon can deter engineering students from learning a key skill: how to adapt readily to change, be it societal, technological, or economic.

This is why the teaching of undergraduate engineering must become holistic, with coursework never privileging any single area of engineering, but rather exploring the broad range of professional activity open to the engineer of the 21st century. Engineering education must create the foundation to allow our future engineers to fully develop, and thrive, in the global economy.

The Future of Engineering Education: Holistic Approaches, Life-Long Learning, and the Importance of Design

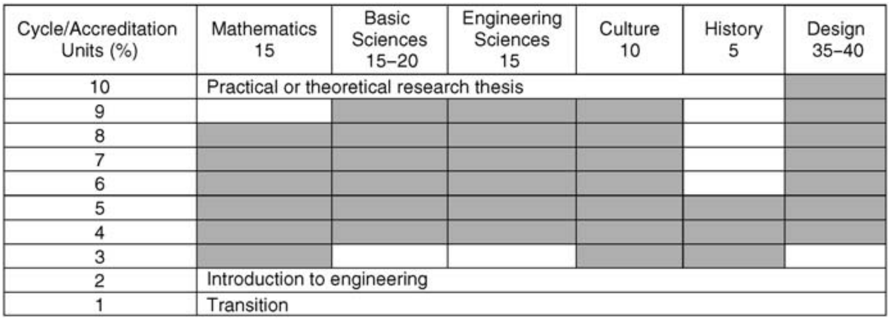
The future curriculum system of Latin America – the set of studies and practices aimed at achieving the holistic engineering characteristics – will be shaped greatly by the context of the university education. At a general level, the university environment in which they study and train to be an engineer is what provides students with their lifelong educational base. As such, this base must foster a commitment to do work that will benefit society and infuse critical thought, rationality, and creativity into students' thinking. The university must also root students into their public responsibility, letting them become involved in contemporary issues and helping them access, discriminate, and manage the constant barrage of information they receive each day. The university must also instill basic skills of effective communication and, finally, it will be imperative that the university graduate professionals extremely capable of "learning to learn" throughout their careers. Emilio Castañeda, an outstanding Cuban engineer and educator, appropriately states

> *...the only educated human being today is the one who has learned that no knowledge is certain.*

Curriculum Proposal

The curricular scheme below was prepared by the author as an example of the holistic approach to engineering education in Sao Paulo University. It includes accreditation units as the measurement of coursework, with one (1) unit of accreditation equal to a 50 minute class. One hour of lab or supervised work is equal to half (1/2) of an accreditation unit.

If we consider ten cycles that last 12 weeks each, there are 30 hours per week of instruction and a ratio of 1 hour of class for half an hour of laboratory or supervised work. In the end, total available accreditation units are around 3,000. The minimum quantities proposed in this curricular scheme and their distribution along career development follow in Fig. 9.1, below:



Cycle/Accreditation Units (%)	Mathematics 15	Basic Sciences 15–20	Engineering Sciences 15	Culture 10	History 5	Design 35–40
10	Practical or theoretical research thesis					▨
9		▨	▨	▨		▨
8	▨	▨	▨	▨		▨
7	▨	▨	▨	▨		▨
6	▨	▨	▨	▨		▨
5	▨	▨	▨	▨	▨	▨
4	▨	▨	▨	▨	▨	▨
3	▨			▨	▨	
2	Introduction to engineering					
1	Transition					

Fig. 9.1 Curricular scheme proposed for "holistic approach to engineering education" at Sao Paulo University

Mathematics: The mastery of mathematics is an essential educational and instrumental skill needed for a career in engineering. Yet not all engineering programs acknowledge that mathematical skill is also one of the most difficult barriers for engineering-inspired students to overcome in order to successfully complete their studies. Furthermore, engineering programs often do not approach or embrace the creative and innovative teaching of mathematics in ways that might allow students to excel, making student mastery of mathematical skill sets an even more daunting hurdle during undergraduate coursework.

Sadly, this disinterest in teaching mathematics well and innovatively to engineers can delay or end the education of students who otherwise might have a true engineering talent and professional career. The lack of support for excellent mathematics training in the engineering curriculum can also completely discourage a student from even choosing to study engineering, which is just as much of a problem as losing existing students from engineering programs.

If we acknowledge that one of engineering's educational faults may be an uninspired or even poor teaching of fundamental mathematics during the undergraduate years, we then realize it is imperative to radically change the approach to teaching mathematics to engineers without losing any depth or mastery. Our objective must be to definitively make sure mathematics are accessible to all students, having them "fall for" math and acknowledge the field as an inseparable companion in their professional engineering journey.

For the future holistic engineer, this objective could be reached with three actions: training more mathematicians to teach students who will not be mathematicians, requiring engineering professors to advance innovative mathematical teaching methods rather than allowing poor math teaching to continue in the engineering curriculum and, most of all, integrating mathematics courses and science and engineering courses more seamlessly so that students may experience the application and power of mathematics through the interpretation and modeling of both engineered objects and natural phenomena.

Basic Sciences and Engineering Sciences: The field of engineering directly impacts the environment in which we live and, as such, engineers must recognize that their work must not only be ethically constrained, but must also be underpinned by basic knowledge of the natural world. This scientific base of core knowledge – in biology, chemistry, and physics, for example – is not only important to address engineering issues, but to sensitize and train students to identify and include the natural world in their engineering design process. Modern society demands that engineers be our leaders in the 21st century, finding an appropriate balance between the complex system of engineering, human activity, and our natural world.

Culture and History: The true objective of every university-based program of study is to produce a cultured and critical mind. The university then acknowledges a student's mastery by accrediting degrees. It is therefore imperative that a university degree requires extensive study of culture and history prior to graduation, no matter the specific field or program in which a student enrolls. These fields sustain and foster a truly comprehensive education, ensuring students contribute to society and providing the base of critical thought and analysis that then further inform their scientific and technical education.

In engineering, students should be required to take courses covering the history of the profession – its achievements and also its mistakes and failures. In so doing, engineering students will graduate possessing historical knowledge and learning from the experience. Learning the historical context of engineering profession and growth also results in a pride of belonging for the student – it enriches their studies and ensures they understand that engineering is not done in isolation. Their work impacts the world, and the people, around them.

Design- & Project-Based Learning: Finally, and most importantly, the study of design is the vital axis of the engineering career. Design courses are where student instruction can be – and must be – most innovative and interdisciplinary. Design courses allow students to integrate acquired knowledge and skills into new and complex problems, posing open-ended challenges and often leading to multiple solutions. Design courses also, more often than not, require engineering students to work in a team, identifying and evaluating a need or problem that requires engineering skill, then moving to justify what will need to be manufactured and collecting the necessary information to define conditioning factors for the solution – yet always understanding the information to be incomplete. This collaborative process of design is the core of a true engineering professional, often requiring lateral – rather than linear – thinking and open-minded approaches to new concepts.

During the design process, students develop their abilities in modeling, analysis, and optimization. Over the course of their studies, students move from very simple modeling to advanced modeling and computer simulations. Students, working in teams and needing to explain multiple options, also build skills in effective communication – oral, written, and graphic – especially as they need to relay their design to the next phase of manufacturing. In a nutshell, the idea is to gradually and increasingly bring the skills needed in professional experience back to the educational process of our next generation engineers. The emphasis on design, collaboration, and team work in the engineer's curriculum gives students skills in information management and "learning to learn" for the complexity of each new project. Sadly, the traditional engineering methods of teaching siloed subjects to students – and arguing that these siloed subjects are essential – are still too far pervasive. These do not serve to truly create engineering professionals and, as soon as possible, must be discarded. The multiple values of a design-centric engineering education are, instead, the future of the field.

Design-based teaching and project-based learning recognize that the best way for students to learn – and most of all to truly understand – is by doing. The best course progression for this new, holistic curriculum in design is to have multiple design-centric courses, each with increasing complexity and demand of the students' powers of synthesis and critical thought. And the design courses do not displace or negate the learning of fundamental engineering skills and concepts – instead, those can and should be built into the design coursework, with students learning the concepts through practice and innovation. In this way, high-level, transferable engineering skills are perfected globally and students discover, as they progress, where they might be most interested in specialization rather than specializing too soon.

Finally, ensuring the design- and project-based curriculum interacts with modern engineering professionals provides students with role models for their future. As they focus on design and on projects in their curriculum, they are simultaneously exposed to real-world professionals and the problems engineers face every day. This comprehensive vision of the engineer is invaluable to the students and, I believe, to the profession itself.

The Need for Core Competencies

In addition to the specific courses outlined above, I argue strongly that four core competencies – the strength of the university education – must pervade the holistic engineer's curriculum: ethics, creativity, communications, and life-long learning. As core competencies, I do not advocate for these being separate courses – in fact, I do not believe they should be separate. Instead, these four core concepts should be embedded within every course throughout the engineering degree. Below, I offer examples and ideas for embedding these concepts in engineering coursework.

Ethics: Ethics in engineering education can, of course, be taught as a course. Students studying ethics separately will learn techniques for conflict analysis and decision-making – skills they can directly utilize in engineering design to enhance societal safety and environmental protection. However, ethics will be most solidly developed in engineering if instruction occurs in a university environment where ethical thought is consistently valued and practiced. The university, therefore, is where we must respect each others' rights, embrace truth and justice and, particularly, instill in our students the value of common good and a respect to future generations utilizing our already scarce resources. The responsibility for ethical modeling and behavior falls to university professors, both in their professional activities on campus as well as outside the academy.

Throughout engineering education, students should be pushed to think ethically and develop their ethical compass for their future profession. The following is a simple questionnaire I have developed for my own students in order to open their minds to finding engineering and design solutions that embrace socially, environmentally, and economically ethical values:

1. Is there any personal, inter-personal, or institutional conflict preventing you from full exploration of the design process?
2. What existing interests will affect and influence the design process and likely solution? Is it, for example, the modification of an existing object with existing users?
3. Is there an ethical problem rooted in the design process? Why? Is it, for example, an object or design that might harm society or the environment?
4. What basic impact will the designed object have on the safety and protection of society and the environment? Is it, for example, a weapon or a war instrument?
5. What scope of natural hazards might affect the design project within its useful life?
6. What alternatives to the design exist? For example, if the design is a bridge, can you change the location to mitigate harmful impact, or can another, creative solution negate the need for a bridge at all?
7. What alternative perhaps better protects the rights of people?
8. What is the fairest alternative?
9. What alternative leads to the best consequences?
10. What alternative better promotes the present and future common good?
11. What alternative better promotes engineers' virtues (courage and compassion)?

12. What alternative enriches and better protects nature and the environment?
13. What is the safest alternative?
14. What is the most economic alternative?
15. Considering an ethical point of view, what is the best object?
16. How compatible is this object with the most efficient and economic one defined in the design process?
17. How would you justify your decision before other competent and sensible people?

In this self-reflective series of questions, the engineer must analyze all of the facts, learned paradigms, and personal preferences inherent in the decision to move forward with a design. I argue that this should be done even if the engineer clearly sees a single solution – or perhaps precisely because she/he thinks there is a single solution. Is the single solution the correct one? I encourage my engineering students never to leave the design stage without going through this exercise.

Finally, once a project is complete, I encourage my students to again evaluate their decisions retrospectively with three more questions:

18. In retrospect, were the design, process, and product the best that could be done, especially taking into account its effect on others lives?
19. Is my conscience at ease with the design, process, and product?
20. Would I be proud or concerned if I saw this design, process, and product published in major newspaper headlines?

Creativity: Much has been said about creativity being a natural quality present in some individuals. My own belief is that creativity is always present in human beings, with its diversity, quality, and depth expressed across a broad spectrum. In other words, creativity is similar to intelligence or to physical dexterity in humans – we all have it, but some are more innately talented than others.

If all human beings truly have creative ability, then creative education must of course align with engineering education. In the case of engineering, creativity should be leveraged as much as possible to allow – and encourage – students to explore design problems for multiple solutions and alternatives. For my own students, I again follow a simple model to expose them to their creative side and explore the opportunity for new engineering thought.

The first step is "immersion in the problem." At this stage, the idea is to define a problem precisely. To do so, you need to actively look for specific and general information on the issue. The response at this stage should always be to explicitly define which problem is actually to be solved. What need should be satisfied? Many students will provide "obvious" solutions to problems at this stage. They should not be accepted as definitive. On the contrary, some time needs to be given to arrive to other solution possibilities.

A second step in fostering creativity is to allow "incubation" of an idea. This is a stage in which our conscience is inactive. Our subconscious is active, and it does not process information linearly but more laterally – or logically.

This means it is able to make unusual connections or combinations. Therefore, once the problem is defined and there are obvious solutions at hand, without dropping the objective, students should have some time to reach the following stage.

As the creative process moves forward, a third step may be called “Eureka!” This is the moment in which sudden understanding coming from the unconscious wells up and the student is capable of presenting one or more innovative solutions to the problem. At this stage, ideally with a group and with significant direction by the professor, proposed solutions must be analyzed rigorously and the practical, ethical, economic, social, and environmental impacts of the “Eureka” idea should be carefully evaluated. Only solutions with comprehensive merits should be accepted for the following stage.

Finally, creativity culminates in “design.” The idea is now going from the problem – the identified need – to the object that the engineer, or engineering team, will duly work to create. The whole creative education process should be necessarily recursive and iterative. At any of these stages, I let students know that they should be able to return to earlier steps to gather more information, review ideas, and generate new solutions. My hope is that the students have become more creative, but also understand and respect the creative process as one requiring patience, discipline, and hard work.

Communication: Without the capacity to effectively communicate, the possibility of success in the professional exercise of engineering is extremely limited. Some engineering programs have tried to provide engineers with the capacity to effectively communicate, including grammar and language courses in the curricula. But, in my opinion, that is not the best way. Although it is not a bad idea to take those courses, the more effective way to bring practical communication skills to engineers is to ensure that their engineering courses actually require, and repeat, communication practice.

Attempts at attaining this objective consist now in relating every fruit of the educational process – be it an exam, essay, monograph, report, or design – to oral and written presentations enriched through graphics and drawings. Grading these engineering presentations should necessarily include an expected rigor for a quality of communication such that, if the presentation is not satisfactory, a student might fail even if technical engineering skills are perfectly developed.

Understandably, this new methodology in emphasizing communication skills must be supported by up-to-date word processing and graphics programs, access to libraries, and other investments in student success throughout the engineering program.

Life-Long Learning: The 21st century engineer is now faced with constant technological change and – if the individual does not want to become obsolete, she/he must learn to be a life-long learner, staying abreast of current engineering thought, practice, and innovation. Students essentially need to spend part of their undergraduate training “learning to learn,” realizing that this is a long-life skill that will serve them in their profession. Life-long learning may be achieved during the education process through the following minimum actions:

1. Emphasizing contextualized engineering ideas rather than techniques, codes, or formulas;
2. Removing purely technical courses from the curriculum;
3. Integrating different engineering areas – mechanical, civil and environmental, electrical, and chemical – in comprehensive student projects;
4. Keeping a complete and updated media access – via newspapers, magazines, and/or internet access – for students to read about current events and issues in society;
5. Encouraging students to attend engineering lectures and colloquia as often as possible.

Beyond the Students – Holistic Engineering Professors

Finally, whenever we as individuals want to learn something new, be it a scholarly subject or doing home repairs, we often take a course or read a book. Common sense leads us to recognize that to do something, and especially to do it well, we must take time to learn the subject in depth. Yet, despite this common sense understanding of how we master new ideas, engineering professors around the world rarely take the time to become well-trained in one of the most important practices of their career: teaching engineering principles to students.

The need to better educate engineering professors about teaching methodologies and proven practice is not only critical to this critically needed, holistic transformation of our engineering education, but far too long overdue. In 1955, The Grinter Report published by the American Society for Engineering Education (ASEE) Committee on Evaluation of Engineering Education wrote, “It is essential that those selected to teach engineering courses should be appropriately trained so they can adequately comply with that function.”

Another ASEE report, this one published in 1998, points out that only 12 universities in the United States – and not the most well-known of them –offer formal engineering pedagogy courses to graduates interested in becoming faculty members who, of course, have as their vocation the responsibility to teach the next generation of engineers. The report also quotes Deans engineering schools, many of whom note that students’ complaints about their professors’ teaching skills were “true horror stories” in incompetence. Sadly, the situation at Latin American universities is undoubtedly much worse than even these US stories indicate.

What must we do globally – and especially to transform the future of engineering education in Latin American – is to not only adopt the more holistic approach to undergraduate education, but also to ensure our engineering students receive the best education in the world from trained teaching professionals. We must no longer tolerate bad teaching. If there is evidence for poor teaching quality from an engineering professor, that faculty member should no longer be approved for tenure or promotion, but must be required to show improvement or be removed from his or her position.

Second, we must reward excellence when we find it. There are engineering professors who are truly gifted in their teaching and sought after by students for their intellect, their passion for teaching, and their innovative approaches to engaging student interest, challenging students to excel, and nurturing student careers. We must invest in these faculty members with both visible and tangible rewards, including public acknowledgment of the professors' education achievements and salary improvement tied to their teaching excellence.

And lastly, we must invest in the future training of engineering educators. Universities must establish and encourage pedagogy courses for both engineering students and engineering faculty who wish to focus their careers in education and successful transfer of knowledge for the future of the engineering profession. To do less undermines the critical transformation toward more holistic engineering education we can, and must, begin in Latin America as soon as possible.

Chapter 10
On the Cultivation of Innovative Engineering Talent

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A country working toward industrialization and leadership in the 21st century must cultivate and train the highest quality, innovative engineering talent in its population. In China, this investment is critical to ensure the best engineers help speed the pace of economic transformation and enable us to weather the uncertainties of the global economy. With numerous studies showing that innovative engineering talent is a key to economic success, the challenge for China – and for countries around the world – is in how we improve cultivation of engineering talent specifically trained for 21st century, complex problem solving. This must be done both through updating engineering education to become more broad-based and design-focused, as well as refining our ability to find, and train, the best and brightest as future engineering leaders.

This chapter addresses these challenges in China by beginning with an initial overview of the fundamental characteristics of engineering knowledge, abilities, and qualities required in the next generation of Chinese engineering talent. It then discusses best current practices in Chinese education to cultivate highest quality, innovative engineering talent who will best serve a 21st century Chinese society and economy. Finally, a new and strategic set of requirements for Chinese engineering education is proposed as "best practices." These include special undergraduate programs with an emphasis on improving design education and the combining of design, creativity, and industry partnerships with university-based research and development programs. Many of these have already been launched at Zhejiang University, with great success for the future of cultivating the best and most innovative engineering talent for China's future.

Fundamental Characteristics of 21st Century Engineering

In order to cultivate and train the highest quality innovative engineering talent of China, it is necessary to first grasp the fundamental characteristics of the engineering

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practice. While many have deemed engineering simply the application of scientific theories, or "applied science," this perspective is far too narrow, and misleading, to truly attract and recruit a next generation of engineering talent.

The true core of engineering is not simply an applied science, but the application of design and creativity to science, which is very different from the "yes and no" or "true and false" judgments of science. Engineers are also distinctively different from applied science practitioners given the requirement of an engineer, by definition, to create wealth and prosperity for the benefit of his or her society, all while working to ensure harmony between public interest and the natural world.

In the 21st century, the core of engineering has been further updated, with far more emphasis on the metasynthesis of multiple scientific and societal inputs than may have occurred in more technologically focused engineering programs of the past. As such, a critical task for developing countries who wish to cultivate the best 21st century engineers is in working to train professionals who understand technical engineering as well as economics, environmental science, and business methods. The challenge is in creating engineering managers who can ensure projects are of highest technical quality, but that outcomes are also in harmony with the community- and environmentally-based needs of the larger society.

Two additional, and distinctive, fundamental characteristics of 21st century engineering are in the profession's increasing reliance upon team work – what could be called a "unity of effort" – and on the recognition that teams will need to work, create, and adapt together over long periods of time for true research and development success. Global and complex engineering projects, by definition, now require engineering teams that have a broad scope, with strong technical skills as well as the ability to be creative and adaptive to new knowledge. It is rare for individuals today, be they in engineering or any other field, to alone make influential innovation achievements in specialized fields. The ability to be part of the new "unity of effort" and manage work in complex teams is an indispensable qualification of the 21st century, holistic engineer. They will need to be able to work together for many years, in some cases, to find success. For example, upgrades to the field of information technology (IT) may require over 10 years of R&D, moving through multiple levels of review – from engineering technicians to engineering managers – before the project is deemed economically viable.

Engineers and Innovation

The 21st century, highest quality engineer will also be an individual who drives and advances rapid innovation for the benefit of his or her society. Yet "innovation" is not a spark of genius or a one-time event. That is "invention." Innovation, instead, is a systematic procedure from the time a creative idea is born throughout its development and – if successful – its commercialization. For engineers to compete not only as 21st century professionals, but also to create wealth and prosperity through innovation, they need practical, as well as personal, abilities.

For example, 21st century engineering innovation needs – at its core – an innovative personality. This is the inner driving force – similar to a pioneering spirit– that pushes an individual into trying new ideas. This "tinkering" and creativity is a crucial trait of the best engineers. The individual must also possess an ability for strategic vision, management, and decision-making in order to take a lead in innovation activity that creates the highest quality, most efficient result. To this end, the best engineers of our future will be those individuals who have the skill to see, and analyze, the overall engineering process – from early R&D to commercialization – and strategically think about cost savings, benefits, and market potential throughout a project – or multiple projects – before making final decisions.

A 21st century engineer must also have market awareness and creative thought. In the past, we largely believed that engineering innovation solely originated from strong skills in science and technology. Today, however, we know that an understanding of market forces and a creative ability to think outside the usual, linear paths of science and engineering is just as critical, if not more so, to innovation success. The evolution might be summarized by the phrase, "Necessity is the mother of technology innovation." Objectively speaking, engineering innovation is driven by an awareness of social needs. Therefore, training our future engineers for market awareness and constant creativity is key to their design of useful, successful products and systems that meet the dynamic demands of our global economy.

Achieving Balance

Sir Francis Bacon said, "Knowledge is power." In the past, the power of knowledge in the engineering field might have been assumed predominantly one gained by the accumulation of fundamental skills and awareness of science and technology. Yet, for the 21st century engineer, the most powerful knowledge is achieved only through a new and dynamic balance of skills and awareness across disciplines, e.g., technical and scientific knowledge coupled with humanistic, social science, and experimental knowledge as well as collaborative and innovation knowledge. All forms of knowledge – the technical and non-technical – are now critical to a 21st century engineer's power and success.

Ultimately, achieving this new balance will be how engineers transform the physical world of our global knowledge economy. They will be the skilled practitioners of science and technology who, as past engineers have done, ultimately take their skills outside of the labs and classrooms and truly engage with the complex issues affecting people, communities, societies, and economies. Achieving a new balance of technical and non-technical skills in the flat and connected 21st century global economy will be critical for those professionals to be effective and thrive.

The Importance of Design

Perhaps more important than all of the other characteristics of high quality, innovative engineering talent that have been described here, it is the ability for a student to design and create that will become a watershed skill differentiating 21st century, innovative engineering talents from applied scientists and engineers of the past. To be blunt, if a country wants to advance, and even surpass its international competitors in industry, it must invest heavily in cultivating engineering design skills, particularly those that allow innovation and creativity to flourish.

Design is the key fundamental for new engineering standards and curriculum. It is the key investment in the “soft,” non-technical skills for engineers that bring understanding elegance, symbolic meaning and human-centric, or empathetic, awareness, as well as value, to modern engineering projects. Where once our society adapted to successfully engineered technologies, now technologies – and engineering overall – must adapt to our society. This can only be done if engineers understand how to design for society’s interests and, of course, its benefit.

An important connection for 21st century engineering education based on design will be the integration of design into iterative programs in research and development (R&D). As Herbert Alexander Simon said, natural phenomena have the appearance of “inevitability” as a result of following the adaptation to millions of years of laws of nature that have created them. Artificial (engineered) phenomena, however, often have the appearance of “contingency” due to their inability, over days or years, to self-adapt to the surrounding environment or evolve anew autonomously. The professional fields of the 21st century – engineering, medicine, commerce, and architecture – all must integrate aspects of adaptable and evolvable design into their R&D programs. We will need to look not just at what things are, but what they can be in the future and how engineered systems get them there. In short, it will be about design.

Ultimately, the emphasis on the importance of design in engineering education is not only about the practice, but also about cultivating the creativity and innovation potential in the best and brightest students that has already been shown key to engineering success in the 21st century. An emphasis on design education allows students to not only grasp design theories and methods, but inspires their creativity and ensures knowledge of the design process is part of their engineering consciousness. Furthermore, design, especially collaborative design, enables engineering educators to bring multiple disciplines and skills directly into hands-on student coursework, building core engineering proficiencies in problem identification, critical analysis, decision-making, and technical communication. Design education has both the function of professional engineering training and the value of general education. Only by putting design at the core of engineering education can students truly integrate their knowledge across disciplines and put it into practice.

Existing Challenges in Engineering Education

The challenges of engineering education – both in the recruitment and cultivation of top talent as well as in transforming engineering curriculum to better develop the holistic, 21st century engineering professional – are global. Taking China as an example: China has approximately 35 million people trained in science and technology, with highly skilled, technically trained engineers accounting for almost one-third of that total, or over 10 million people. China is, therefore, first in the world in its population of highly skilled engineers. Combined with the rapid increase in China's industrial production in recent years, there has also been a continuous – and increasing – cultivation of engineers, scientists and technicians needed for rising industry specialties.

The Challenge of Implementing a Comprehensive Curriculum

Despite this vast number of skilled engineers in its population, however, China's approach to engineering education shares the challenge of a "legacy" curriculum that does not sufficiently train engineers to adapt to the needs of 21st century – its complexity, societal needs, and increasing environmental awareness. Therefore, while the quality and level of technical engineering skill in Chinese engineers is high, our overall 21st century engineering education falls short of the more "holistic" – or comprehensive – competitive skills needed for the modern industry and the global economy.

Simply put, there is not enough comprehensiveness or interdisciplinarity, nor the necessary emphasis on innovation and design, in China's current engineering education model. In some universities, the proportion of laboratory courses has lowered and students have fewer hours to conduct hands-on experimental activities by themselves. Where there are independent design experiments – which are not new and have been advocated for many years – the courses are becoming more and more difficult to implement given faculty resistance or non-interest. Overall, students are "visiting" projects more and implementing them less, with hands-on experience and interaction with modern engineering practice waning while idle theorizing and a reliance on book learning increase in the classroom.

Sadly, it is likely the incentives we have given to faculty to ensure scientific research is their most important effort that has led to this state. Teachers attach excessive importance to their students written theses rather than practical projects and, at the most, support only those engineering projects established, pre-formed, from the government rather than a more diverse and dynamic set of ideas from international industry. This is because engineering – as a practice – is unfortunately often neither conducive to publications in high-level, theoretically focused scientific research journals to which faculty aspire. Nor is the practice designed for multiple publications for a faculty member given the length of time from concept to result. As a result, more and more university faculty have little incentive to invest in engineering design and practice themselves, but – for their careers – pursue more theoretical studies.

The Challenge of Promoting Innovation

In addition to the challenges listed above, identifying, cultivating, and rewarding and the high-quality engineering student's innovative spirit is a significant challenge for

Chinese engineering education, and likely globally as well. The challenge is made even more difficult given that overall engineering education is still not clear as to whether it is creating practicing engineers, or pre-professional engineering talent, at the end of their coursework in a university. With the pursuit of research funding and prestige as a most important investment by higher education professionals (faculty), the engineering practice is often avoided or dismissed, as discussed above. Thus, in universities, specific knowledge education is strong while "capacity" education – how to be innovative, learning how to learn, and/or connecting ideas across disciplines – is weak: universities have well-established, traditional, and specific infrastructures and programs for teaching specialized knowledge in specific disciplines, but they are far less adept at teaching students how to acquire and use abstract, cross-disciplinary information and to invest in design and creativity in their engineering program – all of which are the foundations of innovation.

The Challenge of Early Overspecialization

In the past, China has been known to cultivate standard engineering talents with very specialized education. While this has created excellent specialists, the talent cultivated through this method has a relatively low degree of adaptability to dynamic changes in global markets or technologies. Many trained this way are also exceedingly challenged by innovation, which is a process rarely happening in a siloed/specialized field, but is instead most often found at the intersection of multiple fields. The opportunity for a student to experience the creativity found at the intersection of fields needs to be further emphasized in Chinese engineering education so that the most talented students for the 21st century will no longer be specialized, but have an ability to innovate throughout their professional lives.

The Challenge of Creating Successful University–Industry–Government Partnerships

Finally, the successful cooperation among university engineering programs, industry, and government is another challenge in which Chinese engineering education has not yet fully realized its potential. These partnerships, which advance students understanding of markets, social needs, and environmental issues while exposing them to industrial practices and providing hands-on design experience, are invaluable. This kind of cooperation is also invaluable to faculty as well, helping them to understand the needs of engineers outside the classroom. The challenge of these partnerships is in the administration of internships, the discontinuity between course progressions and students' needs to be off-campus, and many others that institutions of higher learning must face.

Opportunities

In addition to addressing the challenges listed above, China has two additional opportunities in engineering education to advance the recruitment and cultivation of highest quality talent. First, China has long known that developing talent to be world-class competitors does not begin with training in higher education, but is a systematic investment throughout a student's education process. In engineering education, therefore, a key challenge in developing the best 21st century engineers and national engineering resource will be to begin planning engineering education linkages from primary school through secondary school, then from college to employment, in a systematic way that furthers the 21st century engineering paradigm.

Furthermore, China's development of a "Registered Engineer System" throughout the country will soon set fundamental norms and quality standards for the entirety of the engineering students. This registered engineer system is being developed not only for China, but also to conform to international standards.

Best Practices to Train and Cultivate Engineering Talent in China

For the past 20 years, Zhejiang University in China has been developing coursework and programs to prepare for a paradigm shift in engineering education for the 21st century that is now emerging in China's higher education infrastructure and being advocated globally. The acceleration of globalization and ascent of the global Information Age, with rapid technological change becoming the norm has made international competition for talent increasingly fierce. At the same time, the rapid development of social networks and influence on technology have given rise to increasingly complex challenges, where solutions are not solely technological in scope, but where the non-technical "soft" skills, as well as an innovative spirit are increasingly critical for global success. As such, the cultivation of this new workforce and professionals must be a primary task of research-oriented universities. By taking full advantage of its comprehensive disciplines and strong integrative strength, Zhejiang University has developed unique "best practices" models for cultivating composite and innovative talents after longtime exploration.

"Mixed Class" Program

The first of these "best practices" is Zhejiang University's "Mixed Class" program. Initially developed and launched as an experiment in educational reform in the fall of 1984 and, today, cultivates the very best engineering talent for China. It does this by taking the top 5% of engineering students in each new class and mixing them with peers from different disciplines, allowing cross-disciplinary discussions and ideas to emerge. Coursework is focused on strengthening the students' ability and capacity in the fundamentals of science and engineering rather than any specific discipline. By exploiting the potential of excellent students and promoting the development of their personal skills (teamwork, communications, and other "soft" skills) in the "Mixed Class" setting, the class allows students to meet the changing requirements of 21st century engineering.

Zhukezhen Honors College

The Zhukezhen Honors College at Zhejiang University followed, being established in 2000 to further promote the model of "Mixed Class" among outstanding students across all disciplines: the arts, science, and engineering. Through this new infrastructure, Zhukezhen Honors College has been able to cultivate a decidedly different generation of students with new perspective and skills. Admission to the College is selective, with a shared curriculum of foundational courses for the first year and a half in all three categories. After the first year and a half, students may choose a major in accordance with their interests and carry out individualized study with their tutors. This model fully reflects the organic integration of education based on learning fundamentals in specific disciplines and allowing both individual study and collaboration. After our 20-year exploration and investment in these new programs, the leadership of Zhejiang University are proud to say that both the "Mixed Class" experiment and investment in the Zhukezhen Honors College model has become a core platform for cultivating the best and brightest, most innovative, student talent for China's future.

"Advanced Class of Engineering Education"

Zhejiang University has another key program we consider to be a "best practice" for the future of engineering education. Called the "Advanced Class of Engineering Education," the class was launched in 1994 in order to specifically cultivate students' aptitudes and interests in engineering design. With a core mission of being "foundation oriented, design oriented, and creation oriented," the class chooses 60 or more first-year undergraduates in science and engineering and puts them into separate classes that emphasizes a discipline in coordination with opportunities in engineering practice.

"Intensive Training Program on Innovation and Entrepreneurship"

Another "best practice" course created to develop more cross-disciplinary education experiences and further build students' aptitude for innovation and creativity –

specifically focused on developing future management professionals – is the "Intensive Training Program on Innovation and Entrepreneurship" course first launched in 1999. For this course, the university chooses approximately 60 students from second-year courses in science, engineering, agriculture, and medicine, focusing their studies on the modern entrepreneurial mentality, as well as operational organization and management, with innovative teaching methods being encouraged and fostered. For engineering students, this includes having faculty work to integrate coursework and hands-on, experiential learning as well as a focus on case studies in engineering and entrepreneurial management.

Long Schooling and Flexible Schooling

At Zhukezhen Honors College, there are two tracks, with education classified into both "general" and "special" disciplinary education programs. The "special" track can be further classified into two tracks that we call "long" schooling and "flexible" schooling, which go beyond the preliminary education of the students' disciplinary choosing.

In this model, "long" schooling is offered specifically to the best student so that they may keep up with dynamic transformations in international markets for services and professionals. In this case, an outstanding student who receives a preliminary education in Zhukezhen Honors College may choose "long" schooling in order to continue their education into a graduate degree, specifically the doctorate. Zhejiang University began this "long" schooling program in 2005 with medical students (known as the Badenian Medical Class) and is now working to implement the program in such disciplines as law, pedagogy, and management study.

On the other track, and aiming to cultivate more interdisciplinary and comprehensive abilities in exceptional students, the "flexible" option provides an "X + Y," or dual-discipline/dual-degree education option. In this case, the student chooses a discipline (X) for their graduate program, and is then provided with options for coursework at the university in specialties as computer, information, foreign language, management law, and business and economics (Y). In contrast to the more linear track of "long" schooling, this "flexible" track is specifically designed to cultivate 21st century, more holistic professionals who can best adapt to the needs of global society and economies. To ensure its success, Zhejiang University has given strong support to faculties and departments choosing to implement the "flexible" option and also recommends its most outstanding students for this track.

At its most simplistic, this new model for engineering education at Zhejiang University is "broad, specialized, interdisciplinary," which means that broad fundamentals are the focus of the first year of undergraduate education, with more specialized coursework in the second and third years, and then a capstone fourth year filled with interdisciplinary ideas and experiences. The model should followed by the best research-focused universities, liberating them from traditional, "legacy," education models that being technical expertise, but also cultivate an innovative and creative spirit in our best students. As mentioned earlier, this concept does not have to start at the undergraduate level, but could be further integrated into elementary education, allowing students in primary and secondary schools to be exposed to science, engineering, design philosophies, and cultural influences long before they reach college.

Four-Term Academic Years

In order to promote independent and research-oriented studies, further accelerate the pace of study, and optimize the curriculum structure, Zhejiang University has also implemented a four-term system for the academic year, with 10 weeks in each term. This system has, we believe, enhanced students' attentiveness to their studies and accelerates the entire pace, which has been highly praised by the students themselves. The system has also further optimized the distribution of class hours and increased the quantitative economical efficiency of courses, which attracts outstanding faculty. In this way, the four-term academic year has both serves and cultivates student excellence while also promoting Zhejiang University's investments in faculty excellence.

Continuing Education Leadership

Another critical aspect of 21st century engineering education – and cultivating the very best in our engineering talent, is that a student's education cannot end at either the undergraduate or graduate level, but it must continue throughout his or her professional career. This continuing education, and the creation of "life-long learners," is extremely important. Globally, the shelf-life of knowledge continues to become shorter and shorter as a result of the rapid development of engineering technologies and systems and "one time" education is no longer suitable for modern engineering professional. To ensure we are educating the most talented, effective, and successful engineers, we must ensure that we provide continuing education to them throughout their careers, and we also instill in them a thirst for knowledge and an ability to learn quickly and adapt that will serve them far beyond their university years.

One program in Zhejiang University has developed to continually meet professional development needs of the engineers is the Masters of Engineering or "MEng" that focuses not only on science and engineering technology skills, but also business, economics, and management. This professional degree serves multiple strategies, including helping build China's science and technology workforce, promoting the integration of science, technology, education, and economics knowledge, providing high-level management skills training for engineering talent – especially those in domestic industrial, mining, and construction enterprises (especially in medium- to large-scale state-owned enterprises) – therefore enhancing the overall market competitiveness of China's engineering industry.

Zhejiang University has taken a lead in the establishment of MEng degrees for many engineering markets, as well as for software engineering, and believes this professional development platform is one that will truly cultivate the best talents in engineering who – with training in entrepreneurship and business practices – can rise to the top of their profession as innovators and leaders.

International Experience

In order to enhance the international competitiveness of China's engineering talent, it is necessary to keep up with educational concepts in engineering around the world. In addition, as internationalization is likely the inevitable trend of higher education as well as engineering projects, Zhejiang University has recognized that engineering education training must include student opportunities to gain international insight and awareness. This is being starting to be done by taking full advantage of the university's international educational and academic network, and Zhejiang will continue to expand its investments in international exchanges, providing the most favorable conditions for students to gain much-needed international experience and exposure to multiple cultures throughout the global network of engineering educators and practitioners.

Real-World Project Experience and Co-operatives

Zhejiang University's reform of engineering education includes reinforcing the connection between engineering schools and colleges with surrounding communities as well as business enterprise with cooperative agreements. The investment in cooperative relationships, especially around research, between universities and industry allow students to receive first-hand experience in engineering practice while – in turn – industry interests receive new access to university-based technical guidance and research that may be beneficial to their markets. It is through this experience that our students will, undoubtedly, gain an understanding of their own capabilities in working with complex enterprises and utilize skills beyond their technological training.

Of perhaps greatest value is the opportunity for our most talented engineering students to use these cooperative agreements to gain real-world experience with some of the most massive engineering projects in China today. China's world-class, state-run projects, such as the Three Gorges Dam, offer ideal experiential learning for our most talented engineering students. Having their education coordinate with these projects – which are incredibly complex and high profile – give engineering students a chance to work with businesses, government ministries, commissions, and multiple districts throughout China while using their engineering skills.

Zhejiang University has put forward the ideology of "high-level and intense radiation" to carry out cooperative projects, working in concert – and strategically – with all of the stakeholders in government, industry, and other academic partners. In this way, Zhejiang University and its best students have helped China launch key state-level engineering projects and programs for public welfare. In return, the coordination with these "real-world" projects also keeps our engineering faculty engaged in cutting-edge engineering practice and helps both faculty and students develop skills that will be critical to engineering innovation.

Conclusion

All of these "best practices" include more holistic models for engineering education reform at Zhejiang University – integrating an emphasis on design, multidisciplinary collaboration, entrepreneurship, partnerships with industry and government, specialized educational tracks, outreach to primary and secondary school education programs, international experience, and creating innovation incentives for R&D directly into the engineering coursework – are very different from the "legacy" models of the past. In the past, we taught core disciplines with electives, or simply had students earn dual degrees. For our students to be successful in the complex, global economy, it will be these new, best practices models of engineering education – many of them already in place at Zhejiang University – embedding 21st century skills directly into the core courses that have greatest value. Adding to those programs with Zhejiang University investments in the MEng program and collaborative, industry–government partnerships, we are also investing in "life-long learning" opportunities for China's most talented engineers throughout their profession. The development of these programs positions Zhejiang University not only as a university sought out by top engineering students and professionals, but also ensures Zhejiang graduates are also extremely competitive and highly valued by potential employers and markets.

Chapter 11
International Education and Holistic Thinking for Engineers

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The dramatic rise in popularity of study abroad programs in the past 30 years has not seen participation by students majoring in engineering and science in US colleges and universities at rates anywhere near the national averages. Despite the increasing awareness of the importance of a global perspective in the increasingly interconnected, flat, hot, and crowded world (Friedman, 2005, 2008), these students have been constrained from participation by the academic requirements of their majors and the demands of their laboratories.

Yet the concern for holistic education for engineering and science students implies, due to the interconnectedness of today's world and the important roles played by engineering and science in international commerce, that engineering students really must have a sensibility about the world beyond their campuses and their nation for them to realize the full potential of their abilities, both in their careers and in their personal lives.

Numerous studies have documented the rise of engineering education around the world, especially in India and China, and the degree to which the United States has fallen dramatically behind other nations in the production of engineering graduates. It remains to be seen what impact this disparity will have on American economic competitiveness, but it is clear that the better informed our engineering and science graduates are about best practices around the world and the ways of transnational collaboration, the better positioned they will be to make full use of the opportunities abundantly available in a global innovation economy. Innovation remains the most hopeful route to economic prosperity and world stability (Carlson and Wilmot, 2006), a message that is increasingly understood around the world.

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Some Important Models

The early forms of study abroad grew out of relationships between particular institutions, where "exchange students" had experiences limited primarily to those of students at the institutions they were visiting. Often these grew into "direct enrollment" programs, where the focus was less on a balanced exchange of students between institutions and cultures than on the opportunity for US colleges and universities to place students at institutions abroad.

Limited though these experiences were, they were important in providing the opportunity for exchange students to experience a different place and point of view in the world, including the views of their homelands as expressed primarily by students and faculty at the host institutions and in the local media. It is not surprising that the most popular programs for US students arose in the English-speaking world, especially in Britain, with Australia gaining in popularity in more recent years.

Large numbers of American engineering students have not participated in study abroad programs: participation comprises less than 3% of all US study abroad students (Boston University website). The major obstacle to greater participation has been the demanding, complex nature of engineering curricula, in which absence from the campus or enrollment in courses not well aligned with the home institution's curriculum can impede progress toward the degree. Some institutions have addressed this problem by identifying courses at host institutions abroad that constitute suitable equivalents to courses that students might have otherwise taken at their home institution. One example is Boston University, which has arranged for direct enrollment in technical and engineering courses at the University of Sydney, Dublin City University, Tel Aviv University, and the Technische Universitat Dresden, among others. Engineering students typically attend these programs in their sophomore or junior years, taking three engineering/science courses and one elective course. Academic experiences are typically complemented by field trips to research institutions, corporations, and technical museums. On successful completion of the semester abroad, students receive full credit toward their degrees (Tufts University website).

A different type of experience is offered by Tufts University, where engineering and science students may enroll for an entire academic year at University College London. This program provides a relatively authentic experience of enrollment "in college" at a British institution, including the challenge of year-end examinations covering the entire corpus of work.

Study abroad programs have evolved into many different variations. Vaz (2008) notes an extensive study by Alan Parkinson (2007) providing a taxonomy of engineering study abroad programs, and comments extensively on the scalability of various models. Of particular interest in that discussion, as it is here, are the less traditional, project-based programs which provide a different approach to holistic education for engineering students.

The WPI Model

My own institution, Worcester Polytechnic Institute (WPI), takes a highly non-traditional approach to international education. It is, however, an approach that is very well aligned with the goals of holistic engineering education as articulated by Grasso and Martinelli (2007). This program, called the Global Perspective Program, is offered in the context of the WPI Plan, the basic elements of which need to be understood before considering the nature and benefits of this program.

