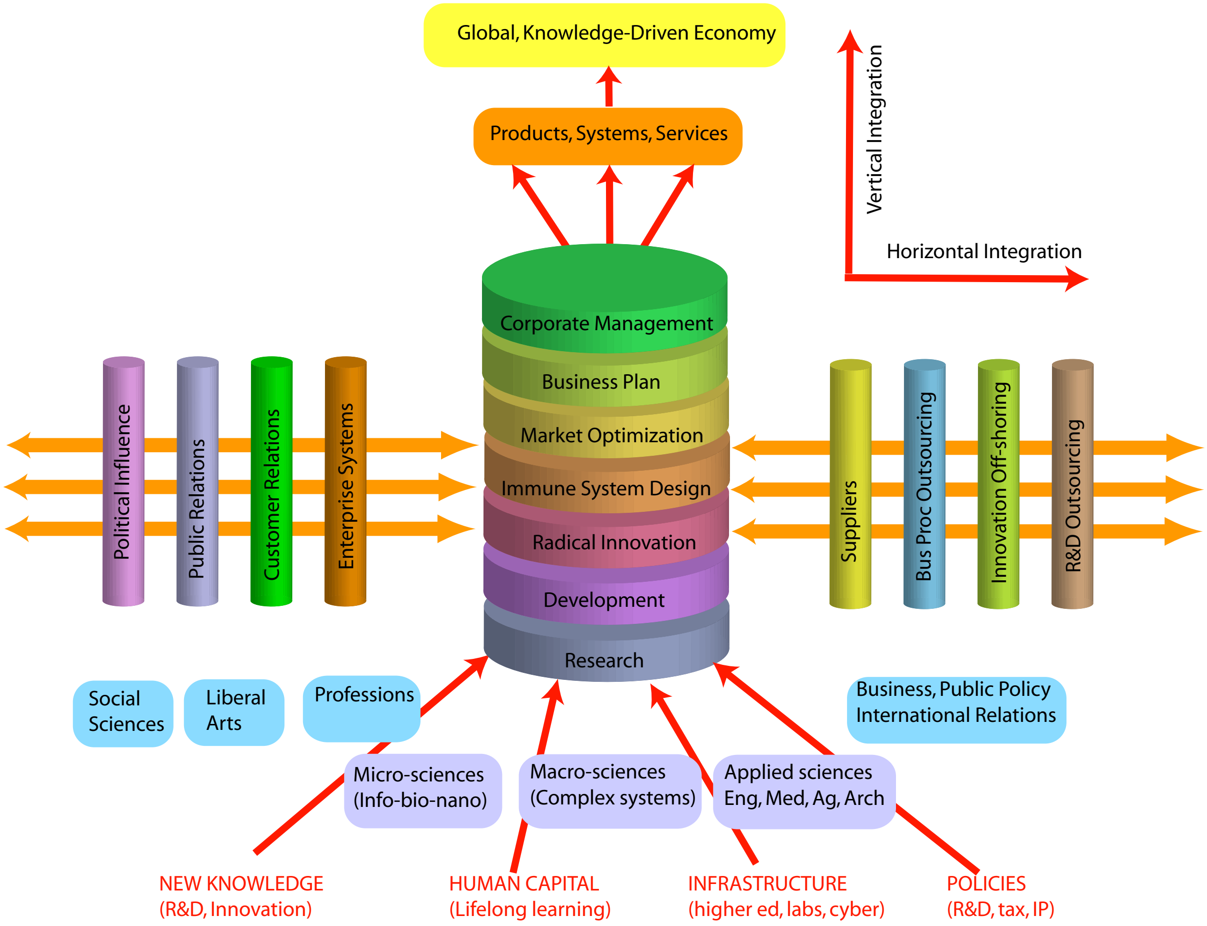
Engineering for a Changing World

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



The Millennium Project
The University of Michigan

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

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Preface

Powerful forces, including demographics, globalization, and rapidly evolving technologies are driving profound changes in the role of engineering in society. The changing workforce and technology needs of a global knowledge economy are dramatically changing the nature of engineering practice, demanding far broader skills than simply the mastery of scientific and technological disciplines. The growing awareness of the importance of technological innovation to economic competitiveness and national security is demanding a new priority for application-driven basic engineering research. The nonlinear nature of the flow of knowledge between fundamental research and engineering application, the highly interdisciplinary nature of new technologies, and the impact of cyberinfrastructure demand new paradigms in engineering research and development. Moreover, challenges such as the off-shoring of engineering jobs, the decline of student interest in scientific and engineering careers, immigration restrictions, and inadequate social diversity in the domestic engineering workforce are also raising serious questions about the adequacy of our current national approach to engineering.

During the past several years there have been numerous studies conducted by organizations such as the National Academies, federal agencies, business organizations, and professional societies suggesting the need for new paradigms in engineering practice, research, and education that better address the needs of a 21st-century nation in a rapidly changing world. Despite the growing importance of engineering practice to society, the engineering profession still tends to be held in relatively low regard compared to other learned professions such as law and medicine. Unfortunately, many global corporations tend to view engineers as disposable commodities, discarding them when their skills become obsolete or replaceable by cheaper engineering services from abroad. There are concerns that the increasing trends of outsourcing engineering services and off shoring engineering jobs are eroding this nation's fundamental technological competence and its capacity to innovate, not to mention eroding the attractiveness of engineering careers to many of our most talented US-born students who opt instead for more secure and better rewarded professions such as law, medicine, or business administration.

The fundamental knowledge undergirding engineering practice increasingly requires research at the extremes, from the microscopic level of nanotechnology to the mega level of global systems such as civil infrastructure, energy, and climate change as well as the mastery of new tools such as cyberinfrastructure and quantum engineering. It also requires far greater attention by government and industry to the support of the long-term basic engineering research necessary to build the knowledge base key to addressing society's needs.

Despite the considerable progress made in recent years through efforts such as ABET's learning-outcomes-based EC2000 and NSF's systemic reform programs, engineering education remains predominantly dependent upon narrow, discipline-focused undergraduate programs. These are increasingly challenged both by the relentless pace of new technologies and their declining ability to attract a diverse cadre of the most capable students compared to other professional programs such as law, medicine, and business administration,

The purpose of this study is to pull together the principal findings and recommendations of the various reports concerning the profession of engineering, the technology and innovation needs of the nation, and the role played by human and intellectual capital, into an analysis of the changing nature of engineering practice, research, and education. More specifically, it considers the implications for 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 *knowl-*

edge 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. More generally, it addresses the question of what our nation should 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.

In a sense, this report asks questions very similar to those posed a century ago by noted educator Abraham Flexner, when he examined implications of the changing nature of medical practice for medical education. His premise, "If the sick are to reap the full benefit of recent progress in medicine, a more uniformly arduous and expensive medical education is demanded", drove a major transformation in medical practice, research, and education. Today the emergence of a global, knowledge-driven economy based upon technological innovation is likely to demand a similarly profound transformation of engineering practice, research, and education.

To conduct this study, we have chosen the approach of strategic roadmapping, beginning with an environmental scan of the changing context for engineering and an assessment of the character and challenges of contemporary engineering practice, research, and education. Drawing heavily from recent studies and informed by the wisdom of several expert panels, we then suggest a vision for engineering tomorrow, conducting a gap analysis to determine just how profoundly it must change from today's engineering, both as a discipline and as a profession. Finally we suggest a roadmap to the future of engineering: a series of recommendations and actions aimed at transforming engineering practice, research, and education, with the fundamental objective of sustaining and enhancing our nation's capacity for the technological innovation key to economic prosperity, national security, and social well-being.

Our analysis has arrived at the following key conclusions:

- 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 provide 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, 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:

- 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.

- 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.

- 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.

- To establish engineering as a true liberal arts discipline, similar to the natural sciences, social sciences, and humanities (and the trivium, quadrivium, and natural philosophy of earlier times), by imbedding it in the general education requirements of a college graduate for an increasingly technology-driven and -dependent society of the century ahead.

- To achieve far greater diversity among the participants in engineering, the roles and types of engineers needed by our nation, and the programs engaged in preparing them for professional practice.

To achieve these, we furthermore offer the following proposals for action:

1. Engineering professional and disciplinary societies, working with engineering leadership groups such as the National Academy of Engineering, ABET, the American Association of Engineering Societies, 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 aim to shape rather than simply react to market pressures.

2. The federal government, in close collaboration with industry and higher education, should launch a large number of Discovery Innovation Institutes at American universities with the mission of linking fundamental scientific discoveries with technological innovations to build the knowledge base essential for new products, processes, and services to meet the needs of society.

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.

4. Undergraduate engineering should be reconfigured 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 professional practice.

5. In a world characterized by rapidly accelerating technologies and increasing complexity, it is essential that the engineering profession adopt 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.

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

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.

We recognize that the resistance to such bold actions 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 off-shored 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 indeed. 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 U.S. 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 U.S. students. Current immigration policies combined with global skepticism about U.S. 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.

Acknowledgments

This effort has been heavily influenced by a number of important recent studies, several of which involved the author as chair or participant. Of particular note were the National Academy of Engineering studies: *The Engineer of 2020* (Parts I and II) (2004, 2005), *Engineering Research and America's Future* (2005, JJD chair); the National Academies studies: *Rising Above the Gathering Storm* (2005), the COSEPUP annual analysis of the *Federal Science and Technology Budget* (1999-2003, JJD chair), the IT Forum and the NAS Committee on IT and the Future of the Research University (2004, 2005, JJD chair), NRC Panel on *Researchers in the Digital Age* (2003, JJD chair); several studies by federal agencies: National Science Board studies on *The Science and Engineering Workforce: Realizing America's Potential* (2003) and *The Future of Engineering Education* (2007), the Department of Energy study *Critical Choices: Science, Engineering, and Security* (2003, JJD participant), the National Science Foundation's Advisory Committee on Cyberinfrastructure (2007, JJD chair), the Secretary of Education's Commission on the Future of Higher Education in American (2006, JJD participant); and several important studies by foundations and individuals, including the Carnegie Foundation for the Advancement of Teaching study by Sheppard and Sullivan, *Educating Engineers: Theory, Practice, and Imagination* and the SEER Trilogy by Frank Splitt.

The author wishes to acknowledge as well the insight and suggestions provided by many colleagues who responded to earlier drafts of this report including Dan Atkins, Arden Bement, Joe Bordogna, John Brighton, Wayne Clough, Norm Fortenberry, Sue Kemnitzer, Jack Lohmann, Rick Miller, Percy Pierre, Proctor Reed, Sheri Sheppard, Frank Splitt, Gretar Tryggvason, Chuck Vest, and Bill Wulf, as well as the influence of many current and past colleagues at the University of Michigan including Linda Abriola, Ed Borberly, Don Chaffin, Steve Director, Deba Dutta, Ron Gibala, Linda Katehi, Dave Munson, Panos Papalambros, and Galip Ulsoy. This study has also drawn heavily from the author's own experience as an engineering faculty member, dean, provost, and university president over the past four decades as well as numerous activities with federal agencies (the National Science Foundation, the National Science Board, the Department of Energy, the Department of Education), national organizations (the National Academies, the Atlantic Foundation), and international activities (the Glion Colloquium, OECD studies, the Salzburg Seminars).

Finally, it is important to acknowledge the support of the National Science Foundation for this study through an NSF Engineering Grant EEC 0502019 as well as the encouragement and support of the former NSF Assistant Director for Engineering, John Brighton.

Contents

Chapter 1

Introduction

An array of powerful forces, including demographics, globalization, and rapidly evolving technologies, is driving profound changes in the role of engineering in society. The changing technology needs of a global knowledge economy are challenging the nature of engineering practice, demanding far broader skills than simply the mastery of scientific and technological disciplines. The growing awareness of the importance of technological innovation to economic competitiveness and national security is demanding a new priority for basic engineering research. The nonlinear nature of the flow of knowledge between fundamental research and engineering application, the highly interdisciplinary nature of new technologies, and the impact of cyberinfrastructure demand new paradigms in engineering research and development. Moreover, challenges such as the off shoring of engineering jobs, the decline of student interest in scientific and engineering careers, immigration restrictions, and inadequate social diversity in the domestic engineering workforce, are also raising serious questions about the adequacy of our current national approach to engineering.

During the past several years numerous studies have suggested the need for new paradigms in engineering practice, research, and education that better address the needs of a 21st-century global, knowledge-driven society. Most prominent among these are:

Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, National Academies (Augustine, 2005)
The National Innovation Initiative, Council on Competitiveness (Council on Competitiveness, 2006)
Engineering Research and America's Future: Meeting the Challenges of a Global Economy, National Academy of Engineering (Duderstadt, 2005)
The Engineer of 2020 (Parts I and II), National Academy of Engineering (Clough, 2004, 2005)
Educating Engineers: Theory, Practice, and Imagination, Carnegie Foundation for the Advancement of Teaching (S. Sheppard and W. Sullivan, 2007)
*The Science and Engineering Workforce: Realizing America's Potentia*l, National Science Board (NSB, 2003)
Moving Forward to Improve Engineering Education, National Science Board (NSB, 2007)

Other more general or related studies include:

A Test of Leadership: Charting the Future of U.S. Higher Education, The Secretary of Education's Commission on the Future of Higher Education in America (Miller, 2006)
Revolutionizing Science and Engineering Through Cyberinfrastructure, the NSF Advisory Panel on Cyberinfrastructure (Atkins, 2004)
The IT Forum, National Academies, Government-University-Industry Research Roundtable (Duderstadt, 2005)
The Federal Science and Technology Budget, Committee on Science, Engineering, and Public Policy (COSEPUP, 1999-2003)
Critical Choices: Science, Engineering, and Security, Department of Energy Task Force on the Future of Science Programs at the Department of Energy (Vest, 2003)

In addition, there are important efforts underway to implement recommendations from these studies:

ABET's EC2000 Program (ABET, 1995)
NSF's Cyberinfrastructure Program (Atkins, 2006)
The President's American Competitiveness Initiative (Marburger, 2006)
The America COMPETES Act (United States Congress, 2007)

This cacophony of reports and initiatives has converged into a chorus of concerns that is likely to drive very significant change in American engineering over the next several decades..

The Warning Signs

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 out-sourcing and off-shoring; 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. Both these challenges and opportunities suggest that major changes will be necessary in engineering practice, research, and education in the century ahead, changes that go far beyond conventional paradigms.

21st century engineering challenges: globalization, demographics, distruptive technologies

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 in and with 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 United States 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 problems arising in contemporary society require highly interdisciplinary engineering teams characterized by broad intellectual span rather than focused practice within the 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

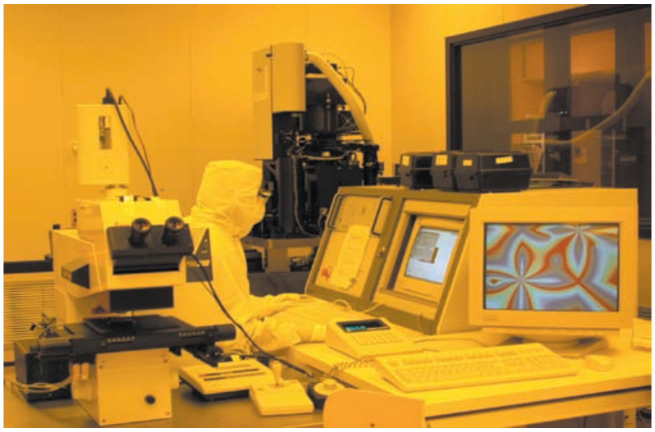
High Tech industry in Bangalore

and design skills toward more innovative solutions imbedded in an 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 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 its evolution from a trade (a "servile art" such as carpentry rather than a "liberal art" such as natural philosophy). But it is also evidenced in the way that industry all too frequently tends to view engineers as consumable commodities, discarding them when their skills become obsolete or replaceable by cheaper engineering services from abroad. So too, the low public prestige of the engineering profession is apparent both in public perception and the declining interest of students in engineering careers relative to other 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 century, in part because neither the profession nor the educational system supporting it have 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 off shoring of engineering jobs of increasing value raise the threat of 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 that leadership in technological innovation is key to the nation's prosperity and security in a hypercompetitive, global, knowledge-driven economy (Council on Competitiveness, 2003). 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).


The changing nature of engineering research

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, 1998-03; Duderstadt, 2005; Clough, 2002; Vest, 2003; 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 five-fold 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.

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) to reflect in its diversity, quality, and rigor the characteristics necessary to serve a 21st-century nation and world (Sheppard, 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 off shoring engineering services from low-wage nations. Cumbersome immigration policies in the wake of 9-11, along with negative international reaction to U.S. 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 both by students and employers. Moreover, it has long been apparent that current engineering science-dominated curricula needs 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.


Where will tomorrow's engineers come from?

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.

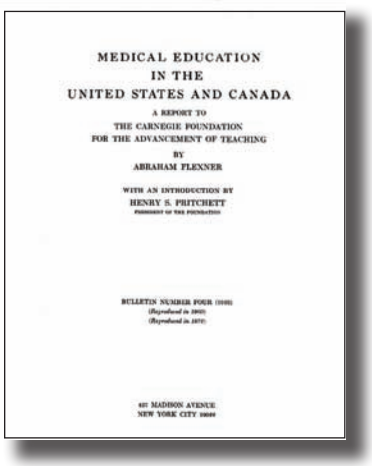
The Purpose of the Study

The purpose of this study is to pull together the principal findings and recommendations of these various reports concerning engineering, the technology and innovation needs of the nation, and the role played by human and intellectual capital, into an analysis of the changing nature of engineering practice, research, and education. More specifically, it considers the implications for 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* necessary to produce the engineers and engineering research critical to national prosperity and security.

More generally, it addresses the question of what our nation should seek as both the nature and objectives of engineering in the 21st-century, recognizing that significant changes are required to address changing national needs and priorities. What is engineering–a discipline, an occupation, a career, or a profession? Whom should engineering serve–industry, government, the nation, the world, students, or the profession itself? Granted that engineering education should not be monolithic, but how can we achieve adequate intellectual depth, breadth, and rigor across a highly diverse engineering enterprise demanded by our changing needs as a society and as a nation?

Note that such a general approach is quite similar in spirit to that conducted for the medical profession almost a century ago. At that time medicine was facing a tipping point when society's changing needs, coupled with a changing knowledge base of medical practice, would drive a very rapid transformation of the medical profession, along with medical education, licensure, and practice. The Carnegie Foundation for the Advancement of Teaching commissioned noted educator (but not physician) Abraham Flexner to survey 150 medical schools over a yearlong period and draft a report concerning the changing nature of the profession and the implications for medical education. During the 19th-century, medical education had evolved from a practice-based apprenticeship to dependence primarily upon didactic education (a year of lectures followed by a licensing exam), losing the rigor of training criti-

Medicine as practiced in 1900



MEDICAL EDUCATION
IN THE
UNITED STATES AND CANADA
A REPORT TO
THE CARNEGIE FOUNDATION
FOR THE ADVANCEMENT OF TEACHING
BY
ABRAHAM FLEXNER

WITH AN INTRODUCTION BY
HENRY S. PRITCHETT

BULLETIN NUMBER FOUR

MADISON AVENUE
NEW YORK CITY

The Flexner Report of 1910

cal to competent health care. Many students had less than a high school education and none required a college degree. As Flexner observed, medical education was a farce as it was taught in most schools, "without laboratories, without trained and salaried men, without dispensaries, and without hospitals".

The questions Flexner raised about medical education still reverberate today (Bonner, 2002): How are scientific principles best joined to clinical problem solving and broadly liberal knowledge in a doctor's education? How should students prepare for medical education and what should be its components? Flexner held up Johns Hopkins University as the standard to which all medical schools should be held, involving a full-time faculty, allied to a teaching hospital and integrated into a university (although other medical schools including Michigan, Harvard, and Pennsylvania had actually pioneered the practice of requiring a college education for admission into programs based on laboratory science and clinical training in a teaching hospital environment).

The Flexner Report of 1910 transformed medical education and practice into the 20th century paradigm of scientific (laboratory-based) medicine and clinical training in teaching hospitals (Flexner, 1910). The key to the impact of the report was to promote educational reform as a public health obligation: "If the sick are to reap the full benefit of recent progress in medicine, a more uniformly arduous and expensive medical education is demanded." Key would be the requirement that all physicians should be well-educated, highly trained diagnosticians and problem solvers who understand the laboratory basis for scientific knowledge and have become skilled through extensive clinical experience. A medical degree would require a four-year post-undergraduate program based on inductive teaching in medicine and science–learning by doing–in a university setting that joined investigative science to practical training.

The Flexner Report ignited a reform movement that transformed medical education and practice over the next several decades. Roughly two-thirds of medical colleges based on the didactic education of undergraduates were closed as the post-baccalaureate training paradigm proposed by Flexner was accepted as the requirement for medical practice.

Here it is interesting to note that during his study of medicine, Flexner raised very similar concerns about engineering education even at this early period. "The minimum basis upon which a good school of engineering accepts students is, once more, an actual high school education, and the movement toward elongating the technical course to five years confesses the urgent need of something more." However, he went on to contrast medical and engineering in two ways: first, engineering depends upon the basic sciences (chemistry, physics, mathematics) while medicine depends upon the secondary sciences (anatomy, physiology), which, in turn, depend upon basic sciences. Second, while engineers take on major responsibility for human life (e.g., buildings, bridges), they usually do so after gaining experience working up the employment ladder, while physicians must deal with such issues immediately upon graduation.

During the past century there have been numerous efforts to conduct an analysis of engineering very similar in spirit to the Flexner Report, including the Mann Report of 1918 (sponsored like Flexner's work by the Carnegie Foundation), the Wichenden Report of 1923, the ASEE Grinter Report of 1955, the ASEE report on Goals of an Engineering Education of 1968, the ASEE Green Report of 1994, the NRC BEEd Report leading to the ABET EC2000 program, and most recently the NAE Engineer of 2020 study (Clough, 2004). As Schowalter observes, "Appearance every decade of a definitive report on the future of engineering education is as predictable as a sighting of the first crocuses in spring"

(Schowalter, 2003). Yet throughout the past century, engineering education has remained remarkably stable–to be sure, adding more scientific content, but doing so within a four-year undergraduate program based primarily upon scientific problem solving and resisting most efforts to elevate it to the post-graduate practice-based programs characterizing other learned professions such as medicine and law.