Nearly 40 years ago the WPI faculty designed and implemented a radical transformation of engineering education that focused on outputs (competencies) rather than inputs (courses). Emphasis was shifted from passing courses via success on conventional measurements to competencies as demonstrated in the successful completion of three major “qualifying projects” and a final, oral “competency exam.” This high-stakes examination required students to demonstrate both mastery of the core disciplines and an ability to think creatively across them. For the qualifying projects, students were encouraged to collaborate in project teams and to develop good communication skills by which the results of the project efforts were conveyed both orally and in writing. Lectures and tutorials took the form of resources in the learning process rather than courses to be passed.

The three major qualifying projects best reflected the new educational philosophy. The “sufficiency project” demonstrated a student’s familiarity with several related areas within the arts and humanities and the successful development of an integrating theme as expressed in a major paper, performance, or creative output. This early appreciation for the importance of “right brain” development in the education of engineers and scientists reflected the notion of the “technological humanist,” and resulted in a rich production of remarkably creative works.

The second project, called the “interactive qualifying project” (IQP), involved teams of 3–4 students applying technology to an interdisciplinary problem in society, usually addressing a significant human need. This project best reflected the Institute’s motto, *Lehr und Kunst* (theory and practice).

The final project, typically completed in the senior year, was the “major qualifying project” (MQP). As the name suggested, this project was a significant research or design project in the major field of study, and was often undertaken in the facilities of an industrial sponsor.

Along with radically restructuring the curriculum, the faculty eliminated failing grades, awarding each project either an acceptance or an invitation to try again. Finally, the academic calendar was reorganized to provide four “terms” of seven weeks each, so that students could focus more intensely on fewer objectives in any single term and, in particular, so that they could devote fulltime effort to one of the major projects during each of several terms.

The result of all of these changes was a learning environment that emphasized cooperation among students rather than competition; their ability to work collaboratively in teams, to deal with ambiguity, and to integrate knowledge across disciplines; and the application of knowledge to productive ends. Of necessity, this environment required a more active approach to mastering the "core knowledge" needed in the analysis and solution of problems, as well the development of strong interpersonal, writing, and presentation skills to facilitate good collaboration, and the effective communication of what had been learned and accomplished in the projects.

During the nearly four decades that have elapsed since the WPI Plan was created it has, not surprisingly, been modified and improved in light of the experience with it. Formal coursework has returned closer to center stage, especially in the first year; the grading system has been expanded to comprise A, B, and C grades, and the NR (no record); and the "sufficiency projects," originally individual efforts requiring one-on-one advising by faculty, have morphed into "inquiry seminars and practica." Nonetheless, the fundamental philosophy of the WPI Plan has remained firmly intact: students are given great latitude and responsibility for shaping their programs; cooperation prevails over competition; and the projects, the IQP and MQP, remain the focal points of the upper class experience.

It is remarkable how well aligned the 1970 conception of the WPI Plan anticipated the vision embodied in ABET's Curriculum 2000 and, more recently, the NAE's vision for the engineer of 2020 (The Engineer of 2020), placing "people skills" on par with technical skills and core scientific knowledge. This common vision is articulated explicitly in WPI's current educational philosophy:

> The goals of the undergraduate program are to lead students to develop an excellent grasp of fundamental concepts in their principal areas of study; to lay a foundation for lifelong renewal of knowledge; to gain a mature understanding of themselves; and, most importantly, to form a deep appreciation of the interrelationships among basic knowledge, technological advance, and human need (WPI Undergraduate Catalogue).

The Global Perspective Program

The structure and philosophy of the WPI Plan and the WPI faculty's strong commitment to such enlightened and broad learning goals provided an ideal setting for the development of a highly innovative and powerful type of international experience. Developed and expanded during the past 20 years, this popular and important component of the undergraduate program is referred to as the *Global Perspective Program*. It is particularly relevant to the notion of holistic engineering education as a kind of *purposeful* learning experience that involves virtually all of what are now being called 21st century skills, from global and intercultural awareness, to interdisciplinary and collaborative learning, to teaming and innovating, to communicating by a variety of means, and to making the world a better place for humankind.

The simplest description of the Global Perspective Program is that it enables students to complete one or more of their required projects (most often the IQP, due to its social nature) at one or more of WPI's several dozen project centers spread literally around the world. It consists of on-location project work, typically involving a high degree of interaction with the local people and culture, aimed at accomplishing something of value for the sponsoring agency and/or host community.

The goals of the Global Perspective Program are strongly aligned with the goals of the undergraduate program:

> The Global Perspective Program aims to instill in WPI students *and faculty* an appreciation of difference and an ability to interact effectively with other peoples and cultures; the ability to apply their skills and knowledge across disciplinary, geographic, and political boundaries; and an understanding of themselves and what roles they might play, professionally and personally, in an increasingly interconnected world (Vaz, 2008).

The Global Perspective Program operates project centers in a wide variety of locations: Bangkok, Budapest, Cape Town, Copenhagen, Hong Kong, Ifrane (Morocco), Kyoto, Limerick, London, Melbourne, Nancy (France), San Jose (Costa Rica), San Juan (Puerto Rico), Venice, Windhoek (Namibia), and Wuhan (China), as well as at several locations in the United States (Silicon Valley, New York, Boston, Nantucket, Worcester). Project centers are essentially virtual, operating for one or two terms during the academic year and occasionally for a summer term. Each project center has a faculty *director*, who, with the Program's Dean, shares the responsibility to recruit faculty advisors, select students, arrange projects, and ensure the necessary logistics (housing, food, transportation, etc.). Many of the project centers have developed out of existing relationships of faculty directors, although the Dean and the staff of the Interdisciplinary and Global Studies Division (the administrative division that oversees the Global Perspective Program) are constantly looking for new project center sites and themes.

Some students complete their humanities and arts requirement at a project center, most frequently in the sophomore year and often in London in association with its Dickens Museum. The majority of participants, however, are completing their Interactive Qualifying Project, or IQP, in their junior year, while a smaller number (including some who have already been to project centers completing their earlier projects) complete their Major Qualifying Project (MQP) at a project center as seniors. All told, about half of all WPI undergraduates complete one or more of their required projects at the international project centers.

As you will see from the examples discussed in what follows, participation in the Global Perspective Program, especially when pursuing an IQP, is an ideal form of holistic education, both for engineering students and for those from other majors (mostly science, mathematics, computer science, and management). Students collaborate in small teams (2–4 students) to attack difficult but important problems. The work often requires problem clarification at the outset, and is frequently fraught with unscripted challenges. Students must understand and appreciate the problem's cultural context and social dynamics. Resources are often scarce, timelines are necessarily short and rigid, and significant parts of the knowledge required to solve the problem must be gained in the field or in the brief period of preparation prior to departure. In short, these are intense experiences in the purposeful application of students' abilities and knowledge in highly interdisciplinary, intercultural, and demanding situations with important goals.

For the IQPs done abroad, faculty project center directors work with local associates and sponsoring organizations (usually governmental or non-governmental agencies) to develop prospective projects, often comprising parts of larger, ongoing initiatives at the project site. Faculty advisors, usually working in pairs, typically support approximately six project teams of four students each. Before departing for the 7-week term abroad, project teams work with faculty advisors throughout the preceding term on project formulation, relevant research, implementation strategies, language and cultural concerns, and overall expectations. Students begin developing the scope and outline of their project report before departure, keep extensive logs of their experiences while abroad, and submit comprehensive written reports on their work once back on campus. An annual competition, for the President's IQP Awards, features selection of finalists based on faculty review of written project reports, and oral presentations by the project teams before a panel of distinguished judges. Student pride in the quality of these projects is comparable to that of championship athletes or award winning artists or musicians.

Some Model Global Projects

Several particular projects are discussed below to give a fuller appreciation for the nature of these activities.

The e-nose: Three WPI undergraduates spent 10 weeks in Ireland completing their MQP working on a gaseous molecule detector, which they called the e-nose. Uses for this technology range from verifying the condition of fresh foods and flowers to sensing gas leaks to detecting explosives. The students' contribution was to design functional prototype circuitry for use at the interfaces of gas particle sensors with small computers. This project was sponsored by the University of Limerick and a private company. While in Limerick the students were hosted in a "home stay" and found time to explore much of the countryside as well as the city.

Water for Palm Trees: A team of four WPI undergraduates undertook an IQP for the New Life for Abused Children Project in Thailand, a non-profit organization that helps abused and homeless children by caring for them generally and teaching them employable skills. This project supported New Life's goal of teaching the children trades based on palm tree oil, from which they could make soaps, lamp oil, and other useful commodities. The particular problem for this team was to determine how a dry field, potentially the site of an orchard, could be made fertile by irrigation from a nearby water reservoir.

The project team surveyed the site, including measuring the depth of the reservoir and respective elevations; researched available technologies and design alternatives; analyzed water samples; and decided upon a potential design for a drip irrigation system for the prospective orchard. Once their design was completed they built a prototype to test its performance, and with verification in hand, wrote a detailed recommendation for how the system could be implemented together with its estimated cost. They then went the extra mile, out of a concern to maximize the possibility of a successful implementation, by also producing a system maintenance manual and promotional materials for the fundraising that would be necessary to pay for the system's installation and operation.

Living quarters at Bangkok's Chulalongkorn University provided an excellent environment for research and (limited) leisure, as well as the opportunity to interact with local students and faculty. Most rewarding, though, was the team's ability to accomplish something of great value in the effort to enable disadvantaged children to have hope for their future.

Better shelters in Namibia: Namibia, Africa, contains some of the most beautiful landscapes in the world as well as dramatic human poverty. WPI's project center, based at the Polytechnic Institute of Namibia, provides eye-opening, life-changing experiences for students wanting to make a difference in the world. One team, with sponsorship from the Renewable Energy and Energy Efficiency Bureau of Namibia, undertook what sounded like a fairly simple project: to design low-cost, energy-efficient improvements to the housing structures of shack dwellers in Goreangab, Namibia. The improvements were to be made from locally available materials with the goal of making the existing structures cooler in summer and warmer in winter.

On their arrival, students were astounded by the extreme poverty of the village: there was no running water, electricity, or means of transportation. Yet the people of the village had an indefatigable desire to survive and to better themselves, which was a powerful source of inspiration to the students. They quickly realized the need to establish trusting relationships with the shack dwellers, and to respect their humble quarters as sources of pride for the occupants. Time spent listening to the villagers and researching the available natural resources led to an innovative use of local plant material to insulate the shacks and make considerable improvements in the thermal performance of these shelters.

Washing stations in Cape Town: One of the most recently developed project centers is in Cape Town, South Africa. The project that won the 2009 President's IQP Award took place in Khayelitsha, an informal settlement on the outskirts of Cape Town, where the Shaster Foundation, the project's sponsor, had already constructed a set of community buildings to provide basic shelter, medical resources, and a community center.

The problem chosen by the WPI project team, after extensive correspondence with the Shaster Foundation regarding the needs of the people in the settlement, concerned the washing of clothes. The nearest source of water for the villagers was a stand pipe located a considerable distance from the village. To do their washing, the women first had to carry jugs full of water back to the village from the stand pipe. In addition to the extreme labor required, this practice resulted in waste wash water being poured onto the village grounds. The team's goal was to design a sustainable, sanitary, and environmentally sound solution to this "laundry problem."

After developing relationships with the villagers and exploring needs and options, the team decided upon the approach of collecting rainwater runoff from the roof of the community center building, storing it in tanks until needed for washing, and then directing it into washing tubs to be located adjacent to the community building. Going a step further, they imagined also that the wastewater from the washing activity could be used to supply an irrigation system to support a garden near the washing station. The students wanted the solution to be reliable and sustainable, so they restricted the design to simple mechanical and plumbing parts, which they determined to be available in Cape Town, without relying on either electrical pumps or a piped-in water supply.

The design called for the pitch of the existing gutters on the building to be reversed in order to bring the rainwater to the location of two large holding tanks, which were mounted on elevated platforms, one above the other. These tanks would provide both a gravity feed to the washing station below and storage capacity for excess rainwater. Village women were consulted in the design of the washing station to ensure that the washing tubs would be at a comfortable height and fully functional. An irrigation scheme was designed so that wastewater could be moved through inexpensive piping to the intended garden and appropriately dispersed. Materials were specified, along with availability and cost. Finally, the team specified, and educated the villagers on the use of, biodegradable laundry detergents to ensure the effectiveness of the irrigation and teach the concept of sustainability and environmental protection.

Although the project team's original goal was only to produce a design for the washing system, the students became so committed to the success of the concept and to the villagers themselves that they decided that they would attempt to construct the complete washing and irrigation systems before their brief, 7-week stay ended. That is just what they did, working nearly around the clock to construct the supporting structure for the holding tanks, the washing stations, and the irrigation system – including the trenching – and assembling all of the piping, plumbing, and mechanical controls. Along the way they became passionately committed to the villagers and to themselves as a team. In retrospect, one student wrote,

> Although I've had internships and completed various projects on campus, none of those experiences can compete with what I learned during my experience abroad. Not only did I learn about a different culture, I saw the true intersection of technology and society and realized the professional opportunities and social responsibilities that exist for engineers.

As well as any, this project captures the holistic nature of WPI's Global Perspective Program. On the one hand, the students had an intense experience with the synthesis of both learning and applying their knowledge. The written and oral reports from this project team made clear the prominent role of *engineering design* in their collaborations, from the avoidance of electrical power in the gravity-feed design of the rainwater collection, storage, and distribution system to the types of materials both available and sufficient for the necessary functionality and endurance. The theme of *sustainability* governed all aspects of the design and implementation. And the *understanding of the relevant social and cultural factors,* gained through many conversations with the shack dwellers and the trust established in their relationship with them, ensured the acceptance, use, and "ownership" of the washing station by the women of the village.

In a more macro sense this project fits into a broader notion of holistic education (and not just engineering education, as project teams typically comprise students from both engineering and non-engineering majors). The team prepared for the term abroad through extensive research on South Africa, local conditions, and particular needs of the villagers as conveyed by the sponsoring agency. The themes of social responsibility, service to mankind, applications of engineering design principles, and sustainability ran prominently throughout their preparations, as did an intense interest in learning as much as they could about the African continent and South Africa in particular. The higher order skills of written and oral communication, effective collaboration, problem definition and clarification, and critical thinking were in constant use.

In the end, the Shaster Foundation commended the project team not only for the excellence of the design and construction of the laundry and irrigation system, but also for the wonderful way the students had served as ambassadors for their institution and for their country. The Foundation assured the students that their work would serve as a model for other washing stations and similar improvements in other settlements in the region, thus noting an added dimension of the project's sustainability – its extension by example to others to come.

In addition to the projects described above, other recent WPI student projects have included:

- Work with the Catchment, Stormwater, and River Management Branch of the City of Cape Town to help mitigate flood risk in the informal settlements;
- Work in Windhoek, Namibia to develop innovative, sustainable HIV/AIDS prevention strategies;
- Work in Costa Rica with trout farmers and the national aquaculture association to improve the efficiency and yield of trout farming;
- Work in Copenhagen to analyze and recommend actions concerning the carbon footprint associated with food consumption;
- Work in Hong Kong to recommend certain improvements in the Victoria Harbour waterfront; and
- Work in Venice, extending a 20-year engagement centered on the canals system with respect to historic preservation, efficiency of operation, economic and cultural factors, and its support of commerce and tourism.

It would have been difficult to describe the above projects without using the term "work," for that is what is involved in each of these international projects. Students learn about the region they visit, and its people, by directly confronting a need, problem, or opportunity, and working with available resources and within the local constraints to, as they put it, "get the job done." It is difficult to imagine, I believe, a higher form of global "community service," or a more intense experience in collaborative applications of core knowledge across disciplines within a learning context of another culture and unfamiliar social conditions.

Requirements and Challenges for this Type of International Program

Like most institutions with extensive international program components, WPI maintains a separate division, called the Interdisciplinary and Global Studies Division (IGSD) which has administrative responsibility for the Global Perspective Program.

This includes the recruitment of center directors, faculty advisors to accompany and supervise project teams, facilitators at the project sites to assist with housing and other logistics, and project sponsors. The IGSD is headed by a dean, with the assistance of an associate dean and a professional staff. Risk management is a particularly important responsibility of the IGSD administrative team.

Other than the leadership of the IGSD, the most important requirement for the success of this program is a willing and supportive faculty. Serving as a co-advisor for a project site requires fulltime attendance at the site for the entire 7-week term, sharing supervisory and instructional responsibility with one other colleague typically for six teams of four students each. Not only does this require familiarity with six projects and almost constant interactions with the students, both individually and in groups, but the co-advisors must also handle all of the administrative issues for the group, including counseling, health, safety, and other concerns. Faculty who serve as center directors (as opposed to project co-advisors) do not have responsibility for particular project teams, nor are they required to be on site while project teams are active, but they bear the important responsibility of ensuring continuing good relations at the site and a steady flow of potential projects.

WPI is fortunate that approximately 20% of its fulltime faculty from across the institute, in addition to several faculty members appointed directly in the IGSD, participate regularly in project center advising.

In addition to having sufficient numbers of faculty available to serve as co-advisors at project centers, the two most prominent challenges are the additional costs to the students (airfare, local subsistence) and simply the unanticipated developments that invariably occur, usually at the worst possible times. Recently, for example, the program experienced record flooding in Venice, which displaced project teams from their living quarters; a political demonstration that closed the Bangkok international airport, where project teams were scheduled soon to arrive; and a fire that destroyed the community center in Cape Town where our project teams did much of their work – with all of these happening in the same week!

Conclusion

Study abroad programs contribute an important dimension to the concept of holistic education. The experience of dealing with seemingly ordinary functions, whether they be academic, work-related, or simply everyday life issues, in a foreign nation, especially outside the English-speaking world, greatly facilitates the understanding of the interconnectedness of the world and also the distinct cultures and social systems in which science, technology, commerce, and economic development proceed. The academic aspects of study abroad experiences are almost always more interdisciplinary and practical in nature, especially in programs involving internships, service learning, or other non-traditional forms of study abroad, because of the need to confront and deal with a foreign culture and different perspectives on the essential work of the program.

The Worcester Polytechnic Institute offers a distinctive type of international experience for undergraduates in that it is entirely project-based, requiring students to work in teams to solve significant problems at the project centers abroad. While it would be difficult for most other institutions to adopt directly, due to its dependence on the 7-week term calendar and the fact that the projects themselves are degree requirements (and thus the experiences do not need to be matched up to particular courses), this model presents a type of highly integrated learning experience, an example of holistic education, that contributes greatly to students' academic, personal, and professional development. We hope that it provides encouragement and insights from which other institutions might build programs well suited both to their own characteristics and to these important goals.

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Chapter 12
Engineering Value Propositions: Professional and Personal Needs

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Engineers Are Value Creators

Simply put, engineers create value. Engineers play a key role in transforming ideas and inventions into innovations that, by definition, create value for users. Engineering sits at the fertile intersection of science and business that drives high-tech economies. But why do businesses exist? According to Peter Drucker, "There is only one valid definition of business purpose: *to create a customer*." (Drucker, 2001) Therefore, engineers must always think about customers and creating value for them. As nicely articulated by Carlson and Wilmot (2006),"Innovation is the successful creation and delivery of a new or improved product or service in the marketplace. Or to put it another way, innovation is the process that turns an idea into value for the customer and results in sustainable profit for the enterprise." First and foremost, engineers contribute to value creation with deep analytical thinking grounded in scientific principles. But successful innovation requires consideration of a broad set of issues (e.g., markets, customers, intellectual property protection, financing, and sustainability) and a broad set of skills (e.g., communication, teamwork, project management, and the ability to spot emerging opportunities).

Unfortunately, these are rarely integrated into an undergraduate engineering curriculum, except perhaps to some extent in senior design course projects. Also, because engineers with strong analytical skills can be found around the world and can compete on the cost for those skills, it is imperative that individuals develop personal skills – what we call a personal value proposition – to compete and thrive in a global economy. Understanding, designing and delivering professional and personal value propositions underlie the philosophy of holistic engineering. As Tom Friedman points out in "The World is Flat" (Friedman, 2006), the present and

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future, which he calls ‘Globalization 3.0,’involves competition and collaboration at the individual level. A holistic view is needed. Are engineers ready?

The Challenge and the Opportunity: The New Economy Engineer

A challenge we face as educators is that, within any engineering discipline, there is a common body of knowledge that graduating engineers are expected to demonstrate expertise in, and we rightly focus considerable attention on ensuring competence in this core knowledge. However, this is no longer enough to ensure a rewarding and sustainable career, because a common body of knowledge and competency has the risk of quickly becoming a commodity (A commodity is typically defined as a product or service that lacks differentiation and competes almost exclusively on price. A commodity is also easily subject to substitution.) in this ‘flat’ world. As famously noted by Theodore Lewitt, “There is no such thing as a commodity. All goods and services are differentiable.” (Kotler, 2003) In our view, commoditization of engineering knowledge and skills can be successfully countered by differentiation, and specifically by attention to (1) ‘individualization’ – the development of personal skill sets that will enable an engineer to compete and collaborate globally, and (2) much better linkage of core engineering education to the demands of the real world, a.k.a. customers, through the design, development, and delivery of value propositions. The Master of Engineering and Management (MEM) program that we oversee at Case Western Reserve University addresses these needs in an integrated curriculum, but we believe that a significant opportunity and need exists to engage undergraduate engineering students in the development of customer-driven (professional) as well as students’ personal value propositions.

Of particular note is the fact that the solid analytical skills characteristic of an engineering graduate is no longer enough to serve as the basis of a professional or personal value proposition. Entry-level engineering jobs used to mainly emphasize analysis, with engineers wishing to move more toward the business and management side having paths available to them to do so over time. However, pure analysis, what we might call ‘transactional analysis,’ (Defined loosely here as analysis in return for pay, without the need to use a broader set of skills beyond quantitative) is highly susceptible to off-shoring and will almost always go to the lowest bidder. Entry-level expectations are now broader.

Engineering education has been generally mapped and translated into a fairly predictable value for employers within the technical and scientific world. Changes with increased globalization and rapid technological innovation, however, will continually challenge the definition of this value. Knowledge and some experience in the fundamentals are assumed, but expectations are now moving from categorical competency toward uniquely separate and highly dimensional traits which distinguish today’s desirable engineer. Therefore, engineers need additional skills to leverage core analytical thinking in order to become continuous creators of value to employers and to society and to compete on more than price alone. These additional skills include, for example, technology opportunity identification and assessment, the process of transforming interesting inventions into true innovations, the ability to communicate clearly in writing and orally to a wide variety of audiences, ethical leadership, and the ability to seamlessly work in teams, many of whose members will not have a technical background (Goldberg, 2006).

An integrated, whole-system approach to education is needed to prepare the next generation of technical, global leaders. Curricula which support and cultivate a sense of responsibility in decision-making from a well-rounded vantage point, allows one to see the profession of engineering as more than preparedness in technical rigor. Considerations must include the context of society at large, economics, environment, quality of life, and service to mankind through innovation (Grasso et al., 2008). In essence, it is about creating value for the enterprise and for oneself. It is about changing existing situations into preferred ones (Simon, 1996). It is about an entrepreneurial mindset. (Being entrepreneurial means being passionate about identifying new and better ways of doing things, followed by actions to implement them, a trait all engineers should exhibit. A holistic view is required.) It is about the merger of left- and right-brain thinking – merging analysis and synthesis (Pink, 2006). It is about what we term “The New Economy Engineer.” (See http://www.mem.case.edu/index.html)

Engineering Customer (Professional) Value Propositions

Crafting a customer value proposition in any area of technology development first and foremost involves understanding customer needs. Indeed, we believe that integration of needs-based thinking broadly into the undergraduate engineering curriculum represents the greatest opportunity to properly prepare engineering students for long, rewarding, and productive careers. A needs-based focus need not, and should not, be left to senior year design projects. For example, at WPI, students are constantly attentive to customer needs through a project-intensive curriculum. At the Olin College of Engineering, all sophomore engineers take a user-centered design course which requires consideration of design constraints beyond technical issues. Consideration of customer (user) needs will frequently reveal that multiple customers may have to be considered, including the potentially complex value chain of end users, suppliers, investors, and collaborators. Experiential learning through course projects, internships, and ‘co-op’ opportunities can emphasize needs-based thinking through exposure of engineering students to a less traditional, inductive approach to discovery, analysis, and interpretation. Opportunities for improvisation create an appreciation, understanding and ability to practice and refine skills of collaboration, project management, and the delicate precision of ‘soft skills’ (“Soft skills” can be a disparaging term, implying little rigor and depth compared to ‘analytical’ skills, but the former do require considerable study and discipline to develop and use these effectively) required to work effectively with others. Cross-disciplinary teams, including students from outside the engineering arena, can provide exposure to different yet complementary learning styles and approaches to problem solving.

To be sure, the analytical skills of an engineer remain essential, but need to be expanded beyond engineering fundamentals to include business-relevant topics such as six-sigma statistical tools, and concepts from accounting including the time value of money and cash flow. Herein lies another significant opportunity – integration of business as well as engineering analysis into the curriculum. After all, as we noted earlier, engineering sits at the intersection of science and business. The details and nuances of this integration are best discovered in action. We believe that a very useful template for the design of a customer value proposition is the 'NABC' (Needs, Approach, Benefits per cost, Competition) framework described by Carlson and Wilmot (2006), one that we successfully use in MEM courses, and which we believe can be readily incorporated into multiple undergraduate engineering courses.

Engineering Personal Value Propositions

In addition to understanding and applying the elements of a professional (customer-focused) value proposition, it is equally important to develop a personal value proposition that differentiates and distinguishes at the individual level. Interpret the phrase 'personal value proposition' quite literally – in essence, it is the measurable and sustainable value that an individual brings to an enterprise (small or large company, government agency, non-for-profit, or university). It is about being both relevant and unique. Relevance is heightened by engineers paying attention to customer needs and the multitude of considerations beyond the purely technical. Uniqueness is the end result of a strong personal value proposition that, in turn, helps to make an individual relevant and hence highly desirable as an employee, colleague, and collaborator.

Relevance is more than a unique alchemy of multiple disciplines, and requires exposure to unique and personal challenges which demand the development and exercise of a different set of competencies. These demands require more than raw and developed intelligence, and also domains of emotional intelligence which call for greater self-awareness and acquisition of distinct self-management competencies – both of which sharpen necessary "attunement" skills for effective relationship management (Boyatzis et al., 2002). Value cannot be created, and the importance of value propositions cannot be taught, without attention to business issues and personal leadership skills needed to collaborate and to influence and execute critical business decisions which further develop a personal value proposition.

We take a minimalist view and suggest that there are three core attributes that engineers need to constantly practice and refine to be relevant and unique, attributes that define a "New Economy Engineer:"

Analysis – specifically, the ability to define and solve problems in quantitative terms. This is the heart of an engineer's education. However, as noted earlier, an engineer's analytical skills can and should be broadened to include applications to business.

Translation – specifically, the ability to translate what you are doing and why, including important concepts and conclusions, into the language of different constituencies (e.g., your boss, investors, non-technical colleagues, and reporters).

Perception – specifically, the ability to perceive new opportunities by connecting disparate ideas from different disciplines in new ways and synthesizing these into new value-added products and services (in other words, being a 'dot connector').

Analysis, translation, and perception (ATP) is the basis of a truly unique, personal mix and can form the foundation of a powerful personal value proposition. Each component needs to be integrated, built upon, and used in order for a personal value proposition to be sustained. Virtually any combination of the three is unique and personal, and the combinations are effectively infinite.

Consider Fig. 12.1, which is a rough sketch of the number of individuals (say, engineers) that will likely give a similar answer (number of like responses) to questions that require analysis, translation, and perception. Many like responses are expected for a problem that requires pure analytical thinking. As we pointed out earlier, pure transactional analysis will seek lowest bidders in our interconnected, digital world. Thus, the personal value proposition for the pure transactional analyst is rather weak, unless of course he or she has a skill (e.g., math, programming) that is truly unique, although this is rather rare. However, if each was asked to explain the meaning and significance of the calculation in a one-paragraph memo for a non-technical reader (an example of translation), there will be many more unique answers. Some will be both technically correct and enjoyable to read, while others will not be able to crisply capture the idea. Hence, the ability to communicate, and more specifically the ability to persuasively translate technical information into the language of different constituencies, can be a powerful individual differentiator and a significant addition to a personal value proposition.

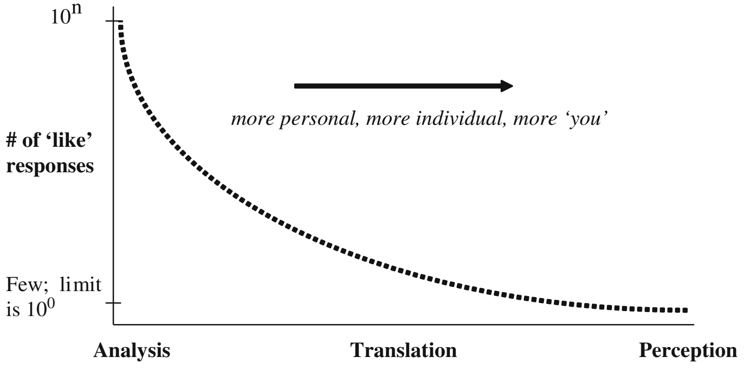

Fig. 12.1 Visual representation comparing the number of individuals expected to give "like" responses (similar answers) to questions that require analysis, translation, and perception

Now imagine asking everyone in this group to suggest new, potentially patentable ideas to build on their analyses. There are likely to be many unique suggestions, perhaps as many as the number of individuals asked (like responses approaching 10^0), even though only some fraction of those will be truly different and useful (Those who are able to translate their ideas into sketches and words for multiple constituencies will have a decided edge.).

The most novel and practical solutions may come from individuals who are able to connect disparate ideas from different disciplines in new ways. In short, the ability to ‘connect dots’ and to perceive ‘out of the box’ is a particularly strong individual differentiator and a powerful driver of value creation (Berns, 2008). Experiential learning opportunities are extremely important, since fresh experiences and the environments these offer can significantly enhance powers of perception. As noted by Berns (2008), our brains need to be bombarded with things never encountered before to see things differently. There are literally infinite opportunities to connect dots, which is a major reason why interdisciplinary collaborations can be so productive. Importantly, the ability to perceive new opportunities in turn begs for their analysis and subsequent translation for multiple constituencies, frequently leading to more ideas that call for yet additional analysis and translation.

“ATP” can catalyze the transformation of commoditization of transactional analysis to individualization, providing the differentiation needed to successfully compete and to thrive. When “ATP” is in balance, the result is effectively an infinite loop connecting all three as shown in Fig. 12.2. There is now the continuing opportunity to help define problems rather than only solve them. Note that the loop can be entered anywhere – there is no “ATP” order.

The “ATP” of the New Economy Engineer is multiplicative – i.e., $A \times T \times P$ – and so it is critical that attention be paid to all three. We also note what we will call the Freidman Inequality (Friedman, 2006)

$$CQ + PQ > IQ.$$

Here IQ is the familiar intelligence quotient, and CQ and PQ are curiosity and passion quotients, respectively. Friedman suggests that the sum of one’s passion

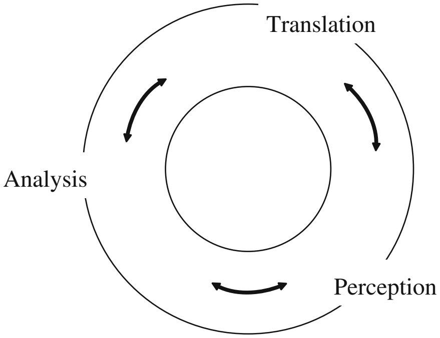

Fig. 12.2 The “ATP” loop

and curiosity can be more important than raw intelligence. Passion and curiosity are key elements of an entrepreneurial mindset and are key characteristics of a New Economy Engineer.

We conclude this section by stressing the importance of leadership and ethics as additional key attributes of a personal value proposition. Leadership is not an expectation of upper-level management only. Rather, leadership is expected at all levels of an organization, and can be demonstrated by, for example, always accepting responsibility along with accountability, showing respect and empathy for others, and demonstrating a willingness to be mentored as well as to be a mentor. Ethical behavior is also an expectation and, as noted by Goldberg (2006) , properly begins with daily, relatively small matters that define how you react to situations that can challenge your integrity. We suggest asking three simple questions of oneself when confronting an ethical challenge: (1) do you practice situational honesty?; (2) do relationships or contexts influence your behavior?; and (3) who are you when no one is looking? While situations and context may suggest relativism regarding ethical decisions, Kawasaki (2008) offers, among other advice for entrepreneurs and engineers, that “there absolutely are absolute rights and wrongs.”

Closing Thoughts: The New Academy Engineer

Engineers are value creators. While broad aspects of successful value creation are the focus of selected post-graduate programs, there is little systemic emphasis in undergraduate engineering programs. The opportunity to do so holistically is both urgent and exciting in order to prepare students for sustainable and rewarding careers in a highly competitive world. Value creation also has a personal element, namely the unique skill sets that an individual brings to an enterprise. Engineering educators thus have the responsibility to promote ‘individualization’ while simultaneously ensuring competence in core engineering and disciplinary fundamentals (and of course value creation broadly). These are not mutually exclusive. Challenging to implement? Surely, but there has never been a more pressing and opportune time to begin to integrate these ideas into the undergraduate curriculum. It is time for educators to define, shape, and deliver the New Economy Engineer. In order to do so, we need focus on professional and personal value propositions and to understand the needs of our customers – New Economy Engineers. We need to become New Academy Engineers.

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Chapter 13
The Missing Basics and Other Philosophical Reflections for the Transformation of Engineering Education

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Introduction

Once again, reform of engineering education is in the air. In the United States, the National Academy of Engineering has published two reports, one specifying characteristics of the engineer of our times (National Academy of Engineering, 2004) and one calling for changes in the ways young engineers are educated (National Academy of Engineering, 2005). A report sponsored by the Carnegie Foundation for the Advancement of Teaching (Sheppard et al., 2008) calls for overhauling the design of engineering education, a national engineering leader has independently called for significant reform (Duderstadt, 2008), and the editor of this volume and his colleagues have called for the education of a more holistic engineer (Grasso and Martinelli 2007, Grasso et al., 2008). The Olin Foundation has gone so far as to have given $460 million dollars to establish a pioneering new curriculum and entirely new school at Franklin W. Olin College of Engineering (Chronicle of Higher Education, 2008) that has now had three graduating classes of seniors. These efforts follow significant funding of eight Engineering Education Coalitions by the National Science Foundation, but a recent report laments the lack of diffusion of those efforts (Spalter-Roth Goldberg et al., 2007).

Although much money, time, and effort has been expended toward engineering curriculum reform, and some successful reform has been achieved, the problems remain daunting, partially because they are complex, surrounded by a lack of

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conceptual clarity, a general confusion about the nature of the engineering enterprise. Two papers elsewhere (Goldberg et al., 2008a, b) have suggested that a primary and underappreciated obstacle to educational transformation is *organizational resistance,* and those papers recommended the formation of a collaborative, interdepartmental curriculum incubator, describing such efforts at the University of Illinois. This chapter asserts that a number of the problems thwarting effective reform are a kind of *conceptual resistance* and are essentially philosophical in nature. The purpose of this chapter is to approach the problem philosophically, reflecting first on what engineering students do not do very well on their first real engineering engagement, continuing by trying to understand some of the conceptual obstacles to aligning engineering as taught with engineering as practiced, and concluding by examining the roles of philosophical analysis in the transformation of engineering education more generally.

Cold War Curriculum Meets Senior Design

The "standard" engineering curriculum of our time was largely set in the aftermath of World War II during the opening days of the cold war period of the 1950s. In the United States, the Grinter report (Grayson, 1993) called for an increase in science, math, and engineering science, and a diminution of shop subjects and graphics. These changes held sway until the 1960s when a number of educators were concerned about a return to engineering design practice in the curriculum (Dobrovolny, 1996). Capstone senior engineering courses trace their beginnings to those discussions, and one of the early leaders in this movement was the Department of General Engineering at the University of Illinois. A Ford Foundation grant in 1966 led to the establishment of an industrial-oriented senior design program, and when the money from that grant ran out, the program was continued using contributions from industry sponsors.

Today, senior design in General Engineering at Illinois continues with successful outcomes for companies and students alike. Currently, teams of three students work with a faculty advisor for an industrial sponsor on a project of practical importance to the company. Additional details about the course are available on the course website (Industrial and Enterprise Systems Engineering, 2008), but the point here is to reflect on this course and the opportunity it provides to diagnose difficulties in engineering education.

Think about it. Here we have students prepared in a fairly typical engineering curriculum who go to work for the first time on a real engineering problem. It is the perfect opportunity to ask, "What don't they know how to do?" As a faculty advisor in Senior Design since 1990, I have learned how to coach students to successfully solve their problems, but I am continually reminded, year after year, about the mismatch between the education a cold war curriculum provides and the demands of a real-world engineering problem. The next section considers what is missing.

Seven Failures of Engineering Education and the Missing Basics

The semester has begun. The projects are assigned, and teams of three student engineers and their advisors are ready to go on the plant trip and find out what the project is really about. Over 19 years of advising such teams, I have found seven important skills that students have difficulty with. Although there is significant variation, the following composite set of difficulties is common enough that most teams require coaching along many, if not all, dimensions discussed.

In particular, senior design students have difficulty

1. *asking* questions
2. *labeling* technology and design challenges
3. *modeling* problems qualitatively
4. *decomposing* design problems
5. *gathering* data
6. *visualizing* solutions and generating ideas
7. *communicating* solutions in written and oral form

Each of these is briefly considered in turn, associating each of these failings with a prominent name in intellectual history (Solomon and Higgins, 1996):

Questions. Students go on the plant trip, and the first job is to learn what the project is, what has been tried, what critical sources of data and theory exist, and what vendors have been helpful in solving related problems. Unfortunately, most student teams have trouble asking cogent questions. We call this a failure of *Socrates 101* in recognition of that philosopher's role in teaching the world to ask.

Labeling. Engineering students learn math and science but are largely ignorant of technology itself, exhibiting difficulty in labeling the components, assemblies, systems, and processes in their projects. Moreover, many projects exhibit novel patterns of failure or design challenge, and the students have difficulty *giving* such patterns names and sticking to those names. This we call a failure of *Aristotle 101* as the systematic naming and categorization of concepts is often attributed to that philosopher.

Modeling. With sufficient coaching, students learn the names of extant components and processes and are able to give names to novel patterns, but then they have difficulty modeling design challenges *qualitatively.* Of course, if the problem lends itself to simple calculus or physics computation, engineering students can plug and chug with the best of them; however, companies do not pay real money for someone to do routine engineering calculation. Where students have difficulty is in making lists of system elements or problem categories or in describing how things work in words. This is a failure of *Aristotle 102* or *Hume 101* because of the connections of those philosophers to categorization and causality.

Decomposition. With some help in understanding key causal and categorical relations the student engineers regain their footing, and then they have trouble decomposing the big design problem into smaller subproblems. We call this a failure of *Descartes 101* because of that philosopher's discussions of the fundamental role of decomposition in the solution of problems.

Gathering data. With the job separated into pieces, usually a number of the pieces depend on careful data collection from the literature or from the design and execution of careful experiments. The students' first impulses are often to model mathematically, but an efficient and effective solution often depends on simple experimentation or library work. We call this failure to resort to empirical work or extant data a failure of *Galileo* or *Bacon 101* because of these individual's contribution to the creation of systematic empirical science.

Visualization and ideation. Students have trouble sketching or diagramming solutions to problems, and more generally they have difficulty in brainstorming a sufficiently large number of solutions. Calling this a failure of *da Vinci 101* because of that individual's renowned imagination and ability to visualize, the problem again is solved with some coaching.

Communication. Finally, the students have solved the problem, done the experiments, put together the analyses, and largely solved the problem, and the time has come to make a presentation or write a report, and to quote the famous line of the Captain from the movie *Cool Hand Luke,* "What we've got here is a failure to communicate." Calling this a failure of *Newman 101* (Paul Newman), the situation again calls for significant coaching.

By associating important figures in intellectual history with each of the seven thinking skills, the listing emphasizes the basic nature and importance of each of the skills. Socrates, Plato, Aristotle, and other Greek philosophers helped launch human thought on a particularly productive 2,500-year stretch of creative dialectic. The thinking skills established and refined at that time of the Greeks, as well as the others in the list of seven, are among the most basic and important habits of thought known to humankind, and so it should cause particular chagrin that engineering students get to the end of a traditional engineering education unable to effectively exercise those skills in the practice of their chosen discipline.

These failures are substantial – certainly they are as much a failure of general education as engineering education – and a senior design faculty advisor helps his or her team by providing just-in-time coaching in the missing basics, as needed. Yet, in one sense, it is quite difficult to understand how such a situation could possibly have arisen. After all, don't engineering faculty members take great pride in teaching a "rigorous" curriculum full of "the basics." And if "the basics" are taught, shouldn't engineering students be able to perform the rudimentary requirements of a real engineering problem in a senior design project without heroic coaching in the needed skills?

The problems here are real enough, but note how the difficulty is exacerbated by the *language* engineering academics use. When engineering faculty talk about "the basics," they are referring to mathematics, science, and engineering science. These subjects are important, but in the context of the current discussion, are they really the most basic subjects critical to being an engineer? This paper argues that they are not, that the seven thinking skills constitute the *missing basics* of engineering education, that the missing basics are fundamental to understanding "the basics," and that engineering education needs to change its thoughts, language, and practices to make the missing basics more central to the engineering canon.

Given that there are linguistic obstacles and a general lack of conceptual clarity in the discussion, it is important for us to understand the origins of the current strains of thought in engineering education and to remove obstacles to clarity in thought, language, and action. These are the tasks taken up in the next section.

Removing Conceptual Hurdles to the Missing Basics

The previous section used an industrial-sponsored, real-world senior design course as a way into understanding some of the shortcomings of engineering education today, and the results were damning. Faculty members defend a “rigorous” curriculum devoted to “the basics” but engineering students have trouble asking questions, naming extant technology or novel technological phenomena, explaining how things work, breaking big problems into solvable little problems, brainstorming and visualizing, and communicating effectively with speech or the written word. For some time, there have been increased calls for reform, and strenuous funding and programmatic efforts have been directed at fixing engineering education’s problems, but the situation remains much as it was.

The previous section suggested that a good part of the difficulty is a lack conceptual clarity in discussions of the fundamentals of engineering education. Human practices can often be better understood by probing their history, and here we start historically and attempt to find the origins of our current educational practices. The section continues its reflection sociologically by examining how sets of social practices can take on a logic of their own, examining Kuhn’s work on paradigms and change in science in the context of engineering education. The section concludes by examining how the engineering academy defines the practice of engineering as applied science, thereafter offering a definition of the discipline that is arguably better aligned with engineering as practiced. Although engineering academics with low regard for “soft” subjects may be dismissive of an analysis that relies so heavily on historical, sociological, and philosophical modes of reflection, the inconsistencies revealed already in this paper and those uncovered in the remainder suggest fairly convincingly that the apparent reliance on more “rigorous” modes of thought by academics steeped in “the basics” has been more or less inadequate to the needs of effective curriculum design; here we are unapologetic in using thinking tools appropriate to the task at hand (Schön, 1983; Toulmin, 2001).