Ironically, although engineering is one of the professions most responsible for and responsive to the profound changes in our society driven by evolving technology, its characteristics in practice, research, and education have been remarkably constant–some might even suggest stagnant–relative to other professions. Over the past century medical knowledge has been transformed from apprenticeship (e.g., the barber shop) to macroscopic science-driven (physiology, epidemiology) to microscopic science (genetics, proteomics, nanotechnology). Medical practice is also continuing to evolve rapidly, from reactive (curing disease) to prescriptive (determining one's genetic susceptibility to disease) to preventive (wellness). The profession of law is also evolving rapidly because of the impact of information technology (e.g., the ability to rapidly search and analyze written material in digital form; new forms of incontrovertible evidence such as DNA analysis; and the evolution of computer-based pattern recognition and psychological profiling to detect lying). Yet many aspects of engineering, including engineering education and professional certification, remain much as they have for decades, despite the rapidly changing nature of engineering practice and technology needs of society.

The Approach: Strategic Roadmapping

So how might one approach a more radical assessment of engineering practice, research, and practice akin to the Flexner Report on medicine? Fortunately it is unnecessary to repeat Flexner's methodical surveys of engineering practice and education, since we can build upon the significant knowledge base provided by the recent studies conducted by organizations such as the National Academies, the National Science Foundation, the engineering professional societies, and the Carnegie Foundation. The challenge, therefore, is to weave these analyses, conclusions, and recommendations into a coherent strategy for the transformation of engineering practice, research, and education in America.

There are many possible approaches to such an effort. For example, the National Academy of Engineering's Engineer of 2020 study (Clough, 2004) utilized scenario planning, in which one constructs several scenarios or stories of possible futures to illustrate limiting cases while taking advantage of the power of the narrative, e.g.,

- The next scientific revolution (an optimistic view where change is principally driven by technologies along a predictable path, with engineers exploiting new science to develop technologies that benefit humankind).
- The biotechnology revolution in a societal context (where social and political issues intervene with technology development, e.g., transgenic foods, stem cell research).
- The natural world interrupting the technology cycle (e.g., natural disasters).
- Globalization including possible global conflict (terrorism, out-sourcing, off-shoring).

These were used to provide the context for a subsequent study of engineering education (Clough, 2005). More recently the Carnegie Foundation study of Sheppard and Sullivan has involved a thorough inventory and analysis of existing approaches to engineering practice and education, drawing both on a deeper understanding of recent developments in cognitive science and comparisons with other learned professions (Sheppard, 2008).

However since the aim of our study is to provide both a concrete vision for the future of engineering and recommendations aimed at achieving this vision, we sought a somewhat broader, more structured approach. Since technology itself is contributing to many of our challenges–globalization, off-shoring, the obsolescence of our manufacturing companies and our low-skill workforce–this study has adopted a common technique used in industry and the federal government to develop technology strategies: technology roadmapping. In a traditional technology roadmap, one begins with expert panels to provide an assessment of needs, then constructs a map of existing resources, performs an analysis to determine the gap between what currently exists and what is needed, and finally develops a plan or roadmap of possible routes from here to there, from the present to the future. Although sometimes characterized by jargon such as environmental scans, resource maps, and gap analysis, in reality the roadmapping process is quite simple. It begins by asking where we are today, then where we wish to be tomorrow, followed by an assessment of how far we have to go, and finally concludes by developing a roadmap to get from here to there. The roadmap itself usually consists of a series of recommendations, sometimes divided into those that can be accomplished in the near term and those that will require longer-term and sustained effort.

In a sense the various studies listed earlier in this chapter have already performed the first stage of roadmapping, since they have involved expert panels of engineers and scientists, industry leaders and educators, to assess the needs of our society for engineering, including the changing nature of engineering practice, the engineering knowledge base, and the necessary skills and capability of the engineer. The task remains to organize these into a roadmapping structure–i.e., today, tomorrow, how far to go–resulting in a roadmap of actions capable of transforming American engineering.

To proceed with the development of a strategic roadmap for the future of engineering, we have organized this report as follows:

Chapter 1: Introduction
Chapter 2: Setting the Context: An Environmental Scan
Chapter 3: Engineering Today: A Resource Map
Chapter 4: Engineering Tomorrow: Needs, Objectives, and Vision
Chapter 5: How Far Do We Have To Go?: A Gap Analysis
Chapter 6: A Roadmap to 21st-Century Engineering
Chapter 7: So...How Do We Get This Done? (The Next Steps)

Concluding Remarks

While many have stressed the importance of engineering research, education, and practice to a nation ever more dependent on technological innovation in a global, knowledge-driven society, most efforts to develop new visions for the profession have remained relatively close to the status quo. Yet at a time when disruptive technologies are driving rapid, profound, and unpredictable change in most social institutions in the public and private sector, it seems appropriate to suggest that perhaps more radical options should be considered.

To this end, this study aims to provide a more expansive roadmap of where engineering is today and where it must be headed tomorrow to serve a changing world, not for a decade but perhaps a generation or more ahead. A key objective of this project is to break out of the box of conventional thinking and to develop and promote new visions of engineering, in all its manifestations and applications, for a 21st-century world, and then to propose the steps that lead toward such visions.

To set our course, let us acknowledge at the outset the elements of the proposed vision for the future of engineering:

1. To establish engineering practice as a true learned profession, similar in rigor, intellectual breadth, preparation, stature, and influence to law and medicine, with an extensive post-graduate education and 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 in 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 -dependent society of the century ahead.

5. To achieve far greater diversity among the participants in engineering, the roles and types of engineers needed by our nation, and the programs engaged in preparing them for professional practice.

The stakes in such an effort are very high. Today neither industry nor the federal government are investing adequately in basic engineering research to provide the knowledge base necessary for technological innovation. Recent studies have well documented alarming trends such as the increasing tendency of industry to regard engineers as commodities, easy to replace through outsourcing and off shoring of jobs. Although most students interested in science and engineering have yet to sense the long-term implications of the global economy, as practices such as off shoring become more apparent, there could be a very sharp decline in the interest in engineering careers among the best students. Current immigration policies threaten our capacity to attract outstanding students, scientists, and engineers from abroad. And our failure to adequately diversify the engineering workforce poses a challenge in the face of the demographic certainty that 90% of the growth in the American population over the next several decades will consist of women, minorities, and immigrants.

If one extrapolates these trends, it becomes clear that without concerted action, our nation faces the very real prospect of eroding 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.

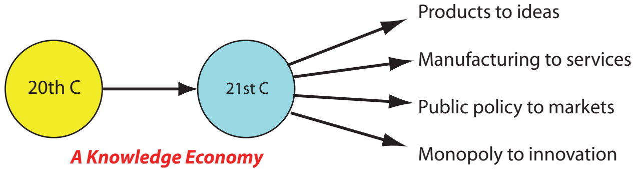
A Cacophony of Reports,
A Chorus of Concerns

Chapter 2

Setting the Context: An Environmental Scan

It is important to provide an appropriate context for the planning process. To this end, we have adopted the approach of environmental scanning, drawing heavily upon many earlier studies that have stimulated this project. We frame this environmental scan as a series of challenges to both our world and to engineering.

Challenge 1: The Knowledge Economy



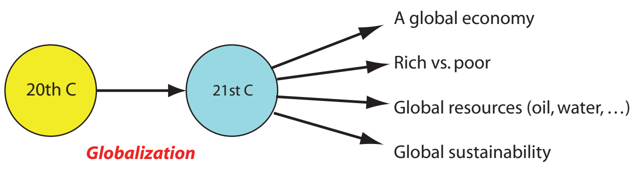
Looking back over history, one can identify certain abrupt changes, discontinuities in the nature, the fabric, of our civilization. Clearly we live in just such a time of very rapid and profound social transformation, a transition from a century in which the dominant human activity was transportation to one in which communication technology has become paramount, from economies based upon cars, planes, and trains to one dependent upon computers and networks. We are shifting from an emphasis on creating and transporting physical objects such as materials and energy to knowledge itself; from atoms to bits; from societies based upon the geopolitics of the nation-state to those based on diverse cultures and local traditions; and from a dependence on government policy to an increasing confidence in the marketplace to establish public priorities.

Today we are evolving rapidly into a post-industrial, knowledge-based society, a shift in culture and technology as profound as the shift that took place a century ago when our agrarian societies evolved into industrial nations (Drucker, 1999). Industrial production is steadily shifting from material- and labor-intensive products and processes to knowledge-intensive products and services. A radically new system for creating wealth has evolved that depends upon the creation and application of new knowledge and hence upon educated people and their ideas and institutions such as research universities, corporate R&D laboratories, and national research agencies where advanced education, research, innovation, and entrepreneurial energy are found.

In a very real sense, we are entering a new age, an age of knowledge, in which the key strategic resource necessary for prosperity has become knowledge itself–educated people and their ideas (Bloch, 1988; Friedman, 2005). Unlike natural resources, such as iron and oil, which have driven earlier economic transformations, knowledge is inexhaustible. The more it is used, the more it multiplies and expands. But knowledge can be created, absorbed, and applied only by the educated mind. The knowledge economy is demanding new types of learners and creators and new forms of learning and education. As a recent survey in *The Economist* put it, “The value of ‘intangible’ assets–everything from skilled workers to patents to know-how–has ballooned from 20 percent of the value of companies in the S&P 500 to 70 percent today. The proportion of American workers doing jobs that call for complex skills has grown three times as fast as employment in general” (*The Economist*, 2006).

Nicholas Donofrio, senior executive of IBM, described today’s global knowledge economy as driven by three historic developments. “The growth of the Internet as the planet’s operational infrastructure; the adoption of open technical standards that facilitate the production, distribution, and management of new and better products and services; and the widespread application of these applications to the solution of ubiquitous business problems. In this increasingly networked world, the choice for most companies and governments is between innovation and commodification. Winners can be innovators–those with the capacity to invent, manage, and leverage intellectual capital–or commodity players, who differentiate through low price economics of scale and efficient distribution of someone else's intellectual capital" (Donofrio, 2005).

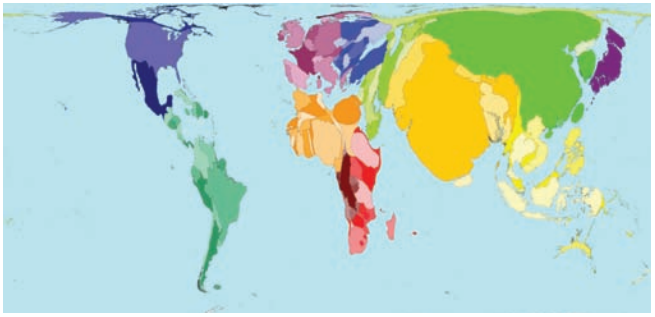
Challenge 2: Globalization



Whether through travel and communication, through the arts and culture, or through the internationalization of commerce, capital, and labor, or our interconnectness through common environmental concerns, the United States is becoming increasingly linked with the global community. The liberalization of trade and investment policies, along with the revolution in information and communications technologies, has vastly increased the flow of capital, goods, and services, dramatically changing the world and our place in it. Today globalization determines not only regional prosperity but also national and homeland security. Our economy and companies are international, spanning the globe and interdependent with other nations and other peoples.

In such a global economy, it is critical that nations (and regions such as states or cities) not only have global reach into markets abroad, but also have the capacity to harvest new ideas and innovation and to attract talent from around the world. However, as former MIT president Charles Vest stresses, one must bear in mind four imperatives of the global economy: i) people everywhere are smart and capable; ii) science and technology advance relentlessly, iii) globalization is a dominating reality, and iv) the Internet is a democratizing force (Vest, 2005). Worldwide communication networks have created an international market, not only for conventional products, but also for knowledge professionals, research, and educational services.

As the recent report of the National Intelligence Council's 2020 Project has concluded, "The very magnitude and speed of change resulting from a globalizing world-apart from its precise character–will be a defining feature of the world out to 2020. During this period, China's GNP will exceed that of all other Western economic powers except for the United States, with a projected population of 1.4 billion. India and Brazil will also likely surpass most of the European nations. Globalization–the growing interconnectedness reflected in the expanded flows of information, technology, capital, goods, services, and people throughout the world–will become an overarching mega-trend, a force so ubiquitous that it will substantially shape all other major trends in the world of 2020" (National Intelligence Council, 2004).



The distribution of the world's population represented by the distorted size of nations. (Worldmapper, 2005)

In his provocative book *The World Is Flat*, Tom Friedman warns that "Some three billion people who were excluded from the pre-Internet economy have now walked out onto a level playing field, from China, India, Russia, Eastern Europe, Latin American, and Central Asia. It is this convergence of new players, on a new playing field, developing new processes for horizontal collaboration, that I believe is the most important force shaping global economics and politics in the early 21st century" (Friedman, 2005). Or as Craig Barrett, CEO of Intel, puts it: "You don't bring three billion people into the world economy overnight without huge consequences, especially from three societies like India, China, and Russia, with rich educational heritages."

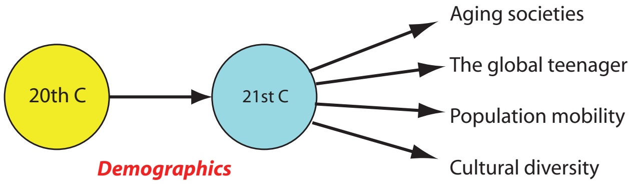
Of course, some would contend that rather than flattening, world economic activity is actually becoming more peaked about concentrations of knowledge-workers and innovation centers. Others suggest that rapidly evolving information and communications are enabling the participation of billions "at the bottom of the economic pyramid" through microeconomic transactions (Prahalad, 2005). But whether interpreted as a flattening of the global playing field or a peaking about concentrations of innovation, most nations have heard and understood the message about the imperatives of the emerging global knowledge economy. They are investing heavily and restructuring their economies to create high-skill, high-pay jobs in knowledge-intensive areas such as new technologies, financial services, trade, and professional and technical services. From Dublin to Prague, Bangalore to Shanghai, there is a growing recognition throughout the world that economic prosperity and social well being in a global knowledge-driven economy require public investment in knowledge resources. That is, regions must create and sustain a highly educated and innovative workforce and the capacity to generate and apply new knowledge, supported through policies and investments in developing human capital, technological innovation, and entrepreneurial skill.

Today's global corporation conducts its strategy, management, and operations on a global scale. The multinational organization has evolved far beyond a collection of country-based subsidiaries to become instead a globally integrated array of specialized components–procurement, management, R&D, manufacturing, sales, etc.–distributed through the world, wherever attractive markets exist and skilled workers can be found. Geopolitical borders are of declining relevance to global business practices. Global corporations are showing less loyalty to countries of origin and more to regions in which they find new markets and do business (Palmisano, 2006).

It is this reality of the hyper-competitive, global, knowledge-driven economy of the 21st Century that is stimulating the powerful forces that will reshape the nature of our society and our knowledge institutions. Again to quote Friedman, "Information and telecommunications technologies have created a platform where intellectual work and intellectual capital can be delivered from anywhere–disaggregated, delivered, distributed, produced, and put back together again, or in current business terms and this gives an entirely new freedom to the way we do work, especially work of an intellectual nature". Today rapidly evolving technologies and sophisticated supply chain management are allowing "global sourcing", the ability to outsource not only traditional activities such as low-skill manufacturing, but to offshore essentially any form of knowledge work, no matter how sophisticated, to whatever part of the globe has populations most capable and cost-effective to perform it. Put another way, "The playing field is being leveled. Countries like India and China are now able to compete for global knowledge work as never before. And America had better get ready for it" (Friedman, 2005).

Clearly, today's companies require new skills and competence that address the challenges and opportunities of globally integrated business. This has particularly serious implications for the future of engineering, since not only must engineers develop the capacity to work with multinational teams and be internationally mobile, but they also must appreciate the great diversity of cultures characterizing both the colleagues they work with and the markets they must compete in. Furthermore, the American engineer faces the additional challenge of competing globally with engineers of comparable talents and determination in economies with considerably lower wage structures.

Challenge 3: Demographics



The populations of most developed nations in North America, Europe, and Asia are aging rapidly. In the United States, the baby boomers are beginning to retire, shifting social priorities to the needs and desires of the elderly (e.g., health care, financial security, low crime, national security, low taxes) rather than investing in the future (e.g., education). In our nation today there are already more people over the age of 65 than teenagers, and this situation will continue for decades to come. Over the next decade the percentage of the population over 60 will grow to over 30% to 40% in the United States, Europe, and parts of Asia. In fact, half of the world's population today lives in countries where fertility rates are not sufficient to replace their current populations. For example, the average fertility rate in the EU has dropped to 1.45 while Japan is at 1.21, compared to the value of 2.1 necessary for a stable population. Aging populations, out-migration, and shrinking workforces are having an important impact, particularly in Europe, Russia, and some Asian nations such as Japan, South Korea, and Singapore (National Intelligence Council, 2004; Baumgardt, 2006).

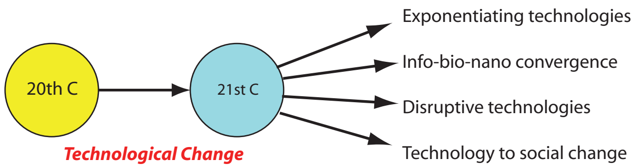
In sharp contrast, in many developing nations in Asia, Africa, and Latin America, the average age is less than 20 (with over 2 billion teenagers in the world today). Their demand for education will be staggering since in a knowledge economy, it is clear to all that this is the key to one's future security. Yet it is estimated that today there are over 30 million people in the world who are fully qualified to enter a university but for whom no university place is available (Daniel, 1996). Within a decade there will be 250 million university-ready people. Unless developed nations step forward and help address this crisis, billions of people in coming generations will be denied the education so necessary to compete in, and survive in, an age of knowledge. And the resulting despair and hopelessness among the young will feed the terrorism that so threatens our world today.

Growing disparities in wealth and economic opportunity, frequently intensified by regional conflict, continue to drive population migration. The flow of workers across the global economy seeking prosperity and security presents further challenges to many nations. The burden of refugees and the complexity of absorbing immigrant cultures are particularly apparent in Europe and North America.

Immigration is the principal reason why the United States stands apart from much of the rest of the developed world with respect to our demographic challenges. Like Europe and parts of Asia, our population is aging, but our openness to immigration will drive continued growth in our population from 300 million today to over 450 million by 2050. Today differential growth patterns and very different flows of immigration from Asia, Africa, Latin America, the Caribbean, and Mexico are transforming our population. In fact, over the past decade, immigration from Latin America and Asia contributed 53% of the growth in the United States population exceeding that provided by births (National Information Center, 2006). As it has been so many times in its past, America is once again becoming a nation of immigrants, benefiting greatly from their energy, talents, and hope, even as such mobility changes the ethnic character of our nation. By the year 2030 current projections suggest that approximately 40% of Americans will be members of racial or ethnic minority groups. By mid-century we will cease to have any single majority ethic group. By any measure, we are evolving rapidly into a truly multicultural society with a remarkable cultural, racial, and ethnic diversity. This demographic revolution is taking place within the context of the continuing globalization of the world's economy and society that requires Americans to interact with people from every country of the world.

The increasing diversity of the American population with respect to culture, race, ethnicity, and nationality is both one of our greatest strengths and most serious challenges as a nation. A diverse population gives us great vitality. However, the challenge of increasing diversity is complicated by social and economic factors. Today, far from evolving toward one America, our society continues to be hindered by the segregation and non-assimilation of minority cultures. Many are challenging in both the courts and through referenda long-accepted programs such as affirmative action and equal opportunity aimed at expanding access to higher education to underrepresented communities and diversifying our campuses and workplaces (*The Economist*, 2005). Yet if we do not create a nation that mobilizes the talents of all of our citizens, we are destined for a diminished role in the global community and increased social turbulence. Most tragically, we will have failed to fulfill the promise of democracy upon which this nation was founded. The achievement of this objective also will be the key to the future strength and prosperity of America, since our nation cannot afford to waste the human talent presented by its minority populations. This has major implications for the future of engineering, a profession where minorities and women remain seriously under-represented.

Challenge 4: Technological Change



The new technologies driving such profound changes in our world–technologies such as information technology, biotechnology, and nanotechnology–are characterized by exponential growth. When applied to microprocessor chips, this remarkable property, known as Moore's Law, implies that every 18 months, computing power for a given price doubles. And for other elements of digital technology, such as memory and bandwidth, the doubling time is even shorter–currently 9 to 12 months. Scientists and engineers today believe that the exponential evolution of these microscopic technologies is not only likely to continue for the conceivable future, but may actually be accelerating (Reed, 2006; Feldman, 2003).

Put another way, digital technology is characterized by an exponential pace of evolution in which characteristics such as computing speed, memory, and network transmission speeds for a given price double every one to two years. Over the two decades, we will evolve from "giga" technology (in terms of computer operations per second, storage, or data transmission rates) to "tera" to "peta" and perhaps even "exa" technology (one billion-billion or 10^{18}). To illustrate with an extreme example, if information technology continues to evolve at its present rate, by the year 2020, the thousand-dollar notebook computer will have a data-processing speed and memory capacity roughly comparable to the human brain (Kurzweil, 1999). Furthermore, it will be so tiny as to be almost invisible, and it will communicate with billions of other computers through wireless technology.

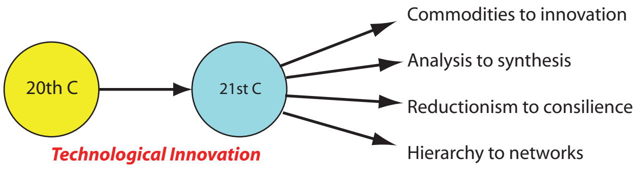
For planning purposes, we can assume that on the timescale of decades we will have available infinite bandwidth and infinite processing power (at least compared to current capabilities). We will denominate the number of computer servers in the billions, digital sensors in the tens of billions, and software agents in the trillions. The number of people linked together by digital technology will grow from millions to billions. We will evolve from "e-commerce" and "e-government" and "e-learning" to "e-everything," since digital devices will increasingly become predominant interfaces not only with our environment but with other people, groups, and social institutions.