A Cold War Curriculum in an Internet World

The subsection title asserts that engineering education is stuck in a cold war time warp, and this begs us to briefly examine events following World War II, consider the missed revolutions that occurred between then and now, and assess major trends of our times.

The Forces Shaping the Cold War Curriculum After World War II

Engineering as taught today can be understood as a response to the technological and economic forces in place after World War II. At that time, economies of scale were dominant, large hierarchical organizations were the rule, and engineers became increasingly scientific in response to perceptions of the high status of science after the war. Whether this status was deserved and whether the reaction should have been as strong as it was can be debated (Goldberg, 1996); however, there is little doubt that these tendencies were reinforced by governmental actions (Bush, 1945) that funded basic scientific research in post-war government labs and universities, thereby encouraging academic engineers to join what was then a new money chase.

The Missed Revolutions

The previous paragraph may raise concerns among some readers, because seeking fame, status, or money directly often turns out badly, but it is quite reasonable to see the post-war move toward specialization and science as an appropriate response to those times. In an era of Sputnik, the cold war, and continued growth in mass production, the idea of large numbers of specialized engineers working out narrow, technical puzzles posed by their business and bureaucratic managers in large hierarchical organizations is a reasonable model for the organization of engineering work, but time did not stand still, and what once made sense in that era has been overturned by what has elsewhere (Goldberg, 2007a) been called the three *missed revolutions.* We will not review these in detail here, but the quality revolution, entrepreneurial revolution, and information technology revolutions have changed the nature of how companies are organized, how they are started, and how they communicate and coordinate their work products with suppliers and markets. The revolutions are "missed" in the sense that the academy teaches elements of quality methods, entrepreneurship, and information technology, but it tends not to integrate the lessons of the missed revolutions into its own business. The point to keep in mind is that much has changed since the 1950s, and an engineering curriculum formed in response to the economic and technological forces of those times may have some problems in the present.

Our Creative Era

In turning to our circumstances today, a number of current authors (Florida, 2002; Friedman, 2005; Pink, 2005) have looked at the globalizing technological and economic changes around the world and concluded that returns to routine analytical work, including engineering, are diminishing, and returns to *creativity* are increasing.

A distinction can be made between *category enhancers*, workers who primarily improve upon existing category of products, and *category creators*, those who develop and market successful new products and services. The mental image of an earlier paragraph of hoards of engineers working in vast corporate enterprises has given way to images of engineers starting new companies in Silicon Valley or even engineers in larger companies working with marketing and customers to forge new features, products, or services.

The analysis here is not suggesting that all engineers should be or become category creators, pure, and simple; however, in a world with opportunities for both enormous creativity and technical prowess, it seems clear that we should not box our students into a model tuned to earlier times when prowess was valued above all else. Moreover, the missing basics are exactly those critical and creative thinking skills that tie science and mathematics to the other things an engineer must think about, know about, and act upon, and even in large hierarchical settings, engineers trained in the missing basics are better able to relate their work to a larger whole.

Kuhn, Paradigms, and all That

These historical analyses help put the past and present in perspective, but they do not explain why practices and attitudes forged in the crucible of World War II and the cold war continue to grip the minds of engineering academics today. To understand this, we must make what is ultimately a sociological move, by turning to Kuhn's famous book, *The Structure of Scientific Revolutions* (1962) to consider his notions of a *paradigm* and *normal science* and apply them to better understand how change in thinking comes about in the engineering academy as a social process.

Briefly, Kuhn argued that science does not progress smoothly, but rather, it progresses in fits and starts. At a given point in time, a dominant model or paradigm of some science exists (for example, Newtonian physics), and the mass of researchers in that science work within the boundaries of that paradigm – they do normal science – unquestionably extending the reach of that science by solving the *puzzles* posed by the paradigm's methods, rules, or laws. Over time, *anomalies* arise within the paradigm that cannot be explained within the paradigm (motion near the speed of light), and theories arise to explain these anomalies (relativity). Two key points to keep in mind are that anomalies often persist without explanation for some time and that new theories are not generally warmly greeted. Eventually, the evidence for new theories becomes overwhelming and the mass of scientists change their minds, not gradually, but in an avalanche of revision.

In the setting of engineering education, we may think of the notion of the engineer as applied scientist as the dominant paradigm of engineering education. It arose in the aftermath of World War II, and the term "physics envy" captures the dominant value and energizing motive behind the mind of the engineering academic. When engineering faculty talk of "rigor" and the importance of "the basics," they may believe they are making an argument; however, they are speaking largely as defenders of the paradigm. If they are making an argument, it is largely an *argument from authority* (Rosenberg, 1984), the vague social authority of the paradigm, not a specific argument with explicit warrants or independent backing (Toulmin, 1958).

Moreover, in asserting the supremacy of “the basics” engineering faculty can become quite smug and superior in their tone, but there is delicious irony in these assertions, and one thing should be made clear. The support of the “the basics,” regardless of the passion of the defender or the degree of haughtiness of tone, is not itself scientific. Where are the data behind the assertions? Where are the careful statistical studies and *t*-tests? For the aficionado of mathematics, where are the axioms and proofs that lead to conclusions about the superiority of these modes of thought. For the physics minded, where are the equations of motion of engineering education that govern how educators, students, content, and curriculum interact?

The simple answer is that none of these things exist. Moreover, given that the tools so prized by the defenders of the basics are not applicable to the educational design problem at hand, the previous paragraph amounts to an existence proof that certain things defy “rigorous” notions of thought using only “the basics.” This point is made even more forcefully elsewhere (Goldberg, 2009a) through a critical examination of the terms “rigorous,” “the basics,” and “soft.” We will not follow the argument in detail here, but with reasonable interpretations of those terms and the added assumption that engineering is practiced in an environment of limited resources, the paper concludes that engineering restricted to a “rigorous” form of the “basics” is inconsistent with the needs of practice. This leads to the suggestion that there is a certain incoherence among engineering curriculum discussions that has largely gone unnoticed, and that engineering faculty members who continue to defend an unexamined faith in “rigor” and “the basics” are guilty of what can be called a certain carelessness of thought. Put another way, those who defend mathematical or scientific rigor against all comers are guilty of a certain kind of philosophical illogic or “softness:” they are making bad or null arguments.

These are strong statements, and I should be careful to add that I respect mathematical and scientific knowledge and knowhow as *part* of what it means to be a good engineer, that I believe we must continue to provide a full measure of mathematics, science, and engineering science education at the undergraduate level; however, to largely equate engineering and applied science and to exclude other modes of thinking important to the practice of engineering are mistakes of striking proportions.

Is Engineering Merely Applied Science?

The previous two sections have scrutinized the origins and persistence of current engineering education practice, finding both to be suspect or wanting. In particular, the post-war idea that “engineering is merely applied science” seems to be quite powerful and enduring. Here, we argue that the idea is widely held in the academy and *philosophically* mistaken. The section starts by offering an analysis of the words and actions of engineering academics, continues with an analysis of the senses in which the term “merely” is used, finding none of them to be acceptable, and then concludes offering a different definition of engineering that results in an actionable threefold decomposition useful for thinking about educational reform.

Engineering Academics Do Believe That Engineering Is Merely Applied Science

The idea that engineering is merely applied science is widely held in the engineering academy, and faculty members involved in engineering education show their true colors and defend the assertion in a variety of ways. Already this paper has mentioned the steadfast use of certain terms such as "rigorous" and "the basics" but there are other examples. For example, engineering academics defend "the basics" against the encroachment of "soft" subjects, and it is even fairly common for engineering faculty to ridicule "soft" subjects and those who teach them; it is the rare engineering department, indeed, that can bring itself to approve course offerings in "soft" subjects and even rarer for engineering colleges to find it acceptable to offer tenure to those with "soft" disciplinary backgrounds. Moreover, the proportion of "soft" subjects in the traditional engineering core is negligible, and tolerance for additions to the "soft" courses outside the core is low.

Although not definitive, the examples above, these choices by academic engineers of routine terminology and actions in the face of important decisions relative to curriculum planning, coursework, and resource allocation, suggest that engineering academics do tend to believe that "Engineering is merely applied science;" however, there remains just one little problem. The idea is profoundly mistaken. To get at this category error, the remainder of the section examines what is usually meant by the term "merely," finding it to be a word of disparagement, containment, or the assignment of temporal priority.

An Analysis of the Term "Merely"

"Merely" is an interesting word. First and foremost, the term is used as a kind of putdown, meaning to disparage the subject of the sentence relative to its object. So when we say, "Engineering is merely applied science," we elevate science and deflate engineering. Elevating pure thought and disparaging thought in application has ancient roots in the Western tradition, as the Greeks were fond of elevating pure philosophical speculation by wealthy gentlemen (or those who had patrons among them) over the workaday thoughts of craftsman and workers, many of whom were less wealthy or slaves. Although the intellectually arbitrary and self-serving class distinctions made by slaveholding gentleman two and half millennia ago may have been useful to them, it is not clear why the cultural predilections of a society so unlike our own continues to cast this particular spell upon us, but culture is nothing if not persistent.

Of course, the term "merely" can mean more than just a simple putdown. "Merely" can also mean something like "simply," "largely a matter of," or "is contained in." Here the intent is less pejorative, but more of an attempt to restrict the subject to the contents of the object. In this sense of the term, the sentence

"Engineering is merely applied science" suggests that engineering is contained in or largely a relatively simple matter of applying science. Walter Vincenti's (1990) important book *What Engineers Know and How They Know It* argues strenuously and persuasively against this point of view, showing that the artifacts of engineering knowledge in the traces of aeronautical history are distinctly different from the artifacts of scientific knowledge. This is not the time or place for a detailed examination of his arguments; however, Vincenti seeks to *demarcate* engineering knowledge from scientific knowledge in ways analogous to the efforts of scientists and philosophers of science seeking to demarcate science from non-science (Kasser, 2006).

Finally, any sense that science predates the engineering of technological artifacts is just historically inaccurate. The systematic design and production of relatively complex technological artifacts goes back 2.5 million years in human history to the Stone Age with the manufacture and use of stone axes by our early human ancestors (Fagan, 2003). Systematic science does not really start until the middle of the second millennium or thereabouts, and one of the fathers of modern science, Sir Francis Bacon explicitly credited the method of the *mechanical arts* of his time for suggesting the way toward a more systematic scientific method (Goldberg, 2006). In other words, if we were to follow Bacon, and give credit where he thought credit was due, we might turn around the locution "Engineering is merely applied science" and say that science is merely the application of engineering method to the evolution of models or concepts.

Thus, our deconstruction of the sentence, "Engineering is merely applied science," is complete and none of the three interpretations makes much sense. The putdown by the lofty of the applied is a class distinction with suspect roots in a slaveholding society much different from our own. The idea that engineering is contained in science is problematic because engineering knowledge has differences when compared to the scientific kind, and the thought that engineering is predated by science is just flat wrong. No doubt engineering uses science, but the real problem here is that this lazy definition does not fully capture much of what engineers do in practice, a problem taken up next.

A View from Engineering Practice

In philosophical terms, the view of engineering as applied science is a bit odd, because it conflates one of the tools used in making technological artifacts, systems, or processes – science – for the end goal of the activity. In philosophical terms, science is *instrumental* to the products of engineering but it is not the product itself. While it is true that there are times in history that particular artifacts are enabled by scientific discovery, it is equally true that there are times in history where scientific advance is enabled by technological artifacts and instruments. Thus, since we define science in terms of its end products, methods, and actors – scientific knowledge, method, and scientists – it seems reasonable and fair to define engineering in terms of its end goals, methods, and actors as well.

Thus, we might choose to define engineering as follows (Goldberg, 2009b):

> *Engineering is the social practice of conceiving, designing, implementing, producing, and sustaining complex technological artifacts, processes, or systems.*

Engineering is largely concerned with making things that help people, where the term “things” is broadly construed; however, the things are not simple things, easily made, but rather they are complex things requiring certain special tools and knowhow to make them. Moreover, the things are not static objects of art or aesthetic appreciation; they are used in some manner or they do something or “work” in some way.

There are a variety of tools, knowledge, and knowhow that go into the engineering process, and those actions are themselves generally fairly complex, drawing on many different realms of human knowledge as well as specialized knowledge and practices developed within engineering itself.

The complexity of engineering is such that it is generally a social undertaking. In small settings, at a minimum, engineering involves the maker and the individual for whom the thing is made, but even this minimalist setting has hidden social complexity in both the web of suppliers that aid the engineer in the production of the artifact as well as the intended and unintended consequences of the use of the artifact by the client in a larger social context. In larger settings, the “social practice” can take on an almost unlimited social complexity, involving a multi-path and multi-step chain from maker to user, moderated by and affecting many institutions, populations, and individuals along the way.

Thinking about engineering this way leads to a different, more balanced conception of engineering and engineering education than is usually proposed. In particular, a threefold decomposition of engineering education called *3Space* (Goldberg, 2009b) recognizes the complexities inherent in the definition above by moving away from an analysis-centered position to one that balances the habits of thought needed to create things in a world of people as follows:

- *ThingSpace:* Engineering creates complex technological things (artifacts, processes, or systems).
- *FolkSpace:* Engineering is an activity performed by, for, and with people.
- *ThinkSpace:* Engineering is a complex process of intertwined thought and action, involving math and science as well as many other critical and creative thinking skills.

We will not elaborate on these here, but the decomposition invites further hierarchical decomposition.

Why Philosophy? Why Now?

When I helped organize the first Workshop on Philosophy and Engineering held in 2007, I thought long and hard about what paper I would present, and I chose to take another page out of Kuhn’s playbook and make an argument about why engineers might be turning to philosophy at this juncture in history (Goldberg, 2007b). Although many remember Kuhn for his notion of paradigms invoked earlier, some forget that he also made an argument to explain why scientists became interested in the philosophy of science in the opening moments of the 20th century. Simply put, Kuhn argued that the disruptive nature of the new physics shook what scientists took as given: long-held notions of space, time, and causality. Kuhn argued that scientists turned to philosophy of science as a way of both understanding the crisis of thought they were going through and as a way to help other scientists make the transition to the new thinking.

That 2007 talk argued by analogy to Kuhn, suggesting that the rapid pace of technological change in the opening moments of the 21st century is as disorienting to engineers as those earlier times were for scientists. It is in this spirit that I think philosophical reflection is particularly important for engineers right now. As I have suggested, whether you believe the cold war paradigm was appropriate to the 1950s or merely a category error, even then, is immaterial. The signs are clear that the old paradigm is breaking down and that new ways of thinking about what it means to be an engineer are emerging from the pace, scope, and sweep of technology in our times.

Against this backdrop, the need for conceptual clarity is greater for engineers now than it has ever been, but it is really troublesome to see such a paucity of good argument, especially at this moment in history, and to see the repeated and not very imaginative defense of the status quo through the invocation of tired code words. To be clear, it seems that it is incumbent on defenders of the cold war paradigm to do something more than call for "the basics" and denigrate certain thoughts by calling them "soft" or "not rigorous."

To raise the quality of argumentation in our community requires more of us to make better arguments. I hesitate to use the term, but in a very real sense, I am calling for a more rigorous mode of conceptual discourse in the engineering academy, and philosophy and related subjects have a role to play in offering appropriate models and methods. Typically, introductory non-symbolic logic courses in philosophy teach the basics of analyzing and making arguments in words, covering many of the common fallacies, and considering the basics of form and support. Argumentation courses in communications or similar departments (Zarefsky, 2001) do likewise, oftentimes building on Toulmin's (1958) model in a unifying way that can be satisfying to mathematicians and lawyers, both.

Moreover, given that the missing basics involve qualitative thought and argumentation applied to engineering problem solving in a very real way, our efforts as engineering academics to make better arguments amongst ourselves may pay off in the discovery of new teaching methods that will help us convey the missing basics more effectively to our students.

These prospects are exciting ones. The path to engineering education transformation is difficult, and there is no single exertion that will set us on the royal road to effective reform; however, a good step along the way is to clear the air philosophically so that we do not remain trapped in the conceptual errors of the past.

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Chapter 14
Dispelling the Myths of Holistic Engineering

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Over the past year, articles by Grasso and others – including *Holistic Engineering* and *Holistic Engineering and Educational Reform*[1] – have followed former IEEE President Joe Bordogna in adopting the term "holistic engineering" to describe a more cross-disciplinary, whole-systems approach to engineering education. It is an approach that emphasizes contextualized problem formulation and encourages innovative changes to traditional engineering training. These articles urged that engineering's greatest and most immediate challenge for the 21st century is to rethink and re-engineer education to ensure the profession is not transformed into a group of skilled technicians on the sidelines of the global economy. Instead, an engineering education should be perceived as creating global leaders: decision makers who actively shape our future with both proven technical engineering ability as well as creative, cost-effective, and innovative management of the complex social, economic, environmental, and communications aspects of modern engineering projects around the world.

These articles were not alone in taking up the issue. Concerns about trends in declining engineering enrollments, a lack of diversity, and the potential erosion of US innovation primacy in global markets have been expressed for over a decade under numerous titles in reports from the National Academy of Engineering, the Millenium Project led by former University of Michigan President James

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Duderstadt, and US business and academic leaders. Many of these reports have called for a change in engineering education to maintain US competitiveness and advance innovation.

Yet, despite these reports and recent articles, the national transformation of traditional engineering education has been slow. In particular, adopting a more holistic approach to engineering education – where traditional, technologically focused engineering curricula is changed to open coursework across both technical and liberal arts disciplines in the first four years of engineering training – continues to meet skepticism in parts of the engineering community. Can we truly educate broad-based, holistic engineers without "watering down" technically rigorous engineering coursework? Will these creative engineers be able to ensure the highest levels of technical proficiency and public safety? Is there truly a market for this kind of engineering talent? And, last but not least, can and should the US engineering education system as a whole be fundamentally reorganized to emphasize and create holistic engineers?

Our answer to all of these questions is a resounding "yes."

The Myth of a Watered-Down Education

The most common skepticism expressed about a holistic approach to engineering education is that any broadening of the traditional undergraduate engineering curriculum will "water down" traditional rigor of the field by including "soft" skills such as language, history, economics, and communication to compete for credit hours during the technically focused engineering degree. While we agree that traditional engineering fundamentals such as statics, dynamics, circuits, thermodynamics, and fluid mechanics must remain the core of the engineering degree, we strongly aver that engineering students are ill-served without complementary fundamentals in creative thought, historical and cultural context, holistic and innovative design, management, and entrepreneurship. This is not "watering down," rather it is empowering US engineering programs to become globally competitive, more rigorous, value-added, innovative, and dynamic in their application.

And this new rigor is not at all impossible to adopt. For example, creating an initial 2-year core of engineering fundamentals, with a modest number of upper-division courses geared toward specific subspecialties, leaves students with multiple elective study credit hours in other disciplines. This is the premise of several engineering B.A. programs already successfully creating more holistic engineers and can also be found in some engineering science B.S. degrees. A more holistic education for all engineering programs means taking the core that most engineering schools teach, then requiring students to contextualize the fundamentals. This includes exposure to studies of the human, societal, and ecological frameworks, followed by more specific technical skills required of various subspecialties, such as environmental, civil, electrical, mechanical, and chemical engineering.

This call to a holistic approach is, in fact, a call to regain the true mission of the engineering profession. Engineers are eloquent in distinguishing themselves from other scientists as the science-based professionals who apply their creative and technical knowledge *in service to humanity*, specifically by designing and building to improve the quality of life for society in both the built and natural environments. Yet, as most practicing engineers know, one of the most difficult phases of any engineering project is initial problem formulation and definition. As presently conceived and executed, our system of education often does not prepare students for the task – an issue eloquently addressed in National Academy of Engineering member Judson King's Issues in Science and Technology essay *Let Engineers Go to College*. Indeed, problem formulation is where technological skill meets the uniquely societal demands of restricted budgets, regulatory frameworks, public–private collaboration complexity, public safety impact, historical context, and public understanding.

If engineers are not exposed to comprehensive project management skills around critical reasoning, cross-disciplinary communication, differing cultural expectations, and knowledge of relevant scientific and historical debates, then we have abdicated our professional responsibility to truly create engineers in service to humanity. Engineers trained only in technology become mere technicians, subject to following the vision of service proffered or defined by others. Taking responsibility for creating well-rounded decision makers in the engineering profession is not "watering down" the curriculum – it is taking on the true challenge and interdisciplinary rigor our profession's core mission deserves.

The Myth of Technological Supremacy

There is a strong belief that credible and top-ranked engineering programs require as many high-level, highly specialized, and highly technical courses as possible to ensure students are truly competitive and successful in today's job market. In other words, the more technical acumen students show on their transcript, the higher the regard in which their graduating program will be held, the higher-paying job they will find, and the more successful engineer they will prove to be.

The premise of this argument is fallacious, simply because it is impossible – and irresponsible – to suggest that any engineering curriculum could ever capture the myriad of rapidly changing technical skill and knowledge needed in the 21st century innovation and information economy. A recent report suggested that much technical information can be outdated within 2 years and even the popular media – in books such as Thomas Friedman's *The World is Flat*, Daniel Pink's *A Whole New Mind*, and Derek Bok's *Our Underachieving Colleges* – recognize that 21st century innovation in technology and the business world now happen at speeds almost incomprehensible by comparison to the times when many current engineering faculty members and practitioners were in college.

Any argument suggesting, therefore, that technically or technologically focused curricula *sensu stricto* provides a 4-year engineering student with either a competitive or intellectual advantage is simply incorrect. Legal educators faced the impossible task of teaching technical legal details of thousands of individual laws created during the 19th century and so moved their educational program to a fundamentals-based paradigm instructing students to learn how to "think like lawyers." Similarly, the engineering profession should not stand in the way of its own growth with an argument that it must teach more and more technology. As argued again recently by Grasso in an IEEE Technology and Science essay, *Dead Poets and Engineers* – and by so many others across the engineering profession – the focus today must be on teaching our engineering students to think creatively across scientific, technological, and liberal arts disciplines.

The Myth of Specialization

It is not, therefore, the drilling-down detail and precision that an early engineering education should give our future engineering professionals, but the ability to learn and reason across (and out of) disciplinary boundaries. Students showing "T-shaped" breadth and depth that comes from a holistic approach to their craft during their undergraduate years – mastering core fundamentals as well as gaining an understanding of areas such as business, foreign language, humanities, and social sciences – will be truly competitive graduates in 21st century engineering markets. They will be able to acquire highly technical, highly specialized skills in postgraduate study, just as surgeons are trained after a solid grounding in more general medicine. World leaders such as IBM, CDM, and MITRE Corporation are already appreciating the value of "T-shaped" thinking with both management investments as well as their deployment of "services" markets that deliver technologies contextualized and customized to the social, economic, environmental, and business needs of individual clients.

More importantly, if we continue training the majority of engineering students in narrowly prescribed technological formats, we will potentially create a resource not for global engineering leadership, but simply another global commodity, traded by markets at its lowest value and dependent upon the economic whims of any engineering employer – an issue discussed in reports and essays including the 2007 National Center on Education and the Economy's *Tough Choices or Tough Times* as well as the aptly named *Engineers as Commodities* by IEEE Life Fellow George McClure.

However, if we train our students to be proficient in engineering thought, as "T-shaped" and holistic thinkers with fundamentals strongly in place as well as the skills to reason, learn, and innovate beyond traditional disciplines, we will have created truly competitive and value-added engineer. This paradigm shift will require engineers pursuing highly specialized fields to gain additional skills in the first few years of practice, similar to the legal or medical professions. It will also allow engineering-trained individuals to bring their skill and acumen to professions ranging from law to finance and policy – all of which should, in fact, be infused with our professional expertise. The holistic engineer is, therefore, the most competitive employee of all.

The Myth of Public Peril

One of the most alarming, yet patently untrue, skepticisms of a broad engineering education is that the holistic engineering education will, despite its good intentions, imperil the public. Without precision engineering skills learned and repeated through those four critical years of college engineering classes, the argument goes, bridges will fall, buildings will collapse, and dams will fail.

As *PE* readers know well, however, the work of engineers is subject to post-graduate licensing and constant review before any project is entrusted to public use, whether engineering degrees of the designers were received from a highly regarded technical program or a small liberal arts school. In all states, engineers serve an apprenticeship period before being allowed to sit for the Principles and Practice of Engineering Exam, and once they pass the exam and meet all other requirements, they are officially sanctioned to call themselves professional engineers.

Furthermore, this argument implies that 4 years of technical training would, in fact, allow an engineer to be qualified to build a bridge or construct a building. Yet, just as a medical student (many of whom gained liberal arts degrees before choosing their profession) cannot, without supervision or oversight, operate on a living being without serving several years as a resident and apprentice before becoming a trusted surgeon, professional engineers are also highly skilled in their craft, with many years expected before mastery of the trade. Suggesting that sufficient knowledge is gained in 4 years of college is simply a false premise for argument.

It is not the broadening of an engineer's education that disserves the public, but the present educational system that does not train professionals to think holistically about the true impact of their technological and scientific creations in society.

The Myth of Institutional Inertia

Finally, skeptics of holistic approaches may argue that true reform of US engineering education is just not feasible at large scales (e.g., while smaller engineering programs such as that of Dartmouth College's Thayer School and the Picker Engineering Program at Smith College have the luxury of developing competitive, integrated, interdisciplinary approaches to undergraduate engineering education, the larger university programs simply cannot implement a broad-based curriculum). Engineering education progress cannot be held hostage to a false premise of institutional inertia. The agents for adaptive change are no further than the distinguished engineering faculty populating university halls and their professional colleagues in the business and governmental community urging and supporting reform.

Indeed, a paradigm shift to the holistic engineering model can be achieved with relatively minor adjustments to existing curricula. For example, offering parallel, alternative, holistic engineering tracks that use existing, traditional engineering courses, such as that being developed by dedicated faculty at the University of Vermont, should liberate, not inconvenience, existing faculty. Under this model, engineering majors are given the flexibility to focus on core engineering requirements, such as statics, dynamics, circuits, or thermodynamics, in their first 2 years and then open their undergraduate experience to cross-disciplinary courses that create truly “T-shaped,” holistic, and competitive engineering skills, all within an ABET-accredited degree format. In turn, as engineering faculty move to a 2-year core curriculum, time can be opened in their professional schedules for more elective course teaching as well as innovative research.

The data for nationwide engineering enrollments, retention, and attrition are currently alarming. Engineers across academia, business, and government know that we are losing the potential of new engineering talent, both men and women. As shown clearly in a 1998 Harris Poll cited by the National Academy of Engineering, far too many students perceive traditional engineering degree programs as too prescriptive, lacking breadth and societal engagement, and without connection to pressing issues of social responsibility, entrepreneurial thinking, and environmental awareness – all issues that connect with the youth’s hearts and minds.

We recognize that this perception is, in part, a message problem and the 2008 National Academy of Engineering publication *Changing the Conversation: Messages for Improving Public Understanding of Engineering* is a good, if belated, start to engaging potential engineering students using the power of our media-intensive, message-driven culture. At the same time, we argue that this is also a substantive, curriculum-based problem that only a true investment in holistic approaches can solve. Even with the most impressive marketing program of NAE, it is impossible to argue convincingly that we teach creativity and innovation in our engineering schools when many schools refuse to let go of a curriculum that has changed little since the 1950s.

If we truly want to attract and retain the best, brightest, most diverse, and most innovative students in the United States, we must invest in, and actively offer, the highest-quality engineering education filled with integrative courses in engineering technology, humanities, and the arts. Broad-based first year and senior design courses engaging local and national business and nonprofit interests should flourish, courses that actively contextualize engineering’s role in public policy debates should be encouraged, and student engagement in forward-thinking activities such as Engineers Without Borders and hybrid-powered race cars should be highlighted to potential students and parents alike.

The Holistic Advantage

A holistic engineering training that includes exposure to global issues and contextualizes technological knowledge within the framework of 21st century, complex economic, social, and environmental issues – is critically needed to ensure the competitiveness and relevance of the American engineering enterprise. The future of leadership and excellence in our profession is one in which we invest in and create engineering practitioners who crave broad knowledge across disciplines and command a diversity of both technical and professional acumen throughout their career, be it for high-tech engineering or the management of a global IT corporation. These engineers are holistic in view, adaptive in the face of challenge, and able to provide continuous, cost-effective value to employers or clients – in rapidly changing markets. They are creative and innovative and will inspire a next generation of engineers to invest in our practice and profession.

While all new ideas deserve critical thought and skepticism, we argue that an investment in holistic engineering – not a new idea, but the encapsulation of many efforts, over many years, to shift the engineering education paradigm – is of critical and immediate importance for 21st century competitiveness of the United States engineering sector. Technologically based engineering training can be outsourced, but engineering creativity and innovation, married to technological excellence, cannot.

The future of the profession relies upon a core investment in holistic approaches to engineering education, creating the truly 21st century engineering professional who can best meet the complex social, environmental, energy, economic, and technical challenges begging for engineering expertise. We hope the engineering community will embrace the holistic approach as an inspiring, exciting, and competitive advantage for future generations.

Chapter 15

The Practice of Systems Engineering: A Foundation for Technical Leadership

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Large-scale engineering projects are often in the news, especially when they fail to realize the value promised. Often these failures result in multibillion-dollar cost overruns, and usually "complexity" is blamed for the failure. But even if complexity is the proximate cause, the underlying cause is probably a failure to establish truly beneficial projects initially, and to address risk as the project proceeds. These problems arise from a complex blend of technological and sociological factors that are often apparent to people involved in establishing and executing projects, and yet a principal method for dealing with them receives very little attention. What is offered here is a perspective on why "technical leadership" is so critical to the success of complex engineering projects, and how the practice of effective systems engineering enhances and enables such leadership.

Unfortunately, the term "systems engineering" is so widely and variously used that it does not convey the importance of the responsibilities, or the excitement of the challenges, in the field. We begin therefore with a discussion of systems engineering and leadership and then offer some examples of leadership challenges taken from the space systems engineering field with which we are most familiar. These examples represent complex systems engineering problems in general, and illustrate that systems engineers acting as technical leaders are the first line of defense in making sure that projects are set up properly, and that uncertainty and risk are addressed. These examples and vignettes are put forward in the open-ended way that business school case studies are done so as to illustrate how they might be used

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for teaching system engineers and for developing future technical leaders. Leaders know intuitively that ambiguity, uncertain outcomes, and unintended problems are all part of the challenge – but engineers are not usually trained this way even though they have a crucial leadership role to play.

What Is Systems Engineering?

Descriptions of the practice of engineering often convey the idea that all engineers are technologists – that is, people who practice the art of applying technology to create machines or structures. A typical description of engineering is as follows:

> The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property (Engineers' Council for Professional Development, 1947).

Similarly, descriptions of systems engineering often state that it is a process or "approach," as in these examples.

> An interdisciplinary approach and means to enable the realization of successful systems (International Council on Systems Engineering (INCOSE), 2000).
>
> Systems engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals (NASA Systems Engineering Handbook, 1995).

But is systems engineering as suggested by these definitions really just the "process" of making the engineering disciplines work together in some optimal way? Systems engineering is often treated as though it were a combination or derivative of other engineering fields, or not true engineering at all, but a topic in management. The way to move beyond this problem is to describe the practice of systems engineering as being the foundation for "technical leadership."

An Analogy to Business Leadership

The scope and meaning of the concept of technical leadership can be outlined by drawing an analogy to business theory and leadership. The analogy is not meant to imply that systems engineering is not engineering, but instead that technical leadership is founded upon systems engineering and transcends it.

Students in MBA programs have long had the benefit of economic and organizational theory to motivate the importance of leadership in business. For example, "theories of the firm" seek to explain why firms are so effective at producing economic value that is larger than the sum of its component inputs. Business leaders are expected to use insights gained from economics to produce such value. Likewise, "engineered systems" are often characterized as providing capabilities that are much greater than the sum of the component capabilities. By analogy to business leadership, systems engineering leaders should be expected to be expert in carefully crafting the use of technology in organizations in such a way that it produces economic value or transforms organizations. Technical leaders should also know when *not* to use technological solutions, but instead change the way that technology is used to effect a solution.

Furthermore, business leaders are expected to be able to use the tools of economics to project the performance of the firm in the future, often under conditions of great uncertainty. They know that every reward implies risk, and they use the risk–reward concept routinely to develop effective strategic courses of action. Likewise, systems engineers are expected to use the tools of engineering to project the performance of engineered systems, often with considerable uncertainty as to how they will actually perform. Systems engineering leaders should be expected to develop effective courses of action with manageable technical risk when they are developing plans for engineered systems.

Finally, the term "general management" in business is usually described as the process of coordinating the work of the various business disciplines of finance, accounting, human resources, marketing, sales, and operations. General managers are expected to not only have considerable experience in at least one of the business disciplines, for example finance or marketing, but to be familiar with the other disciplines as needed to guide the firm toward strategic goals. Likewise, systems engineers are often characterized as being grounded in one of the relevant engineering disciplines (e.g., mechanical engineering), but also familiar in varying degrees with the others. They are expected to coordinate the actions of various engineering disciplines and produce "interdisciplinary results." However, engineering leaders are not coordinators. They are more properly thought of as architects who guide engineering projects toward strategic goals for clients, as captured in this statement by Dr. Eberhardt Rechtin.

> An architect is not a 'general engineer,' but a specialist in reducing complexity, uncertainty and ambiguity to workable concepts (Rechtin, 1991).

The analogy offered here illustrates that systems engineering can be described in terms that emphasize its value rather than its techniques or steps, and that technical leadership is required to leverage the most important facets of systems engineering so as to produce economic or social benefits.

Why Do We Care About Systems Engineering and Technical Leadership?

We should care about systems engineering and technical leadership because together they can transform the economics of entire industries, or the effectiveness of government missions such as national defense. These transformations arise when engineered systems are integrated into increasingly more capable systems-of-systems, or into improved system architectures.

A typical transformational pattern is to introduce a new system solution into a previously existing web of capabilities, which in turn transforms the way people work together or the tools that they use to do their work. An example is the development of space-based navigation signals in the 1960s that resulted in the present-day Global Positioning System (GPS).

Case: Project Establishment for the Global Positioning System

The commercial shipping industry, the airlines, the military, and others have long had a need for precise information about the real-time position of their assets around the globe. In the 1950s there were many navigational aids, some of which sent out long-range signals, such as the LORAN system. Each of these systems had drawbacks related to coverage, accuracy, precision, timeliness, and other factors. After the launch of Sputnik in 1957, scientists monitoring the radio signals from Sputnik realized that they could determine the position of the satellite by measuring the Doppler shift of its radio signals, using the known position of the ground receiver. Several years later, scientists working on the problem of determining the position of submarines at sea realized that they could reverse this process and determine the position of the submarine if the position of the satellite was known. This realization sparked several systems engineering projects within the military in which different concepts for orbiting constellations, timekeeping methods, and navigational signals were proposed and analyzed. For example, precise timekeeping is essential to be able to get good navigation solutions from the system. In one-system concept, the clock signals were sent from the high-precision clocks on the ground to the spacecraft; and in another, the spacecraft carried a high-precision clock on board. In some cases these concepts were tested in flight by launching spacecraft. Each concept had advantages and disadvantages with respect to how accurate the navigation solutions were and how robust the overall system was. Systems engineers developed concepts and designs, projected how they would perform, and presented their ideas to government officials for funding. Ultimately, the system we now know as the Global Positioning System was funded and deployed (An interview with Brad Parkinson. http://news.stanford.edu/pr/95/950613Arc5183.html; Maier and Rechtin, 2009).

We can make several observations concerning systems engineering and technical leadership from this example, as discussed below.

Transformational Effect

In this case, engineers introduced new high-accuracy, global-coverage navigation signals into a pre-existing network of people who were using other sources of navigation signals. GPS technology provided for the first time ever, unambiguous position information with high accuracy and availability. But the transformational effects occurred because the system was designed to allow everyone to receive the standardized GPS signals and invent their own uses for them independently. Most of these secondary inventions and their effects on people and organizations were probably not envisioned by the inventors. But in many cases, technical leaders are in a unique position to set up the conditions under which such transformations can occur.

It should be noted however, that some large-scale engineering projects are undertaken with the expressed purpose of transforming the way people are organized and operate. This is done by envisioning a new operations concept along with equipment and software that will make it possible. An example is the Army's Future Combat System. This project is being undertaken with the principal purpose of transforming the existing Army organization into a new organization that has smaller, "lighter" units that utilize new equipment specifically designed to help them operate effectively in these smaller units with less support when deployed. The new organizational concept is only possible due to a new concept of operations, which in turn is enabled by new equipment and information networks (United States Government Accountability Office, 2008).

Advocacy and Leadership

Typical descriptions of systems engineering tend to imply a support role for engineers in an organization. But in the GPS example above, systems engineers were advocates and visionary leaders. In other circumstances, systems engineers should be objective advisors and instead serve as "thought leaders." Indeed, one of the services that system engineers can offer is that they can provide an array of alternate technological approaches with associated characterization of cost and risk that are based on analysis. In either case, there is a role for active technical leadership based on sound systems engineering.

Consensus Building and Decision-Making

All technological projects, no matter what the scale, will proceed through a series of approval decisions in which funding is made available. Systems engineers are very likely to be involved in defining and presenting the technological aspects of the project at such decision-making gates. In the GPS example above, systems engineers led the process of identifying appropriate technologies and developing system concepts. This led directly to a determination of which design concept should be pursued, and helped develop the technical rationale for why it should be done. Such decisions cannot be made properly unless they are accompanied by characterization of risk provided by systems engineers, who will have a unique perspective based on an appreciation of the engineering challenges involved. Technical leaders will drive toward better results in making sure all options are considered and the right technical know-how is applied to solve the problems discovered.

On multibillion dollar projects there may be dozens of major investors or government officials involved in the decision to proceed. The process of getting a go-ahead decision may span several years and could involve a highly interactive discussion between funders, developers, operators, regulatory agencies, and others. To navigate this decision-making process, a technological approach with various options for executing the project must be established and skillfully presented. Indeed, many projects are so complex that the initial project go-ahead is not given until months or years of conceptual design and requirements analysis are completed. Furthermore, the project may have to be repeatedly re-justified at major decision points. Throughout this process, the system engineer has to ask the big questions: Are we working the right problem? Have we examined the right trades at the architecture level, the system level, and the subsystem level? Technical leaders must have the technical expertise to ask the probative questions in areas where they are not the subject matter expert. Technical leadership also means having the fortitude and courage to sometimes challenge customers, co-workers, bosses, and suppliers; and to redirect the team if it is not working the right issues or it has chosen the easier rather than the smarter path.

Uncertainty and Cost Risk

The GPS example also illustrates that in the earliest phase of many projects, systems engineers are working in an environment in which none of the major parameters of the project have been firmly established or even clearly identified, and yet they are called upon to develop design concepts and make estimates of performance and cost. This estimation and design process is both creative and analytical, and requires special analytical tools, expertise, skill, and experience. A principal service provided by systems engineers during this phase is to identify which parameters are most important with respect to cost and performance and to clarify for investors or government funding agencies why these are important and how they vary if the requirements are changed. The ultimate purpose of these actions is to engender discussion about risk and feasibility to inform funding and strategy decisions, as it did in the example.

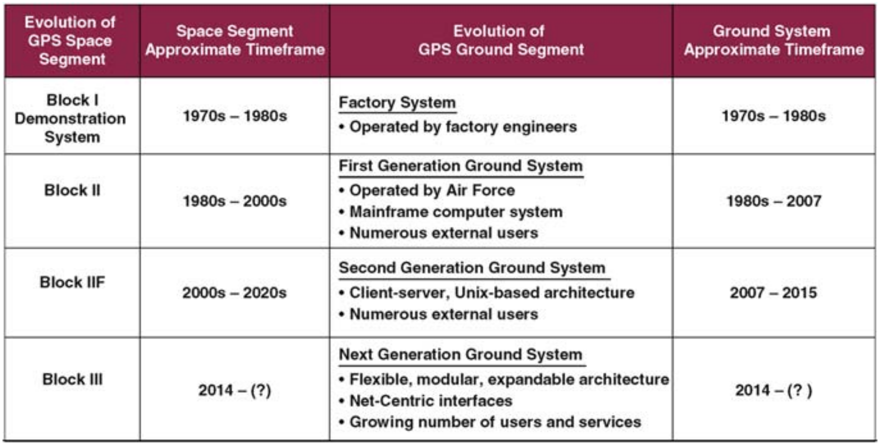
"Architecting" as Systems Engineering and Technical Leadership

Many, if not most engineered systems that are to be developed and deployed must become part of a pre-existing "system architecture." These architectures represent collections of people, organizations, processes, and equipment that are already performing some function that the new engineered system will presumably augment. Transforming or modernizing any such existing architecture must usually be done incrementally, and yet the natural desire is to envision (and "architect") the desired end-state for the modernized system architecture. Usually the cost of modernization is high and this necessarily limits how much of the system architecture can be changed. Often, existing assets cannot be taken completely out of service in order to upgrade them. Therefore it is usually necessary for systems engineers to promote the optimization and evolution of system architectures by gradually changing portions of the architecture as opportunities arise, and in ways that support and augment services that people are currently using.

Case: Modernizing Ground Systems That Support Satellite Operations

The challenge posed by modernizing through incremental upgrades is well illustrated in the current efforts to upgrade ground systems that support orbiting spacecraft. In the earliest days of space operations, ground systems were simple stations that provided data or services to small numbers of experts who were familiar with space systems. As spacecraft have become more capable, the number of people using services from space systems has grown to include those who have little or no knowledge of space systems. This has been made possible by increasing sophistication in ground systems that now provide highly processed products very quickly to end-users throughout the world.

The evolution of ground systems supporting the GPS satellite constellation provides one of the clearest examples of the modernization challenge. Since the GPS system is now a "utility" that cannot be taken out of service, it must be incrementally modified while in operation. These incremental modifications are packaged as "block" changes, as shown in Fig. 15.1. The ground and space segments are evolving separately and the development cycles often overlap. For example, the Block IIF



Evolution of GPS Space Segment	Space Segment Approximate Timeframe	Evolution of GPS Ground Segment	Ground System Approximate Timeframe
Block I Demonstration System	1970s – 1980s	Factory System • Operated by factory engineers	1970s – 1980s
Block II	1980s – 2000s	First Generation Ground System • Operated by Air Force • Mainframe computer system • Numerous external users	1980s – 2007
Block IIF	2000s – 2020s	Second Generation Ground System • Client-server, Unix-based architecture • Numerous external users	2007 – 2015
Block III	2014 – (?)	Next Generation Ground System • Flexible, modular, expandable architecture • Net-Centric interfaces • Growing number of users and services	2014 – (?)

Fig. 15.1 Evolution of major segments of the GPS system architecture

development cycle was still underway when the Block III development cycle began, and development of the second generation ground segment overlapped with Block IIF and Block III space segment development. Thus, as modernized ground systems are designed, they must also be "backwards compatible" with spacecraft from previous blocks that are still in operation in orbit, leading to significant engineering leadership challenges.