IBM's Blue Gene P supercomputer, capable of a sustained speed of 1 petaflop–roughly the speed of the human brain

The information and communications technologies enabling the global knowledge economy–so-called *cyberinfrastructure* (the current term used to describe hardware, software, people, organizations, and policies)–evolve exponentially, doubling in power for a given cost every year or so, amounting to a staggering increase in capacity of 100 to 1,000 fold every decade. It is becoming increasingly clear that we are approaching an inflection point in the potential of these technologies to radically transform knowledge work. To quote Arden Bement, director of the National Science Foundation, "We are entering a second revolution in information technology, one that may well usher in a new technological age that will dwarf, in sheer transformational scope and power, anything we have yet experienced in the current information age" (Bement, 2007).

Beyond acknowledging the extraordinary and unrelenting pace of such exponentially evolving technologies, it is equally important to recognize that they are disruptive in nature. Their impact on social institutions such as corporations, governments, and learning institutions is profound, rapid, and quite unpredictable. As Clayton Christensen explains in *The Innovator's Dilemma*, while many of these new technologies are at first inadequate to displace today's technology in existing applications, they later explosively displace the application as they enable a new way of satisfying the underlying need (Christensen, 1997). If change is gradual, there will be time to adapt gracefully, but that is not the history of disruptive technologies. Hence organizations (including governments) must work to anticipate these forces, develop appropriate strategies, and make adequate investments if they are to prosper–indeed, survive–such a period. Procrastination and inaction (not to mention ignorance and denial) are the most dangerous of all courses during a time of rapid technological change.

Challenge 5: Technological Innovation

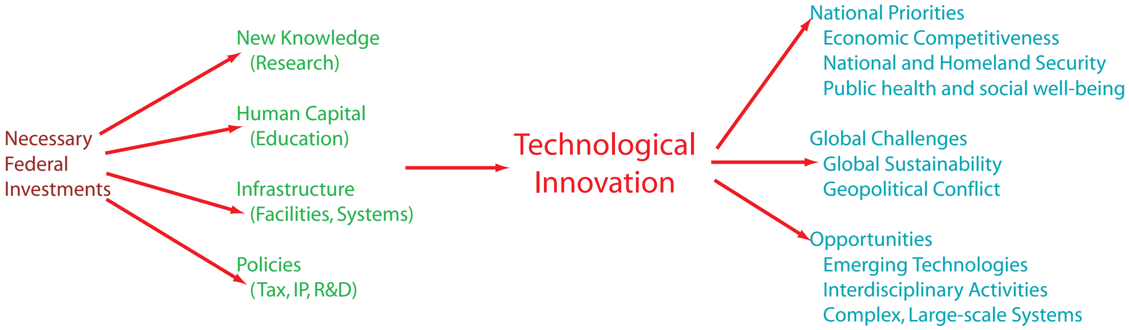


In its National Innovation Initiative, the Council on Competitiveness, a group of business and university leaders, highlight innovation as the single most important factor in determining America's success throughout the 21st century. "American's challenge is to unleash its innovation capacity to drive productivity, standard of living, and leadership in global markets. At a time when macro-economic forces and financial constraints make innovation-driven growth a more urgent imperative than ever before, American businesses, government, workers, and universities face an unprecedented acceleration of global change, relentless pressure for short-term results, and fierce competition from countries that seek an innovation-driven future for themselves. For the past 25 years we have optimized our organizations for efficiency and quality. Over the next quarter century, we must optimize our entire society for innovation" (Council on Competitiveness, 2005).

Of course innovation is more than simply new technologies. It involves how business processes are integrated and managed, how services are delivered, how public policies are formulated, and how markets and more broadly society benefit (Lynn, 2006).

However it is also the case that in a global, knowledge-driven economy, technological innovation–the transformation of new knowledge into products, processes, and services of value to society–is critical to competitiveness, long-term productivity growth, and an improved quality of life. The National Intelligence Council's 2020 Project concludes, "the greatest benefits of globalization will accrue to countries and groups that can access and adopt new technologies" (National Intelligence Council, 2004). This study notes that China and India are well positioned to become technology leaders, and even the poorest countries will be able to leverage prolific, cheap technologies to fuel–although at a slower rate–their own development. It also warns that this transition will not be painless and will hit the middle classes of the developed world in particular, bringing more rapid job turnover and requiring professional retooling. Moreover, future technology trends will be marked not only by accelerating advancements in individual technologies but also by a force-multiplying convergence of the technologies–information, biological, materials, and nanotechnologies–that have the potential to revolutionize all dimensions of life.

In summary, the 2020 Project warns that "A nation's or region's level of technological achievement generally



The role of technological innovation in the knowledge economy will be defined in terms of its investment in integrating and applying the new globally available technologies–whether the technologies are acquired through a country's own basic research or from technology leaders. Nations that remain behind in adopting technologies are likely to be those that have failed to pursue policies that support application of new technologies–such as good governance, universal education, and market reforms–and not solely because they are poor."

This has been reinforced by a recent study by the National Academy of Engineering that concludes, "American success has been based on the creativity, ingenuity, and courage of innovators, and innovation that will continue to be critical to American success in the twenty-first century. As a world superpower with the largest and richest market, the United States has consistently set the standard for technological advances, both creating innovations and absorbing innovations created elsewhere" (Duderstadt, 2005).

Many nations are investing heavily in the foundations of modern innovation systems, including research facilities and infrastructure and a strong technical workforce. Unfortunately, the United States has failed to give such investments the priority they deserve in recent years. The changing nature of the international economy, characterized by intense competition coexisting with broad-based collaboration and global supply chains and manifested in unprecedented U.S. trade deficits, underscores long-standing weaknesses in the nation's investment in the key ingredients of technological innovation: new knowledge (research), human capital (education), and infrastructure (educational institutions, laboratories, cyberinfrastructure). Well-documented and disturbing trends include: skewing of the nation's research priorities away from engineering and physical sciences and toward the life sciences; erosion of the engineering research infrastructure; a relative decline in the interest and aptitude of American students for pursuing education and training in engineering and other technical fields; and growing uncertainty about our ability to attract and retain gifted science and engineering students from abroad at a time when foreign nationals constitute a large and productive fraction of the U.S. R&D workforce.

The Grand Challenges to Engineering

Beyond the urgent needs of today's increasingly global and knowledge-driven society, engineering must address several "grand challenges" of our world in the years that can only be addressed by new technologies implemented on a global scale.

Global Sustainability

There is compelling evidence that the growing population and invasive activities of humankind are now altering the fragile balance of our planet. The concerns are both multiplying in number and intensifying in severity: the destruction of forests, wetlands, and other natural habitats by human activities leading to the extinction of millions of biological species and the loss of biodiversity; the buildup of greenhouse gases such as carbon dioxide and their possible impact on global climates; the pollution of our air, water, and land. It could well be that coming to grips with the impact of our species on our planet, learning to live in a sustainable fashion on Spaceship Earth, will become the greatest challenge of all to our generation. We must find new ways to provide for a human society that presently has outstripped the limits of global sustainability. This will be particularly difficult for the United States, a nation that has difficulty in looking more than an election cycle or quarterly income statement ahead, much less the vision over decades or generations required for major global issues.

The greatest challenge for 21st century engineering:
global sustainability

Evidence of global warming is now incontrovertible–increasing global surface and air temperatures, receding glaciers and polar ice caps, rising sea levels, and increasingly powerful weather disruptions, all confirm that unless the utilization of fossil fuels is sharply curtailed, humankind could be seriously threatened. The recent Intergovernmental Panel on Climate Change concluded that: "Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change." (IPCC, 2007) Although there continues to be disagreement over particular strategies to slow global climate change–whether through regulation that restricts the use of fossil fuels or through market pressures (e.g., "cap and trade" strategies)–there is little doubt that energy utilization simply must shift away from fossil fuels toward non-hydrocarbon energy sources. Yet as John Holdren, president of the AAAS, puts it, "We are not talking any more about what climate models say might happen in the future. We are experiencing dangerous disruption of the global climate, and we are going to experience more. Yet we are not starting to address climate change with the technology we have in hand, and we are not accelerating our investment in energy technology R&D." (Holdren, 2007)

But global sustainability faces other challenges. In 2005 the United Nations projected the Earth's population in the year 2050 as 9.1 billion, 50% larger than today. Which of course raises the logical question: Can we sustain a population of that magnitude on Spaceship Earth? In fact, the basic premise of the United States free market system, which relies on steady growth in productivity and profits, based in part on similar growth in consumption and population, must be challenged by the very serious problems that will result from a ballooning global population, such as energy shortages, global climate change, and dwindling resources. The stark fact is that our planet simply cannot sustain a projected population of 8 to 10 billion with a lifestyle characterizing the United States and other developed nations with consumption-dominated economies.

To be sure, there are some signs of optimism: a slowing population growth that may stabilize during the 21st century, the degree to which extreme poverty appears to be receding both as a percentage of the population and in absolute numbers, and the rapid economic growth of developing economies in Asia and Latin America. Yet as a special report on global sustainability in *Scientific American* warned: "As humanity grows in size and wealth, it increasingly presses against the limits of the planet. Already we pump out carbon dioxide three times as fast as the oceans and land can absorb it; mid-century is when climatologists think global warming will really begin to bite. At the rate things are going, the world's forests and fisheries will be exhausted even sooner. As E. O. Wilson puts it, we are about to pass through 'the bottleneck', a period of maximum stress on natural resources and human ingenuity" (Scientific American, 2005).

Energy

There are few contemporary challenges facing our nation–indeed, the world–more threatening than the unsustainable nature of our current energy infrastructure. Every aspect of contemporary society is dependent upon the availability of clean, affordable, flexible, and sustainable energy resources. Yet our current energy infrastructure, heavily dependent upon fossil fuels, is unsustainable. Global oil production is expected to peak within the next several decades. While there are substantial reserves of coal and tar sands, the mining, processing, and burning of these fossil fuels poses increasingly unacceptable risk to both humankind and the environment, particularly within the context of global climate change. Furthermore, the security of our nation is threatened by our reliance on foreign energy imports from unstable regions of the world. Clearly if the federal government is to meet its responsibilities for national security, economic prosperity, and social well-being, it must move rapidly and aggressively to address the need for a sustainable energy future for the United States. Yet time is not on our side.

Recent analyses of world petroleum production and known reserves suggest that global oil production could peak as early as the next decade (with gas production peaking roughly a decade later). "Holding off the peak until 2040 would require both a high–and much less certain–total oil resource and adding more production each year than ever before, despite having already produced all of the world's most easily extractable oil." (Science, 2007) The consequence of passing over the global production peak is not the disappearance of oil; roughly half of the reserves would remain. Rather it would be a permanent imbalance between supply and demand that would drive oil prices dramatically higher than today's levels–$100/bbl, $200/bbl, and beyond–with corresponding increases at the pump. The rapidly increasing oil and gas demands from developing economies such as China, India, and Latin America make this imbalance even more serious, particularly when it is noted that the United States currently consumes 25% of world production (Goodstein, 2004).

To this should be added the growing consensus that utilization of fossil fuels in energy production is already causing significant global climate change. Although there continues to be disagreement over particular strategies to slow global climate change–whether through regulation that restricts the use of fossil fuels or through market pressures (e.g., "cap and trade" strategies)–there is little doubt that energy utilization simply must shift away from fossil fuels toward non-hydrocarbon energy sources (IPCC, 2007).

A recent assessment by the U. S. Department of Energy in the spring of 2005 warned, "The world has never faced a problem like this. Without massive mitigation more than a decade before the fact, the problem will be pervasive and will not be temporary. Previous energy transitions (wood to coal and coal to oil) were gradual and evolutionary; oil peaking will be abrupt and revolutionary" (Hirsch, 2005).

The unsustainable nature of current energy technologies (fossil fuels) puts at great risk America's existing industry and future economic prosperity. Spiking of gasoline prices to Asian and European levels (currently $6 per gallon and above) would likely obliterate what remains of the American automobile industry, since it is unlikely that domestic companies would be able to shift rapidly enough to the small, fuel-efficient cars produced by Asian manufacturers or be adept enough to exploit hybrid, electric, or hydrogen fuel technologies. Furthermore, manufacturing industries currently utilize 38% of the nation's electricity, produced primarily from coal-fired plants. Should electrical power generation from fossil fuels be sharply curtailed or should prices skyrocket through regulatory requirements for carbon sequestration, this component of our industrial capacity would be severely handicapped in the global economy.

The end of oil?

Alternative energy technologies such as electric- or hybrid cars, hydrogen fuels, nuclear power, and renewable energy sources such as solar, wind, or biofuels still require considerable research and development before they evolve to the point of massive utilization. Numerous studies from groups such as the National Academies, the President's Council of Advisors on Science and Technology, and the American Association for the Advancement of Science have given the very highest priority to launching a massive federal R&D effort to develop sustainable energy technologies. In fact, a high level task force created by the Secretary of Energy's Advisory Board stated in the strongest possible terms (Vest, 2003):

> America cannot retain its freedom, way of life, or standard of living in the 21st century without secure, sustainable, clean, and affordable sources of energy. America can meet its energy needs if and only if the nation commits to a strong and sustained investment in research in physical science, engineering, and applicable areas of life science, and if we translate advancing scientific knowledge into practice. The nation must embark on a major research initiative to address the grand challenge associated with the production, storage, distribution, and conservation of energy as both an element of its primary mission and an urgent priority of the United States.

The scale of the necessary transformation of our energy infrastructure is immense. It is estimated that over $16 trillion in capital investments over the next two decades will be necessary just to expand energy supply to meet growing global energy demands, compared to a global GDP of $44 trillion and a U.S. GDP of $12 trillion. Put another way, to track the projected growth in electricity demand, the world would need to bring online a new 1,000 MWe powerplant every day for the next 20 years! Clearly this requires a federal R&D effort comparable in scale to the Manhattan Project or the Apollo Program (Lewis, 2007).

Yet today there is ample evidence that both the magnitude and character of federal energy R&D programs are woefully inadequate to address the urgency of the current energy challenges faced by this nation. Over the past two decades, energy research has actually been sharply curtailed by the federal government (75% decrease), the electrical utility industry (50% decrease), and the domestic automobile industry (50% decrease). Today the federal government effort in energy R&D is less than 20% of its level during the 1980s! Here one might compare the $2.7 billion proposed for the President's Advanced Energy Initiative with the $17 billion NASA budget, the $30 billion NIH budget, or the $83 billion R&D budget for DOD. More specifically, of the current annual $23 B budget of the Department of Energy, only $6.1 B goes for basic scientific research and technology development related to energy.

How much should the federal government be investing in energy R&D? A comparison of the size of the energy sector ($1.9 T) compared to health care ($1.7 T) and national defense ($1.2 T) would suggest annual R&D investments in the range of $40 to $50 B, roughly ten times the current investments. Clearly Washington has yet to take the energy crisis seriously–and as a consequence our nation remains at very great risk.

Beyond scale, there are few technology infrastructures more complex than energy, interwoven with every aspect of our society. Moving to sustainable energy technologies will involve not simply advanced scientific research and the development of new technologies, but as well complex issues of social priorities, economic and market issues, international relations, and politics at all levels. Little wonder that one commonly hears the complaint that "The energy crisis is like the weather; everybody complains about it, but nobody does anything about it!"

Global Poverty and Health

During the past several decades, technological advances such as the "green revolution" have lifted a substantial portion of the world's population from the ravages of poverty. In fact, some nations once burdened by overpopulation and great poverty such as India and China, now are viewed as economic leaders in the 21st century. Yet today there remain substantial and widening differences in the prosperity and quality of life of developed, developing, and underdeveloped regions; between the North and South Hemisphere; and within many nations (including the deplorable level of poverty tolerated in our own country).

It is estimated that roughly one-sixth of the world's population, 1.5 billion people, still live in extreme poverty-defined by Jeffrey Sachs as "being so poor you could die tomorrow", mostly in sub-Saharan Africa, parts of South America, and much of central Asia. Put in even starker terms, "More than 8 million people around the world die each year because they are too poor to stay alive. Malaria, tuberculosis, AIDS, diarrhea, respiratory infections, and other diseases prey on bodies weakened by chronic hunger, claiming more than 20,000 lives each day" (Sachs, 2004).

These massive global needs can only be addressed by both the commitment of developed nations and the implementation of technology to alleviate poverty and disease. The United States faces a particular challenge and responsibility in this regard. With just 5% of the world's people, we control 25% of its wealth and produce 25% to 30% of its pollution. It is remarkable that the richest nation on earth is the lowest per capita donor of international development assistance of any industrialized country. As the noted biologist Peter Raven observes, "The United States is a small part of a very large, poor, and rapidly changing world, and we, along with everyone else, must do a better job. Globalization appears to have become an irresistible force, but we must make it participatory and humane to alleviate the suffering of the world's poorest people and the effective disenfranchisement of many of its nations" (Raven, 2003).

Infrastructure

Engineering of the 20th century was remarkable in its capacity to meet the needs of a rapidly growing global population, building great cities, transportation networks, and economic infrastructure. To be sure, it also developed horrific weapons of mass-destruction that laid to waste entire nations and their populations in global conflict. Yet eventually rebuilding occurred, and at least in much of the world, the infrastructure is in place to provide for societal well being and security.

Yet much of this infrastructure is aging, already inadequate to meet not simply population growth but growing economic activity. The patchwork approach used all too often to rebuild civic infrastructure–electrical distribution networks, water distribution systems, roads and bridges–has created new complexities poorly understood and even more difficult to address. These infrastructure challenges are intensified by demographic trends toward urbanization, where jobs and resources are found. A recent United Nation's study notes that for the first time in human history, more people are living in cities than rural areas. Over the next 30 years, more than two billion people will be added to the population of cities in the developing world, where within the next decade urban will exceed rural populations.

When combined with the incredible strain on urban systems in developing nations caused by population concentrations in mega-cities of tens of millions or transportation networks overwhelmed by the desire for mobility, it is clear that entirely new technologies and engineering approaches are needed to build and maintain the infrastructure necessary to accommodate a global population of 8 to 10 billion while preserving the capacity of the planet to support humankind.

Clearly U.S. engineering must play a critical role in meeting the most basic needs of the world's population. New technologies are needed to address urgent needs for food, water, shelter, and education in the developing world. Yet even in our own country the increasing complexity of our society requires new levels of reliability and confidence. When levies fail in New Orleans, a bridge falls in Minneapolis, a blackout occurs in the Northeast, or a national computer network goes down under cyberattack, people become not only more aware of the impact of technology on personal safety and public health, but moreover question the competency of American engineering to design and manage such complex systems. Such failures, both unavoidable and yet predictable, diminish our ability to contribute value to society, placing a high premium on reliability and, when necessary, recovery and forthright communication.

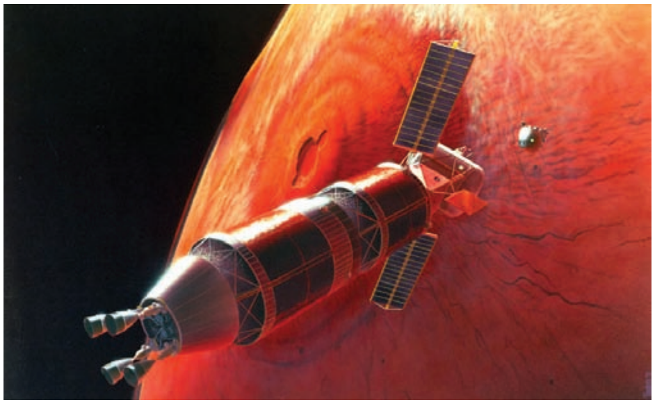
As economic activity shifts from exploitation of natural resources and the manufacturing of material goods to knowledge services, i.e., from atoms to bits, we will need entirely new intellectual paradigms to create value in the global knowledge economy. Just as two decades ago new methods such as total quality management and lean manufacturing reshaped our factories and companies while triggering entirely new forms of engineering, today we need to develop the new methods capable of creating innovation in a services economy characterized by extraordinarily complex global systems. The engineering profession will be challenged to develop new and more powerful approaches to design, innovation, systems integration, and entrepreneurial activities in support of the global knowledge economy (Donofrio, 2005).

Over the Horizon

Still other possibilities might be considered for the longer-term future. Balancing population growth in some parts of the world might be new pandemics, such as AIDS or an avian flu virus, that appear out of nowhere to ravage our species. The growing divide between rich and poor, between the developed nations and the third world, the North and South hemispheres, could drive even more serious social unrest and terrorism, perhaps armed with even more terrifying weapons.

Then, too, the unrelenting–indeed, accelerating–pace of technology could benefit humankind, extending our lifespan and quality of life, meeting the world's needs for food and shelter and perhaps even energy, and enabling vastly new forms of communication, transportation, and social interaction. Perhaps we will rekindle our species' fundamental quest for exploration and expansion by resuming human spaceflight and eventually colonizing our solar system and beyond.

The acceleration of technological progress has been the central feature of the past century and is likely to



Perhaps mankind will once again launch an era of space exploration....to Mars and beyond.

be even more so in the century ahead. But technology will also present new challenges that almost seem taken from the pages of science fiction. John von Neumann once speculated, "The ever accelerating progress of technology and changes in the mode of human life gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue." At such a technological singularity, the paradigms shift, the old models must be discarded, and a new reality appears, perhaps beyond our comprehension. Some futurists such as Ray Kurzweil and Werner Vinge have even argued that as early as this century we are on the edge of change comparable to the rise of human life on Earth. The precise cause of this change is the imminent creation by technology of entities with greater than human intelligence. For example, as digital technology continues to increase in power a thousand-fold each decade, at some point computers (or large computer networks) might "awaken" with superhuman intelligence. Or biological science may provide the means to improve natural human intellect (Kurzweil, 2005).

Clearly phenomena such as machine consciousness, contact by extraterrestrial intelligence, or cosmic extinction from a wandering asteroid are possibilities for our civilization, but just as clearly they should neither dominate our attention nor our near-term actions. Indeed, the most effective way to prepare for such unanticipated events is to make certain that our descendants are equipped with education and skills of the highest possible quality.