A specific example of these leadership challenges arises from the fact that the need for new capabilities in the GPS system continues to evolve in the user community. These evolving needs generate new requirements that are gradually incorporated into the design of each new block. For example, the uses of GPS signals have become so sophisticated that many government agencies now need data from the GPS ground segment in addition to the broadcast navigation signals that come from the satellites. The longstanding approach to satisfying requests for such information has been to write an "interface control document (ICD)" that specifies the data or services to be exchanged, along with formats, timeliness, locations, etc. This has resulted in dozens of ICDs, each of which may require months or even years to negotiate. These agreements then result in requirements that must be levied on the engineering design of the ground system, and may change the design of the system at its lowest levels, as shown in Fig. 15.2. To verify the effectiveness of such design changes, tests must be conducted sequentially up through higher levels of the integrated system, and also coordinated between the two segments.

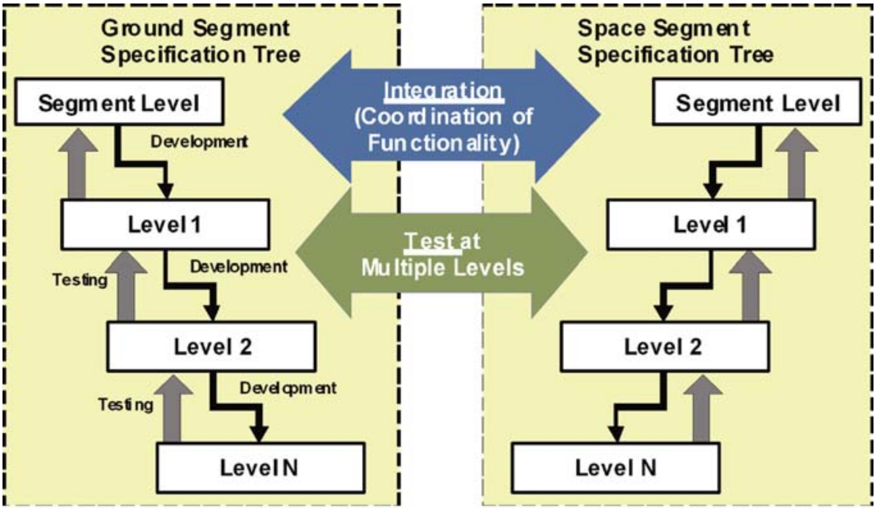


Fig. 15.2 Development and test cycle

Therefore changes in user needs may ultimately ripple through the design of the entire system in a complex way, requiring modification to both operational systems and new systems under development. Additionally, many ICDs provide for the same or similar data to be sent to different users, which leads to a duplication of interface definitions and an increase in the complexity of managing these interfaces. It is possible therefore that the strategy of negotiating a custom ICD for each customer could easily become impractical if the number of users of GPS data continues to grow rapidly, which is the expectation. These circumstances have led to a different strategy for future blocks in which GPS data would be provided in a "net-centric" fashion via a government network called the Global Information Grid. In this net-centric approach, authorized users would be provided with a way to search and discover the GPS data needed to accomplish their tasks, rather than negotiate the data they need in advance.

Several observations about system engineering and technical leadership can be drawn from this example, as discussed below.

Evolving System Architectures

Space system architectures may evolve continuously, even while portions of them are being upgraded. The GPS example is instructive. Each succeeding generation of GPS space and ground system has been more capable, which in turn has inspired new uses of GPS, which in turn has generated changes to the space and ground segments. This co-evolutionary process can be guided but it cannot be completely controlled. As a result, changes to the GPS system specifications may ripple asynchronously through the project, as illustrated in Fig. 15.2. A principal lesson from this example is that technical leaders are working for the benefit of the some larger community (i.e., GPS users), but grappling with complex technical and organizational issues that may be driven by unrelated priorities and constraints (i.e., funding, technical problems, etc.).

Backwards Compatibility

In the GPS example, each succeeding modernized system must be compatible with previous blocks. For example, each new ground system must be compatible with several generations of spacecraft (e.g., GPS IIA, IIR, IIF, III), each of which were designed to different requirements. The operational procedures for the older spacecraft (e.g., GPS IIA) that are in operation may be changing while the development team is designing and building the next generation system (e.g., GPS III). Therefore, changes to preceding generations may inject changes into the new system while it is being designed. As new projects become larger and more complex, the problem of fitting the new project into the existing system architecture may become so complex that it strains existing organizational and engineering methods for approaching such problems.

Architecting for Transformational Effect

The GPS system architecture is following a common pattern of evolution, in that early systems are somewhat customized for users, but later systems move toward developing standards and "standard interfaces" that allow users to design their own methods for using the system. The architecture that implements this strategy must allow the standardized interface to evolve over time, and when it is changed, must allow changes to be made in such a way that they do not affect other users or parts of the system (i.e., modularity). The objective of this approach is to decouple the development cycle of "user systems" from that of the GPS ground system, while not impeding the ability of users to discover new uses for the GPS system and implement them. The development of such standards is a very challenging process that must be led by system engineers who can develop good technical strategies and conduct successful negotiations with the agencies involved.

This case illustrated the fact that the complexity and risk we see in many engineering projects are not simple artifacts of the size of the project; they are defining features of the systems engineering problem in general.

A second example illustrates that in some cases the system architecture should be modified largely through changes to operational procedures, and not by adding new engineered systems or components to address a need.

Case: Improve Timeliness of Weather Data

Accurate, timely, and comprehensive weather information has always been of paramount importance to the economy and public safety, and to meet the need, various organizations gather weather information, analyze it, and distribute it. This "weather system" was not explicitly designed as a whole; it evolved over a long period of time to meet exigent needs. In the early 1960s, the first weather satellites introduced global coverage, and gradually transformed weather prediction by adding a new stream of sensor data that was more timely, more detailed, and more geographically diverse than anything that had existed to date.

At present, the National Oceanic and Atmospheric Administration operates government weather satellites. One of the weather satellite constellations is a group of satellites that crosses both poles of the Earth at an altitude of 540 miles and orbit the Earth approximately once every 100 minutes. The satellites provide information that is essential for effective disaster-response planning and timely response to severe weather conditions, such as tornadoes and floods (National Polar Orbiting Environmental Satellite System. www.ipo.noaa.gov). Current orbiting systems can provide data to end-users in hours or days, but to make quick response to weather emergencies more effective, new satellite systems in development are being designed to provide data to end-users within 15 minutes.

Systems engineers familiar with the weather satellites currently in orbit began to analyze methods by which these existing satellites might be made to meet the new requirement, even though they had not been designed to do so initially. They recognized that current satellites download data only to ground stations in the northern hemisphere. Since the satellites orbit the Earth approximately once every 100 minutes, data downloads must occur more frequently each orbit in order to reduce the data latency. The orbiting satellites cannot be altered, but they can be commanded to download data more frequently. However, little money is available for upgrading the existing ground station system, so innovative approaches had to be considered.

Engineers who were familiar with the existing NASA ground system network architecture discovered after some analysis that NASA's existing McMurdo ground station in Antarctica, used by the National Science Foundation (NSF) and NASA, would be a perfect location within the southern hemisphere to download data. The concept involved adding a receiver to an existing ground station, and then sending the data back up to existing communications satellites for relay to processing centers in the United States, as shown in the concept drawing in Fig. 15.3.

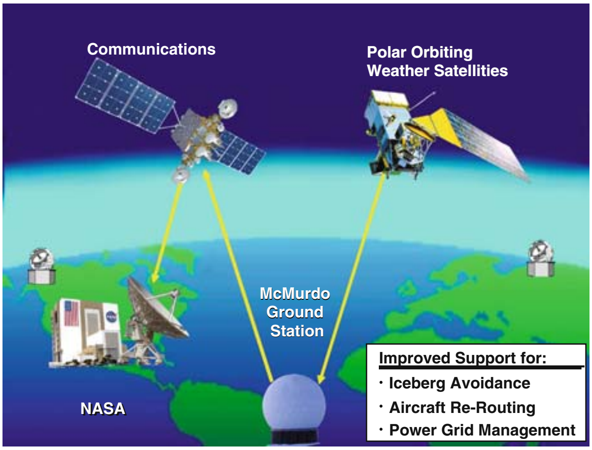


Fig. 15.3 New concept for weather data relay from satellites

Systems engineers briefed this concept to officials at NASA, the NSF, and other agencies, and gradually created a consensus concerning the need and feasibility of the project. Eventually funding and approval for a demonstration project was given and the system was successfully tested, with the same engineers coordinating the use of needed assets owned by different government agencies.

We can make several observations concerning systems engineering and technical leadership from this example.

Non-technical Solutions

The change to the weather data system above was largely a change to operations, and involved relatively few changes to engineered systems. But the systems engineers who recognized the opportunity and developed a plan for implementation had deep technical knowledge of the system architecture, and are unlikely to have been successful without it. In this case, the orbiting assets and ground stations were controlled and operated by different agencies. Changing the operating procedure required the ability to identify a need, propose a system solution that was agreeable to all, and obtain funding in which the disparate stakeholder organizations (NASA, US Air Force, and NSF) contributed. In this case, systems engineers exercised technical leadership by finding a solution that was beyond the usual bounds of engineering. Their negotiating skills and technical credibility were necessary to reach agreement and implement something new. The results in these cases can be just as transformative as if a new engineered system had been built.

Innovation and Project Origination

Systems engineers acting as technical leaders are in a unique position to identify certain kinds of helpful innovation, and build consensus for new projects that will utilize it – two skills that are central to entrepreneurship. While the need for new capabilities often originates with business leaders in marketing, for example, or with government leaders, technical leaders are often "entrepreneurial" throughout the life of projects. Businesses that have a highly technological nature, such as aircraft, chemicals, petroleum, or pharmaceuticals should expect that many of the best ideas for innovations will originate in "operations." Most importantly though, systems engineers are probably uniquely familiar with the system architecture, and may be in a position to offer ideas for improvements or see problems that others simply will not see. As any system architecture becomes more complex, it will involve ever more complex interactions with other people, processes, and the environment. In some cases these interactions will represent opportunities and in others, unintended consequences. We should expect technical leaders to be active and ethical entrepreneurs in the sense described here.

The discussion above has illustrated technical leadership as it pertains to customers and beneficiaries of the system. We now turn our attention to technical leadership as it pertains to internal project execution – that is, producing the expected engineering results. Systems engineers are often the bridge between these two very dynamic areas.

Technical Leadership in Guiding Projects to Their Ultimate Aim

Large-scale engineering projects can take more than a decade to complete. During this extended period, program requirements are being translated into myriad engineering requirements and these are further translated into the operations concepts involving the people who will use the system, and into the actual hardware and software needed. During project execution, systems engineering leaders help guide technologically difficult projects to the expected technical capability at the expected cost.

While systems engineers are not usually responsible for controlling the cost of projects, their help in matching requirements to resources, evaluating technological readiness, and identifying technical risk as the project proceeds is essential to controlling cost. There are many examples of projects that overrun their intended cost, or otherwise fail to meet expectations. In 2009, the Government Accountability Office (GAO) released a report that found that the cost of major US weapon programs is exceeding initial estimates by a “staggering sum” of nearly $300 billion. The cost to buy the 96 major defense initiatives the GAO studied is $1.6 trillion, or $296 billion more than first estimated for these systems. That is a small improvement from last year, when the GAO found $301 billion in cost growth for the same programs (United States Government Accountability Office, 2009). The reasons for cost overruns are typically extremely difficult to discern and are affected by a variety of complex factors. Somewhat paradoxically, some studies have concluded that excessive attention to cost control without due attention to technical risk is a primary factor in cost overruns (Joint Task Force of the Defense Science Board, 2003). We can discover some of the potential sources of this technical risk, and the role of technical leaders in addressing it, by examining the engineering workflow during project execution.

Systems engineering during program execution is often presented as a process whereby the system specification is translated and allocated to subsystem specifications, and then into lower-level specifications. This results in a list of specifications in which top-level requirements are gradually refined and then allocated to engineered products, as shown in Fig. 15.4.

The motivation for this specification tree is to get large groups of people organized and working effectively together on large projects. This technique leads to the

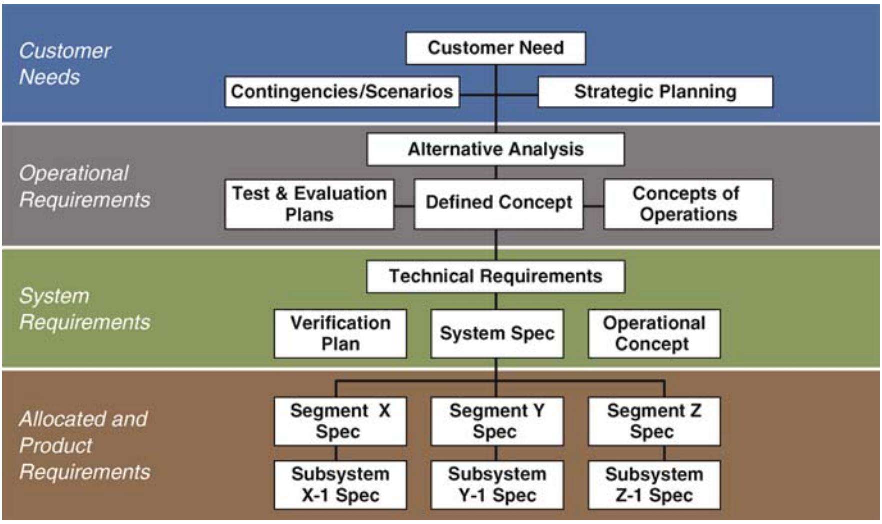


Fig. 15.4 Notional specification tree

common view that system engineering is concerned with the "engineering management" of a project. But this decomposition of a system description into subsystems and then into lower levels of the system is not a mechanical coordination process. It is usually a sophisticated piece of engineering in itself, and one that requires considerable experience, skill, and leadership. The initial decomposition of the system requirements may have to be done with very little information about the ramifications on the complexity of resulting system. Decision-making about the decomposition is based on the coordinated use of sophisticated design tools in a process of iterative analysis that predicts the performance of the system under various conditions. Poor decisions about the decomposition may lead to a collection of subsystems that contain overly complex designs that are riskier to develop than is necessary.

Furthermore, the decomposition process creates "interfaces" that must be coordinated, and this is also the domain of systems engineers and technical leaders. Often these interfaces span not only system or subsystem boundaries, but organizational boundaries as well. Most projects are divided into pieces that are implemented by different organizations and companies, which results in complex organizational and contractual problems. Technical leaders are therefore confronted with these "organizational interfaces," which may be more complex than technical interfaces. Organizations, after all, are complex systems in their own right, people-based, but nonetheless systems, elements working together to a larger purpose (Rechtin, 1999). The typical approach to dealing with this is to write detailed technical specifications to guide the relationship between the organizations, but such specifications rarely contain all the needed information, and often serve only as a framework for discussion. Technical leaders are called upon to actively clarify misinterpretations, solve engineering problems in the interface, and negotiate mutually agreed solutions.

As the project moves through the usual cycle of "Requirements–Design–Test," the engineering team will make decisions about which design approach to use for each subsystem and component, and how to verify performance through test. Often, the design approach selected is not the lowest risk approach, and technical leaders should be identifying design alternatives and making the team aware of the effects of design choices on overall program risk. As the design unfolds, plans to acquire early test information about critical areas should be developed, even though it is often costly to do so. Technical leaders should be working to justify and explain the need for such expenditures.

Finally, plans for verifying that the system meets requirements must begin early in the project, and must be continually re-planned throughout the project. There is often considerable and unexpected "organizational complexity" here as well. In some cases the company or agency that will do the testing and "acceptance" of the product is external to the company that is producing the product – and this implies a process of negotiation that must begin very early for complex projects. Some space systems have several hundred "system level" requirements, and these may generate 20,000–30,000 or more total requirements that have to be designed into a system, tested, and shown to meet requirements. In the case of government-funded projects, the government agency doing the acceptance procedure is often not the same government agency that managed the development project, and usually has a different interpretation or perspective on the way to do acceptance testing. Technical leaders are active in interpreting how requirements should be tested throughout the multiyear span of the program, and in negotiating with other divisions, companies, and agencies as to how the products of the development project can be "sold-off" to the client.

There is a temptation to view the development process described above as something that can be designed and controlled, but we can view the process from a different perspective that emphasizes its leadership aspects. At the beginning of a project, the team has a set of "mission needs" (shown near the top of Fig. 15.4) but may have no knowledge of what the specification tree below it will look like. As the project proceeds, design work gradually reduces the uncertainty in the project by defining pieces of the system around which further definition in the system can coalesce. In this sense, "system engineering" can be interpreted as the work of gradually reducing uncertainty, and therefore program development risk as the project proceeds. Design work generates not only a picture of top-level features and performance of the system, it generates (ideally) consensus among team members about the analysis and approach. The development team essentially learns how to interpret and implement requirements in increasing detail as the project proceeds. This process can be viewed as "value creation," (McManus, 2005) in which the original vision is translated into what is needed at manageable risk and cost. From this perspective, technical leadership is value creation.

Systems Engineering Tools for Addressing Program Risk

As systems engineering projects have become more complex and more costly, the cost of failure has become enormous. Improved and practical methods for dealing with program risk should be a central pursuit for system engineers and technical leaders. The term "program risk" as used here simply refers to the risk that the product will not meet customer needs at the agreed cost. The most common means for addressing program risk on development programs is to use the project's own engineering team as a surveillance network for identifying risks, and as a problem-solving network for building consensus about how to proceed. Most engineering projects of any size are set up with considerable internal structure to promote this behavior, which often takes the form of "design reviews" or "peer reviews," backed by structured requirements-allocation processes and "work package" systems that guide the execution of the work. However, there are many difficulties stemming from engineering interpretation of uncertain information, as well as organizational boundaries that may block effective consensus building and risk management.

Here we briefly mention engineering tools in the areas of concept design, mission assurance, and software engineering that have been developed for use at The Aerospace Corporation to address program risk issues on space system development projects.

Conceptual Design Tools and the Concept Design Center

In the early phases of complex engineering projects it is not easy to predict which engineering design parameters are most important for controlling program risk. This of course can lead to a lack of awareness on the part of the project management (and clients), which ultimately can lead to projects that are set up initially with more risk than is realized. A collaborative design process and tool called the Concept Design Center (CDC) is used to address this problem. The collaborative process helps build group consensus, or at least shared understanding, of the technical approach and plan being chosen (Smith et al., 2001).

A conceptual design study is a quick look at what is feasible to build and how much it could cost. The intent is to gain insight into a project's requirements, not to determine the precise value of each design parameter. To get a feel for the questions that such studies answer, consider the example of a proposed mission to detect forest fires from space. What is the size of the smallest fire that the spacecraft must be able to detect? What types of sensors can be used? Who needs the data? How quickly must it be obtained? How many spacecraft are required? How much will the mission cost?

Using the CDC, engineering specialists, project management, and customers work together in a series of sessions in which design concepts that meet customer requirements can be proposed and discussed rapidly (several times per day). The tool uses linked engineering models of architecture, spacecraft, ground, and payload subsystems in order to predict weight, power, volume, and other performance parameters. Using this information, the system can provide nearly instant visualization of the mission orbit parameters, the overall shape and layout of the spacecraft, the ground system functional layout, or payload subsystem details. Analysis of the interplay of the system components is readily available. The value of this information is that customers can see how their requirements are actually translated into a space system, and get a better sense of the engineering options and constraints.

Each participant in a CDC study has a specific role on a design team, as illustrated in Fig. 15.5. A systems engineering study leader guides the group through a series of design iterations, which are each followed by discussions with customers about which design parameters are most important or costly. The visualization tool for the design concept and mission parameters are usually helpful in explaining this. In turn, engineering team members often learn something about how customers intended their requirements to be interpreted, and which requirements they really value most highly.

The CDC approach has been used to study most of the space mission areas, including for example, very complex space communication architectures such as that shown notionally in Fig. 15.6.

These studies are often spurred by the government's need to transmit growing amounts of voice, data, and video information through space systems, or to assess whether new technologies have made it possible to do so. To begin such a communications system study, analytical models in the CDC are updated to account for technical advances such as phased array antennas, lightweight centralized

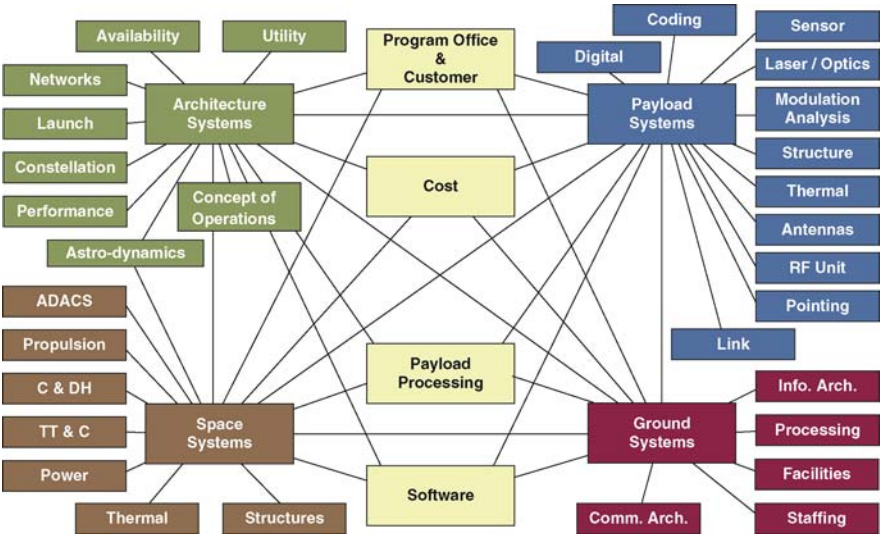


Fig. 15.5 CDC team interactions

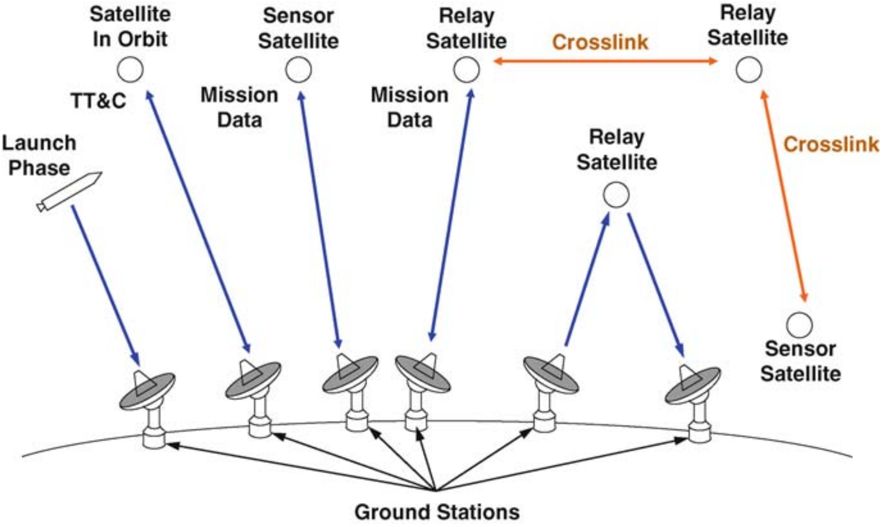


Fig. 15.6 Elements of a space communications system architecture

processing, and network packet switching. Specific system concepts are then developed and their performance is analyzed.

The primary metrics considered in these studies include life cycle cost, satellite availability, space vehicle mass, space vehicle power, and coverage, as described below:

- *Life cycle cost:* Life cycle cost refers to the total cost for space, launch, and ground segments over the life cycle of the mission.
- *Satellite availability:* Satellite availability is the probability that a specified number of satellites in the constellation will be functioning and available for communication services. This is typically a function of the satellite sparing and replenishment strategy, as well as the mean mission duration (MMD) and design life of the space vehicles.
- *Space vehicle mass:* The space vehicle mass is defined as the wet (with propellants) and dry (without propellants) mass of the integrated payload and spacecraft bus.
- *Space vehicle power:* The space vehicle power is defined as the power generated by the space vehicle at beginning-of-life (BOL).
- *Coverage:* Geographic coverage as viewed from each satellite is calculated for the defined minimum elevation angles. A fold of coverage is the number of satellites that can be seen from a location.

An example of the kinds of information that can be developed is shown in Fig. 15.7, which identifies the number of satellites needed for continuous global coverage as a function of satellite constellation altitude and minimum elevation angle of the satellite.

Information of this kind can be used by systems engineering experts to explain the "big picture" and constraints of the problem to those who are not expert in space systems. With this information and the other metrics shown above, various system concepts can be compared and judged as to their value, effectiveness, utility, technical performance, feasibility, and risk.

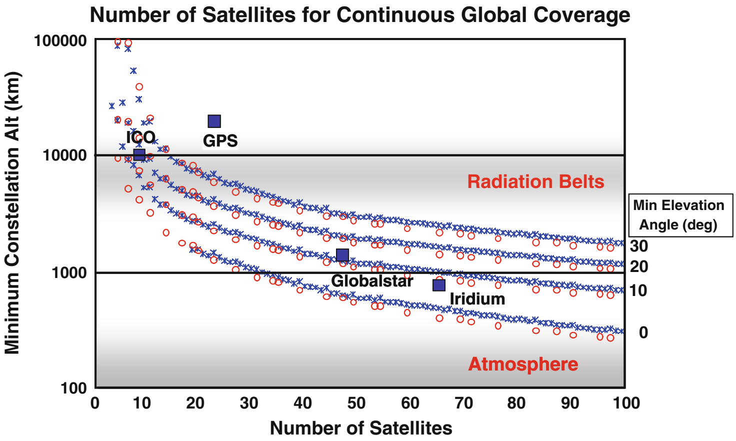


Fig. 15.7 Example of system design trade-off information

Mission Assurance Tools

In the late 1990s, NASA and the DoD lost $3 billion dollars in space assets to launch failures (Ballhaus, 2005). This led to renewed calls for reinvigorated "mission assurance" processes to prevent such losses. The phrase "mission assurance" is used in space programs and elsewhere to refer to a disciplined application of systems engineering, risk management, and program management principles that leads to high confidence that the system will perform as needed by the end-user (Guarro, 2007). A principal method for achieving high confidence is to methodically identify and address technical problems in the design or manufacturing process using a rigorous "design-test-verify" cycle. Confidence grows incrementally as the project team learns about each problem, develops solutions, and receives test results. But in practice, the rigor of the engineering process is limited by time and resources, and project managers must decide where to apply such limited resources using engineering judgment and advice from the project team. To support this process, systems engineers are often called upon to gather information about engineering problems and assess risks and solutions. A common method for doing this is to utilize the expertise of the engineering staff as a risk surveillance and problem-solving network. This technique, however, is prone to certain subtle problems.

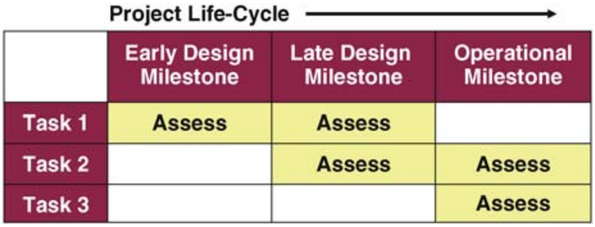
A common problem is that engineers working on components of the system may recognize a risk element but be unable to "elevate" or communicate the importance of the problem to management. The principal cause of this phenomenon is that many engineering assessments are actually projections of what might happen under certain specified conditions, which may or may not occur, and are therefore probabilistic in nature. Not only are such projections subject to debate, but they are often not factored into decision-making processes correctly. As a result, such problems may be addressed at too low a level in the organization, or may not receive the management attention or perspective they should. This apparently happened prior to the space shuttle *Challenger* accident, for example. As we now know, the O-ring problem was not addressed properly even though engineers on the program were aware of the limitations of the O-rings and voiced their concerns prior to launch (Presidential Commission on the Space Shuttle Challenger Accident).

The multiyear duration of development cycles may also lead to errors in judgment about risk. In some cases, design problems may be identified months or years before information is available to assess the risk and develop solutions. In the interim, it is possible to become accustomed to initial risk levels over time, and even layer further risk elements into the program without full awareness of the overall impact. And as time progresses, resources become more limited and the root cause of previous problems may not be fully determined in the press to move forward.

"Organizational complexity" may also significantly affect the ability of the project team to assess risk. A large engineering project may engage hundreds of engineers, some of whom may be working in different companies or divisions, often in different locations (sometimes different countries), and always busy with deadlines. Sometimes, a project is "matrixed" into a larger organization so that it has a small full-time project staff supplemented by part-time engineering matrix support that is part of a different management structure. These organizational boundaries may make collaborative action on risk assessment very difficult, for obvious reasons.

In these environments, risk discussions do not naturally "roll up" to senior project managers and system engineers in an addressable manner, and a special framework to identify and assess program risk across these organizational boundaries and lengthy timelines is necessary. An example of a tool that provides such a framework is the "integrated Mission Assurance Tool (iMAT)," which is being developed and deployed at The Aerospace Corporation to improve assessments of progress and risk on space programs.

One of the functions of iMAT is to help a group of experts reach consensus on the technical risk in a project at key milestones. The framework in its simplest representation is a list of tasks that the project must complete during the course of the project, along with specific milestones at which an assessment of the progress and risk on the task will be done, as illustrated in Fig. 15.8.



	Early Design Milestone	Late Design Milestone	Operational Milestone
Task 1	Assess	Assess	
Task 2		Assess	Assess
Task 3			Assess

Fig. 15.8 Notional task and assessment structure in iMAT

Each task has an owner (responsible engineer), a set of criteria by which it will be evaluated, and a risk matrix. This is all presented to project team members through a Web browser to allow everyone to see the progress and risk of other tasks, as well as to work together on risk assessments. A risk assessment for each "assess box" in Fig. 15.8 is captured on an "assessment sheet," as shown in Fig. 15.9.

The purpose of these assessments is to gather technical risk judgments methodically throughout the life of the project, and to use them to do a risk "roll up," as illustrated in Fig. 15.10, that gives a sense of project-level status and risk areas at regular intervals.

The purpose of the roll-up is to involve the project team in a discussion that results in an awareness of risk areas in the project, which are represented by yellow areas in Fig. 15.10, and how these might affect overall project risk. The task of developing an integrated picture of project risk when the project is evolving in time (years), fragmented across organizations (dozens), and profoundly complex is one of the most difficult tasks for systems engineers and technical leaders. A large portion of this difficulty proceeds from the nature of the evidence upon which risk evaluations by technical experts are produced at the component and unit level. In most cases such evidence is in fact qualitative, or quantitative in a form that does not easily map into the standard risk metrics (e.g., probability of a specific type of impact) that are relevant at the system level. As a result, the significance of

Mission Assurance Assessment Sheet - Microsoft Internet Explorer

Assessment Sheet

Standard Verification Task	Reviewer's Participation	Task Status	Adequacy or Impact
Assess the Design and Component Qualification Status Against the Mission Requirements and Operational Plan	Analyze & Assist	Open (On Plan)	Adequate

Discussion of Risk

Rationale

Responsible Engineer: John Q. Smith In Work

Role	Name	Concurrence

Fig. 15.9 Risk assessment sheet in iMAT

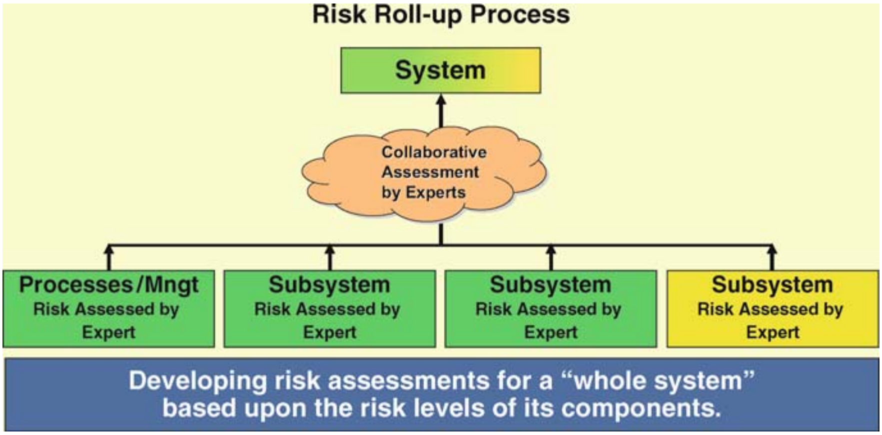


Fig. 15.10 Risk roll-up process

the lower-level "risk symptoms" is often unclear and subject to debate at a higher rolled-up level.

The collaborative process depicted in Fig. 15.10 provides a mechanism to address the roll-up issue. In the more difficult and contentious situations it may actually become necessary to develop and apply formal risk models for the issue at hand. These models seek to represent in explicit logic format the possible impacts that lower-level risk conditions may produce at the system level. For example, a formal mission risk or reliability model may be utilized to evaluate the potential mission risk contribution of a given component and to understand what level of additional testing may provide sufficient confidence in its reliability performance. Or, as another example, a formal schedule simulation model may be used to understand the potential impact on the system and program critical path of test/retest delays affecting a specific unit. A discussion of the principal formal risk modeling techniques that may be applied to address these challenging situations can be found in Guarro and Vesely (2004). In general, the collaborative process that we have mentioned above is used to determine whether a qualitative risk roll-up judgment is possible, or whether a more in-depth assessment of risk implications at system or subsystem level may be necessary.

Software Process Modeling

In 2004, the Government Accountability Office reported that the Department of Defense may have spent approximately $21 billion on software development, and that roughly $8 billion (40%) of that amount may have been spent on reworking software because of quality-related issues (United States Government Accountability Office, 2004). A principal cause of this problem is that it is notoriously difficult to get the project resources needed to implement rigorous engineering processes (requirements–design–test–verify) and early risk-reduction efforts on software projects. One of the reasons for this reluctance is that it is often difficult to visualize the complexity of the software development process, and therefore common to underestimate the resources, time, and processes necessary (Greer et al., 2005; Houston et al., 2009, 2001). We can gain deeper appreciation for this complexity using a systems dynamics model with which we can model the engineering work process for each software "build" (version), as shown in Fig. 15.11.

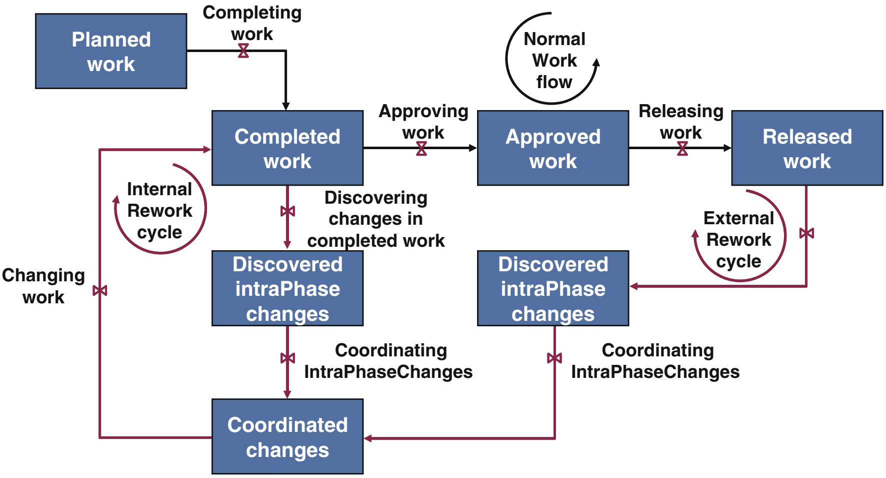


Fig. 15.11 Example systems dynamics model of software process for a "build"

Although we often think of these software builds as though they were "widgets" on a production line, quality problems (rework) and design changes actually feed back into current builds or feed forward into builds scheduled for later release. For example, the next build is often entering a "requirements phase" at the same time a previous build is being tested. This leads to overlapping schedules and then to "interphase coordination" and rework that ripples through related software activities, as shown in Fig. 15.12.

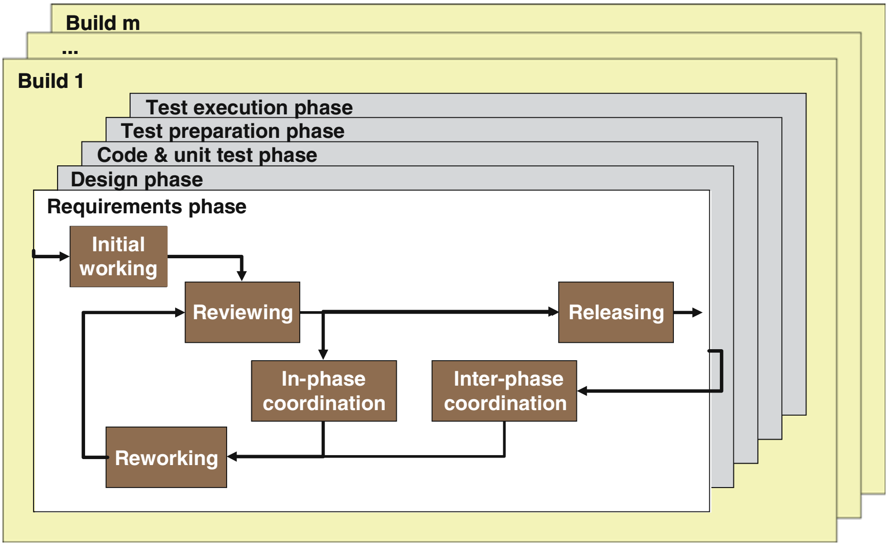


Fig. 15.12 Interphase coordination in software development projects

This complexity in engineering processes leads to workload-planning issues that are extremely difficult to grasp by relying only on managerial experience or engineering intuition. Using the dynamic models just described, it is possible to show quantitatively the effect of various engineering problems (e.g., defects) on the workload and time, as shown in Fig. 15.13.

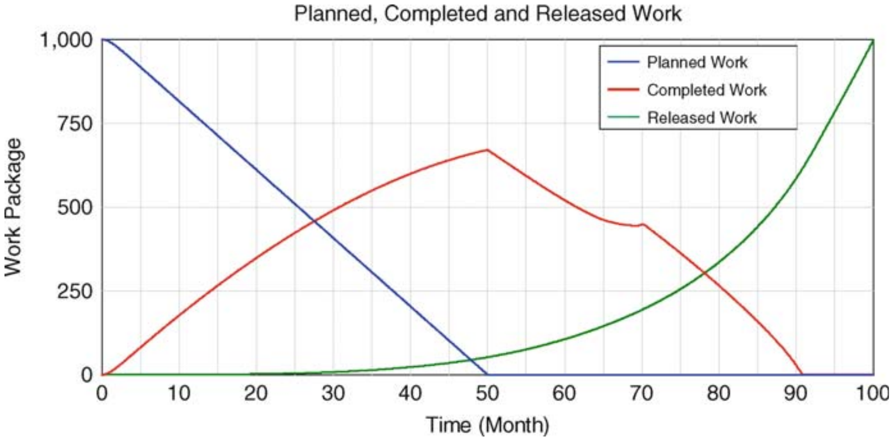


Fig. 15.13 Software development workload modeling

Work packages move from "planned" status to "completed," and then to "approved" and "released," according to the model in Fig. 15.11. As work is approved, the number of completed work packages should decline to zero prior to the 50-month point, but rework of "completed" and "released" packages continues for 90 months, giving a completely different profile of work than what was envisioned. These types of models can be used to demonstrate the beneficial effects of early problem detection, because the cause of specific workload problems can be traced back through the model and related to the engineering approach, and results can be shown quantitatively. These types of system engineering tools will be essential to dealing with risk and complexity associated with engineering management problems in the future.

The systems engineering tools discussed in this section are just three examples of tools that are specially designed to promote a disciplined and consistent approach to systems engineering and risk management. On complex development projects, systems engineering leadership skills that are supported by specialized tools such as these are essential to guiding development, adjusting to changes, and correctly assessing risk.

Engineering Ethics – Realities of an Imperfect World

After the global financial and economic crisis in 2009, business leaders wondered whether MBA schools were adequately addressing business ethics, especially with regard to controlling risk. In many cases, the economic risks to an individual business can be reduced in such a way that "systemic risk" to the entire economy is increased. It is also commonly known that a short-term focus may place the long-term health of the business in jeopardy.

Systems engineers have to deal with similar ethical challenges where the implications of their decisions can transfer, defer, or exacerbate risk. Systems engineers may in fact be the only people in an organization who can correctly assess the implied risk of alternative engineering options from both a technological and managerial perspective, which are implied by a particular system design or architecture. The complexity that necessitates architecting of systems brings ethical complexity as well. The complex unprecedented systems-of-systems that systems engineers are developing have the potential for severe consequences that may not be immediately apparent but nonetheless have long-term effects.

A survey of Rutgers University students found that in graduate school, a significant number of students admitted to cheating (MBAs 56%, engineering 54%, education 48%, and law 45%). The Ethics Resource Center's 2007 national business ethics survey results showed that within the corporate environment, 56% of employees have observed misconduct; 36% fear retaliation; and 54% are skeptical that a report would matter (Ethics Resource Center, 2007). Management may not be aware of misconduct, since 42% of employees who observe misconduct do not report it.

While the survey data sources are limited, the results suggest that, nationwide, our standards have been eroded and that unethical behavior is widely tolerated.

In striving for results, it is important to exercise ethical technical leadership and engineering judgment. The goal should be sustainable solutions with effective use of resources, resulting in a net positive benefit for society. There are two key dimensions to engineering ethics: objectivity and integrity.

Objectivity requires that the engineering assessment be based on facts, data, and algorithms that are not subject to interpretation. The initial conditions set by a customer may vary to generate different solutions, but the engineering rigor that is applied to the problem must be technically sound. This may result in an answer that is unpopular or fails to meet other constraints such as cost and schedule. The gives the systems engineer a new challenge of negotiating with the customer for less stringent or fewer requirements, schedule relief, or adjustment of cost goals.

Integrity requires that the systems engineer be accountable for the quality of the work performed and that the engineering results be completely open and honest. Any possible conflict of interest, whether individual or organizational, real or perceived, should be declared before the start of the project so that it can be mitigated.

While it would be impossible to make an exhaustive list of what constitutes good engineering ethics, most would agree that "you will know it when you see it." When faced with an ethical crisis, one litmus test that is useful for determining an appropriate course of action is the "Washington Post Test." If your planned action was described on the front page of the newspaper, would you still be comfortable with your decision? Or, alternatively, the "failure investigation board" test: if your decision came under scrutiny after a failure occurred, would it hold up to an in-depth inquiry?

Unethical actions are counterproductive and costly. They are usually discovered late in the process, which may result in embarrassment, penalties, and loss of capabilities, in addition to the cost of repairing the flawed system. As technical leaders, systems engineers have ethical obligations to identify and help manage financial and business risks in addition to technical risks for their customers and for the larger community.

Where Are the Next Systems Engineering Challenges?

We have discussed some of the transformational systems engineering projects from the recent past. In each instance, the value of the solution arises from the fact that the overarching architecture responded well to evolving requirements, complexity, and significantly increased user communities. As systems engineers, it is important to shift from a traditional isolated problem-solving viewpoint to a more holistic approach of creating capabilities that will evolve to meet yet undefined emerging needs. As we look to the future, our knowledge-driven, technology-dependent global economy will require new paradigms in order to innovate for the next generation of transformational solutions. Research is required to foster new ideas and new approaches to development in order to address complex, non-uniform systems-of-systems that "fail soft" and are still well-behaved under unanticipated or contested conditions. Interestingly, recent efforts to inspire that innovation have recognized the inherent value of interdisciplinary engineering teams working on "Research Grand Challenges."

A Research Grand Challenge for engineering pursues a series of goals that are recognized as being one or two decades in advance of current technology. Many people are familiar with the DARPA Grand Challenge autonomous vehicle competitions. Cash prizes are offered to further DARPA's mission to sponsor revolutionary, high-payoff research that bridges the gap between fundamental discoveries and their use for national security. The 2007 DARPA Urban Challenge was an autonomous vehicle research and development program with the goal of developing technology that will keep warfighters out of harm's way. The Urban Challenge featured autonomous ground vehicles maneuvering in a mock city environment, executing simulated military supply missions while merging into moving traffic, navigating traffic circles, negotiating busy intersections, and avoiding obstacles (See the DARPA Website: http://www.darpa.mil/grandchallenge/overview.asp).

An initial set of Research Grand Challenges for Systems Engineering was proposed by Kalawsky (Kalawsky, 2008), which included the following:

- Ultra-scalable "human in the loop" systems
- Ultra-scalable autonomous systems
- System verification, validation, and assurance of extremely complex systems
- Modeling and simulation (M&S) – total systems representation
- Through-life information and knowledge management

The Conference on Systems Engineering Research (CSER) has a primary objective to provide practitioners and researchers in academic, industry, and government a common platform to present, discuss, and influence systems engineering research with the intent to enhance systems. Conference themes include systems science and thinking, and systems engineering technical processes, management processes, knowledge and information management, and support processes. CSER 2008 focused on the following research areas:

- Systems architecting and architecture tradeoff analyses
- Model-based systems engineering
- Application of systems engineering to the extended enterprise
- Agile systems architecting and engineering
- Systems engineering process design and management
- Integrated systems and software engineering
- Cognitive engineering and human-systems integration
- Socio-technical considerations in systems engineering

The International Council on Systems Engineering (INCOSE) has published its Systems Engineering Vision 2020, which provides a list of topics considered crucial to the advancement of the profession and the relevance of systems engineering to solving the problems of the future (INCOSE Systems Engineering Vision 2020, 2007). Five focus areas were identified:

- Global systems engineering environment
- Systems and their nature
- System engineering processes
- Models and model-based systems engineering
- Systems engineering education

Using systems engineering to address socio-technical global challenges will be an increasingly important area of future research for the strong benefit of all humankind.

One key challenge to being able to enhance the body of knowledge and state of the art of systems engineering is the critical shortage of qualified talent in science, technology, engineering, and mathematics (STEM). Recommendations to address these STEM issues have been suggested and pursued by Norman R. Augustine and the National Academies (Committee on Prospering in the Global Economy of the 21st Century, 2007).

Conclusion

We began by examining some definitions of systems engineering that described the process of engineering but not its value. A more holistic definition, one that speaks to its emergent value, might engender a more holistic approach in the field itself. We propose an addendum or postcript to existing definitions that speaks to this larger context:

> Systems Engineering is a transformative discipline that brings technical leadership and emergent value to the creation of complex systems for the benefit of society's current and future challenges.

It is imperative that existing definitions convey the exciting challenges and important responsibilities in systems engineering leadership that have been discussed here.

We also drew an analogy between technical leadership and business leadership in which we proposed that technical leaders know how and when to apply technological solutions to problems, know how to address uncertainty and risk, possess the team-building skills that enables leaders to work effectively across different organizations, and can guide projects toward strategic goals. Business leaders have similar responsibilities and challenges, but systems engineering leaders are in a unique position to see technical problems and opportunities that others simply will not see. Failure to address such problems simply shifts the burden to others, especially those who must absorb cost overruns, or suffer ill-conceived application of technology or unintended consequences to the environment.

For these reasons, systems engineers have both responsibility and a unique opportunity to practice technical leadership. Valuable new ideas and solutions are obviously welcome, but it is increasingly difficult to augment and transform the existing layers of complex systems-of-systems or the web of relationships represented by existing system architectures to produce such value. The systems engineer is in a unique position to apply broad technical and organizational insights to create a shared vision of the system architecture, and to bring together the unique capabilities of diverse disciplines and individuals to achieve success. A holistic worldview, one that appreciates these relationships, will be required to make more effective use of resources in the future.

Educators will be challenged to develop the engineer of the future, one who has the appropriate balance of technical, managerial, and leadership skills required to develop robust innovative solutions. The traditional case-study method using real-world examples, much like team design projects, is an effective way to develop the skills required for interdisciplinary and collaborative engineering teams that will be required to tackle complex problems. Research in grand challenges for systems engineering will not only foster innovation, but create working environments in which students can be exposed to the kinds of problems discussed here, and other even more complex problems such as those represented by non-uniform systems-of-systems that "fail soft."

Given the complexity of the systems being developed, a new set of tools is required to support the systems engineer whether they are working at the architecture level for a set of functional capabilities, or at a subsystem level where specific performance is being optimized. Risk and uncertainty are constant companions for the systems engineer since most problems require decisions be made without perfect knowledge. This requires disciplined risk management throughout the planning, design, and development processes. These complex projects require technical leadership with vision, initiative, risk management skills, team building skills, and a commitment to excellence. As is the case for the development of every leader, systems engineers need a lot more than technical training; they need to practice their profession and gain the insights that come with experience. The systems engineer is charged with ensuring that the right problem is being worked, the right engineering trades have been made, the right tools are being utilized, the appropriate priorities have been set, and that all contributors are working in unison to transform the architectural blueprint into reality.

Being a system engineer and, by definition, being the technical leader is a tall challenge, a tremendous opportunity, and an extremely rewarding endeavor.

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Chapter 16
Holistic Systems Integration

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Introduction

Systems engineers can no longer expect to design and build single-purpose systems that operate flawlessly in isolation. Instead, they must assume that they will create new systems by integrating independently developed elements to function harmoniously in a new framework and that their creations, in turn, will become components of larger, evolving, and unpredictable systems. To paraphrase John Donne, in today's increasingly interconnected world no *system* is an island.

A video available on YouTube, *The Big Brother Pizza Shop*, illustrates this point (http://www.youtube.com/watch?v=-zh9fibMaEk&NR=1). The video, produced by the American Civil Liberties Union, is designed to alert viewers to the sinister implications of large-scale information integration in the absence of privacy protection, but it does double duty by illustrating the clearly observable trend toward increasing systems integration. It portrays a phone call coming into a customer service operator at a future (and not distant future) pizza shop. Thanks to caller ID, the operator immediately knows who is calling, as well as the caller's address, date

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of birth, and national identity number. When the caller says he is not at home, the operator clicks on his employment information and offers to deliver the pizza to his work address.

After the caller orders two double meat special pizzas, the operator receives a pop-up alert to impose a surcharge (along with a handling fee) based on the specifics of the caller's medical history (which are also displayed to the operator) that will go to his health insurer unless he signs a claim liability waiver. A healthier food choice brings the price back down and the operator discovers from her online data that the caller's wife subscribes to a magazine containing a coupon that would lower the bill even more. The price is raised again, however, to cover the increased delivery risk to an "orange" crime area (derived from the inputs of the delivery address and crime statistics that update in real time via geographical information system technology). In the course of the conversation, it becomes clear that the operator also has easy "clickable" access to the caller's travel itineraries, his library borrowing history, all his purchases (including medications and clothes sizes), and his financial/credit issues.

Scary? In this example, yes. Technically feasible? Yes again. Such information integration is already taking place, enabled by technologies that allow systems to interoperate for data exchange. A clear demand for even greater integration comes from both businesses that see competitive advantage in creating new value-added services and military users who see mission capability enhanced by better fusing of multiple intelligence sources and automated connections between systems speeding up their ability to take decisive action. Citing just one commercial example, a few hundred dollars now buys a Global Positioning System (GPS) unit that not only detects a driver's position and can map out a route to his or her destination, but also ties into real-time traffic report data to help the driver avoid congestion.

Easy? Yes and no. Today's technology allows system "mashups" to create (some) new capabilities in hours and days, not months and years. However, this only becomes possible through rigorous, multifaceted systems thinking and engineering, which over time have defined a set of adopted standards, design patterns, and business models that create clear advantage. The enabling framework that has delivered these capabilities requires governance that facilitates enterprise-wide decision making to integrate systems across organizational boundaries.

Combining broader scope for integration and the demand to realize new capabilities in shorter time is not easy. Ensuring that separately developed systems work together in unanticipated contexts with ill-defined boundaries, when no one program manager controls all components and a plethora of stakeholders with different priorities may influence funding for each element, calls for techniques and skills beyond those taught in a traditional systems engineering curriculum. The techniques rest on architectural and technical design precepts enabled by modern technology, while the skills include the imagination to visualize a system from multiple perspectives and in multiple contexts: internal and external, present and future.

The perspectives and examples in this chapter primarily reflect the experience of The MITRE Corporation (http://www.mitre.org), which for 50 years has provided systems engineering services to government agencies. MITRE operates three federally funded research and development centers sponsored by the Department of Defense (DoD), the Federal Aviation Administration, and the Internal Revenue Service and Department of Veterans Affairs, respectively. These activities have given MITRE extensive experience in designing and managing large, challenging systems engineering and integration programs in the notoriously complex government environment. They require MITRE's systems engineers to maintain current awareness of commercial technology developments, both as curious and occasionally eager adopters and as agents of our government sponsors. This service to government has yielded insights that we hope have universal relevance.

Broadening the Scope of Systems Integration – Implications for Systems Engineering

Systems engineers in both the commercial and government sectors must assume that individual systems will eventually be connected (often virtually, not physically) and share information with others as part of an "extended enterprise." Information technologies provide the necessary interconnections that enable information exchange among systems, enabling them to provide new capabilities and support faster, more accurate, and efficient decision making. Improved decision making, based on the ability to sense, process, and make mid-course corrections in response to real-time information, confers an invaluable competitive advantage in both commercial and government operations.

While new technologies provide great benefits, they can also increase the complexity of sharing information across heterogeneous systems built for different businesses and users. This challenge is compounded when systems originally designed for standalone operation suddenly must connect to other systems and share information with them. The availability of standards and integrating technologies appears to offer a simple and straightforward pathway toward system integration and interoperability. As a result, well-intentioned chief information officers proclaim integration mandates, but these mandates cannot by themselves achieve the goal of integration and interoperability across an enterprise. This does not imply that "mandates" are useless, but rather that success depends on solid systems engineering and understanding of the larger enterprise.

Simply stated, achieving interoperability for integration is hard work and requires an enterprise perspective. Hence, systems engineering must consider the system's potential impact on the entire enterprise, as well as the impact of the enterprise on system development. We will refer to this broader perspective in systems engineering as enterprise systems engineering (ESE).

Complex Adaptive Systems

Complex adaptive systems theory may inform the practice of enterprise systems engineering in this fluid environment. The theory states that complex systems evolve on the basis of principles of variation (generating viable options), shaping (influencing the evolutionary environment), and selection ("pruning" the resulting evolving system); see Fig. 16.1. This implies that such systems cannot be fully specified and engineered "from the top down." Instead, they respond to change as ecosystems or species do by demonstrating emergent behavior: evolving (for good or ill) in ways that are not completely predictable.

Natural selection drives species evolution, with recognized shaping factors such as climate change, the introduction of a competing species, or the shock of a disaster (e.g., a large meteorite). As a systems engineering analogy to natural selection, consider the World Wide Web. No individual or organization fully envisioned its current form; it certainly did not result from a deliberate plan conceived and executed by the pioneers of the Internet, or anyone else. Its current state has come about through evolution, with its development shaped by bursts of variation (e.g., the dot-com boom) and periods of rapid selection (the dot-com bust). Influencing factors include regulatory policy, the availability (or lack) of venture capital, and the invention of new technology (e.g., Web 2.0). The Web continues to evolve, and no one today knows what form it will take in the future.

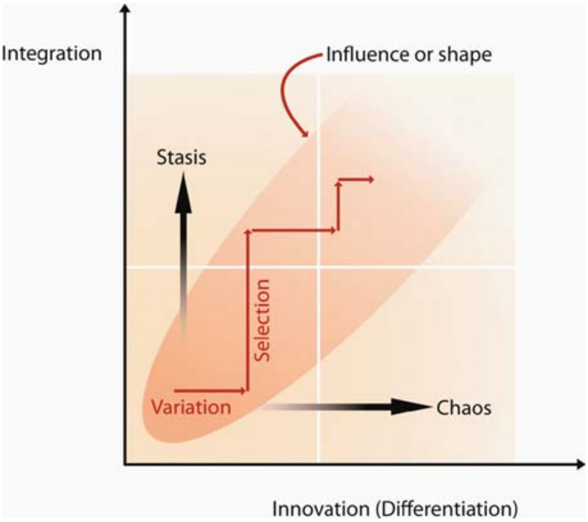


Fig. 16.1 Evolution of complex systems. Source: Adapted from Gharajedaghi, Jamshid, *Systems Thinking – Managing Chaos and Complexity* (Butterworth-Heinemann, 1999, and Axelrod, Robert M., and Michael D. Cohen), *Harnessing Complexity – Organizational Implications of a Scientific Frontier* (The Free Press, 1999)

More generally, initial success stimulates similar ventures, whose results often supplant the original product due to market competition. Over time, and as conditions change, some ventures adapt and continue (and perhaps grow and flourish), while others – including those that became "winners" by being optimally matched to the prior conditions – depend too strongly on those particular conditions to continue to compete successfully. The US automobile and steel industries offer additional examples of large enterprises that behave according to the principles of complex adaptive systems, and, to a degree, have fallen victim to natural selection.

Understanding Complex Systems Engineering Environments

To design systems that can perform as components of large-scale, complex enterprises, engineers must look beyond the system itself and consider the characteristics of the enterprise in which the system will function and the context in which the system is being developed and acquired. Engineers at MITRE have found a tool developed by Renee Stevens – the Enterprise Systems Engineering Profiler^{TM} – and shown in Fig. 16.2 useful for characterizing systems in context and visualizing system integration problems along multiple dimensions. The Profiler builds on ideas presented by Jackson and Keys (Jackson and Keys, 1984), who proposed a classification scheme for systems engineering problems that takes into account the nature of the decision makers as well as the nature of the system itself. It also draws on work by Dvir et al. (2003), Dvir and Shenhar (2007), and DeMeyer et al. (2002). We present it here as a possible addition to the systems engineers' toolbox.

The Profiler provides a structured approach to characterizing the context in which a system must operate, as well as an expanded set of factors that today's systems engineers must consider. Later in this chapter we describe a Systems Engineering Competency Model to guide the development of systems engineers who can effectively manage these factors. The Profiler can also serve as the basis of a situational model that assists management and engineering teams to select the most appropriate processes, tools, and techniques for a particular system and to adjust them as the system context changes over time. By drawing attention to the wide range of factors that affect system development, it guides engineers in identifying topics that they must understand, aids organizations to define team composition, and helps determine if staff should seek additional training.

Profiler Structure

As Fig. 16.2 shows, the Profiler is divided into four quadrants and three concentric rings. The quadrants describe the different contexts in which a system will operate and evolve, while the concentric rings represent levels of complexity and uncertainty.

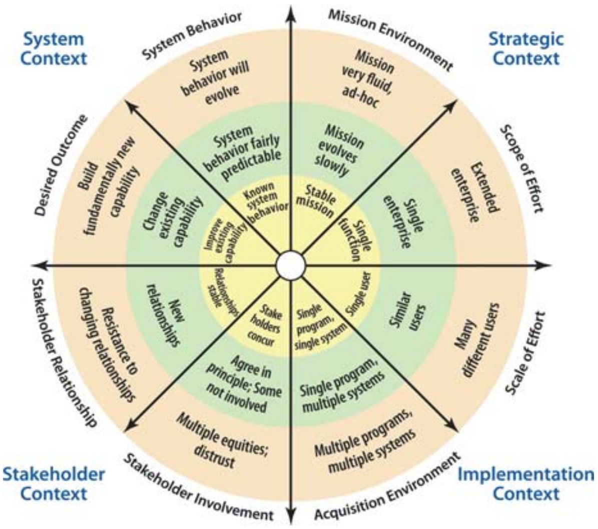


Fig. 16.2 Enterprise systems engineering profiler. Source: © 2008 IEEE. Originally published in Stevens, Renee, "Profiling Complex Systems," in *SysCon 2008 – IEEE International Systems Conference*, Montreal, Canada, April 7–10, 2008. Reprinted with permission

The Quadrants

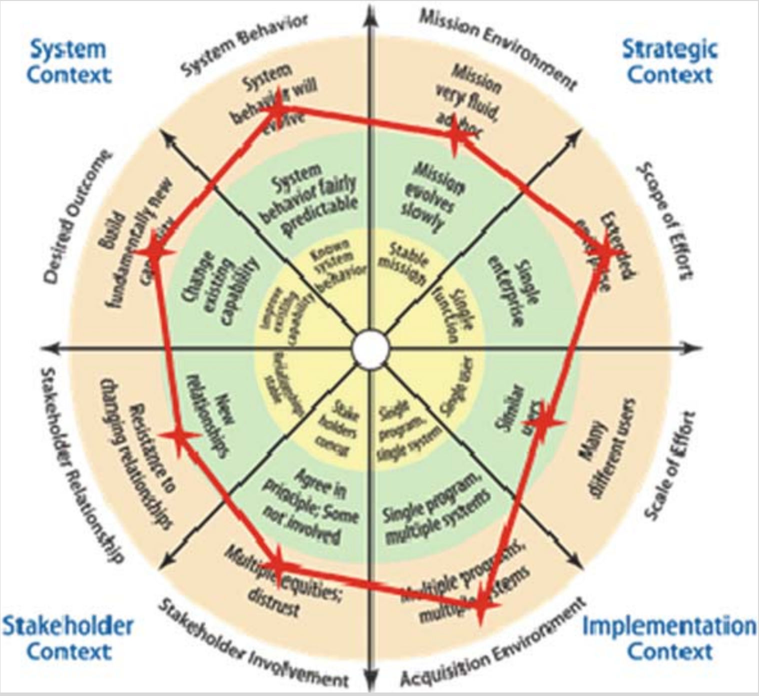
The strategic context focuses on the problem and opportunity space being addressed. It encompasses the mission and the organizational attributes within which the system will function and gauges the level of interdependence that the system must achieve with other systems. This quadrant helps engineers to envision the future and the broader application of the solutions provided. Engineers must often make greater use of experimentation with end users as mission environments and scope move toward the edge.

The implementation quadrant highlights differences in the scale and structure of an effort. This context can range from a single program established to produce a single system to a coordinated set of activities associated with multiple programs that are organized to implement several operationally interrelated systems. The implementation context will reveal best acquisition practices. As the complexity of implementation increases, systems engineers may apply portfolio management techniques to manage the trade space across programs. For example, manufacturers developed GPS navigation systems, proximity sensors, and cellular telephones as stand-alone systems. In designing a new car, an automotive engineer then adapted these systems to function together within the vehicle. However, that automobile is only one of many environments that incorporate these components; engineers who work for the individual manufacturers must take these many potential applications into account as they develop their systems.

Identity Verification

To secure the nation’s borders, the Department of Homeland Security (DHS) must establish a virtual border for identity verification that extends to visa applications and travel reservations made in foreign countries. This requires the implementation and integration of many independent systems containing biographic and biometric data, designed and operated by multiple organizations and agencies. Enabling technologies include Web-based traveler interfaces for data collection and status verification, biometrics collection, database storage and management, algorithms for matching biographic and biometric data, analytics, and reporting, which are in various stages of maturity.

Each of the many stakeholder communities has unique issues and concerns that DHS must address through technology and/or policy. Particularly complex issues include protecting personally identifiable information and achieving the best balance between screening travelers thoroughly and encouraging trade and travel. In each quadrant of the Enterprise Systems Engineering Profiler the overall environmental context falls into the outer region of complex and uncertain efforts.



The stakeholder perspective presented in the third quadrant allows engineers to assess the level of agreement on the goals and objectives of the effort, as well as the relationships among different stakeholders. Changing relationships, and the extent to which stakeholders welcome or resist the changes, can play a decisive role in shaping the system environment. This quadrant is especially important, as it drives the governance necessary to manage different stakeholder expectations and priorities.

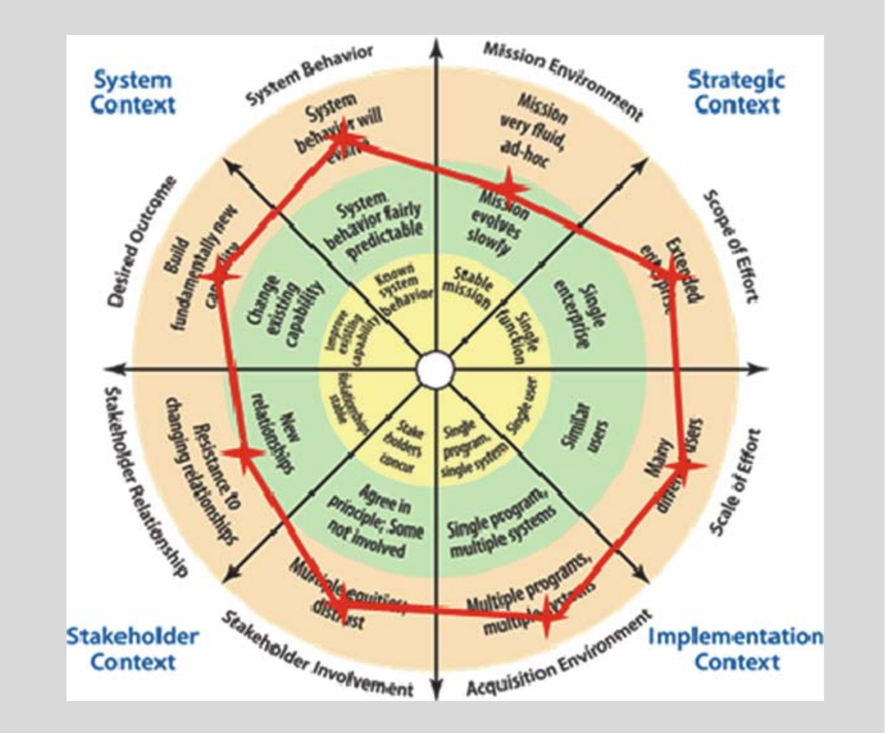
The fourth quadrant delineates the system itself: both its purpose and its expected behavior. Desired outcomes can range from modest improvement in an existing, bounded capability to the creation of a fundamentally new capability. The Profiler describes system behavior primarily in terms of predictability: highly innovative systems are especially likely to exhibit unanticipated behavior and to evolve both during development and after fielding, generally because users employ the system in unexpected ways. This quadrant also draws attention to the maturity of the technologies incorporated in a system. Engineers will have little difficulty in understanding the performance and interactions of proven technologies; technologies in development or still undergoing exploration may behave in unforeseen ways.

The Rings

The concentric rings reflect increasing complexity, uncertainty, and variability as one moves out from the origin. The innermost ring is the domain of traditional program management and traditional systems engineering. Such efforts are usually characterized by well-bounded problems, predictable behavior, and a stable environment.

Improving Health Care and Reducing Costs

One approach to reducing the costs of health care will require integrating and standardizing data from diagnostic and monitoring devices, clinical records, imaging systems, insurance and benefits administration systems, laboratories, pharmacies, patients' personal health records (e.g., Google Health or Microsoft Health Vault), and other sources. To achieve this goal and maintain utility as the details of healthcare delivery change over time, the information technology (IT) systems supporting the healthcare industry must accommodate data gathered by new kinds of diagnostic devices and treatment protocols, and must also protect highly sensitive patient health information. Stakeholders include patients, healthcare providers, insurance companies, and equipment vendors as well as public health agencies, clinical researchers, and standards development communities. As in the identity verification example, the overall environmental context for management and sharing of electronic healthcare information falls into the outer region of each quadrant of the Profiler.



The middle band can be considered the transitional domain. In this region of end-to-end systems engineering, the engineer works across system and program boundaries and probably finds it necessary to exercise influence rather than direct control to achieve some success objectives.

The outermost band – termed the “messy frontier” – represents situations where program managers and systems engineers must deal with a highly fluid environment. At this frontier distributed development activities occur without a global blueprint; multiple stakeholders have independent, sometimes conflicting equities; and the system’s behavior is likely to change over time.

Addressing Uncertainty and Complexity

Understanding internal and external influences and mapping a proposed system in the four quadrants of the Profiler will help engineers to plan strategies and practices for system integration in uncertain environments, and to adapt those strategies to changing circumstances. For example, an integration strategy that initially focuses on pilot activities has proven especially valuable when systems must cross multiple seams, such as systems intended to work across an enterprise or to link strategic partners in an extended enterprise. This approach becomes particularly important when the partners lack a history of working effectively with one another. Such pilot activities would address a selected slice of the overall effort and be directed as much to building trust as to addressing substantive issues of terminology, operational patterns, technology, or desired features.

In the implementation context, as more separately managed systems are required to work collaboratively to provide the needed capability, engineers should place more emphasis on defining the common design patterns, the minimum set of agreed-to standards, and recommended best practices. When a mission calls for integration of multiple legacy systems and when the nature of the interactions among them is difficult to anticipate, the best design patterns would emphasize flexibility and adaptability. A loose coupling approach (described further in “Building Systems That Work Together”) facilitates design of resilient interfaces, since it limits interdependencies among components and reduces the risk that changes in one component will produce unanticipated changes in others. In contrast, tight coupling design patterns are best suited to situations that depend on high levels of rapid synchronization.

The greater the diversity among the key stakeholders, the more critical it becomes that engineers and program managers understand the priorities and interests of each stakeholder and actively work to identify areas of potential intersection. Techniques such as stakeholder analysis are especially important. Bringing stakeholders into the process, for instance by engaging them in trade-off analyses, offers opportunities to develop acceptable strategies. When stakeholder positions diverge significantly it may be impossible to meet all the separate requirements, but the program leaders must identify the intersecting set and establish that as the focus of the priority effort. In the sidebar example on health care, the community recognized the need to handle this complexity and responded by forming the collaborative Certification Commission for Health Information Technology (CCHIT) to bring many of the stakeholders together to address interoperability issues.

In the systems context, the more novel the effort, the more difficult it becomes to predict the behavior of the deployed system with any degree of confidence. As noted above, systems that incorporate immature technologies are vulnerable to unexpected behaviors. In such circumstances, the systems engineering strategy should take advantage of the full range of opportunities for early and continuous discovery, including early prototyping, exploratory integration test-beds, field trials, and experiments. These approaches provide useful insight into the interactions among the elements of the system under development, and between the system and its anticipated users.

Building Systems That Work Together

The accelerating rate of technology change not only leads to more rapid system obsolescence, but also places increasing burdens on the individual designer to keep abreast of the dramatic changes and opportunities new technologies bring. As if this were not challenging enough, systems must interoperate with, respond to, and co-evolve with an environment that itself changes constantly. These trends have an especially significant impact on information-intensive systems, since the IT on which they depend is experiencing an exponential rate of change.

This situation has ushered in a new era in the design of information-intensive systems. On the one hand, users expect and demand customized innovations to meet their own local needs, based on how fast technology changes in their own personal lives. On the other hand, engineers can no longer consider systems in isolation. Instead, an intricate network of interdependencies demands integration priorities that reflect the growing reality that no user, system, or organization works alone. Thus, information-intensive systems must embody a delicate balance between these seemingly conflicting needs: for local innovation and global integration.

Systems that meet this goal, which would have been considered unrealistic only two decades ago, now represent real objectives. The world has seen the Internet and the World Wide Web seemingly support rapid local innovations while maintaining the appearance of a globally connected community. Even more interesting is the absence of centralized control, as that worldwide community relies on self-organizing behaviors to create what is arguably the largest and most complex system in existence. Paradoxically, we see centrally managed developments of large information systems fail dramatically in both civil and federal sectors. Yet these "large" systems are in many ways much less complex than the World Wide Web. What are the key drivers to successfully building large, complex, information-intensive systems?

Layered Architectures, Loose Couplers, and Bowties

Underlying what is perhaps the most proven technique for managing large information-intensive architectures is to apply the concept of layered architectures. The Internet, for example, is a layered architecture that provides a common model to organize the diverse collection of communications and network technologies used to provide seamless global connectivity. The World Wide Web represents another layered architecture that is itself an evolution of a series of layered architectures used in software design (from the two-layer client-server model, to the three-layer separation of data, applications, and presentation, to the N-tier architecture for Web 2.0 designs). Layered architectures offer the powerful advantage of encapsulating implementation choices and details rather than exposing this complexity outside of the layer's boundary. This divides up a complex set of system functions into different layers. Each layer can then evolve independently to take advantage of new technologies or innovations without having to coordinate with other functions resident in separate layers.

Layers exchange information through well-defined interfaces. The classic example of such an interface is IP (Internet Protocol). Often referred to as the "waist" of

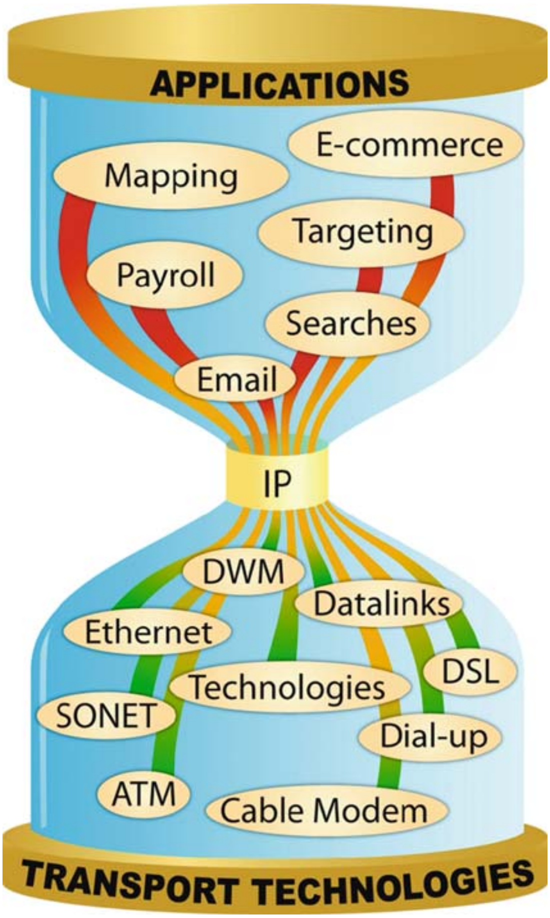


Fig. 16.3 The protocol hourglass. (a) All applications convert to a common IP protocol that is agnostic both to the application source and to the transport choice that carries the IP packets across any part of the global network. (b) Bowtie patterns of diversity → convergence → diversity are the fundamental features of all complex networks

the protocol hourglass (see Fig. 16.3), IP acts as a convergence point between the many applications "above" the IP layer and the many network and datalink technologies "below" the IP layer in the protocol stack. Ideally, each layer's interface would consist of a simple set of key information items using a market-driven standard such as IP. Thus, all the innovations inside a layer must convert to the common interface to exchange information with other layers. This common convergence standard can then convert information into diverse innovations inside the next layer. The result resembles a bowtie: many innovations inside a layer converge to the "knot" of the bowtie represented by a common interface standard. The other side of the "knot" leads into another layer, which itself contains a diverse set of innovations.

This pattern of rich diversity hidden inside layers and connected to other layers by simple convergence standards is fundamental to all complex systems. Key to its success is that the interface "knot" requires minimal knowledge between innovations that are located in different layers. Interfaces that demand such minimal a priori knowledge are often termed "loosely coupled," since connecting to the interface imposes little burden on any individual element.

In this way, the use of layers permits system engineers to insert innovative solutions to local, specialized needs independently and rapidly. Identifying and strategically selecting the best loose couplers is critical to allowing many independent innovations to be integrated at these converging points in the architecture. Connecting between layers using loose couplers enables all of these seemingly disjoint efforts to be integrated globally.

Engineers can leverage this universal bowtie pattern in many ways. For example, today's system architectures often separate data from applications so that any application may leverage any existing data source. Conceptually, this is a very powerful idea. However, in practice many data sources are extremely rich and complex, having been optimized for local needs that make the data standard excellent for one community to use but difficult for others to adopt. The Air Force's Link 16, probably the most powerful and successful data standard for air operations, has thousands of pages of message descriptions. It has never been fully implemented or tested due to its complexity, yet this complexity has not limited its usefulness for the air community. The Army uses JVMF (Joint Variable Message Format), another very successful but complex data standard. One JVMF position message has over a quadrillion variations, making the overall standard impossible to ever fully implement and test. This does not mean that complex standards are bad, but that the very specializations that meet the needs of a particular community make them difficult, if not impossible, to integrate across communities.

A simple, loosely coupled data standard, similar to IP, can integrate across these diverse rich data standards, especially as not all data are created equal. For example, a study of hundreds of thousands of Link 16 messages revealed that 80–90% of the traffic simply relayed positional data on "what," "where," and "when." Other large military standards followed the same pattern, which prompted the creation of a simple data loose coupler called Cursor on Target. Spreading rapidly through a grassroots effort, Cursor on Target has connected well over 100 different systems of all types since it is inexpensive, fast, and carries the bulk of the most important data that systems must share. The DoD, Intelligence Community, and civil sectors of the government have expanded on the concept of leveraging a data loose coupler for integration, resulting in Universal Core, which is emerging as the next iteration of this approach.

Even the use of loose couplers is now on the verge of a major transition as it expands from the network and data layers to the application layer. Service-oriented architectures (SOAs) are today one of the most talked-about technical approaches for building large complex, information intensive systems. Such architectures are designed to produce reusable, loosely coupled services that enable users to access the functions encapsulated in the application layer. In this context as well, loosely coupled services minimize the a priori knowledge needed by unanticipated users.

For example, any first-time user of Amazon can buy a book in minutes with no real training or special software.

In contrast to the traditional focus on tightly defining requirements and resisting requirements creep in systems development, SOAs will instead focus on constantly adding new services. Rather than being optimized for predefined requirements for specific needs, these services will be optimized for general applicability to many possible needs. SOAs will embrace new user requirements as additional guidance for extending the value of these services. Only those services that contribute significantly to composability will be loosely coupled; as we saw in the case of data loose couplers, more complex (and more tightly coupled) services that require specific innovative solutions may operate "behind the scenes" of the loosely coupled services. Figure 16.4 illustrates the concepts described above.

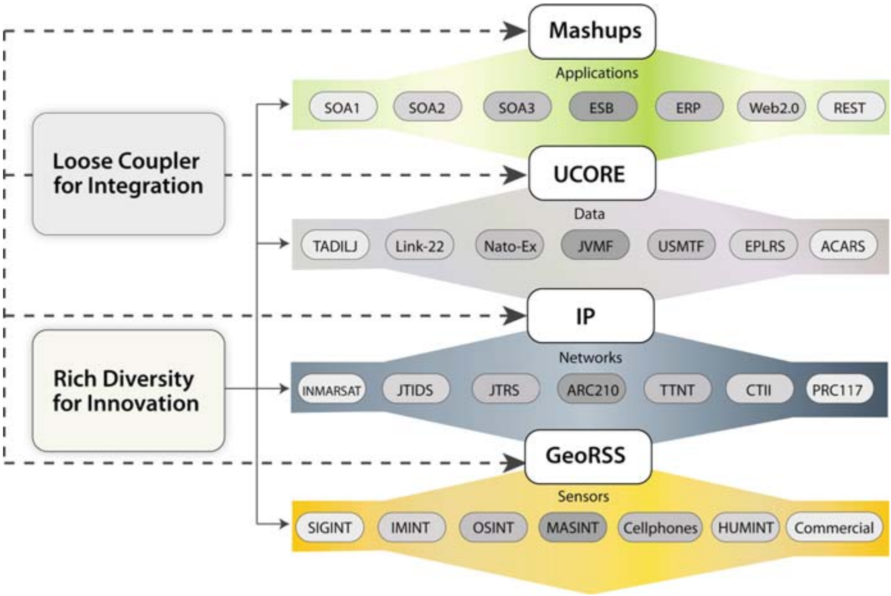


Fig. 16.4 Composable systems use bowties to balance integration and innovation

Composable Capabilities on Demand

IP gave us connectivity, but not understanding of the data that traveled over this globally integrated network. Data loose couplers such as Cursor on Target gave us the ability to share data among a large number of existing systems, but not to rapidly compose radically new systems. Loosely coupled services will enable users to compose new systems on demand, choosing from a staggering design space of possible system configurations to best match the need at hand. To underscore this power, think of *N* loosely coupled services on a network. The number of unique combinations of these *N* services grows exponentially, as Reed's Law predicts the power of a network grows as 2^N. In theory, it is actually unbounded if we choose the right primitive services and the proper integration strategy to combine them. Think of a software programming language's set of commands and syntax to string commands together. The number of programs that can be created is essentially unbounded, just as a vocabulary and grammar make it possible to write books about virtually any topic. This, then, is the incredible promise of loosely coupled services for the way we build systems. It will be more important to build services that are easily understood, easily combined, and exhibit high reliability than to build a specialized service that is optimized for one need.

The DoD sought to take an initial step toward this kind of services-based architecture when it instituted its Net-Centric Enterprise Services (NCES) program to develop information technology infrastructure services for the Global Information Grid. NCES will provide foundational services, such as security, collaboration, and discovery (of people, data, and services) needed by many programs. As more and more systems adopt the approach of providing many loosely coupled services as the standard way to access the power of applications (including any new innovations encapsulated inside the application layer), all users will become able to compose unique combinations of services on the network optimized for their current task or need. Such composable capabilities on demand will dramatically affect the way we build, use, and think about systems. We use the term "capabilities" instead of "systems" because the concept of a "virtual system" that lasts only as long as the need for that specific capability should replace our traditional view of a physical system with clean boundaries.

Mashups represent an excellent example of systems in which the whole is greater than the sum of the parts. We already see thousands of mashups created from combining simple services that allow easy access to maps, photos, and databases. Any of the base services could be made more sophisticated, but this would inhibit their composability with other services. As these mashups mature, systems engineers will begin to build larger functions and eventually full systems with the same speed and agility that users show in constructing today's mashups.

Capabilities on demand will stretch engineers' thinking about how systems are defined, built, maintained, and evolved. This concept implies three significant cultural shifts:

1. Stop thinking about system boundaries and think about boundary-less services.
2. Shift from optimizing functions for pre-defined requirements to optimizing for flexibility and composability from a "basis" set of loosely coupled services that can be used to create any system.
3. Accept that system development has neither a beginning nor an end, as the interdependence among existing and future services will be a critical consideration for the current services being developed.

The key technical and conceptual shifts described in this section will lead to composable capabilities with many political, organizational, and economic implications.

Such a loosely coupled ecosystem will shape and require new business models and new stakeholder relationships.

Enterprise-Scale Skills

A mix of interdependence and unpredictability, intensified by rapid advances in technology and eventually by the boundary-less composable capabilities on demand design pattern, demands new systems engineering techniques. When large numbers of systems are networked to achieve some collaborative advantage, interdependencies spring up among the systems. Moreover, when each of the networked systems individually reacts to changes in technology and missions, the environment for any given system becomes essentially unpredictable. As described in "Building Systems That Work Together," unpredictability can also arise from the continual composing of new capabilities from services and system components, leading to both risks and opportunities that systems engineers will have to recognize and address. Despite techniques to reduce coupling between systems, this combination of massive interdependence and unpredictability means that systems engineers cannot define success in terms of an individual known system, but rather for the network of constantly changing systems.

Web 2.0 is driving the trend toward collaborative advantage and an ability to readily adapt systems. Systems engineering methods must evolve to fit this situation, which is characterized by several specific features:

- Users face extremely complex problems in which stakeholders often disagree on the nature of the problems as well as the solutions. These problems and solutions are both technical and social.
- Missions change rapidly and unpredictably. As a result, systems must interoperate in ways their designers never envisioned.
- Even without a predefined direction, systems will continue to evolve and respond to shifting needs and emerging opportunities. The network is inherently adaptive.
- People are integral parts of the network. Their purposeful behavior will alter the nature of the network. Individual systems must be robust to changes in their environment.

Thus, the systems which engineers design and build today face additional, fundamentally different challenges from those they confronted in the past. When systems were bounded by relatively static, well-understood requirements, the methods of traditional systems engineering (TSE), well codified in industry standards (i.e., ANSI/EIA-632, IEEE-STD-15288, and IEEE-1220), were sufficient and powerful. The increased complexity of problems and solutions necessitates extending the discipline into the domain of ESE.

Enterprise Systems Engineering

ESE augments and balances TSE practices with those practices and approaches, both technical and non-technical, that apply to more complex problems such as those characterized above and illustrated in the examples in “Broadening the Scope of Systems Integration – Implications for Systems Engineering.” As further elaborated in “Building Systems That Work Together,” complexity is exacerbated by the rapid evolution of technology, resulting in an exponential rate of change. ESE seeks to address these complex problems through building effective and efficient networks of individual systems to meet the objectives of the entire enterprise by managing uncertainty and interdependence. In this context, “enterprise” signifies a network of interdependent people, processes, and supporting technology not fully under the control or influence of any single entity and subject to the stresses in the environment (see Fig. 16.5). ESE spans engineering of both the enterprise and the systems that enable the enterprise.

From the perspective of a systems engineer (or program manager) of a particular system, the people component (all the stakeholders) associated with the enterprise introduce much of the attendant uncertainty and complexity. A key factor for success is discovering how best to align the stakeholders, thereby turning uncontrolled elements into influenced elements. Therefore, systems engineers must help end users shape their enterprises, aligning technology to support their goals. They must also understand and participate in processes such as business planning, policy making, and investment strategy setting in order to exert the stakeholder influence required.

Successful systems engineering calls for a combined holistic approach and understanding of which techniques are suited to achieve success. This is depicted in Fig. 16.6.