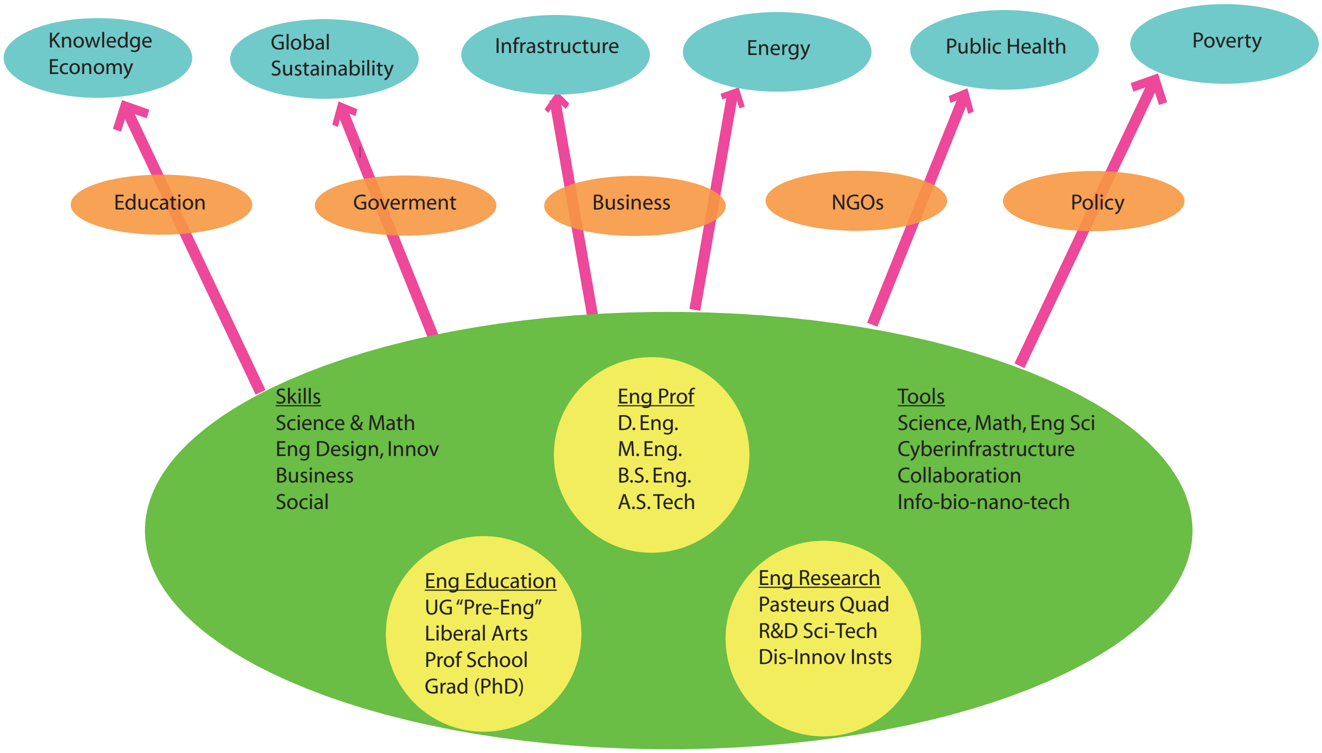
A Time of Challenge, Opportunity, and Responsibility

It is certainly true that many of the characteristics of our nation that have made the United States such a leader in innovation and economic renewal remain strong: a dynamic free society that is continually renewed through immigration; the quality of American intellectual property protection and the most flexible labor laws in the world, the best regulated and most efficient capital markets in the world for taking new ideas and turning them into products and services, open trade and open borders (at least relative to most other nations), and universities and research laboratories that are the envy of the world. If all of this remained in place, strong and healthy, the United States would continue to remain prosperous and secure, even in the face of an intensely competitive global knowledge economy. We would continue to churn out the knowledge workers, the ideas and innovation, and the products and services (even if partially outsourced) that would dominate the global marketplace.

Yet today more than ever the nation's prosperity and security depend on its innovative spirit, technological strength, and entrepreneurial skills. The United States will need robust capabilities in both fundamental and applied engineering research to address future economic, environmental, health, and security challenges. To capitalize on opportunities created by scientific discoveries, the nation must have engineers who can invent new products and services, create new industries and jobs, and generate new wealth.

Broadly speaking, the most daunting challenges facing the nation–global competitiveness, health care delivery to an aging population, energy production and distribution, environmental remediation and sustainability, national and homeland security, communications, and transportation–all pose complex systems challenges that require both new knowledge and new skills for engineering practice.

Of course it was a very similar environmental scan, articulated through narrative scenarios, that the National Academy of Engineering study *The Engineer of 2020* used to illustrate the various challenges to engineering (Clough, 2004). In fact, a century earlier Abraham Flexner utilized a very similar process to build a compelling case for the radical transformation of medical education and practice. Hence the question we must first pose today is similar to that Flexner posed for medicine a century ago: "Are today's engineers–their profession, their tools, and their education–adequate to address either today's needs or tomorrow's grand challenges?"



The Grand Challenges of 21st Century Engineering

Chapter 3

Engineering Today: A Resource Map

A key step in any roadmapping process is an accurate assessment of the current situation, since we need to first pin down the starting point before developing a map to a final destination. To this end we begin by considering engineering today from several perspectives: the practice of engineering, the engineering knowledge base, the skills and competencies of today's engineers, and the current state of engineering education.

Of course these are moving targets. Engineering practice and its supporting knowledge base are changing very rapidly. Although the current skills, competencies, education, and training of engineers are changing somewhat more slowly, the changing nature of engineering students–more diverse, more tolerant of change, more comfortable with cyberinfrastructure (e.g., "born digital")–and ongoing efforts to improve engineering education are driving change in these areas as well. However we will also find each of these characteristics fall considerably short of what will be needed by our society in the years ahead, creating a considerable gap between engineering as it is today and what it must become tomorrow.

Engineering Practice

Some Definitions

Perhaps the best place to begin is to define the term engineering. The formal definition provided by many professional societies goes something as follows:

> Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, natural and man-made materials and the forces of nature for the benefit of humankind.
>
> Engineers are persons who, by reason of their special knowledge and use of mathematical, physical, and engineering sciences and the principles and methods of engineering analysis and design, acquired by education and experience, are qualified to practice engineering.

However there are numerous other less formal definitions that better capture the nature of engineering. William Wulf, former president of the National Academy of Engineering, suggests that engineering is "design under constraint", noting Theodore Von Karmen's contrast between science, which aims to understand nature, and engineering, which is about creating what has never been (Wulf, 2003). Joseph Bordogna, former Deputy Director of the National Science Foundation, prefers Fumio Kodama's definition: "Engineering is the integration of all knowledge to some purpose" (Bordogna, 1993).

In a more general sense, engineers are problem solvers, creators of ideas and concepts, builders of devices, structures, and systems. They apply their knowledge of science and technology to meet the needs of society, to solve its problems, and to pave the way for its future progress. The intellectual activities of engineering are heavily based on synthesis, design, and innovation through the integration of knowledge.

But engineering is more than an intellectual discipline like physics or chemistry. It is also a vocation characterized by great diversity. For example, most engineering students would likely describe their career interests in terms of their engineering major, e.g., civil engineering, mechanical engineering, electrical engineering, industrial engineering, or one of a growing array of engineering specialties (e.g., aerospace, agricultural, architectural, atmospheric, automotive, biomedical, computer, environmental, manufacturing, materials, metallurgical, mining, nuclear, petroleum, sanitary, system, and transportation). Yet as graduates move into engineering practice, they are more likely to define their occupation in terms of specific roles and activities, e.g., product design, manufacturing engineering, systems engineering, research and development, construction engineering, project management, operations engineering, testing, sales and marketing, management, consulting, and teaching (academe).

Beyond its character as a discipline or occupation, engineering is also a learned profession, similar to law and medicine. As such, it meets the tests of such professions:

* It requires certain skills, which can only be acquired through formal education and experience.
* It is governed by a code of ethics.
* Engineers must pass licensing examinations to call themselves "professional engineers" in some fields.
* It is shaped by professional organizations such as the National Society of Professional Engineers and the National Academy of Engineering.

Yet these characteristics of engineering as a discipline, a major, an occupation, or a profession are increasingly out-of-date with the changing nature of engineering practice. While one traditionally thinks of engineering as focused at the macroscopic level on devices or systems, many engineers work at the microscopic level (e.g., micro-electromechanical systems or MEMS or, more recently, nanotechnology and quantum technology) while others function at the mega levels (civil infrastructure, transportation systems, cities) or even "meta" level (knowledge services such as global supply chain management or systems integration). The shifting nature of national priorities from defense to economic competitiveness, the impact of rapidly evolving information technology, the use of new materials and biological processes–all have had deep impact on engineering practice. So too has the emergence of a global economy that demands engineering within a broader cultural and geopolitical context. All suggest that tomorrow's engineers will spend most of their careers coping with challenges and opportunities vastly different from those most currently practicing engineers–or currently teaching faculty–have experienced.

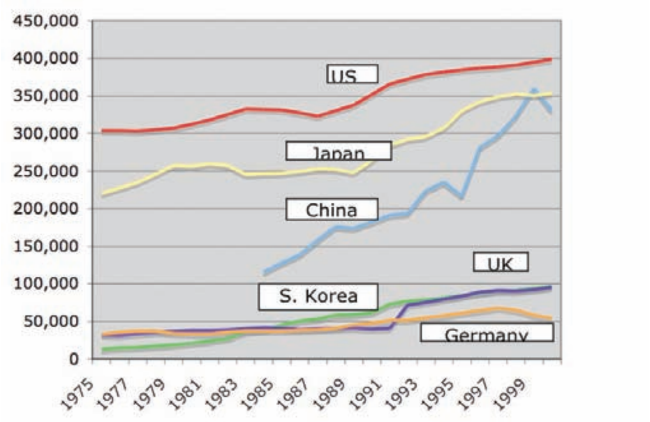
The Challenges

In recent years there has been a growing concern about the supply of American engineers (Augustine, 2005). To be sure, there are several warning signs. While there is always an ebb and flow in college enrollment in various disciplines, there has been a noticeable decline in student interest in careers in science and engineering over the past two decades. In the United States, baccalaureate engineering graduates dropped from 85,000 per year in 1985 to 61,000 in the mid-1990s, recovering only recently to 74,186 (Gibbons, 2007). However there are new warning signs as undergraduate enrollments have now leveled off and begun to decline over the past three years from a peak of 373,000 students, with only 55% of those entering engineering programs eventually completing their degrees.