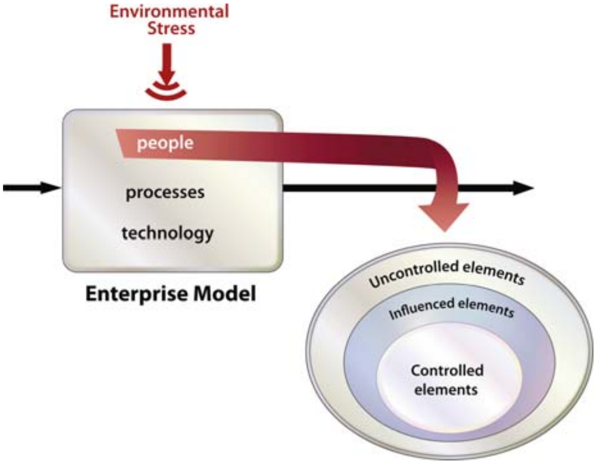


Fig. 16.5 Enterprise characterization. Source: Rebovich, George Jr., *Enterprise Systems Engineering and Practice, Vol. 2: Systems Thinking for the Enterprise: New and Emerging Perspectives*, MP 05B0000043, Bedford, MA: The MITRE Corporation, November 2005

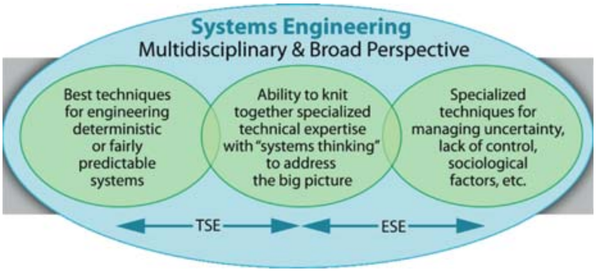


Fig. 16.6 Combined holistic approach to systems engineering

Engineering Skills for the 21st Century

Engineers who can perform effectively in these new enterprise environments need a skill set that encompasses individual technical expertise, systems thinking, and additional knowledge in areas such as the social and behavioral sciences (e.g., change management and social dynamics) as well as complex systems science (see "Broadening the Scope of Systems Integration – Implications for Systems Engineering"). To meet these enterprise-level needs within MITRE, we developed a Systems Engineering Competency Model and a Leadership and Management Competency Model. These models can help an organization characterize its skill base and build development and training programs to fill identified gaps.

The Systems Engineering Competency Model describes a comprehensive set of behaviors, skills, and knowledge, both technical and non-technical, needed to build an effective systems engineering capability at the enterprise level. It incorporates individual technical competencies identified by standards bodies, including INCOSE, IEEE, and ISO, and drawn from commercial competency models (e.g., Raytheon and United Technologies) and government competency information (e.g., the Jet Propulsion Laboratory [JPL], Air Force, and National Aeronautics and Space Administration [NASA]). The model covers the following areas:

- *Enterprise Perspectives:* critical competencies that characterize how engineers think about and approach systems engineering efforts. They include taking a comprehensive viewpoint by understanding the system's context, its environment, and technical and non-technical factors; learning to view uncertainty as an exploitable opportunity and taking innovative approaches to address ambiguous opportunities; understanding stakeholder motivations and fostering stakeholder relationships; and knowing how to communicate the strategic work needed to support and influence users' decisions.
- *Systems Engineering Life Cycle*: fundamental competencies that systems engineers require throughout the systems engineering life cycle, including architecture and systems integration.

- *Systems Engineering Planning and Management*: competencies that systems engineers need for planning and technical management of systems engineering activities, including transformational planning, knowledge of government acquisition processes, and continual improvement of shared systems engineering processes.
- *Systems Engineering Technical Specialties*: specific technical competencies and – even more important – the vision and ability necessary to leverage technical specialties as part of a project team. The specialty areas include information engineering for the enterprise.
- *Collaboration and Individual Characteristics*: important, universal communications skills and personal characteristics such as integrity, building trust and being trustworthy, successful team building and leadership, persuasiveness and influence, and championship of change.

Our Leadership and Management Competency Model, derived from our successful leadership experiences, highlights additional non-technical competencies, including team-oriented skills. These skills, and those of the Systems Engineering Competency Model, must be applied in the appropriate mix for a given context and set of circumstances.

Applying Enterprise-Scale Skills

Apple Computer Company offers one example of how a company applies certain enterprise-scale skills. Apple's recent product offerings, including the iPod and the iPhone, illustrate the end result of successfully applying a stakeholder-oriented, holistic systems engineering approach. As we observed earlier, people are now part of the system. According to Brunner and Emery, "Apple has built a design-driven culture that knows how to connect with its customers in a deeply emotional way" (Brunner et al., 2008). Apple combines industrial design techniques and human–machine interface considerations in the design of these products and their integration in the Apple on-line store.

Apple's product design focuses on the end-user experience. In the case of the iPod, Apple correctly assessed that listeners would want as many songs as possible on a device. This realization drove the human interface design that facilitates selection of tunes. Defining a simple interface meant Apple had to envision the entire architecture and remove clutter that would compete for the end user's attention (Fairs, 2003). "The design approach used in iPod development considered the end-to-end integration of hardware and software with the physical interface that exploits and controls iTune applications" (i.e., jukebox software and the online music store) (BIG Magazine, 2008). Apple's design practices of prototyping and repeated refinements also exhibit some of the evolutionary principles discussed in "Broadening the Scope of Systems Integration – Implications for Systems Engineering". For the iPhone, Apple balanced innovation and integration through tight control of the product's architecture and underlying design while allowing integration of other applications.

MITRE's experience in using communities of interest (COIs) to accomplish systems (data) integration also illustrates the application of enterprise systems engineering techniques. COIs support a distributed approach to information sharing by providing an organizational construct that enables stakeholders to define, prioritize, and manage their cross-organization information sharing needs. Particularly notable is a maritime domain COI that has demonstrated several early successes and lessons learned. Capabilities based on this COI's collaborations aid situational awareness of vessel positions on navigable waterways. Multiple services and agencies use this information in missions such as law enforcement and border protection.

To address this COI's challenges, the technical and non-technical enterprise systems engineering techniques applied included:

- Technical and operational (domain) understanding of the information engineering problem to be solved and knowledge of how to apply enterprise-friendly technology (see "Building Systems That Work Together").
- Understanding of the key stakeholder motivations (e.g., decision makers, acquirers, users, oversight bodies, and engineers) and their potential conflicts.
- Comprehensive viewpoint, including knowledge of environmental factors (e.g., policy, process, and economics) that might constrain (or provide opportunities for) a solution.
- Approaches that emphasized championing change, balancing competing interests for the good of the enterprise, and building trust to address stakeholders' concerns. The COI accomplished this by defining and communicating the scope, expectations, and resource commitments at the outset as well as quickly delivering incremental capability improvements.
- Organizational knowledge to establish a governance structure. This included working groups that developed technical solutions and addressed process concerns, as well as executive committee(s) that promoted the activity and fostered stakeholder relationships and participation.

As we analyze other successful examples over time, we can expect to see additional best practice patterns emerge in stakeholder stewardship, architectures to support complex implementations, government acquisition approaches to support fluid mission needs, and strategic, enterprise engineering leadership.

Enterprise Engineering Leadership

Leading a multi-disciplinary team, melding traditional engineering skills with non-traditional ones, and focusing them both on the system being developed and integrated and on influencing the environment to assure success, is itself a special skill. While previous generations of systems may have incorporated less complexity, leading systems engineering projects have always been challenging and the underlying imperatives for technical excellence remain unchanged. Looking back through MITRE's history at projects that led to notable successes, such as the Semi-Automated Ground Environment (SAGE), Air Space Management, and the Airborne Warning and Control System (AWACS), we often find individuals who exercised "heroic leadership." Despite little formal leadership training, they not only inspired their teams but also recognized the environmental pressures that impacted the likelihood of system success and exerted influence to overcome them. However, especially as large-scale systems integration becomes increasingly complex, relying on chance to produce a heroic engineering leader seems imprudent.

To reinforce the need for change, consider the federal IT acquisition environment, which has experienced highly visible failure of many programs to deliver on time and on budget, and only a few notable exceptions (Flint, 2005). This environment is characterized by such rapid technology evolution that some system components become obsolete while the programs are still in development. IT systems and business processes are increasingly interconnected within and across agencies, making it difficult to achieve consensus on vision, operational concept, and requirements. The federal government's stretched fiscal and human resources further complicate the situation. Government agencies have traditionally drawn on highly specific assumptions about far-term conditions as they plan their systems, for example that the requirements are known at the onset of a program and never change. To increase the likelihood of success substantially, these agencies must reconsider outdated assumptions and make associated changed to acquisition and systems engineering processes and governance (see "Governance").

System Adaptability

If a system (or component of a system) is expected to face constant conditions during its lifetime, then optimizing it for those conditions makes sense. Optimization may be needed to meet tight space, weight, or power requirements or to save production cost. A short-lived or throw-away component (e.g., an inexpensive cell phone) meets these criteria. Under these conditions, tight integration is appropriate, since the design need not move along an evolutionary path. However, other circumstances demand that engineers give more thought to adaptability. Here design precepts such as standards-based layered architectures, separation of data from business rules, modular designs, carefully chosen convergence layers (e.g., the Internet Protocol "hourglass"), and exposure of data (and metadata) become important. Building composable (and re-composable) capability can also help to achieve cost-effective adaptability. Mash-ups and service-oriented architectures represent two currently favored technical (and associated governance) methods.

Engineering teams must also think about the value of building options into designs. Engineers should envision possible extensions in advance, as well as the likelihood that they would be needed, when they might be needed, and the cost of extending the design rather than creating an entirely new replacement. Often it may prove worthwhile to spend extra money on the initial design to facilitate future options (i.e., build in the design "hooks"). As an example, consider the forethought that led the designers of the George Washington Bridge over the Hudson River between New York and New Jersey to build the original structure so that it could support a second level of roadway, even though the greater capacity would not be needed until many years in the future.

Therefore, today's environment, in which people and systems must operate across boundaries, demands new leadership skills. The broader scope of integration implied by these increasing dependencies requires not only new design precepts but also teams whose members can play greatly expanded roles beyond those of technical expert or program manager (Brooks et al., 2008). They include establishing strategic direction for an effort, building trust, developing strategic partnerships, assessing the environment, exerting influence, and championing change. Successful leaders must address and integrate both technical and non-technical factors (i.e., political/social, operational, and economic issues) and recognize their implications. They must recognize how to trade off the advantages of optimizing for current conditions and building in adaptability. They must also recognize and act on opportunities for influencing the environment to create shaping conditions advantageous to their goals. In addition, engineering leaders must ensure that their team members constantly refresh their technical skill base to keep pace with rapid advances in technology.

It is important to recognize that new leadership approaches also are required. Deborah Ancona's research work on successful enterprise teams (dubbed X-Teams) indicates that a distributed (versus hierarchical) leadership model is particularly effective in these complex environments (Ancona and Bresman, 2007). That leadership must permeate all levels of the organization. X-Teams also projected upwards and outwards, established cooperative relationships, sought out key information from other teams and outside sources, evangelized the team's mission to key stakeholders, and actively sought support from management.

Impacts on Engineering Skill Development

Traditional engineering education and training have not prepared graduates to understand the dynamics of an evolutionary design paradigm and to apply that understanding to large-scale systems engineering and integration. These skills require holistic and integrative education across the spectrum of political/social, technical, economic, and operational domains. Thus, organizations must make systematic efforts to recruit people with the special talents needed as well as to offer on-going professional training – and engineering schools must adapt their curricula to foster those talents in their students. The engineering curriculum can help develop the leaders of large-scale systems engineering projects by providing training in these skills, or by encouraging students to enroll in relevant courses offered by other departments, such as psychology or business. At MITRE, for example, we seek to develop our engineering leadership according to our competency models and to tailor the application of their skills toward the complex adaptive environment of our government customers. We suggest that others should also explore engineering leadership in the complex environments that their large engineering and integration efforts now face.

However, much remains to be discovered, particularly in the social sciences disciplines and complex systems science. We have identified a framework for systems engineering research that comprises political/social, operational, economic, and technical factors. Institutions such as the Engineering Systems Division of the Massachusetts Institute of Technology advocate case-based research and empirical studies that can help engineers to meet the requirements they will face in the world of increasingly interconnected systems. Their suggested topics include approaches to understanding systems contexts, factors underlying competence in a workforce, the enablers, barriers, and precursors to systems engineering efficacy, and ways to promote systems thinking at individual, team, and enterprise levels (Rhodes, 2008). These institutions also believe that such research would take the form of a cycle: collecting empirical data from practice, developing hypotheses and theory, and then evaluating them in practice. Such a cycle suggests the value of additional partnerships between academia and industry.

Governance

Even when talented engineers apply these skills to create highly effective systems, system integration will fail without a supportive, effective governance process that focuses on minimizing the seams between separate systems and promoting interdependence across boundaries. Classically defined, governance is the strategic decision-making process that grants authority, assigns accountability, defines expectations, and verifies performance. Governance also determines organizational objectives and monitors performance to ensure those objectives are attained.

However, when multiple organizations, each with its own governance process, collectively create new capabilities by novel compositions of their systems and services, the classical governance model breaks down. How can authority be granted when there is no single source of authority? How can accountability be assigned (or accepted) when success depends upon the performance of other organizations? What are the objectives against which performance is measured in an evolutionary model where there is no "end state?" How are conflicts between individual organizational objectives and the "common good" adjudicated?

In the complex, evolutionary development model of system integration, effective governance is needed at both the organizational and the enterprise levels. Without an effective governance process, an organization cannot consistently execute individual system developments successfully. Without effective enterprise governance, an evolutionary development ecosystem cannot develop and thrive.

Grant Authority and Assign Accountability

Within an organization, the governance function grants authority and assigns accountability for the areas of budget and finance, investment portfolio management, business processes, and program and project management. Two core principles underlie good organizational governance: executive freedom for the program manager to lead the program without undue restraints and effective accountability commensurate with the degree of executive freedom exercised. In successful programs, specific accountabilities and responsibilities of organizations and individuals are formalized, understood, and properly executed. Programs fail when accountabilities are not understood and assigned and consequent responsibilities are not met.

The complexity of governance increases when programs cross organizational boundaries and intersect the responsibilities of multiple governing bodies. Simultaneous, uncoordinated oversight by multiple organizations limits options, lengthens decision cycles, adds volatility to funding, and effectively removes accountability.

Experience has shown that creating a "board of directors" for enterprise and cross-organizational program governance is a best practice to promote coherent system development. The board should comprise representatives from each stakeholder organization and serve as the single authority for strategic decisions and oversight. It is within this forum that conflicts between individual organizational objectives and the "common good" are adjudicated. However, a board of directors can govern effectively only if its members have the authority to commit their organizations to following the board's governance decisions and to meeting commitments upon which other organizations depend. Without such empowered members, a board of directors merely complicates governance, increases oversight burdens, and delays decision making. Both the Internet and the World Wide Web, often cited as examples of successful evolutionary developments with “no one in charge,” have strong governing “boards of directors”: the Internet Engineering Task Force (IETF) and the World Wide Web Consortium (W3C), respectively.

Define Expectations

The governance function must balance enterprise and organizational equities and ensure that the enterprise fulfills its obligations and responsibilities to its stakeholders. Stakeholders usually state their interests in the form of requirements. However, they often establish those requirements without considering cost, schedule, and technology maturity. This creates expectations for program performance that cannot be satisfied within the constraints on the program and creates an imbalance between enterprise and stakeholder equities.

Numerous studies (Defense Acquisition Performance Assessment Report, 2006) identify unrealistic and unstable requirements as the root causes of program failure. In fact, the way requirements are managed can make the difference between a successful and a troubled development program. Successful programs establish initial requirements and expectations through interactive dialogue with actual users (not user surrogates). During these discussions, users, program managers, and funding providers can work together to modify or eliminate requirements that adversely affect cost, performance, or schedule. By contrast, ineffective discussions put the program manager in the position of agreeing to a plan that cannot be executed on the schedule agreed to with the resources allocated.

Successful programs also carefully manage the inevitable changes to requirements that result from advancing technology and new user needs. Those charged with governance must consider system requirements as “living” but manage them with a controlled process using regular trade-off analyses to determine the value and benefit of a change.

At the enterprise level, expectations should be defined by an enterprise capability roadmap that defines the strategy for enterprise capability evolution over time. To navigate the dynamics and uncertainty of today’s environment successfully, the enterprise capability roadmap should be structured as a portfolio of manageably sized capability increments that deliver capabilities in shorter time frames. This portfolio-based approach allows the planning and management flexibility to adapt the capability roadmap as the environment and enterprise priorities change.

To enable evolutionary development along the enterprise capability roadmap, all organizations must be guided by a stable enterprise architecture, adhere to a common set of standards, and deliver advertised services that perform to defined service-level agreements. The board of directors can serve as an effective mechanism to ensure the adoption of the enterprise architecture and common standards. The “loose coupler” strategy discussed previously makes it easier to reach agreement on these common foundational elements. Limiting the need for universal agreement to a relatively small number of architectural loose couplers can greatly facilitate integration across system and organizational boundaries while allowing individual organizations sufficient flexibility to address their individual needs. Attempting to reach enterprise-wide agreement on all elements to the lowest level of detail is doomed to failure.

Verify Performance

Those charged with governance must exercise their stewardship responsibility and authority and hold program managers accountable for performance. However, oversight should not substitute for program management. Instead, it should focus on enterprise capability roadmaps, the long-term funding envelope, and the overall capabilities that individual programs should deliver.

To maximize the probability of success, oversight authorities and program managers must work in partnership to expose and mitigate program risks through open discussion and allocation of resources to contingency plans. Unfortunately, the typical approach to oversight gives greater attention to programs that have gone from “bad to worse” than to those that have gone from “bad to better” or “better to best.” This negative dynamic adversely effects decision-making. No program lacks risk. When program decisions are made primarily to minimize negative reactions by oversight authorities, risks are often hidden or obfuscated until they reach the level where they have a major impact on cost and/or schedule. This behavior increases the likelihood of program failure.

At the enterprise level, the capability roadmap provides the framework for managing evolutionary development performance by allowing programs to demonstrate success or to “fail early.” Peter Temes, president of the ILO Institute, has suggested that organizations “lower the cost of failure” to accommodate the realities of program management as technology changes rapidly and priorities constantly shift (Big Company Innovation Picking up Speed, but Marketplace Interest Lags, 2007). According to this model, oversight authorities would reward a program manager for terminating a failing initiative and allow the program manager to shift the remaining resources toward more productive efforts within his or her portfolio. The intent is to shift the program manager’s raison d’être from success on every initiative for which he or she is responsible to making progress toward the overall program’s contribution to the desired capability. Such an incentive shift would help program managers align their activities with cost-effective success at the enterprise level. In the context of systems engineering, this approach would encourage a project team to acknowledge early, and without penalty, that a particular design concept had not achieved results instead of the behavior that is too often seen of concealing problems, defending the chosen design, and spending more time and money than is warranted trying to fix it. Admittedly, such a departure from traditional practice may be difficult if an organization has already invested large amounts of time, effort, and money in a particular solution. As part of this approach, oversight authorities should ensure that the program has put contingencies in place and funded them.

The enterprise oversight function can provide additional value beyond its “due-diligence” responsibility. Focusing equally on programs that have gone from “bad to good” or “good to great” can reveal best practices that an enterprise can apply more broadly. Program managers will become more effective as they gain exposure to structured, thoughtful discussions that address both why some troubled programs fail and why some improve. Forums where real-world experiences are discussed and analyzed to understand why programs improve would serve the overall goal of improved outcomes.

Good Governance Enables Program Management

While successful programs require unambiguous governance, the discussion above shows that governance does not simply equate to program management. Program management focuses on tactical-level execution and the delivery of individual capability increments, while governance operates at the strategic level to establish the enterprise capability roadmap and policies, approve programs, allocate resources for those programs, and enforce accountability through oversight. Effective governance cannot substitute for competent program management. However, ineffective governance increases the likelihood that even an excellent program management team will fail. Good governance enables good program management by defining clear measures of success at the macro (capability roadmap) level versus the micro (program) level and allowing program managers the freedom to balance performance, funding, and schedule during execution. Good governance also recognizes that major programs are increasingly complex endeavors, and that problems will arise in even the best organized program. The key is how one “rights the ship” when problems develop. Thus, program success depends on experienced and empowered leaders at both the governance and program management levels who collaborate in an environment of mutual trust to expose and manage program risks.

Providing governance for complex systems is highly challenging, especially when these systems have multiple interrelating parts that cross boundaries and are embedded in changing environments that can at most be influenced and not controlled. Governance authorities must provide firm guidance and exercise appropriate control while granting program managers flexibility to adapt to new conditions and promoting management behavior that benefits the overall enterprise rather than narrower equities.

Conclusion

Throughout this chapter, we have stressed the dynamic nature of systems development in the 21st century, and the associated unpredictability of a system’s “final” form. As they design systems to perform defined tasks, engineers must increasingly assemble their systems from existing systems, and recognize that their "complete" systems will in turn become components of still larger systems of systems, using the component systems for purposes quite different from those for which they were originally designed. This increasingly complex systems engineering environment calls for a broader set of skills, and a different type of governance, than those that created the bounded systems characteristic of the 20th century.

While this fluid environment poses challenges, it offers opportunities for engineers to apply creativity to system design and construction. Systems engineers can apply intellectual tools, such as complex adaptive systems theory, and practical tools, such as the Enterprise Systems Engineering Profiler described in this chapter, to develop an encompassing vision of the planned system's role within the larger enterprise where it will operate. Traditional engineering skills, augmented with technical and non-technical capabilities such as those identified in MITRE's Systems Engineering Competency Model, will enable them to translate that vision into highly effective systems. ESE principles can then guide systems engineers in combining components in layered architectures that can encapsulate high levels of technical complexity using loose couplers that enable integration of a range of disparate systems.

Academia, industry, and government have vested interests in the development and training of systems engineers who can succeed at this type of large-scale systems integration. All of these sectors play key roles in advancing the state of the art and practice in systems engineering and integration. We hope that organizations such as MITRE, private industry, and research organizations will explore promising new techniques that can help the next generation of systems engineers to succeed in the unpredictable framework of the 21st century. Meanwhile, engineering curricula must change to equip the systems engineers of the future with the knowledge and mindsets they need to apply the new techniques and envision the systems of tomorrow. The holistic approach to systems engineering education holds promise for fostering the broad outlook necessary to foster systems engineering at the enterprise level, as well as management and governance practices that help systems engineers to achieve their objectives.

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Chapter 17
Engineers of Tomorrow: Holistic-Thinking System Engineers

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Introduction

Are we ready for the technology challenges of tomorrow? I hope so, but fear not. Unless we revolutionize and act now, it is possible that we will not have the technical and scientific workforce in the quantities needed for tomorrow. In addition, those who pursue technical careers will have to start thinking more globally and more holistically to address all aspects of the challenges and competitions of tomorrow's world.

We live in an unprecedented time in which the world is far different from the world that existed when our educational systems were established. Most educational systems were created prior to the Industrial Revolution, and many of the precepts on which they were founded, though sound at the time of establishment, have now evolved and are in need of review and transformation. Just as Internet improvements and e-learning demands have forced re-examination of the traditional learning methodologies, global changes and pressures are forcing the re-examination of many of our legacy practices and thought processes. The rapidly changing population demographics, the volatile economies of the world, and increasing global interactions are just a few of these forcing factors. Two areas which need to be reviewed will be addressed here. First, will we have the technical and scientific workforce to fulfill our future needs? Second, will the technical workforce be holistic thinkers and systems engineers, able to integrate complex systems addressing the impacts and implications of future designs and innovations?

Background

"Beam me up, Scotty," the famous phrase attributed to Captain Kirk when he wanted physical transport back to the ship in the original Star Trek series, seemed so unreal,

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so science fiction, so unthinkable, and so impossible back in the 1960s. The thought of each person having a means for instant communication, let alone for instant transportation upon request, seemed extreme and near impossible. Yet, we are nearing that time faster with each passing day, as technology advances and innovative ideas become reality.

Gone are the simpler days of the Wright Brothers, when the accomplishment of flying an aircraft was an achievement. The aircraft itself was somewhat stand alone and was considered to be a system in itself, an independent platform which communicated with the outside world only when needed for actions such as landings and take-offs. The engineers of this design period could concentrate on creating and perfecting the aircraft in its own specific world, improving internal system designs, propulsion functions, flight controls, etc.

Now, the capability to fly is just a "given." Today's requirements are far more complex. Today an airplane is merely a node in a system of systems. Take the example of a fighter aircraft dealing in a military encounter. It must interact with the ground control, with other aircraft in flight while identifying friend or foe, with ground forces and also be linked into a multitude of information sources on ground, in air or on sea, just to name a few. To get to this point of technical sophistication has meant that the skills of the engineers and developers of today's and tomorrow's complex products and systems have to think differently and must be educated differently. It is a more complex and integrated world that must now be addressed.

We live in an ever changing world which is more global and more integrated than imagined just a decade ago. It is different from the world at hand when our educational systems were established. Back then, it was a simpler world, less complex in its nature, with the technical and scientific requirement being much more basic. It was a time when communities were small, designs were simpler, and technology was advancing at an acceptable pace. It was a time when the impacts of actions were not necessarily the concern of a community upstream as pollutants were emptied into the local waterways and contaminants left in the ground for future generations to find and to handle.

Today, we all have concerns about environmental impacts, climate change, resource scarcity, population growth, economic changes, and scientific and technological innovation around the world. These common concerns offer us the opportunity to foster global collaboration. The days of engineers creating designs and structures without an understanding of the impacts created by the end product are over. It is time for engineers to be educated more broadly and to think differently – to think of system-wide impacts and implications and to practice holistic engineering.

A key imperative for success of engineering field in the 21st century is the development of a more holistic and more diverse scientific and engineering workforce. To ensure this workforce is available in the quantities needed and prepared for the future, two areas need to be addressed:

- *Issue 1: Filling the Pipeline:* Will the pipeline have the number of engineers needed? Will we have enough engineers for the future? Are they now in the educational pipeline? Are they getting the right technical and scientific backgrounds to be able pursue engineering?

- *Issue 2 – Need for Holistic Engineers:* Will future engineers have the right education? Will they have a holistic way of thinking? Are our educational systems preparing them for the challenges of the 21st century which will be more complex, integrated and global in character and scope? And are they being prepared to think broader in their engineering designs? Will they have the skills needed to integrate complex systems?

Defining the Issues

Issue 1 – Filling the Pipeline

Will the pipeline have the number of engineers needed to populate the scientific and technical workforce?

Current Situation

To discuss the future, we must understand the current situation. There are several key factors which must be addressed and integrated including: need for growing workforce, age of existing work force and impending retirements, number of students graduating with technical degrees, and the changing demographics of the United States.

- *Need for Growing Workforce:* Looking at the Census information for the United States, the population was approximately 306 million at the beginning of the century. Census information also shows that over half that population (155 million people) was in the workforce. In the next 10 years, according to the Bureau of Labor Statistics, more workers will be needed, with the workforce growing by approximately 15 million people.[1]
- *More Retirements Expected:* Next, we must look at what is happening to the average age of the workforce. It is getting older and the number of people over 50 years old has increased dramatically. If we look at census data on the percent of the workforce over 50 years old, the trend has been on the increase and is predicted to grow as follows:

  - 1900: 13% of the workforce over 50 years old
  - 2000: 27% of the workforce over 50 years old
  - 2020: 35% of the workforce over 50 years old

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[1] US Census Bureau Website

Over the past several decades, the majority of the workforce has been populated by the "Baby Boomer" generation. However, the Baby Boomers are about to start leaving the workforce. As per the Census Bureau:

> In 2006, the oldest of the baby boomers, the generation born between 1946 and 1964, will turn 60 years old.[2]

While the Baby Boomer generation has the knowledge, the experience and the determination that helped to make this country what it is today, they also have reached the retirement age. This does not mean that they will all be retiring immediately, but it does indicate the potential for a mass exodus of the most knowledgeable workforce we have departing the field over the next 20 years.

- *More Science and Engineering graduates needed*: The US enrollment and graduations in Science and Engineering are not maintaining the levels necessary to meet the increased needs of the future. In the 2008 NSF report on "Science and Engineering Indicators 2008," the following conclusion was stated:[3]

  > Most of the growth in S&E education occurred in science fields. In engineering, bachelor's and master's degrees increased in recent years, but have not yet attained the levels of the 1980s. Engineering enrollment, both undergraduate and graduate, and engineering doctorates declined somewhat in recent years.

  There is global competition for students in the scientific and engineering areas, particularly as countries have started to understand that knowledge growth leads to economic growth. The NSF study found the following:

  > In the United States, S&E degrees are about one-third of U.S. bachelor's degrees. In several countries/economies around the world, the proportion of first degrees in S&E fields, especially engineering, is higher. More than half of first degrees were in S&E fields in Japan (63%), China (56%), Singapore (59%), Laos (57%), and Thailand (69%). Many of these countries/economies traditionally awarded a large proportion of their first degrees in engineering. In the United States, about 5% of all bachelor's degrees are in engineering. However, in Asia, 20% are in engineering, and in many other countries worldwide, more than 10% are in engineering.[4]

- *Changing Demographics:* Now into the formula, add in the population growth and the changing demographics of the United States. The US population is continuing to grow. However, the demographics of the population are changing drastically. One area that is changing most significantly is the influx of immigrants into the United States. The National Center for Public Policy and Higher Education has recently stated that as the "U.S. Workforce is becoming more

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[2] US Census Bureau Website

[3] NSF Indicators in Science and Technology 2008 http://www.nsf.gov/statistics/seind08/c2/c2s5.htm

[4] NSF Indicators in Science and Technology 2008 http://www.nsf.gov/statistics/seind08/c2/c2s5.htm

diverse, the racial/ethnic groups that are the fastest growing are also the least educated."[5]

The Policy Alert summarized it succinctly when it stated:

> If current educational gaps remain, there will likely be a substantial increase in the percentage of the workforce with less than a high school diploma – and declines in the higher levels of education completed.[6]

So, back to the question on the pipeline for education – will we have the number of students we need in the educational pipeline to meet the workforce needs of the future? Based on the above, the answer is no.

Integration of the Factors

Integration of all of these factors gives leading indicators to the future.

None of the factors mentioned above are independent. Each contributes to the outcome of our current and future situation. If we summarize all of the factors above and integrate them, we find

- Increased needs in the workforce in the next decade
- Decrease in current labor force (due to large numbers of Baby Boomers exiting the workforce)
- Increased needs in the number of students emerging from the pipeline, prepared with proper math and science foundational knowledge for careers in technology (i.e., will need an increase in the number of college grads in scientific and technical disciplines, especially in engineering).

As all of these conditions and requirements happen at the same time, we have the ingredients to make for a perfect storm.

Issue 2 – Need for Holistic Engineers

Will Future Engineers have the right education? Will they have a holistic way of thinking?

Current Situation

Whereas ensuring we have the engineers in sufficient quantities, ensuring that future engineers think differently and with a broader perspective is perhaps the more pressing issue. Moving to this new paradigm of holistic engineering is not a natural

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[5] National Center for Public Policy and Higher Education website

[6] National Center for Public Policy/National Policy alert

transition; it is not an evolutionary process but a revolutionary one! It will take a concerted effort to recast the basic standards of engineering, expanding our expectations of students and demanding a more integrated approach to design and development. It will require engineers who understand and practice the art of systems engineering while thinking holistically and understanding the impacts and ramifications of their creations and innovations.

It is a different world today than the past centuries when most of our educational systems were founded. Society as a whole has broader interests and higher expectations of the products, processes, and services being developed for today and tomorrow. The sustainability of products and surrounding environment is an essential component which must be taken into consideration throughout the entire life cycle. The design itself must be technologically sound. However, many broader influences and factors must be considered:

- Climate changes
- New rules and regulations
- Environment and Energy concerns
- Resource concerns – people, natural resources, fuels, food, water
- Population growth
- Economic change
- Post 9/11 activities and new norms
- Foreign students composition changes
- Homeland security and defense issues added constraints

Simply put, increased globalization and sustainability concerns are reality. This ever changing reality has been brought about by a myriad of influences. Some of the influences include: the invention and worldwide dependence on the Internet; more open international boarders; ease of transportation almost anywhere in the world; cheaper labor rates found globally; and more countries subscribing to the understanding that ‘Knowledge Growth Leads to Economic Growth.’

The advantages of globalization are many: global collaboration and partnerships; increased innovation; increased career opportunities; increase ability for teams to work around the clock; and the ability to work virtually – anytime, anywhere on any project. Of course, there are challenges that come with globalization including language issues, special handling of competition sensitive/proprietary information, new National Security Issues, and a new emphasis on the need for increased communication.

The days of engineers creating designs, structures, and platforms as an independent product without an understanding of the end product, the intended use, and the unintended consequences are over. Engineers need to be trained to think differently – to think of systems-wide integration, impacts, and implications, while practicing holistic engineering.

Systems Engineering and Holistic Engineers

Two terms are key to the discussion when we talk about the future state of engineering: systems engineering and holistic engineers. Systems Engineering is a disciplined process, one that has been developed over the years, recognizing that specified requirements and consistent processes are needed to ensure the integrity of complex designs and integrated systems. Holistic engineering is a way of thinking. It is looking at the broader implications of the end product. It is determining, addressing, and preventing the unintended consequences and features of the design.

Systems Engineering

Systems Engineering is a disciplined process which must be implemented to ensure that the end product meets the defined requirements and produces the desired end result. Systems Engineering is an interdisciplinary approach which focuses on early definition of customer needs and an understanding of the required functionality of the end product. It includes all phases of the design process and moves methodically through development, all the way through systems validation, fielding of the product and its eventual disposal. As per INCOSE, the International Council on Systems Engineering, a broader definition of systems is needed, extending from component level to entire systems of systems level:

> Fundamentally, a system is a collection of components (that could be systems as well) that work together in an orchestrated manner to accomplish some goals or provide some functionality. Systems Engineering is the discipline whose members seek to develop and practice increasingly better and more efficient methods and processes for realizing systems.[7]

Systems Engineering is a detailed process applied at all product levels. Good Systems Engineering processes and implementation will ensure that the final products meet the requirements of the customer. Systems Engineering is defined different ways by many constituents, but it includes some basic core steps in the process:

- Analyze customer requirements
- Plan the technical effort
- Define potential candidate solutions and conduct trade studies
- Optimize and evaluate alternatives
- Design
- Verify/validate requirements are met

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[7] International Council of Systems Engineering (INCOSE) web site www.incose.org

Holistic Engineering

A Holistic Engineer goes beyond practicing the steps of the Systems Engineering process discussed above. Holistic Engineering, as defined by Dr. Domenico Grasso in his article titled "Holistic Engineering", is

> . . .a new kind of engineer. . . who can think broadly across disciplines and consider the human dimensions that are at the heart of every design challenge. In the new order, narrow engineering thinking will not be enough . . ..[8]

This concept is sometimes foreign to the technical community that has so often prided itself on practicing the scientific approach, methodical, and straight forward. For too long there has been a separation between the technical and liberal arts paths that has not leveraged the positive aspects which could be received from the broadening of thinking and viewpoints offered by concepts of the liberal arts.

Holistic Engineering takes into consideration the human elements and implications of product designs. The word holistic means "relating to or concerned with wholes or with complete systems rather than with the analysis of, treatment of, or dissection of the parts."[9] By this definition, a holistic engineer looks at the end product and tries to understand and address all of the conditions of the product and complete systems. It becomes a way of thinking, constantly reviewing and understanding the big picture of product use. It encourages looking at all different aspects of the problem and solution and asking "what-if " scenarios as the norm, because understanding the potential impacts and implications of the system is essential. It is trying to determine the unintended consequences and then addressing them in the original design process. Holistic Engineering is a way of thinking with no borders and provides new, boundaryless solutions.

Proposed Solutions

The late President John F. Kennedy once said, "When written in Chinese, the word 'crisis' is composed of two characters – one represents danger, and the other represents opportunity."[10]

So, what do we face today? It is clear is that we are at crossroads in the educational system and the road we take will determine the future. This impending crisis in our future workforce presents opportunities to avert the troubles of tomorrow. How we respond to these opportunities will clearly steer the future of the United States and our global partners.

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[8] Holistic Engineering, The Chronicle Review, by Domenico Grasso and David Martinelli' March 16, 2007

[9] Merriam Webster dictionary

[10] President Kennedy's speech; 4/12/59 in Indianapolis, IN and 10/29/60 campaign address is Valley Forge, PA

To prepare engineers for the future, we must conceptualize what the years ahead might look like. Based on the path we are currently following, the vision for 2025 and beyond is as follows:

- The demographics of the United States will continue to change, with the population reflecting more diversity of backgrounds, knowledge, expectations, and education.
- The electronic world will continue to evolve rapidly. For the generation currently growing up, and those yet to be born, the electronic world is the norm. They know little of pen and paper writing and believe that even e-mail is somewhat antiquated. The expectations and demands will be for more communication, instantly, with anyone, any place in the world, at any time. The concept of everyone having a "communicator" previously mentioned from the old Star Trek series is moving more and more toward reality. Perhaps a communications identification number or chip will be provided to all at birth.
- Industry interactions will be global and transparent. Travel and living internationally will be common. This will put greater demands on understanding cultures and knowing languages.
- Technology will continue to advance faster than we are capable of using it. The challenge will be whether or not we can incorporate the 'newest' technology into existing and evolving processes and products before the 'newest' technology itself becomes obsolete and antiquated. Invention and innovation will abound. New materials such as nanotechnology offer advances not yet understood. However, a cautionary note – as we learn more about the materials and substances in our products, we are learning about the potential hazards and implications to humans and the potential negative impacts to our environment and our planet.
- Newly graduating students may discover within years, or even months, after graduating, that the "latest" methodologies learned during the university years will be surpassed and antiquated.
- Communication systems will be more integrated and interactive. Phone, e-mail, web access, TV, video games, etc will be handled on one compact device, interactive worldwide, and able to be accessed from any distance. CDs, video tapes, and DVDs are virtually extinct. Video, audio, entertainment media, and all communication capability will be available on demand.
- Manufactured products, such as automobiles or aircraft will no longer be independent platforms, but will be nodes in integrated and comprehensive systems of systems. Automobiles will have sensors, making them an integrated part of the highway and transportation system. Sensors will help control traffic, provide directions, monitor health of the vehicles, and provide the intelligence to prevent collisions and accidents.
- Business systems and interactions will be global and available around the clock. Industry will be able to perform 24/7/365. Facilities and teams in the United States will be able to work the first shift, with the next team overseas able to pick up where the previous "shift" in the other locations left off. By the time a

person returns to their work station on the next day, the global teams will have been progressing the design, development, test, or checkout of a system from locations around the world.

- Virtual and telecommuting work situations will be the norm. The advanced communications will enable more professionals to work out of the home or to work with minimum travel. Telecoms, web meetings, live meetings, and video teleconferences will be the accepted method of conducting business. This will allow employers to cut down on expenses of having large office areas, thus reducing costs such as utilities. This has numerous positive impacts, including improvements and reductions in the area of energy savings. Workers will be able to save on fuel costs and other expenses. Telecommuting will be expected by the Gen X, Gen Y, and future generations. Yet, challenges will exist, with the need to collaborate and need to stay connected with others and the rest of the team increasing due to distances.
- The loss of the knowledge of previous generations will be felt. There will be a need to try to re-capture and transfer knowledge and know-how to future generations. To do this, industry and academia will be seeking assistance from past employees, retirees, and those who have left the technical fields, to help lead this knowledge transfer effort.
- There will be more mergers, more consultants/contractors, more mobility, and less stability. Today's major industries may not exist, with the world economy dictating global products.
- The need for work life balance and individual choices will be more evident. Health and wellness will be stressed for employees, not only for their own good, but also to help prevent and reduce health care expenses.
- There will be more diversity, more inclusion. The challenges of multiple generations and variety of backgrounds and experiences will be many, but the work environment will be more innovative and productive.

Recommendations for Issue 1: Filling the Pipeline

Will we have the number of engineers we need in the future? There are a myriad of great programs and exceptionally good ideas already in existence to encourage students to stay in science and math. However, this is a situation in which activity, no matter how good, does not equate to progress. It has been found that engineering as a career is not understood by most students. It does not have the prestige or the familiarity of many of the other professions. We must change the perception and ensure there is understanding that engineering is a desirable and exciting career choice. To this end, the following concepts are presented for consideration:

- *There should be a National Task Force created to focus attention on this problem and to develop a nationwide solution directed at capturing the interest of students and finding ways to get more students into math, science, and engineering.*

- *This National Task Force should be composed of industry, government, academia, etc. It should consider revolutionary ideas and take bold steps to create a national program with goals and incentives for solving the problem.*
- *The engineering community, including industry, universities, professional organizations, and all stakeholders must have committed involvement and partnership in the Kindergarten-12 educational system.*

Proposal: Create a National Task Force to develop options for a nationwide program directed at increasing the number of students in science, mathematics, and engineering, leading to an increase in the technical workforce of tomorrow.

Currently, there are hundreds of competing programs, all which are good efforts. However, these efforts could be much more effective if they were focused toward a common goal. Many of the programs are excellent, but would more appropriately be defined as good activity. There is little measurement as to whether or not they are really making a difference in the end result or if they are effecting change. There is too much activity and churning, with little significant progress and no focus. Having a lot of activity and a lot of participation should not be confused with making progress. The proposed Task Force does not need to spend much time on defining the problem. It has been defined numerous times. This Task Force must take action which will lead to real change.

Proposal: The National Task Force (composed of Industry, government, academia, etc) should take a bold move to create a national engineering education/career program (e.g., JROTC-type program, or industry sponsored education and career programs) which starts in high school and carries through to college, offering college scholarships, or guaranteed education in return for commitment to work in the engineering discipline.

Not much has worked to entice students to pursue technical careers. So, it is time to do something drastically different. It is time to think of revolutionary concepts to allow us to take a major step forward. One novel idea is to start a nation-wide program to encourage students to study math and science in high school, similar to JROTC programs. The students have the obligation to study the math and sciences and do well, in exchange for paid education in engineering. In turn, there must be a commitment from the students to enter the engineering field after graduation.

A slightly different concept would be for industry to create programs by partnering with academia to provide education and the job opportunities. Industry will be the ones that need this workforce to survive the future decades. They have a vested interest in the students and therefore might be willing to focus their efforts and funds on creating apprentice and training programs.

Proposal: The engineering and technical community, including industry, universities, professional organizations, and all stakeholders, must have committed involvement and partnership in the K-12 educational system to attract and retain students in science, math, and engineering courses.

To keep the pipeline full, we must ensure that the students in K-12 are pursuing the fundamentals of math and science. It is true that this is a case of ‘easier said than done,’ as there seems to be a general attitude that math and science are not needed and will not be a useful in the future as adults. The use of the disciplines and its applications in everyday life are not grasped. There must be a concerted effort to reach out to the students, to make science and engineering seen as exciting and viable career path.

What must be avoided is ‘dabbling’ in the schools without the commitment. Again, activities and a lot of action do not equate to progress and change. The vision and expected outcomes must be established at the forefront of any program or involvement, as well as the specific goals to achieve, and the criteria to measure the success.

Recommendations for Issue 2 – Need for Holistic Engineers: Preparing Enlightened, Holistic System Engineers

As we struggle with making sure the pipeline is full, the question remains as to whether these future students are equipped with the knowledge and wide-view perspective needed for the next generation of engineers. As the world has gotten more complex, so have the designs, products, and implications. No longer will we have simplistic designs, independent of one another. One must understand the concepts of interoperability and integration of systems. For example, in the design of transportation vehicles, not only the complexity of the platform design itself must be taken into consideration, but the capability to operate within a system of systems, in the air, on the ground, and at sea, just to name a few items that must be considered.

But, beyond integration of the systems, will we have the creative thinkers to think of the system holistically such that they can see beyond the requirements and intended use? In other words, will they be able to deal with the unintended consequences of the original design, and make modifications accordingly to address those potential consequences? A more expansive training beyond the structured engineering teaching is recommended to encourage this broader, more inclusive, way of thinking. Taking a look at the current education process is in order. Several recommendations include

- Teach Systems Engineering
- Nurture and Grow Holistic Engineers
- Create courses which will be continuously updated for new technologies, findings, and trends
- Teach international culture, business ethics for future global interactions.

Proposal: Teach Systems Engineering processes in the Engineering Curriculum.

Systems Engineering is an interdisciplinary disciplined approach focusing on early identification of customer needs and an understanding of the required functionality of the end product. It includes all phases of the design process and moves methodically through development, all the way through systems validation and fielding of the product. The Introduction to Systems Engineering process should be taught as part of the undergraduate programs. A Masters in Systems Engineering/Integration should be developed and offered in major universities.

Most of our great and most advanced technological communities have adopted systems engineering processes. Systems engineering is now taught and practiced by national agencies, such as NASA and the DoD, and is used throughout industry as a whole. It is time we educate our new engineers in the same process. In the NASA Systems Engineering Handbook you will find the following definition Systems Engineering:

> Systems engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals. The approach is usually applied repeatedly and recursively, with several increases in the resolution of the system baselines (which contain requirements, design details, verification procedures and standards, cost and performance estimates, and so on).[11]

Proposal: We Must Nurture and Grow Holistic Thinkers.

There has been a tendency over the years to keep separate the liberal arts and engineering curriculum, recognizing the differences in thought processes, students, and interests. This has enabled the students to follow different paths, and over time, we have found that rarely do the two meet. The separation has had different labels to describe the different path of each: right brain vs. left brain, feelers vs. thinkers, creative vs. structured, liberal arts vs. engineering and technical degrees, etc.

As shown in recent studies, the dominance of either the right or left side of the brain allows each of us to process information and learn differently. In general, each of us tends to have one side of the brain which dominates the way we think, understand, and act. Most technical persons are left-brain dominant, which typically means structured and logical thinking. Left brainers are often more sequential. Most computer experts and engineers tend to be left-brain dominant. However, right-brain dominance is often described as broader vision, seeing the big picture, more conceptual, and more holistic.

> Other general characteristics of right-brain thought processes include the tendency to synthesize rather than analyze, and to relate to things in a concrete rather than a symbolic fashion. Where left-brain thinking tends to represent wholes by abstraction (using one piece of information to represent something larger), the right brain is more likely to interpret data through analogies – seeing relationships between wholes. Right-brain functioning is nontemporal, nonrational, holistic, and intuitive, relying on leaps of insight, hunches, or visual images. Discoveries about the right- and left-brain hemispheres have led some researchers and educators to advocate educational reforms that would allow right-brain modes of thought a greater place in the current educational system, which reflects society's overall tendency to reward the verbal, analytical left-brain skills.[12]

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[11] NASA Systems Engineering Handbook, http://human.space.edu/old/docs/Systems_Eng_Handbook.pdf

[12] Encyclopedia of Psychology http://findarticles.com/p/articles/mi_g2699/is_0002/ai_2699000296/

Most engineers tend to have more left-brain attributes. The challenge is to leverage this knowledge and to train engineers to expand their ways of thinking and to become more visionary. How do we teach engineers to think more holistically? Adding more liberal arts background, concepts, and training to the engineering basics can provide a vehicle to bring about this metamorphosis. Hence, we are seeing more students trained in the liberal arts, migrating to engineering and bringing with them this holistic thought process.

Proposal: Academia should create a senior-level required course focused on New Technologies to ensure students are constantly taught the newest, most innovative ideas and technology.

Do we have the right curriculum to ensure students learn the latest and greatest technology? The answer is an obvious yes and no. The current courses ensure students learn the fundamentals. No one is prescribing that the basic engineering curriculum be watered down. A strong foundation and understanding of the basic principles is required. However, the current curriculum should be reviewed to determine what modifications and updates are needed. Subject material should be expanded and constantly updated to reflect current and changing technology. Recent topics of interest could include nanotechnology, power, energy, and environment/go green, to name just a few.

Proposal: Academia should offer a course in international cultures, virtual communications, business ethics, etc. required for all engineering students. Semesters or time abroad should be considered at partner international universities.

The student will be entering a global society and we must ensure they are prepared for it. New global skills and cultural knowledge will be expected. Included in this should be international studies, foreign exchange opportunities, global communications, ethics, etiquette, and language. The more global knowledge, the better equipped they will be to solve the challenges of the world.

Concluding Remarks

We are at a crossroads now which will determine the future of technology and innovation within the United States. It is a many-faceted challenge which must be addressed now, before it is too late. It begins with the youth of today and ensuring they have the interest and training in math and science now. In short, we must be able to rapidly provide solutions for the following:

- We must have the quantity of engineers needed for the technical workforce of tomorrow.
- We must ensure we educate our future engineers and provide them the right foundation to prepare them for worldwide challenges and global interactions.
- We must broaden the thought process and create holistic-thinking systems engineers, encouraging out of the box thinking and ensuring they have a wide enough aperture to see all aspects and implications of the product.

The future is in our hands to take aggressive action and to ACT now. There is no time for evolution in our response to this crisis and our future. It will take a concerted and focused effort with goals and objectives for all sectors of our society – government, industry, academia, professional associations, etc. It is a global challenge and we must act now, or prepare for the consequences of inaction. It will take holistic-thinking system engineers to help orchestrate the solution and then get it implemented. It will take all of us, acting now so we protect the future and are ready for the technology challenges of tomorrow.

Chapter 18
Collaborative Innovation and Service Systems

Implications for Institutions and Disciplines

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Introduction: Growth and Collaborative Innovation

Historically, as new industries form at a national level, the three pillars of economic growth have been professions, infrastructure, and investment. More fully, these pillars are necessary skills and career development paths for new types of professionals (human capital), technological and institutional infrastructure (capital deepening and governance), and research and development (R&D) investment (innovation for efficiency and transformation). However, going beyond the boundaries of a single nation, new industry growth based on professions, infrastructure, and investment faces new challenges in light of global marketplace realities. With regard to IBM, no longer are we focused exclusively on the development, manufacture, and delivery of information technology, but rather on the application and integration of technology to deliver new and lasting value to our clients around the world. We have conducted an end-to-end transformation of our business, driven by major new global marketplace realities and opportunities. As a company with over $100 billion in revenue, and which operates in nearly 200 countries, we are aligned around a single, focused business model – collaborative innovation. Collaborative innovation is multidisciplined, open, and global.

Collaborative innovation is the new imperative because of a fundamental market shift. All markets by their very nature exist to promote win–win interactions. The interactions are motivated by the premise that entities that interact will be better off after interacting than they were before, that is, interactions for both

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entities result in value creation, also known as *value-cocreation*. Historically markets promoted interactions that exchanged possessions to cocreate value. In that old world, the three pillars of growth – professions, infrastructure, and investment – performed quite well. Modern markets promote interactions that apply knowledge and competences (service) to transform the world and help people realize ambitions and aspirations. In this new world, the three pillars need revision. Open markets allow a wide range of entities (individuals, businesses, institutions, etc.) to interact and engage in collaborative innovation. Collaborative innovation is driving a new level of global, socio-economic transformation. We are in the midst of one of those rare inflection points that will forever change the way work is conducted, the way new opportunity is created and how value is extracted from our endeavors.

As traditionally conceived of, the three pillars of growth – professions, infrastructure, and investment – work well for markets that are primarily directed toward product and production process innovation. However, for markets that are directed toward the innovation of business and societal systems and networks, the three pillars must be reconceived in the context of collaborative innovation. For example, professions require both deeper expert thinking and multidisciplinary complex communication skills; infrastructure, both technological and institutional, becomes more open and adaptive; and investment, both short-term and long-term, is globally interconnected and interdependent. New opportunities and risks abound.

Nations and businesses that seek to overcome the challenges and thereby realize the new growth opportunities available through collaborative innovation are coming to understand a simple truth. Success does not depend on simply creating more scientists and engineers, but on creating new types of scientists and engineers. In the remainder of this chapter, we first explore the trends associated with growing in new markets and the imperative of collaborative innovation. Next, we explore the nature of the new type of science (service science) and the new type of engineering (holistic engineering) that are needed to succeed.

Implications for Institutions: Nations and Businesses

The Three Drivers

We believe that the drivers of growth are different today and will remain so for the foreseeable future; they are propelling information technology and business services, and they are affecting not only IBM and the IT industry, but also the global economy as a whole. Further, a major factor in the accelerated growth of the American economy in the post-1995 period has been the increase in productivity gained by the application of information technology to business performance transformation services.

The economy today is moving into a new era, underpinned by cyber-infrastructure, a new architecture of computing as well as both the new business models and institutional infrastructures they enable. The essential ideas about the networked organization and global economy are clearly taking hold. Those changes are driven by the convergence of three historic developments:

Network Ubiquity: Global interconnectedness creates greater opportunities for collaboration. In roughly a decade, the Internet – the most visible evidence of an increasingly networked world – has reached over a billion people and is projected by some analyst to reach half the world's population by 2020. The Internet has not only connected people and opened up access to the world's information; it is rapidly becoming the planet's operational infrastructure. It is linking people, businesses, and institutions, as well as billions – ultimately trillions – of devices. It is facilitating and transforming transactions of all kinds – from commerce, government services, education and health care, to entertainment, conversation, and public discourse.

Open Standards: Collaboration is required to establish open standards. Technical and transaction specifications underpin all industries. When they become standards – that is, when they are widely adopted – they enable growth by spurring the creation of many new kinds of products and services. Standards made possible electrical, telephone and TV networks, CDs, DVDs, credit and debit cards, and global financial markets – and by extension, all the other business and public services those systems enabled. Today, standards are truly taking hold in information technology. They determine how computers operate and software applications are developed, how digital content is produced, processed, distributed, and stored, and how transactions of all types are managed. These standards are "open" – that is, not owned or controlled by any one company or entity. (The Internet itself, for example, is built on open standards.) This is common in other industries, but a radical departure for the information technology industry.

New Business Designs: The simultaneous emergence of the networked world and open standards is enabling entirely new business designs, giving CEOs and other decision-makers options that were not feasible before. Companies can now be far more flexible and responsive to changes in the economy, buyer behavior, supply, distribution networks, consumer tastes, geopolitical realities – even the weather. That is because their business operations can be integrated horizontally, from the point of contact with customers through the extended supply chain. And because vital information is captured and managed enterprise-wide, networked companies can anticipate and respond much faster, or, in other words, on demand.

These fundamental shifts are creating significant competitive advantages for institutions around the world that master collaborative innovation, particularly in the management and integration of their business processes through networks. Companies are innovating in areas, such as supply chain management, engineering design services, human resource management, after-sales services and customer care. Governments are transforming their legacy agencies to organize around missions rather than departments. Academic institutions are delivering their courseware through the Internet in addition to the traditional classroom. Institutions are radically innovating in their business operations and processes using information technology and the services and expertise associated with business process transformation that embraces collaborative innovation.

Collaborative innovation is a worldview. The worldview we are espousing is based on entities interacting (people, businesses, institutions, nations, etc.), forming global networks, defining open standards to reduce transaction costs, and continuously benefiting from finding new business models to collaborate and improve each others' capabilities. Implementing the fundamental driver concepts is affording new growth opportunities in both economic and societal activity. Seizing the opportunities demands unique foresight and capability. As collaborative innovation takes hold, the availability of professional talent, infrastructure, and investment are increasing everywhere, making the world more tightly integrated and dependent on collaborative innovation to survive and thrive. For companies, governments and educational institutions, the choice is either innovation or commoditization.

The Changing Nature of Innovation

Perhaps the most important innovation occurring today is in the changing nature of innovation, itself. It happens much faster today and it diffuses more rapidly into our everyday lives; it is far more open; it spans virtually all disciplines and professions; it is increasingly global. Innovation almost never arises in the isolated laboratory anymore. It arises in the marketplace, the workplace, the community, the classroom. Innovation is a two-way interplay of creation and its uses, supply and demand, also known as value-cocreation. Understanding the changing nature of innovation is the first step toward marshalling our energies and resources to prosper in this new environment.

In 2004 IBM embarked on a first-of-its kind initiative to explore the changing nature of innovation and what it means for business, academia, and society. IBM brought together hundreds of ecosystem partners from multiple disciplines around the world to focus on crucial societal issues that cut across businesses, industries, borders, and cultures. Again, they included issues such as health care, work-life balance, and effective government. The initiative was called the Global Innovation Outlook. Among its key findings:

- Because innovation requires continual collaboration, workers in the 21st century no longer can rely on the expertise they learned early in life to keep them at the forefront of the skills queue.
- Colleges and universities are struggling to keep abreast of the fast-changing dynamic nature of work.
- Aspiring knowledge workers will need cross-disciplinary programs and degrees in order to compete. Historically, universities have found it difficult to provide such programs.

The Global Innovation Outlook also revealed that tighter collaboration among government, academia, and industry is essential. It is the only way to spark innovation and drive solutions to the pressing problems we face. We heard this loud and clear, over and over, from government leaders, university presidents, and senior business executives alike.

The Innovation–Commoditization Cycle Dilemma

Like other major structural shifts before it, the new era – globally networked, built on standards and with wholly new business and institutional models – is opening up new possibilities for profit and growth for business, while also affecting other realms of societal and economic activity – from government, to health care, to education.

Seizing the opportunities presented by that shift, as always, requires unique foresight and capabilities. Despite the turmoil in the economy in recent years, some nations have managed to increase their prosperity, advance the frontiers of science and learning, and build multiple kinds of new expertise. For them, the result today is an economy poised for sustained growth in traditional markets and robust growth in the new markets.

Professional capabilities, infrastructure, and investment are increasing everywhere. Global interconnections make it possible for people to work from virtually anywhere. The world is indeed becoming more tightly integrated. For businesses in a broad range of industries – as well as governments – the choice is either innovation or commoditization.

Businesses that create new, high-demand technologies and services enjoy, for a time, barriers to entry, as well as superior margins and pricing power, since there are few other providers of that technology or service. However, alternative technologies or capabilities inevitably emerge, decreasing the innovator's advantages. In short, that segment of the industry "commoditizes." There are still attractive opportunities to be pursued, but with much less profit potential.

The global innovation–commoditization cycle has never been more pronounced than it is today, and it forces distinct choices. Winners can be the innovators – those with the capacity to invest, manage, and leverage the creation of intellectual capital – or the commodity players, who differentiate through low price, economies of scale, and efficient distribution of other parties' intellectual capital.

Perhaps the greatest risk is to get squeezed in the middle – being attacked by low-price competitors, while lacking the expertise and intellectual capital to keep up with the most aggressive innovators.

The innovation–commoditization cycle dilemma affects nations and businesses. Understanding, anticipating, and managing the forces of innovation and commoditization can address many of the challenges to national economic success. Today, companies and organizations are coming to a new way of conceptualizing and managing the transformation and evolution of their systems and networks. Essentially, they are choosing to move to a higher value space in the overall national economic picture. A networked, interconnected model enables them to achieve higher levels of responsiveness, flexibility, and efficiency than legacy, Industrial-Age business models. This new flexibility offers great potential for growth, by increasing productivity and by creating entirely new capabilities.

There are many examples of new capabilities. In health care, for instance, we now see personalized medicine on the horizon – as the integration of patient histories and genomic data is changing the nature of diagnosis and patient care. In insurance, we see products and services tailored to the driving habits of individual policyholders.

Collaborative innovation has become the new arbiter of national competitiveness. We must recognize collaborative innovation as a national priority. For the United States or any nation to thrive in the hyper-competitive world economy they must, with urgency, mobilize business, government, educators, and researchers to adopt collaborative innovation as a core strategy to build the foundation for a 21st-century knowledge-based economy.

Collaborative innovation success will be a product of many stakeholders collaborating and sharing the risk of change. To facilitate the process, national policy architectures must be modernized to address the changing nature of innovation and growth. The redesign of national innovation policies must be balanced, consistent and coordinated, and focused on crucial challenges.

Professions in a Knowledge-Intensive Service Economy

Professions relate to skills (education, training, and workforce development) and career paths (job roles, advancement, and opportunities). Competitive advantage today comes from expertise – and expertise is not static. The collaborative innovation challenge requires maintaining deep and diverse collection of business and technology innovators, supported by advanced collaboration systems and a culture that enables continuous learning. In the Agricultural Age, land and farm production defined competitive advantage. In the Industrial Age, it was raw materials and manufacturing capability. Today, it is the ability to create and apply intellectual capital based on multidisciplinary expertise.

Workforce skills must include both technology and business expertise. An understanding of technology – its current capabilities as well as its future potential – is now integral to business decision making. Business leaders need innovation partners who are at the frontiers of research and deeply steeped in the issues and dynamics of specific industries.

To advance business expertise, the nation's structural transition to a knowledge-intensive service economy needs to be supported by a deepened understanding of how service systems and networks support and interact with manufacturing and other more traditional activities. In fact, in today's global economy, the service sector provides the bulk of employment in high-wage economies.

A wide community is beginning to discuss the technical and social effects of new developments in global connectivity, automation, technology integration, and Web services and a new scientific discipline is being opened. Leading universities are beginning to work with IBM to better understand the social and technical issues involved in collaborating across global enterprises. For example, the University of California at Berkeley has implemented a service science curriculum in conjunction with IBM Research – much in the way the first computer science department was initiated at Columbia University. Federal research investment and collaboration could significantly accelerate learning in this area.

To advance technology expertise, we are convinced that education must be transformed and realigned to prepare students to become adaptive innovators. Reform must start with curriculum. Creative and integrative instruction can be achieved through the development of integrated problem-based learning (PBL) and challenge-based learning (CBL) – both methodologies that are sure to enhance the development of much-needed skills – especially in the engineering and technical professions. PBL is specifically helpful in the development of scientific, mathematical, and technical talent. It focuses on ill-structured problem solving, and provides deeper meaning, applicability, and relevancy to classroom materials and the development of crucial analysis skills that are required in the workplace. CBL engages students in working on complex real world problems that have not been solved yet. An education system designed to support curriculum focused on acquiring discreet skills and memorizing information will not produce the leaders and innovators the world needs.

The information technology sector is experiencing a pronounced shift in demand for specialized skills that fuse industry-specific knowledge, information technology capability, and business expertise. These skills enable the business performance transformation services described earlier. Organizations seek more integrated and customized technology and services solutions that create competitive advantage and enable innovation. New information technology jobs are mushrooming in areas like business analytics, security analysis, vendor management, service management, and system integration. IBM's clients seek business acumen, project management and leadership skills along with specific IT skills linked to open standards, networking, and e-commerce. These emerging occupations require higher skills and they are well paid.

Finally, we must realize that we benefit greatly from a diversity of talent, a diversity of culture, a diversity of thought and insight from all over the world – intra-national and international. Collaborative innovation does not happen in isolation. For most innovations, the days of the lone inventor are over. Collaborative innovation happens across the diverse communities required to sustain economic leadership in the 21st century. Every region needs immigration policies that enable it to attract and retain the diverse minds of the world. Regions with diverse populations can more easily connect globally.

In an expertise-based, global marketplace, the expansion of business into more diverse services is forcing us to re-think the types of skills and educational degrees that are needed to drive America forward. In fact, the whole services paradigm is enabling us to be more innovative in our approach to talent development.

Applied more broadly, our experience drives us to conclude that collaborative innovators need a culture of learning and skill building. Specifically, it means that technologists and business experts need to work closely together, not simply to share insights, but to create entirely new intellectual capital for competitive advantage – new types of value-cocreation mechanisms We must build the capacity to apply new intellectual property to nurture and launch new high-value businesses.

Unlocking innovation also demands that we rethink our ideas about intellectual property (IP). Some believe the best way to provide incentives for innovation is by fiercely protecting the inventor's proprietary interest. Others argue that we should open the doors and give full access to intellectual assets. An approach that offers a balance of those two extremes may be most beneficial.

While IP ownership is an essential driver of innovation, technological advances are often dependent on shared knowledge, standards, and collaborative innovation. The IP framework must enable both. We must protect truly new, novel, and useful inventions. And we need to recognize that open standards can accelerate the interoperability and expansion of the global infrastructure. Because collaborative innovation is relatively new, the structure and processes to accommodate ownership, openness, and access are evolving, and new creative models are emerging.

Economies around the world are replicating the characteristics that have given Western nations such an innovation advantage – highly-trained professionals, technological and institutional infrastructures, and R&D investments, and highly-trained professionals – operating with an open market system. Many companies in rapidly developing nations such as China, India, Brazil, and Russia are leapfrogging to new cyber-infrastructures and business designs. Emerging nations with limited legacy infrastructures are developing specific innovation strategies. They plan to drive economic growth by leapfrogging in infrastructure development, providing tax incentives that attract global investment, and seeking parity or even superiority in the value delivered by skilled professionals. These approaches are creating a highly competitive global economy.

Higher Education in a Knowledge-Intensive Service Economy

Higher education is part of the institutional infrastructure of nations. Beyond the always-crucial role of producing graduates in the science, engineering, and professional disciplines, institutions of higher learning must collaborate with government and industry to transform how the pipeline of future skills is being built – skills that are needed in a global, knowledge-intensive service economy.

Many of the brightest frontiers of knowledge lie at the intersection of traditional disciplines. Advances in medical technologies, for example, integrate biology with physics, mathematics, materials sciences, and software engineering. We have to find ways to break down traditional stovepipes and encourage collaborative and multidisciplinary learning.

In addition to learning across scientific disciplines, we should encourage collaboration across technical, business, and social sciences. Innovation requires individuals able to recognize how new knowledge could meet societal demands and translate potential into practice. That creates real and lasting value.

Universities and community colleges are key components of successful regional economies. Universities should embrace a culture of commercializing knowledge and be active partners in regional growth strategies with government and industry. Community colleges, too, should play a prominent role in an innovation economy. The NII recommends, for example, that we establish innovation management curricula for entrepreneurs and small business managers. Community colleges have a history of adapting to the skill needs of their localities.

When it comes to growth through innovation, the debate usually centers on the post World War II formula for innovation – namely, more money for developing knowledge-intensive professions, especially in STEM (science, technology, engineering, and math education) areas, needed technical and institutional infrastructure, and R&D investment to create new knowledge. Today, we must set ourselves on the path to do far more.

We need creative and bold policies that recognize the need for a more systematic approach to research and teaching in service science and holistic engineering; that recognize the need for more multidisciplinary research; that recognize universities as the key component of regional innovation economies.

We have consistently found that open, standardized approaches to problems provide the fastest path to innovation and success. It is foolhardy, in this modern era, to have a cacophony of competing, non-complimentary approaches to managing records.

We also must recognize the need for structural change. Even if federal and state higher education resources were to increase dramatically, that, alone, would not achieve the objective of meeting the full career path needs of our citizens in a global, knowledge-intensive service economy.

Frankly, academia and government must be open to new ways of leveraging industry and private-sector resources to address our challenges. We are not tapping into this remarkable asset – global business acumen – to address issues such as teacher training, new measures of institutional performance and standards of learning, and reform in the accreditation process. Many of the most exciting PBL (problem-based learning) and CBL (challenge-based learning) projects will require even stronger collaborations.

The forces of global economic integration, and advances in technology, are presenting complex challenges that can be addressed only by embracing opportunities for change and future prosperity. The status quo cannot be an option.

Institutions of higher learning must open up and collaborate with industry and government to create a US educational climate and culture that enables innovation to thrive. No institution can go at this alone. It must be a joint stewardship of industry, government, and academia.

America has a long and proud history of recognizing when change is required, and then rising to the challenge. We are at such an inflection point today. As we work to transform our rhetoric into action, innovation must be our engine and urgency must be our fuel. Innovation – the process of innovation – the collaborative, multidisciplinary, open nature of innovation – will enable all of us to build a brighter future for generations of students and our nation.

R&D Investment in a Knowledge-Intensive Service Economy

New knowledge is the fuel that invigorates professions and transforms national infrastructures, both technological and institutional. R&D investment increases the knowledge intensity of the global service economy. Effective R&D investment is based on directional roadmaps, associated progress measures, as well as supportive and aligned policies.

Achieving collaborative innovation success is complex. It requires far more than the management of ideas, technology transfer, and research and development. The challenge is not only to generate fresh ideas and intellectual property, but to transform ideas and intellectual property into new value in an open marketplace of continuously transforming entities. Commercially successful transformation services are highly prized in the new open marketplace. The private sector is the primary agent for innovation. The Federal government, however, has enormous influence over the pace of fundamental knowledge advances, the incentive for private enterprises to invest in innovation and the conditions under which innovation may thrive.

Collaborative innovation is not just R&D investment driven (a supply side thought). It needs to be viewed on both the supply and demand side, from a global, value-cocreation perspective. A basic prerequisite for the next generation of innovation policies is to move toward a thoughtful balance between internal supply development and external demand development. The push and pull of supply and demand do not occur in a vacuum. They are strongly influenced by public policy and the overall infrastructure for collaborative innovation offered by our society. Public policies related to education and training, research funding, regulation, fiscal and monetary tools, intellectual property, and market access demonstrably affect our ability to generate supply and respond to demands.

The same can be said of infrastructure – be it transportation, energy, health care, information technology networks or communications. Taken together, the institutional policy and infrastructure environments create a national infrastructure platform that can accelerate – or impede – the pace and quality of collaborative innovation.

Many of the critical choices lie outside the traditional sphere of research and development investment and innovation supply policies. Policies which influence the supply of talent, risk capital, the demand for innovative goods and services and the robustness of regional innovation networks also are important. A higher level of national innovation performance will result from an integrated end-to-end (idea to market) approach by the federal government. The vitality of the ecosystem will stimulate innovation. Focusing only on the discrete components – investing in schools or sector-specific initiatives – is not enough. To stimulate collaborative innovation, we must find ways to address the entire ecosystem, including efforts aimed at the following four areas:

1. Creating new metrics for the national innovation ecosystem to drive performance and monitor results. New metrics of the knowledge-based economy should include knowledge indicators, such as those derived from contractual agreements like strategic partnerships, IP licensing, and conditions for innovation, such as economic demand, public policy environment, and infrastructure readiness. Implementing a legal and regulatory framework encourages voluntary and more complete disclosure of business intellectual (“intangible”) assets and longer term

innovation strategies. Such disclosures provide a basis for better metrics of the knowledge-based economy.

2. Implementing new tax incentives to provide scholarships for the next generation of scientists, engineers, and innovators and changing immigration policies to attract and retain the brightest talent from around the world. Tax incentives can also help shift resources to the most impactful emerging areas of science and engineering.
3. Modifying the long-term Federal R&D investment portfolio by a new priority on emerging science and engineering areas, setting aside an increased proportion of research funding to basic, novel, high-risk, and exploratory research, including establishing a research program for the service science and holistic engineering, encouraging multidisciplinary research, and making permanent a restructured R&D tax credit including university–industry collaborations. Capitalizing on innovation opportunities in emerging areas such as new energy and materials, nanotechnology, green technology, mobile and social, medical records and health care, modeling and simulation of complex business, and social systems.
4. Coordinating and focusing federal economic development programs on regional innovation hotspots and creating more dynamic innovative industry clusters. Accelerating innovation-oriented learning environments at the K-12 level, enhancing careers options, and the adaptability of workers through portable learning benefits. Development of professional capabilities can be accelerated by innovative infrastructure, both technological and institutional.

The directional roadmap for R&D investment in a global, knowledge-intensive service economies is aimed at building collaborative innovation capacity throughout the ecosystem of entities that participate in the open marketplace.

Succeeding in Collaborative Innovation

CEOs, government officials, academic, and community leaders around the world are all counting on "innovation" to be the fundamental driver of economic opportunity, job creation, business competitiveness and advances in education, health care, and a vast range of other disciplines. Investing in innovation, they say, is the surest way to survive and thrive in today's complex, connected world.

But what do they really mean when they talk about innovation? Inside the information technology industry, innovation has been defined historically by the process of invention and discovery, and driven by R&D investments. Bell Labs, Xerox PARC, and IBM Research, along with basic research programs at the world's leading universities, epitomized the innovation engines of the 20th century.

They also operated in classic "ivory tower" mode – highly secretive and proprietary in their approaches, sharing little with others and, as a result, sometimes suffering from painstakingly slow paths to market for their best ideas. But the world has changed dramatically over the past decade – and even more so the basic nature of innovation itself. This shift to collaborative innovation first became evident with the rise of the internet, open standards, and new business models that threatened incumbents.

One of the key themes that emerged from a 2006 CEO study we conducted was that external collaboration is indispensable for innovation. We interviewed nearly 800 CEOs, representing a wide swath of geographic areas, a range of annual revenues, and everything from small and medium businesses to large, global enterprises. When asked which sources their companies relied on for their innovative ideas, "business partners" were right near the top of the list, just behind the general employee population.

"Customers" rounded out the top of the list, meaning that the top three significant sources of innovative ideas are predicated on open, collaborative approaches, including reaching outside the organization. In fact, CEOs said they are getting about twice as many innovation insights from customers as they are from their own organizations.

Perhaps most surprising was that "Internal R&D" was second-to-last on the list. As a career engineer and scientist-turned businessman, I would argue that those who do not see value returning from their R&D investments are not managing their portfolios to reflect the changes underway in the marketplace. In other words, they still are not collaborating externally and working directly with their customers. IBM Research is in the midst of a renaissance as a result of embracing market input.

The CEOs also told us that partnering – whether crossing internal or external boundaries – is easy in principle, but very difficult in practice. This is not at all surprising. Working with different groups to achieve common objectives usually requires a change in the culture of most organizations, and cultural transformations may be the hardest of all. We are convinced that to truly embrace a culture of collaboration you must accept limitations in your ability to get things done without help.

This is particularly important for those companies, like IBM, who are addressing problems in business, government, health care, technology, and science that are very sophisticated in nature and pushing the limits of what is possible. We have learned that we cannot work on problems such as information-based medicine, integrated supply chains, or advanced engineering design unless we have established a very close relationship with clients, business partners, and even other vendors who might very well be competitors.

In such an environment, to boast about being "the best" would frankly be considered crass, a sign of corporate insecurity rather than the strength of a confident leader and partner in the value-cocreation game. Instead, you want to be known as a company that helps all the various members of the team succeed in whatever problems are being addressed. Rather than claiming that you are the most innovative of companies, you want to be known as a company that helps those with whom you work become more innovative themselves.

The open movement makes all of that possible. It holds the potential to spark remarkable innovation – and also turn historical cost structures and investment models on their ears. The Linux operating system, for example, is owned by no one, yet owned by everyone at the same time.

Thousands upon thousands of programmers around the world contribute to it and make it better, creating a checks and balances system that would be impossible with proprietary, closed systems.

Historically, we know it takes about $1 billion to bring an enterprise-ready operating system to the marketplace for one computing platform. By working with the open community, we at IBM were able to get Linux across our entire product line with about one-fifth the investment we would normally make for just one platform. We did it through a combination of Linux code developed by the community, Linux code we contributed to the open community and Linux code we developed uniquely to better support it on our products. As a result, our offerings are better tested, more robust and are market-ready more immediately.

The open movement creates a common base for infrastructure, so that the wheel never has to be re-invented. The basics are already there and agreed upon by the global community. That enables creators to leapfrog over the mundane, and jump right to the innovative – being assured that the infrastructure is sound and secure because it has been refined and tempered by great thinkers around the world.

When more people have access to the building blocks of innovation, rich new perspectives and diverse influences are injected into the creative process. People begin to think in an interdependent, collaborative way – across disciplines, and collaborating at the intersections between them.

True innovation, then, is driven by the ecosystem; by listening to and learning from the various constituents with whom you exchange dialog and who may add value to the discussion. By embracing your ecosystem, you tear down the boundaries of culture, geography, and organization to rapidly generate ideas and act on changes.

The first step is modeling your organization's own ecosystem – all the major constituency groups that are vital to your business success. There really is no right or wrong model, unless you choose to go it alone.

Second, you need to commit to a two-way dialogue with each of these constituencies – and also foster interaction between them, both with you and without you. You cannot control them anymore, or simply pump one-way messages and demands out to them. They will go elsewhere and collaborate with more receptive partners.

Networks are not a new idea, of course. The business world has always comprised constellations of people working together to create value. But in the past, those relationships have generally been more limited and exclusionary in nature, bound by strictly defined legal agreements and financial understandings.

Over the past decade, however, the proliferation of communication networks has not only connected people, places, and ideas in unprecedented ways, but also catalyzed the evolution of social structures. With the freedom to transcend physical and geographic borders more easily, we are more willing to partner within and outside our traditional boundaries of organizations and countries.

Because of that shift, the 20th-century business enterprise as we know it could be history. Increasingly, the motivating force that brings people together for work is less “a business organization” and more the collective enterprise – activities driven by a common set of interests, goals, or values.

The trend is accelerating, and it will have profound implications on how companies think about everything from leadership to managing and motivating global talent. It will change the way companies approach innovation, itself. As boundaries dissolve, as more fluid relationships form, as ecosystems expand and as networks get larger, the very nature of decision-making for individuals, businesses, and the world takes on a new shape. Local actions now have global consequences, and the reverse is true as well.

To pursue open, collaborative innovation, enterprises simply must find ways to tap into the potential of the skill, talent, and creativity of people from different teams in different organizations across the globe. A company can only be as innovative as the collective capacity of the people who make up its ecosystem. And to attract and retain talented people, a company must enable those people to feel respected, as individuals, as professionals and as members of a team. The company must trust those people and encourage them to collaborate and innovate with colleagues within and outside the business, driven as much by pride of contribution as by loyalty to the company.

These new models for collaboration offer a financial payoff as well. Studies show that companies that outperform their peer groups are much more likely to have adopted business models that focus on core expertise and collaboration with partners, rather than by strengthening their command and control posture.

Consider Bharti Tele-Ventures, the largest private telephone company in India. It recently outsourced and integrated its core functions – such as network and program management, help desk support, disaster recovery, IT, and billing – which freed it to focus exclusively on marketing and customer service strategies. As a result, Bharti tripled its subscriber base – from six to 18 million subscribers – in just 20 months.

But success stories like that do not come easy. As fewer companies directly control all aspects of their operations, it becomes harder to ensure that brand experience consistently lives up to brand promise. How can a company ensure that the individuals and business partners who power its network fully understand its brand and are motivated to protect and uphold it?

During the Global Innovation Outlook sessions, several participants advanced a concept built around the term “Reputation Capital.” It describes a kind of currency for building trust in a prospective worker’s personal and professional qualifications. They cited examples such as Wikipedia and eBay, both of which built successful brands based on the contributions of hundreds of thousands of non-affiliated individuals.

In each case, there are standards in place enabling people to see and rate the integrity and credibility of contributors. The more a contributor consistently demonstrates a high level of accountability and quality, the more value the contributor garners. Even for businesses not built around the contributions of individuals, reputation capital has intriguing possibilities – especially for emerging global players who have only a virtual presence and no visible brand of their own.

We are convinced that the art of collaborative innovation will be the most distinguishing leadership characteristic of the 21st century. Universities need to teach it. Government policies and regulations need to facilitate it. Businesses need to practice it.

For collaborative innovation to become part of our collective DNA, we must accept the notion that the surest way to make progress and solve problems is to tap into the collective knowledge of the team. Networked enterprises are the future. No individual enterprise, no matter how large and talented, can afford to go it alone in today's highly competitive, globally integrated marketplace.

Success in tapping into such a global marketplace of innovators and experts requires companies to first develop a sound understanding of the collaborative landscape and then decide on an approach that suits them the best. One size does not fit all in this regard.

Different models of networked innovation and offer a set of guidelines for companies to identify and prepare for the most promising collaborative innovation opportunities. As they emphasize, success also requires us to rethink the very nature of our relationships with innovation partners – what we need to control and what we need to let go.

Implications for Disciplines: Science and Engineering

Growing Number of Disciplines

In "Implications for Institutions: Nations and Businesses," we focused on the realities that drive nations and businesses to make collaborative innovation a top priority. In "Implications for Disciplines: Science and Engineering," we focus on what collaborative innovation means to science and engineering disciplines. Just as no nation or business is an island, no science or engineering discipline is an island. More specialization in the world creates both more disciplines and many more boundary zones that interconnect disciplines. In fact, linear growth in the number of disciplines creates exponentially more possible boundary zones, or points for collaboration between disciplines (Tables 18.1 and 18.2).

While these lists are not comprehensive (e.g., should expert systems engineering be in the list), it does provide some confirmation for the assertion that a major new engineering discipline is established about once a decade. We have no reason to believe this pace will slow down as we move into the future, and some reasons to believe it may actually accelerate. For example, robotic engineering, nanoscale engineering, virtual world/game engineering and design, organizational engineering and design, and crime scene investigation are just a few of the emerging areas. As global population grows, specialization and division of labor is likely to continue and intensify. However, wherever people (and their determination of value) play

Table 18.1 Shows the growth of about one new engineering discipline per decade for the last two centuries. We indicate a specific year based on the formation of professional associations in the United States (or internationally)

Year	Engineering discipline	Association	Artifacts & Industries
Antiquity	Military	DoD	Cannons, tactics, supply chain
1852	Civil	ASCE	Roads, bridges, buildings
1880	Mechanical	ASME	Steam engines, machinery
1884	Electrical	AIEE/IEEE	Generators, grid, appliances
1907	Agricultural & Bio	ASAE/ASABE	Crops, orchards
1908	Chemical	AICE	Fertilizers, fuels, compounds
1948	Industrial & Systems	ASIE/IIE	Factories, conveyors
1948	Computing machinery	ACM	Computers, Info Tech (IT)
1954	Nuclear	ANS	Reactors
1955	Environmental	AAEE	Sustainable construction
1963	Aerospace	AIAA	Jets, rockets
1968	Biomedical	BMES	Medical instruments
1985	Genetic technology	AGT	Bacteria, plants, animals
1992	Financial	IAFE	Derivatives, options
1993	Software	JCESEP	Applications, websites
2007	Service systems	SRII/SSMED	Healthcare, B2B IT Consulting
2008	Holistic	?	Healthcare, transportation

Table 18.2 Shows the conceptual relationship of these emerging disciplines to some fields of science and mathematics

Year	Engineering discipline	Science	Fields + Mathematics
Antiquity	Military	All	Ballistics, metallurgy
1852	Civil	Physics	Mechanics, materials
1880	Mechanical	Physics	Mechanics, materials
1884	Electrical	Physics	Electromagnetism (EM)
1907	Agricultural & Bio	Biology	Cellular mechanisms
1908	Chemical	Chemistry	Thermodynamics (TD)
1948	Industrial & Systems	All	Operations research (OR), CSD
1948	Computing machinery	Phys/Logic	EM, OR, CSD, Algorithms
1954	Nuclear	Physics	Nuclear
1955	Environmental	All	Complexity/System dynamics (CSD)
1963	Aerospace	Physics	Fluid dynamics
1968	Biomedical	All	Sensors, EM, TD
1985	Genetic technology	Bio/Chem	Genetics
1992	Financial	Economics	Algorithms, Econ, OR, CSD
1993	Software	Logic	Psych, Social, Econ, OR, CSD
2007	Service systems	Economics	Psych, Social, Econ, OR, CSD
2008	Holistic	All	Psych, Social, Econ, OR, CSD

an important role in the dynamics of complex systems, as in industrial and system engineering, financial engineering, software engineering, service systems engineering, and holistic engineering, we can also see an integrative force, working against specialization alone.

Reasoning About the "Shape" of Professionals

The "shape" of a professional is a term we use to understand whether a professional is a deep specialist in one area ("I-shaped"), deep specialist in two areas ("H-shaped[1]"), deep in just one area, but with good knowledge and communication skills across many other areas ("T-shaped"), or not deep, but with good breadth, a generalist ("Dash-shaped"). Clearly, an even more intricate shape language could be created when one factors in distinctions such as rigorous theoretical knowledge ("book learning") and practical professional experience ("real-world relevance"). For our purposes, most of the points we are concerned with can be discussed in the context of the four basic shapes above. However, it should be noted that given a set of science and engineering disciplines, the learning and work experiences of any particular scientist or engineer could be used to create a more complex shape language of professionals. Also, given the close conceptual relationships between certain areas of science and engineering, as well as overlaps in tools and methods, one might expect considerable variation in the amount of time it takes for a professional to attain certain shapes for particular sets of disciplines.

I-shaped professionals may be very good as a "lone" innovator, but not so good at collaboration, unless teamed with someone else who shares the same area of depth. Hence, they may have great difficulty with collaborative innovation, unless they work in teams with people of other shapes that overlap the I-shaped professional's area of depth. Then the others on the team are able to communicate with and benefit from the I-shaped professional's deep knowledge in solving new problems.

On the other hand, dash-shaped professionals may be very good at collaboration, but not so good at innovation, since they lack deep knowledge that can allow them to solve new problems.

H-shaped professionals may be even better than I-shaped people at innovation, and even better at collaboration. The challenge of course is that it takes a great deal of time to gain depth, so depth in two areas typically takes a substantial investment of time.

T-shaped professional may be very good at collaboration, and good innovators, solving new problems in their area of depth as well. Like H-shaped people though, it takes a lot of time to master complex communication skills across a breadth of other disciplines.

In sum, H-shaped and T-shaped professionals may take twice as long to create as I-shaped and dash-shaped professionals, but in general we would expect H-shaped and T-shaped people to be much better at both innovation and

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[1] H-shaped are also sometimes referred to as *Hybrid* professionals. Many applied computer scientists are H-shaped, deep in computer science as well as some application domain such as meteorology, physics, or another area in which they build simulations or application software to perform research. If a person is deep in two areas, and also has good breadth for complex communication across disciplines, they are referred to as Pi-shaped. A professional journalist is typically T-shaped, deep in communication theory as well as a versatile communicator in many topic areas. Professional science masters students tend to be T-shaped with depth in one area of science, as well as with broad communications skills across many business functions.

collaboration – or being good collaborative innovators. Alternatively, in a population of life-long learners, we might find more H-shaped and T-shaped people at later stages in their careers, and more I-shaped and dash-shaped professionals early in their careers.

Levy and Murnane (2004) analyzed 30 years of occupational descriptions used by the US Department of Labor, and found evidence for a strong trend in which types of skills were mentioned in newer occupational descriptions. Occupational descriptions show a clear trend toward requirements for expert thinking (problem solving) and complex communication (collaboration skills). These finding are consistent with the growth of a knowledge-intensive service economy. Both more specialization (expert thinking) and more integration (complex communication) are consistent with collaborative innovation becoming an increasing priority of organizations, and then reflected in their descriptions of occupations.

Computational organization theory researchers (Cataldo et al., 2001) have used simulation techniques to explore the productive capacity of organizations in which the ratio of specialist (I-shaped professionals) to generalist (dash-shaped professionals) was varied. These studies indicate that in times of low rate of environmental change (fixed demand), organization composed of all specialists could maximize productive output. However, in times of rapid environmental change (shifting demand), organizations with higher numbers of generalists could out-perform other organizations. Again, these experiments support the notion that in a world where collaborative innovation is an increasing priority, organizations will compete best that are able to complement their I-shaped professionals with more H-shaped, T-shaped, and dash-shaped professionals as the rate of environmental change increases.

Understanding Terminology Related to Disciplinary Relationships

The term "disciplinary" refers to a body of knowledge on a subject. People can have different levels of facility with the body of knowledge that circumscribes a discipline; some are novice and some are expert. For example, some people may only understand a discipline well enough to talk about some aspects of it, while others may be able to apply the knowledge in appropriate contexts and use the knowledge to solve problems, and still other may be able to contribute to the growth of the body of knowledge to solve even a wider range of problems. Students may only be able to talk about the knowledge, while practitioners possess the knowledge and use it in value-cocreation activities, and researchers can add to the growing body of knowledge that is their discipline, and hence allow a wider range of problems to have a solution within the discipline.

In discussions about collaborative innovation, one often hears the terms multidisciplinary, interdisciplinary, cross-disciplinary, and transdisciplinary. Some people use these terms almost interchangeably, but they are in fact different. Along with the term disciplinary (perhaps more correctly termed "intradisciplinary"), these five terms can be used to describe knowledge, people, types of research or educational activities, and teams of people.

The distinctions are sometimes subtle between these five: (1) disciplinary or intradisciplinary, (2) interdisciplinary, (3) multidisciplinary, (4) transdisciplinary, and (5) cross-disciplinary. Perhaps the simplest way to understand the distinctions is to imagine a population of people who value knowledge for its ability to stimulate productive relationships with others and help solve problems together (later, when we discuss service science, we will see that this is a simplified version of the *service systems ecology microworld*). Imagine these people know about a set of problems, some of which can be solved, and some of which cannot be solved. Very frequently, new problems are discovered as well. Very rarely, problems go away or are solved once and for all, and never need to be solved again in practice. Of all the problems this knowledge-valuing people know of, two are especially thorny, (1) making sure that knowledge is passed down to the next generation in an efficient manner and (2) expanding the overall body of knowledge to allow new, urgent problems to be solved. Of course, we recognize the first problem as the education (knowledge transfer) problem and the second problem as the research (knowledge expansion) problem.

A disciplinary community or project is made up of people who use their disciplinary knowledge to primarily solve problems. In addition to solving problems (service provider and customer relationship), the knowledge is also used to teach other as they join the discipline (teacher and student relationship) as well to create new knowledge and identify new problems that practitioners need to solve (researcher and practitioner relationship) that fall within the discipline boundaries. Disciplinary teams deal primarily with the knowledge application problem.

A multidisciplinary community or project is made up of people from more than one discipline that come together as equal stakeholders to work on complex problems that cannot be solved by a single disciplinary community alone. If the complex problem can be broken down into a set of problems that each discipline can solve separately and then reintegrate to solve the whole, multidisciplinary teams can be very efficient at repeatedly solving versions of the challenge. A multidisciplinary person is a person with the knowledge to be a member of more than one disciplinary community. Multidisciplinary teams must deal primarily with problem decomposition and solution recomposition problems in addition to the knowledge application problem.

An interdisciplinary community or project is made up of people from more than one discipline that come together as equal stakeholders to work on very complex problems that cannot be solved by disciplinary or multidisciplinary communities alone. Interdisciplinary teams accept that more than a decomposition into existing disciplines is needed, but that new knowledge is required that may lie outside any existing discipline. Interdisciplinary work may result in the formation of new disciplines, the merging of existing disciplines in light of new knowledge, or the disappearance of old disciplines, as new disciplines take their place. Typically, an interdisciplinary person is multidisciplinary in two or several disciplines, with excellent complex communication skills across even more disciplines. Interdisciplinary teams must address the knowledge expansion problem as well as the knowledge unification problem – typically this leads to more disciplines, but can occasionally result in fewer disciplines, as some merge or are subsumed.

A transdisciplinary community or project is an ideal state that is unlikely to be achieved, but makes a compelling inspirational goal for many people. In a transdisciplinary community all members of the community have the complete knowledge of all disciplines, so in some sense discipline boundaries are irrelevant. In a sense the common knowledge of a transdisciplinary community is the sum of all the distributed knowledge of a multidisciplinary community. Transdisciplinary teams may address the knowledge transfer problem by first solving the knowledge unification problem, so less needs to be taught. For example, a transdisciplinary team might advocate Esperanto, as a standard language that could be taught to all people, providing a common language to solve any communication problem. Of course, this could also be viewed as transforming a multidisciplinary community (of many languages) into a disciplinary community (one language). Transdisciplinary is the belief that one "super-discipline" can be used to solve all problems and erase all discipline boundaries. An aspiration toward the unity of all knowledge underlies the notion of transdisciplinarity.

Finally, a cross-disciplinary community or project is one that is addressing the knowledge transfer problem, or the education problem. For example, when people in the music community want to learn physics, cross-disciplinary communities or projects may have created material that allows one discipline to be taught from the perspective of another. Cross-disciplinary teams address the knowledge transfer problem, not necessarily by unifying knowledge (to decrease the amount to teach), but by elaborating knowledge from more perspectives. Cross-disciplinary communities increase as the square (second power) of the number of disciplinary communities (e.g., discipline X taught from the perspective of discipline Y).

Armed with an understanding of the growth of disciplines, the shape of professionals in terms of discipline knowledge, and nature of the relationships between disciplines, we can now return to the challenges of collaborative innovation.

Service Science

The service sector accounts for more than 75% of the US GDP (Gross Domestic Product). Given the total US population (about 309 million people, or 5% of the world's population), approximately half are employed and approximately 75% of those employed have jobs in the service sector. About half of the service sector jobs are knowledge-intensive (e.g., government, healthcare, education, business, and professional) and the other service jobs provide numerous entry level as well as executive-management positions (e.g., retail, hospitality, and leisure). While service jobs are often thought of in pejorative terms, well more than half the service sector is knowledge-intensive segments and those segments are growing. Business and professional services, as well as healthcare services are the two fastest growing segments (Fig. 18.1).

The knowledge-intensity of many segments is growing as government, industry and universities invest to develop the workforce of the future. Even many sales jobs require a certain degree of technical skill in a knowledge-intensive service economy.

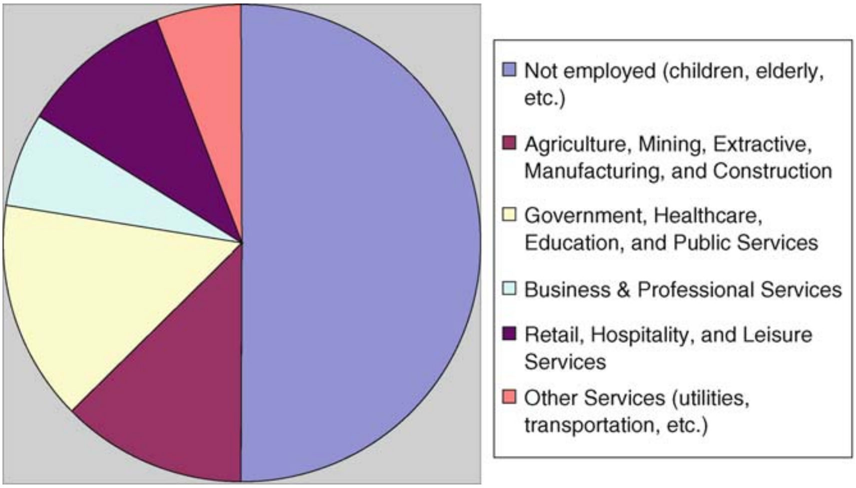

Fig. 18.1 US population and employment by segments

Service science[2] is emerging as a significant research discipline, initiated by IBM and university, industry, and government partners. SSMED brings together ongoing work in computer science, operations research, industrial engineering, business

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[2] Service science, an integrative science, is short for Service Science Management Engineering and Design (SSMED). From a business perspective, service science should explain how to invest (internal, external, and interface) in exploration and exploitation (March, 1991). Investment is required to attain higher value-creation, value-capture, and opportunity-share future states. From a research perspective, service science can be conceived of as a science of the artificial. Simon (1996) in "The Sciences of the Artificial" provides a great deal of the conceptual foundations for what we now called service science. The outline of Simon's book provides an overview of the relevant topics: (1) Understanding the Natural and Artificial World, (2) Economic Rationality: Adaptive Artifice, (3) The Psychology of Thinking: Embedding Artifice in Nature, (4) Remembering and Learning: Memory as an Environment for Thought, (5) The Science of Design: Creating the Artificial, (6) Social Planning: Designing the Evolving Artifact, (6) Alternative Views of Complexity, (7) The Architecture of Complexity: Hierarchic Systems. Over 200 universities in 50 nations have begun SSMED-related education programs (Hefley and Murphy, 2008, and personal communications update). These programs use a great variety of reference books, some undergraduate programs start with the accessible book by Teboul (2006), masters programs have started to use Ricketts (2007), and doctorate programs used the well established and top-selling Fitzsimmons and Fitzsimmons (2007), complemented by many other textbooks, books, and readings (see Spohrer and Kwan (2009) for an annotated reference list, which has been placed on-line – http://www.cob.sjsu.edu/ssme/refmenu.asp). Those seeking to formalize service science have benefited from "Reasoning about Knowledge" (Fagin et al., 2003). Economist approaching service science for the first time have benefited from "The Economics of Knowledge" (Foray, 2006). Business practitioners approaching service science for the first-time benefit from a focus on value propositions provided in "Value Merchants" (Anderson et al., 2007). SSMED books have begun to appear (Springer Series: Service Science: Research and Innovations in the Service Economy, Eds. B. Hefley and W. Murphy), and there are increasing activities, including a nascent professional organization (www.thesriii.org – Service Research and Innovation Initiative), integrations into an established annual conference (Frontiers in Service), as well as integration into an established

strategy, management sciences, social and cognitive sciences, and legal sciences to develop the skills required in the knowledge-intensive service economy of the 21st century. SSMED students and faculty explore the current and future processes of business, as well as its human, technological, and strategic elements. The SSMED course focuses on the issues involved in aligning people and technology effectively, to generate new value for both service providers and service clients.

The development of new skills – and combinations of skills that integrated technical and business disciplines – must begin at the university level, along with methods to scale the application of those skills. Over the past 20 years, academic centers have slowly increased the advancement of practical and theoretical knowledge of service businesses. SSMED encourages an interdisciplinary focus on service, as well as a more systematic approach to research and teaching the body of knowledge associated with service (i.e., service systems and service interactions). We believe these efforts will play a vital role in helping universities both improve the relevance of existing disciplines to the service sector and to overcome some academic disciplinary boundaries that were created in a bygone era.

The theoretical foundations of service science are based on ten concepts (Spohrer and Kwan, 2009):

(1) Resources: Every named thing is a resource. Four types of resources are: physical-with-rights (people), physical-with-no-rights (technology, etc.), not-physical-with-rights (businesses, nations, universities, etc.), non-physical-with-no-rights (information). All physical resources have a lifecycle that includes a beginning, middle, and end. All not-physical resources exist as patterns in the possible physical states of physical resources, and are subject to coding errors (imperfect patterns).
(2) Access rights: Four types of access rights are owned-outright, leased-contracted, shared-access, and privileged access.
(3) Service system entities: Dynamic configurations of resources, people, organizations, shared information, and technology (Spohrer et al., 2007). At least one of the resources has access rights, directly or indirectly, to all the other resources in the configuration. Normatively[3], service system entities interact with other service system entities to cocreate value. However, this is not always the intention or outcome of real service system entity interactions, which can be more like the outcomes of any two player game: win–win, lose–lose, win–lose, and lose–win.

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top-rated journal (Journal of Service Research). A growing number of existing academic and professional organizations have established SERVSIG groups (e.g., AMA, INFORMS, etc.). A service scientist is a T-shaped professional, with deep, expert, contributory expertise in at least one of these areas, and broad, complex communications, and articulatory expertise across them all (Collins and Kusch, 1999; Levy and Murnane, 2004). Finally, nations are creating service innovation roadmaps to establish investment priorities (IfM and IBM, 2008).

[3] Normatively means when things behave as they ought to. Ought implies a value judgment by some entity.

(4) Value-propositions-based interactions (value-cocreation mechanisms): Normatively, service system entities interact to maximize short-term and long-term value-cocreation. They do so by communicating and/or agreeing to value-propositions with other service system entities.
(5) Stakeholder perspectives: All service systems can view themselves and be viewed by others from multiple stakeholder perspective. Types of stakeholders include the four main types: customer, provider, authority, and competitor. A good value proposition from a provider's perspective is one that is in-demand (customers need or want it, and do not prefer self-service), unique (only the providers can perform it), legal (no disputes with authority), and superior (no competitor can propose anything better).
(6) Service system network: A set of service system entities that interact via specified types of value propositions during a specified time interval. Routine interactions are also known as business models. The simplest service system network is a customer and a provider connected by a value proposition relationship. A more complex service system network might include more actual customers, potential customers, employees, competitors, one or more authorities, and all the value propositions that connect these entities as well.
(7) Governance mechanisms (dispute-resolution mechanisms): A type of value proposition (often invoked by authority types of service system entities) when value is not created as mutually agreed, or when service system entities interact in non-normative ways.
(8) Measures: Four types of measures are quality (customer as judge), productivity (provider as judge), compliance (authority as judge), and sustainable innovation (competitor as judge).
(9) Outcomes: From game theory, two player games have four types of outcomes: win–win, lose–lose, win–lose, and lose–win. Normatively, win–win is the desired outcome of service system interactions. However, service science proposes ten possible outcomes via the ISPAR (Interact–Service–Propose–Agree–Realize) model, based in part on the four stakeholder view: customer, provider, authority, and competitor (Spohrer et al., 2008).
(10) Service system ecology: The population of all types of service system entities that interact over time to evolve new types of the previous nine items; new types of (a) resources, (b) service system entities, (c) access rights, (d) value-cocreation mechanisms, (e) stakeholder perspectives, (6) service system networks, (7) governance mechanisms, (8) measures, and (9) outcomes. History is the trace of all outcomes over time.

Holistic Engineering

Grasso and Martinelli (2007) state "In this evolving world, a new kind of engineer is needed, one who can think broadly across the disciplines and consider the human dimensions that are at the heart of every design challenge.... Pursuing the holistic concept of the 'unity of knowledge' will yield a definition of engineering more fitting for the times ahead.... Building quantitative-reasoning skills should still be a top priority for American engineering education, but that rigor should be complemented with developing students' ability to think powerfully and critically in many other disciplines. To be sure, it will be a challenge, but a challenge with tremendous benefit."

Grasso and Martinelli offer several examples of holistic engineering from the redesign of the Golden Gate Bridge to prevent suicides, to "cap and trade" permit programs to address acid rain, to "tax and drive" system to address traffic problems in major metropolitan areas. They note that "[IBM] has embarked on a research-and-business model that applies technological and manufacturing models to the holistic delivery of services."

Holistic engineers are not simply problem solvers, but must also be problem definers and leaders of multidisciplinary teams. As the world creates more and more traditionally engineers, the risk of converting engineers into a commodity is quite real. The solution lies in the quality, and not simply the quantity of engineers. The 21stcentury challenge is both the additional time required to create better quality engineers and the establishment of higher value career paths for professional engineers. Service science may become exactly the type of integrative science on which holistic engineering can be firmly established.

Succeeding in Collaborative Innovation

Given the conceptual foundations of both service science and holistic engineering, we can create the notion of a *service system ecology microworld* that is intended to be recognizable as akin to, but a greatly simplified version of, the real world in which we all live. Imagine six types of service system entities: people, universities, businesses, nations, disciplines, and professions. Further imagine that each service system entity is given a generous initial set of technology resources that are owned-outright. People are given both shared-access and privileged-access to different sets of information resources that correspond to common knowledge and distributed knowledge in the society. People have a primary allegiance to specific universities, businesses, nations, disciplines, and professions. Nations provide shared access to many technology and information resources. Shared access physical resources have capacity limits, so that when requests arrive they may already be engaged. We will assume that information resources have no capacity limit, so access to them can scaled tremendously at very little cost (e.g., the Internet and World Wide Web). However, we will assume that knowledge resources (e.g., people) have capacity limits, so while access to them can be scaled, it comes at a much greater cost.

For the purposes of this paper, we will assert that T-shaped knowledge resources have at least two advantages over I-shaped knowledge resources, and one big disadvantage. The advantages are (1) lower communication and collaboration costs, and (2) lower learning and adaptation costs. The big disadvantage is that they cost twice as much to create in the first place, so that only if the nature of the world demands more communication, collaboration, learning, and adaptation can the initial investment cost be recouped. The world needs both I-shaped and T-shaped people, but getting the balance right is where simulations based on a service system ecology microworld may prove most useful. Of course, if everyone where to be made T-shaped, there would be a huge economy of scale targeting the creation of the broad part of the T. This could help significantly lower the cost of creating T-shaped professionals in a society.

Concluding Remarks

On any leader's agenda these days, few priorities are higher than collaborative innovation. It drives high-margin growth, strengthens competitiveness, and creates jobs. It is no wonder that so many business and political leaders around the world have made collaborative innovation their number-one priority. From a service science perspective, people, businesses, nations, and other organizations, even disciplinary and professional organizations, are all examples of service system entities. Service system entities seek to interact (normatively – one might even say rationally) to create win–win interactions, and avoid lose–lose, win–lose, and lose–win. Only win–win interactions are good for both entities reputations and build trust, the catalyst of more win–win interactions (Normann, 2001). Of course, in reality all interactions are not win–win, and thus there is a need for a deeper understanding of service system entity interactions (service science) and their design (holistic engineering). However, for collaborative innovation to work, we must stress these are not the same professionals, specialists, and deep experts of the past. Service science and holistic engineering are integrative disciplines, and while professionals still must be deep in some area (traditional disciplines), they must also have complex communication skills across a wide range of other disciplines. Fundamentally, this is the change in human capital that is required to make collaborative innovation truly successful. The challenge is that educating T-shaped people may take twice as long and be twice as complex as training I-shaped people. Only this qualitatively different type of scientist and engineer can take us to the next level of growth through innovation.

For much of the past century, the United States was the world's innovation engine. Citizens of the United States, like those in key nations before us, can point with some measure of pride at both the technological and organizational innovations that have transformed the world in which we live. Today, more players are joining in this modern innovation game driven by rising skill levels of professionals, by open markets enabled by new technological and institutional infrastructure, and by significant R&D investments. Countries that until recently played a less visible role on the global innovation stage are emerging – China, India, Brazil, Russia, Finland, Israel, and South Korea, to name just a few. Collectively, those countries are producing five to eight times the number of science and engineering graduates than the United States. Moreover, 50% of America's science and engineering workforce is approaching retirement. Innovation is the arbiter of national competitiveness. Simply creating more scientist and engineers is not what the United States needs. The United States and all nations who want to excel at collaborative innovation need qualitative different types of scientists and engineers.

World-class scientists and engineers have always been fundamental elements of US innovation, even before this era collaborative innovation. But let us not forget that the management of ideas, open markets, infrastructure and institutions, the enrichment of R&D capabilities and the development of new business models and process innovations are crucial, as well. In today's hyper-competitive global economy, science and engineering leadership, though very important, is not enough to achieve innovation. To strengthen collaborative innovation capabilities, it is not enough simply to intensify current stimuli, policies, and management strategies and to make incremental improvements to organizational structures and curricula. For the 21st century, what matters most is what we find at the intersection of technology and human insight. Increasingly, the most important innovations will be those that transcend any particular business or technology; they will be those that have a broad societal impact and improve the lives of real people.

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Chapter 19
Technology and Policy

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Many academic programs in the United States, and elsewhere around the world, focus on the social studies of science, technology, and public policy. Indeed, the bulk of the programs listed in the AAAS guide to graduate education in science, engineering, and public policy[1] fall in this category. In contrast, the number of programs that combine deep technical education and understanding with modern social science and policy analytic knowledge and skills is very limited.

Of course, there are many policy problems "about technology," in which there is no need to get "inside the black box."[2] Indeed, for many such problems, spending too much time considering those details is a distraction, or may even lead the analyst astray. However, there is a subset of policy problems in which the technical details really matter – where a failure to consider and address the substance of those details can lead to dumb or silly results. Table 19.1 provides an illustration of problems of both kinds.

Today, many science and engineering educators are quick to recognize the importance of preparing students with technical backgrounds who can address policy problems in which the technical details matter. This was not always true. In the 1960s and 1970s, and on some campuses even today, the strong tradition of engineering science that grew up in engineering education in the post-war period, produced an environment in which many faculty belittled any activity that was not laden with partial differential equations. Fortunately, recent decades have witnessed a rebalancing of engineering education. However, even today, developing and sustaining programs in technology and policy present numerous challenges. These include

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[1] See www.aaas.org/spp/sepp/index.htm

[2] The phrase was used by Nathan Rosenberg, *Inside the Black Box: Technology and economics*, Cambridge University Press, 304 pp.,1982.

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DOI 10.1007/978-1-4419-1393-7_19,

Table 19.1 Examples of two problems involving direct satellite communication, one that is "about technology" (i.e., the technical details are not critical to a solution of the policy problem) and one in which it is essential to "get inside the black box" (i.e., a reasonable technical solution requires a deep familiarity with and consideration of the technical details)

A problem "about" technology	A problem in which technical details are centrally important
Delivery of continuing adult education via direct-broadcast satellite to rural India. In order to adequately address this problem, the analyst does not need to know much at all about how direct-broadcast satellites work. So long as he or she knows what the technology costs, who they need to run it, and similar details, a non-technical policy analyst can address this problem very well. Indeed, getting too bogged down in the technical details could easily distract the analyst from the most important issues.	*Developing India's negotiating positions for an upcoming international conference to reallocated parking orbits for geostationary satellites.* In order to adequately address this problem, the analyst must have a deep technical understanding of the relative advantage of gain on the ground versus gain on the spacecraft, the likely future cost and performance of microwave amplifiers, and a variety of similar issues. Without such knowledge, the resulting policy conclusions could be seriously misinformed.

- Processes for academic promotion and tenure that apply traditional disciplinary templates in evaluating junior faculty;
- Limited numbers of faculty candidates who combine deep technical knowledge and skill with good modern social science and policy analytic knowledge and skills;
- Large number of faculty candidates educated in the more qualitative social sciences, or in social studies of technology, who have limited interest in or ability to address policy problems with deep technical content;
- The nature and interests of the sources of funding and ease with which funds can be secure; and
- A lack of imagination in defining interesting research questions and in keeping an eye out for, and building upon, generalizable insights in this field.

Building and Sustaining a Program in Technology and Policy

I remember very well a conversation that I had years ago with physicist Ray Bowers (who together with chemist Frank Long started the program in science, technology, and policy at Cornell). Ray talked about why he thought the Harvard Program on Technology and Society (1964–1972) run by Emmanuel Mesthene had not survived despite a generous endowment from IBM. Ray argued that the problem was that the Harvard program had not been integrated into the academic fabric at Harvard, but had been built off on the side. Thus, he said, it had no one to defend it "among those with real power in the University." I can remember Ray telling me that at

Cornell he and Frank were working hard to get S&T policy woven into the academic fabric of the university. In that they succeeded. The department that grew out of their early efforts, Science & Technology Studies, is now an established department in the College of Arts and Sciences at Cornell. It does not, however, continue to do the kind of deep technically focused policy work that Bowers and Frank pioneered.

For a number of reasons, sustaining a program in technology and policy in which the technical details matter involves an unstable equilibrium as shown in Fig. 19.1. Unless efforts are continually made to maintain the unstable balance, a program will either evolve into more conventional forms of engineering, or into social studies of technology.

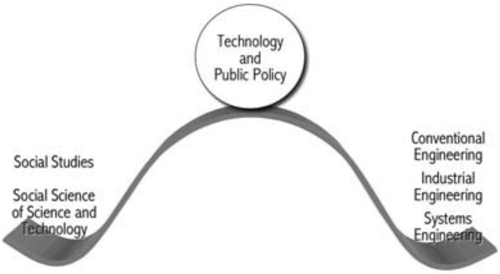

Fig. 19.1 Schematic illustration of the unstable equilibrium faced by academic program in technology and policy. Continuous attention and energy from faculty and administrators is required if the program is to remain balanced with substantial technical content, modern applied social science, and good policy-analytic methods

The latter is what happened at Cornell. When Bowers and Long left the scene, they were followed by a number of very excellent non-scientists, including sociologist Dorothy Nelkin and linguist and lawyer Sheila Jasanoff. While Walter Lynn (now emeritus) continued to contribute a technical perspective, as the program grew and was merged with a program in the history of science, it evolved into a very different kind of effort. Today, the undergraduate major in Science & Technology Studies "aims to further students' understanding of the social and cultural meanings of science and technology." Using perspectives and tools "that cross the traditional boundaries of sociology, philosophy, politics, and history," doctoral level studies in the Department treat "science and technology as historical and cultural productions." The "approach throughout is both descriptive (aimed at understanding how science and technology are done) and normative (for example, showing where actual practices and professed norms are in conflict)."[3] While such work is clearly interesting and important, it is very different in focus from the early pioneering technology assessment activities of Ray Bowers and his colleagues on topics such as video telephone and solid-state microwave devices.

Another way, in which activities that start out in technology and public policy may move, is toward conventional public policy. Again, I make no normative

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[3] Quotations in this paragraph are drawn from www.sts.cornell.edu.

argument. Clearly, there are important problems in public policy that are *about* technology, where a deep understanding of the technical issues is not important, or can even get in the way of developing adequate insight and policy solutions.

Another example of a movement away from an unstable equilibrium toward the left side of Fig. 19.1 is provided by the evolution of the Association of Public Policy and Management and it is journal *JPAM*. When APPAM was first formed, folks at the Sloan Foundation and academics, such as Charlie Wolf, Pat Crecine, Toby Davis, and Ray Vernon, worked hard to include scientists and engineers in the workshops that led to the Association's creation. A serious effort was made to include technical people in the early mix of folks who were involved in the organization. However, over time, it became clear that most members of the Association, and most readers of its journal, *JPAM*[4] (now called *Policy Analysis and Management*) had no deep interest in technical issues. As a result, the technical folks drifted away to spend their time working with other more hospitable societies and journals.

On the right-hand side of unstable equilibrium in Fig. 19.1, we have the example of the Department of Technology and Human Affairs in the School of Engineering and Applied Sciences at Washington University. Under the leadership of Chemical Engineer Robert (Bob) Morgan (no relation to me), the Interdepartmental Program in Technology and Human Affairs was established in 1971 and grew into a full-fledged department in the engineering school in 1976. Its name was subsequently changed to the Department of Engineering and Policy. The department offered a full range of degrees from B.S. to M.S. and Ph.D. However, when Bob Morgan stepped down, the new department head and several deans developed interests in pursuing activities such as in mid-career continuing technical education, and did not continue to invest the necessary energy to sustain the program. Ultimately, the program collapsed and the Department has now disappeared.

In addition to requiring continuing balancing energies from faculty and administrators, programs that have survived and grown have each evolved in ways that are adaptive to the strengths and limitations of their host institutions. However, all have faced some common problems, of which finding appropriate faculty who combine strong technical knowledge with good policy analytic skills, is perhaps the greatest. The careers of most of the first wave of faculty active in this area, evolved from traditional roots. Some of these people had already developed strong technical careers were safely tenured, and thus had the luxury to move into more interdisciplinary undertakings. In other cases, young faculty took rather considerable career risks to pursue an intellectual venture that they viewed as critically important.

In the Department of Engineering and Public Policy at Carnegie Mellon, the strategy has been to never compromise on the technical credentials of new faculty. In some cases, we have been fortunate to find faculty candidates, such as Marvin Sirbu or Jon Peha (both in telecommunications policy), who already had built strong backgrounds in both technology and in policy. More recently, many of our junior

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[4] For a number of years I was a regular contributor of book reviews for *JPAM* in the area of technology and public policy.

hires have been folks with strong technical background and clear policy interests, but little formal or practical policy background. Because Carnegie Mellon has an environment that actively encourages interdisciplinary work, it has been practical to hire such folks and then grow their policy dimensions over time. Many institutions cannot do this. For example, years ago, after MIT had "stolen" one of our up and coming young faculty who we had started as an assistant professor and promoted up through the ranks to full professor, I had a conversation with the provost during which I asked him "why do you have to steal our folks, why don't you grow your own." With a smile, the answer came back "because you can and we can't." Fortunately, with the growth of the Engineering Systems Division at MIT, this situation is now changing. But, at many other institutions, promoting and tenuring junior faculty with backgrounds that do not fit traditional disciplinary templates remains a serious problem.

Undergraduate Programs in Technology and Policy

Relatively few programs in technology and policy are focused on undergraduate engineering education. Those that are, largely focus on offering double degrees or minors. In contrast with many other programs, which focused from the start on graduate education, the Department of Engineering and Public Policy (EPP) at Carnegie Mellon actually began as an undergraduate program designed to add some additional dimensions and skills for students who will go on into conventional engineering careers. This is done by taking over all the technical and non-technical elective course space in the undergraduate curriculum and shaping the courses students take to make up the second part of the degree. All students are requited to take an introductory course in microeconomics, and a course either in decision analysis or a course in behavioral decision theory. Beyond that, students choose from a variety of "social analysis electives."

On the technical side, EPP has evolved a number of courses and course sequences in areas such as energy systems; air pollution; telecommunication policy; computer security and privacy; risk perception, assessment, and analysis; and the management of technical innovation. These courses are regular technical electives in the college of engineering (often double-listed with traditional departments) and are open to all students in the college who meet the prerequisites. It is not at all unusual for a large portion of the students in EPP courses in telecommunication policy to be single majors in EE. Similarly, many students in the EPP courses in air pollution are from single majors such as CivE, ChemE, or MechE.

Project courses are an important feature of the EPP undergraduate curriculum. These courses are run jointly for undergraduates by faculty in the Department of Engineering and Public Policy and the Department of Social and Decision Sciences in the College of Humanities and Social Sciences. The typical course involves 25–30 students. Projects address some real world problem in technology and public policy, typically with an outside client for whom the work is being done. See Table 19.2 for

Table 19.2 Examples of topics addressed by a number of recent undergraduate technology-policy group project courses in the Department of Engineering and Public Policy at Carnegie Mellon University. The Department has run project courses since 1970. Today, it runs two such projects every semester

- Policy Dimensions of New Space Technologies (Spring 2008).
- Should Police Use Mobile Computing (Fall 2007).
- Unmanned Aircraft in the National Airspace System (Spring 2007).
- Post-market Recommendations for Unanticipated Complications from Implanted Cardiac Devices (Spring 2007).
- The Siting of LNG Terminals: Public perception and community impacts (Fall 2006).
- U.S. Oil Refineries: Spatial dimensions of economics, regulatory policy and environmental justice (Fall 2005).
- Hybrids and Diesels in the American Automobile Fleet: 2005–2020 (Spring 2005).

A full list of past EPP project courses can be found at http://www.epp.cmu.edu/httpdocs/undergraduate/summaries/project_list.html

an example of recent topics addressed. Students start the semester with a vaguely defined problem area and various background materials which they use to define and shape a workable problem and then undertake the necessary analysis to frame and address the problem. There are usually two faculty advisors and two Ph.D. students who serve as managers.

Over the first few weeks of a project, the students work on developing a thorough understanding of the subject and defining the focus of the work they propose to do. About a third of the way into the semester, students make a first formal presentation at which they present their plans to an outside review panel of experts who represent different expertise and points of view in the problem area. The review panel assists the students by providing critical comments on the way in which they have structured the problem and by suggesting various resources and information sources. About two-thirds of the way through the semester, students make a second presentation to the project review committee at which they present a progress report and receive steering suggestions from the review panel. At the end of the semester, the students prepare a final written project report of about 100 pages and make a final verbal presentation of their findings and conclusions to the review panel. Of course, it is impossible for 25–30 people to work a single problem all together; so much of the work in project courses gets done in smaller working groups of four to eight students.

Project courses serve several important educational functions. First, they are the one place where students get an opportunity to put together the various technical and social analysis components of their education and gain hands-on experience working on real world problems. Second, project courses provide valuable opportunity for students to develop and refine their verbal, oral, and presentation skills. In the real world of daily engineering practice, these skills are every bit as important for success as the more traditional mathematical and quantitative analytical skills.

Project courses are a great deal of work. Students often complain that they are too much work. On the other hand, over the course of the past 20 years, EPP has run three surveys of all its double major undergraduate alumni. In all three cases, the strong response has been “project courses were the single most valuable experience in my four years at Carnegie Mellon,” because they taught students how to work in interdisciplinary teams, how to quickly master an entirely new problem domain, how to work to a schedule, and how to produce a set of high-quality professional products.

The EPP double major program has been carefully designed to fit with all the traditional engineering undergraduate majors in such a way as to produce curricula that meet ABET accreditation. When they review the engineering college, ABET sends a separate accreditor to visit EPP to confirm that the fit with all the traditional majors is in compliance. Additional details on the EPP undergraduate program can be found at http://www.cmu.edu/esg-cat/.

For a few years, the Department also offered a single major accredited degree in Engineering and Public Policy. Students still had to focus their technical studies in one of the traditional fields of engineering, but did not have to take enough courses to meet the requirements of an accredited degree in that field. The idea was that this broader degree, involving more engineering courses in other fields, and more social analysis content, would offer a good background for a student who wished to enter a career in something like patent law or science and technology journalism. The department graduated a few single majors, but faculty observed that every time a student proposed to do a single major, they immediately set out to talk them out of it, arguing “just three more courses and you can get a conventional engineering degree . . . life is uncertain . . . you never know when that might be valuable . . . etc.” After a few years of talking students out of doing the single major, the faculty decided they really did not believe in it, and stopped offering the degree.

Graduate Education and Research in Technology and Policy

The Technology and Policy Program (TPP) at MIT was one of the first, and is still one of the largest and most successful M.S. programs in technology and policy. While students in this program are not strictly required to have an undergraduate background in science or engineering, most do. Students participate in a series of core courses, and then take additional technical and social science courses from across the Institute. Because MIT is such a large and diverse place, many students come in to the program without support but then farm out across the Institute to find a research program to become involved in and through which they can obtain support.

For many years the TPP program was operated by a single tenure-track faculty member, Richard de Neufville, working together with a number of instructors supported on soft money. Finally, when MIT established its Engineering Systems Division, TPP became part of the Division, and is now well staffed by a number of tenure-track faculty.

At Stanford, the Department of Engineering Economic Systems[5] (EES) was one of the first to offer Ph.D. degrees, focusing heavily on methodological development in decision analysis. When Carnegie Mellon's EPP also added a Ph.D. program, it focused somewhat more heavily on "dirty handed engineering," although many of the problems it addressed were also motivated by a concern about developing basic generalizable tools and insights in fields such as the characterization and treatment of uncertainty.

The number of problems that fit the definition "policy problems in which the technical details are of critical importance" is enormous. As a consequence, successful programs have chosen to focus their efforts on a sub-set of this space. Rather than adding faculty in several completely unrelated problem areas, they have chosen a strategy of recruiting faculty with overlapping interests, thus building several focal areas.

A factor that has often shaped the way a program evolves is the relative ease with which support for research can be secured. While this does not tend to be a big problem in an area such as energy or the environment, in other areas, such as telecommunication policy, there is very little government or private foundation support. Firms in an area such as telecommunications tend to be reluctant to provide support for policy-related work (for example on spectrum policy) unless they can be assured in advance that conclusions and policy recommendations reached will support their positions. In such a case, where there are only a few sources of interested-funding it is hard to put together a balanced portfolio of support.

If a program is able to attract large amounts of support from private firms with relatively greater ease than they can write competitive proposals to NSF, that can pull the focus or research away from *public policy* into focusing primarily on private sector issues and problems.

Jobs for Students in Technology and Policy

Today, graduates at the doctoral level from programs in technology and policy, who want to enter academic careers, face similar problems. The difficulties of finding hospitable academic homes in traditional academic departments are not serious in fields such as energy or environment. However, in other areas such as telecommunications or information policy, graduates with outstanding technical credentials still cannot find jobs in EE departments. They do, however, find positions in schools of information systems, in business schools, or in schools of public policy.

Looking across the roughly 170 Ph.D. graduates from the Department of Engineering and Public Policy just over 40% have gone to academic positions. Just

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[5] At Stanford, the Departments of Engineering Economic Systems and of Operations Research were later merged. Some years after that, a second merger occurred with the Department of Industrial Engineering. The resulting department is now called the Department of Management Science and Engineering.

under 60% are in non-academic jobs including 21% in think tanks and consulting firms, 17% in private-sector firms, and 19% in government and national labs.

Key Programs and Their Evolution in Technology and Policy

In the United States, most programs in technology and policy date to the early 1970s. However, an earlier high-visibility program was the Harvard Program on Technology and Society, created with a substantial endowment from IBM. This program, which ran from 1964 through 1972, was directed by philosopher Emmanuel (Manny) Mesthene. The focus was not particularly on policy analysis but rather on technology's impacts on society and on technology and social change. The program published a series of high-visibility annual reports. However, the program was never successfully integrated into the mainstream of academic life at Harvard. Some of the endowment was later used to support the professorship of Louis M. Branscomb, who ran the Science, Technology, and Public Policy Program in the Belfer Center for Science and International Affairs of the Kennedy School. In contrast to Mesthene, Branscomb had a much stronger involvement in policy-analytic work.

In the early 1970s, Arthur Singer at the Sloan Foundation made a series of grants to develop programs in science, technology, and public policy. A few years later William Blanpied at the National Science Foundation also made a number of grants to build programs in this area. Since the late 1970s there have been no major ongoing sources of foundation or government support in the United States to build academic programs in science, technology, and public policy, although from time-to-time foundations, such as the Exxon Education Foundation, have made a few grants.

While a number of the programs that began in the 1970s have now disappeared, four of the early programs in this area continue to operate today. They are the Technology and Policy Program at MIT (an MS program that has now become part of MIT's Engineering Systems Division), the Department of Management Science and Engineering at Stanford University (a portion of which began life as the Department of Engineering–Economics Systems), the Energy and Resources Group at U.C. Berkeley, and the Department of Engineering and Public Policy at Carnegie Mellon.

Over the years, a number of other programs have come and gone. Today, there are several newcomers that are showing significant promise. For example, at the University of Maryland, the Clark School of Engineering, and the School of Public Policy are jointly offering an M.S. in Engineering and Public Policy. The Department of Technology and Society in the College of Engineering and Applied Sciences at SUNY Stony Brook offers both B.S. and M.S. degrees and has recently initiated a Ph.D. Program in Technology, Policy, and Innovation.

In addition to US programs that are defined broadly as working on a range of issues in technology and policy, there is a much larger number of programs that work on more narrowly focused domains. In telecommunications and policy, there has long been an M.S. program at the University of Colorado. There are a large number of environmental programs, including the strong programs at the Yale School of Forestry, the Department of Environmental Studies at UC Santa Cruz, the program in Environmental Science and Engineering at the University of North Carolina, and many others. New programs continue to appear such as the Nicholas School at Duke.

In Canada, under leadership by David Keith, formerly of EPP at Carnegie Mellon, the University of Calgary is building a major program in the area of technology and policy. Also in Canada, McMaster University has built an undergraduate Engineering & Society Program and is considering adding M.S. level activity.

In Europe, there is more activity in the area of technology and policy among universities in the Netherlands than in all the rest of the continent combined. The leading program is the faculty in Technology, Policy, and Management at TUDelft, but there are also substantial programs at TUEindhoven and Utrecht, and nascent programs at several other universities. Portugal is the other center of serious academic work in Continental Europe in the area of technology and policy. The IN+ program at IST Lisbon has long operated one of the strongest technology policy masters programs in the world. A number of Portuguese universities are now collaborating with MIT and with Carnegie Mellon to build M.S. and Ph.D. level programs on a variety of issues in technology policy.

At Cambridge, the M.Phil. program in Technology Policy was originally developed as part of the MIT–Cambridge program. It continues as a vigorous one-year masters program. The program explains that “Most students seeking to become leaders in technology-based organizations will follow the standard professional practice track, but for those interested in doctoral studies, there is also a research stream available.” Also in the UK, the School of Civil Engineering and Geosciences at Newcastle University, Earth Systems Science, Engineering and Management (ESSEM) does a significant amount of policy work with deep technical content. While it was established by folks with substantial technical backgrounds, and still has a number of such people on its staff, most of the work now done in the Science and Technology Policy Research program (SPRU) at the University of Sussex, has relatively modest science or engineering content.

There are also a few programs in other parts of the world. For example, the Division Engineering & Technology Management in the faculty of engineering in the National University of Singapore offers a variety of M.S. programs and is in the process of building a Ph.D. program.

Table 19.3 lists the addresses for the web pages of the programs noted in the preceding discussion.

Impacts

To date, while several programs have done limited assessments, there has not been a systematic national or international assessment of the educational, research, and public policy impacts that academic programs in technology and policy have had. Anecdotal evidence suggests that the impacts are large and are growing. Virtually

Table 19.3 Web addresses of a number of the academic programs in technology and policy discussed in this chapter

Program	Web address
Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburg, PA	http://www.epp.cmu.edu
Energy and Environmental Systems Group (ISEEE), University of Calgary, Alberta, Canada	http://www.ucalgary.ca/ees/
MPhil. in Technology Policy, Cambridge Judge Business School, Cambridge, UK	http://www.jbs.cam.ac.uk/programmes/mphil_techpol/index.html
Faculty of Technology, Policy and Management, Delft University of Technology, Netherlands	http://tbm.faculteiten.tudelft.nl/index_en.php?id=f4145950-c485-44fc-b01e-ad9d03bebbb6&lang=en
Industrial Engineering and Innovation Sciences, Department of Technology Management, Eindhoven University of Technology, Netherlands	http://w3.ieis.tue.nl/en/
IN+ at Instituto Superior Técnico, Lisbon, Portugal	http://in3.dem.ist.utl.pt/
Engineering and Public Policy, University of Maryland	http://www.mepp.umd.edu/
Engineering Systems Division and Program in Technology and Policy, MIT, Cambridge, MA	http://esd.mit.edu/ http://tppserver.mit.edu/
School of Civil Engineering and Geosciences at New Castle, UK	http://www.ceg.ncl.ac.uk/about/index.htm
Division of Engineering and Technology Management, University of Singapore, SINGAPORE	http://www.eng.nus.edu.sg/etm/
Department of Management Science and Engineering, Stanford University, Stanford, CA	http://www.stanford.edu/dept/MSandE/
Faculty of Geosciences, Utrecht University, Netherlands	http://www.uu.nl/EN/faculties/geowetenschappen/Pages/default.aspx

all programs can identify faculty and graduates who have made major contributions in government or private sector decision making.

Thanks in large part to work done in several of the programs in technology and policy, today modern policy analytic work is much improved, both in terms of the way in which problems are framed and the analytical tools that are employed, than was the case 30 years ago. For example, techniques such as decision analysis, the systematic characterization and analysis of uncertainty, and methods in quantitative risk analysis, that were pioneered in several of these programs, are now almost ubiquitous.

Perhaps most importantly, today the thousands of graduates of programs in technology and policy approach their work in a more holistic way than their more conventionally educated engineering colleagues.

Subject Index

Note: The letters ‘f’ and ‘t’ following locators denote figures and tables respectively.

D. Grasso, M.B. Burkins (eds.), *Holistic Engineering Education*,
DOI 10.1007/978-1-4419-1393-7,