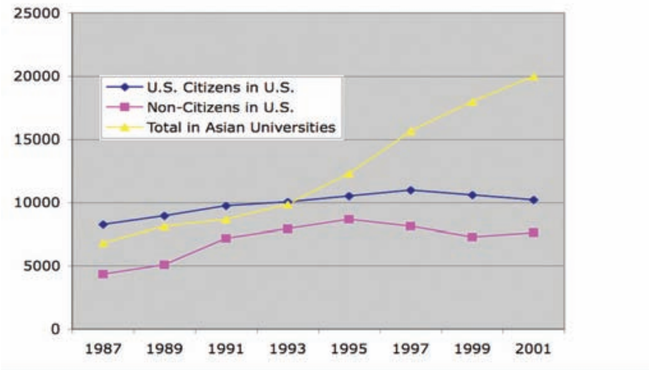
There are concerns of a different nature at the graduate level. Although American universities graduated 39,015 masters degree students and 8,351 PhDs in 2006, masters degree enrollments peaked at 91,000 in 2003 and have declined to 83,000 in 2006, while PhD enrollments have leveled off at 57,000. Of more concern is the fact that today 40% of the engineering masters degree recipients and 61% of the new engineering PhDs in the United States are foreign nationals, raising the concern that students who are U.S. citizens show declining interest in graduate studies in engineering (a situation we will return to discuss in more detail later in this section).

Although recent estimates of engineering graduates in rapidly growing economies such as China and India are somewhat suspect, ranging from 350,000 to as much as 517,000 for China and as high as 450,000 for India and likely including many lower-level technical skills, the growth curve is of more concern, roughly doubling over the past five years (Wadhwa, 2007). To put this in context, the United States currently accounts for less than 8% of the new engineers produced globally each year. In the United States, only 4.5% of college students major in engineering; in Europe, this rises to 12%; but in Asia, over 40% of college students major in engineering (Wulf, 2003). China's production of engineering PhDs is already up to 8,000 per year and doubling every 5 years (NSB, 2006) and will soon pass the United States.

As Friedman observes, India was lucky, in a way,



The growth of science and engineering first degrees



The rapid increase in science and engineering doctorates already exceeds the U.S. and Europe.

since it was already well positioned by major investments two decades ago to build a chain of Indian Institutes of Technology–their version of MIT–that now produce the talented scientists, engineers, and managers that fuel their rapidly evolving knowledge economy. China's leaders, while starting only a decade ago, are just as determined and even more focused to train young people in the science and technology skills necessary to produce world-class scientists and engineers. Perhaps because Chinese leaders have backgrounds and experience in science and engineering themselves (unlike American leaders, most of whom have law and business backgrounds), they also place a far higher priority on engineering research and education (Friedman, 2005).

In the past the United States has compensated for this shortfall in scientists and engineers to a considerable degree by attracting talented students from around the world. But post 9-11 constraints on immigration policies and an increasingly cynical view of American foreign policy have cut deeply into the flow of international students into our universities and industry (Augustine, 2005). This situation is compounded by our nation's inability to address the relatively low participation of women and underrepresented ethnic minorities in science and engineering. Today nearly two-thirds of today's engineering students who are U.S. citizens are white males, at a time when the largest growth in our workforce over the next decade will come from women and underrepresented minorities. More specifically, while women account for 47% of the American workforce, they represent only 9% of engineers. Furthermore, women students comprise 56% of college enrollments and receive 60% of college degrees, yet account for only 20% of engineering degrees and 11% of engineering faculty. The situation is even more alarming for underrepresented minorities, with African American and Hispanic American engineering enrollments remaining below 5% and 6%, respectively, and engineering faculty participation at 2.4%, although comprising 13.4% and 14.5% of the American population in 2005.

As presidential science advisor John Marburger concluded: "The future strength of the U.S. science and engineering workforce is imperiled by two long-term trends: First the global competition for science and engineering talent is intensifying, such that the U.S. may not be able to rely on the international science and engineering labor market for its unmet skill needs. Second, the number of native-born science and engineering graduates entering the workforce is likely to decline unless the nation intervenes to improve success in educating S&E students from all demographic groups, especially those that have been underrepresented in science and engineering careers" (Marburger, 2004).

Of course, some would argue that the marketplace itself should determine the number of engineering graduates, and that the erosion of student interest in these fields may reflect the realities of both future job opportunities and future need. It is also the case that recent studies of salary and employment data fail to find indication of a shortage of engineers in the United States (Wadhwa, 2007). Most companies indicate that they are able to fill 80% of engineering jobs within four months. Furthermore, many companies actually limit the head count of U.S. graduates in preference to off shoring any growth in domestic engineering capacity, motivated both by lower costs and greater flexibility (Lynn, 2006). However, as Charles Vest argues, no one can look at today's labor market for engineers and predict what students will experience in 30 years. "A generation ago computers and communication technology were esoteric fields with relatively small job demand. Yet today virtually every industry is at heart about information technology and communications in one way or another, which will only intensify as the United States completes its shift from a manufacturing to a knowledge services economy. Virtually every industry is already dependent upon sophisticated logistics, global supply chains, and an integrated global economy. The success of our economy–not to mention our democracy–will require more people with technical knowledge and skills, not less." As Vest puts the question before us: "The world is changing remarkably fast, and leadership in science and engineering will drive it. Where will this leadership come from? China? India? The United States? The choice is ours to make" (Vest, 2005).

Given the recent trends in business, it is perfectly understandable why engineering enrollments have declined in this country over the past two decades. Students are very market sensitive. As Norm Augustine suggests, "All the signals are wrong to attract kids into engineering these days" (Augustine, 2005). Imagine the impact on student perspectives of engineering careers when they read a recent headline in a leading Detroit newspaper: "GM Fires 500 Engineers", which quoted a company spokesman's rationalization: "It is all about aligning the workforce with our business needs" (Detroit News, 2006). Students are very sensitive to such actions, and although many have the aptitude and interests to major in engineering, they view it as a dead-end profession, subject to this commodity treatment and associated with too many risks, in contrast to broader professions such as law, medicine, and business. The same ambiguity characterizes public perception, with images of large rooms of rows upon rows of engineers working on narrow elements of large systems such as airplanes or automobile platforms until the next round of layoffs. Particularly during these days of economic stress, these images are more prevalent than those of master engineers creating the highly innovative products and systems that address critical human needs while adding economic value.

Ironically, even as the need for engineers and engineering services continues to intensify in this country, the global marketplace is drawing many engineering activities offshore. While initially this was for more routine engineering services, primarily driven by the wage differential between the U.S. and off-shore providers (particularly in India, China, and Eastern Europe), today we find the off-shoring of engineering services is rising rapidly up the value chain to include sophisticated functions such as product design, research, and development.

Politicians usually rationalize the current phenomenon of off-shoring, the increasing tendency for companies to export knowledge-intensive service jobs like engineering and information services to developing nations like India, China, and Eastern Europe, by suggesting that it is the low wage rates that shift jobs overseas (typically 20 cents on the dollar in India, for example). But increasingly companies are going off shore because they sometimes find higher quality engineering services in high-tech areas like computer software development. They also seek to use off shoring to penetrate new markets. Why? Many of the nations benefiting from the global sourcing of engineering benefit from cultures with strong pre-college education in science and mathematics, a stronger interest of college students in majors in science, mathematics, and engineering, which are seen as the route to leadership roles in business or government, and large populations from which to draw top talent. Furthermore many of these nations are making massive investments in higher education, particularly in technology-intensive areas like engineering and computer science, to create a more highly skilled workforce at a time when our nation and states have been throttling back such investments.

Yet despite the advantages of off shoring engineering services–cost savings, 24/7 development cycles, access to new markets–there are also concerns of a bandwagon psychology in which companies, driven by the short-term focus of investors, are moving too many activities off shore, losing their domestic core competence in key technological areas. To be sure today's globally integrated companies no longer embrace the linear, vertical process for value creation characteristic of 20th century industry–from R&D to product design to manufacturing to sales to distribution. Today's global supply chain depends on a horizontal process, in which each activity is allocated to wherever it can be performed at highest quality and acceptable costs, and then integrated back together again to produce products, services, and values. A company can now procure the best product or service or capacity or competency from anywhere in the world because of the new knowledge infrastructure. Such global sourcing changes quite dramatically the incentives for sustaining domestic capacity in many areas including engineering.


Shanghai's high-tech Pudong area


Bangalore's rapid growth of high-tech engineering

Yet many worry that as near-term cost pressures drive companies to outsource and off shore activities of increasing complexity and value, the United States is sliding down a slippery slope of disinvestment in and weakening of domestic innovation systems (Lynn, 2006). This applies particularly to American engineering. To be sure, there remains great uncertainly about the number of U.S. engineers required in the future, with not only the global sourcing of more routine engineering services to a growing engineering population overseas, but as well the declining interests of the best students in engineering careers and particularly advanced studies in engineering and our inability to build a domestic engineering workforce reflecting the growing diversity of the American population.

It is no longer clear that the investment of time and money in an engineering education–particularly at the graduate level–is cost-justified in view of the current compensation experienced by the engineering profession and the risk associated with off shoring. Today many companies view engineers and engineering services as consumable commodities, necessary for the moment to be sure, but easily discarded once their value has been exhausted and eventually replaceable through down-sizing or off-shoring as costs or technical competency dictate. Of course the most successful technology-based industries employ engineers as highly skilled professionals to design critical products and systems or provide the innovation that drives the knowledge economy. Some companies understand the importance of innovative engineering and provide their engineers with opportunities for innovation and risk-taking. Yet many other companies simply do not view engineers as valuable human resources, deserving of future investment in education and training to maintain their relevance and value throughout their careers–similar to their investments in executive business education. Instead they respond to short-term economic priorities through massive layoffs or off-shoring engineering services. Succumbing to the pressures of impatient shareholders and the threat of litigation, they discourage risk-taking and bold innovation on the part of engineers and instead tightly constrain engineering activities.

Of comparable concern are the very narrow pigeon holes that industry and government employers frequently force engineers into, stunting their intellectual growth and adaptability. It is almost as if many large companies actually prefer "grunt engineers" they can utilize as disposable commodities. Here it is interesting to contrast the utilization of engineers in traditional

American manufacturing companies striving to retain market share in increasingly competitive markets (such as the automobile industry) with those in high-tech companies primarily dependent upon radical innovation to develop new products and perhaps entirely new industries (e.g., Google).

The inability of engineering to attract the best and brightest, as it does in most other nations, is due in part to the way engineering is perceived by prospective students, teachers, parents, and society more broadly (NSB, 2007). Society at large simply does not have an accurate perception of the nature of engineering. While the public associates engineers with economic growth and national defense, they fail to recognize the role of engineering in improving health, the quality of life, and the environment. They are relegated to the role of technicians rather than given the respect of other learned professions such as medicine and law. In sharp contrast to most other nations, one rarely finds engineers in leadership roles in business or government and hence they have relatively inadequate impact on the key strategic issues facing our nation and world.

To a large extent, this lack of public prestige and influence is self-induced, through the excessively narrow education provided to most engineering students, the all-too-frequent tolerance of narrow technical roles in their careers, and the inability of engineering societies to overcome the cacophony of disparate interests and create a unified voice promoting the profession similar to those mounted by organizations such as the AMA and ABA for medicine and law. In view of these shortcomings, today's best students appear to be making quite rational decisions in choosing other careers with apparently more influence, reward, and stability.

Clearly, one of the great challenges to American engineers in the hypercompetitive knowledge economy is to provide several times the value added of foreign competitors, since that is the wage differential they must face in competing with the global sourcing of engineering services. But it is also one of the great challenges to our nation to realize both in public policy and business practices that in a global, knowledge-driven economy, the keys to economic success are a well-educated technological workforce, technological capability, capital investment, and entrepreneurial zeal–a message well-understood by other developed and developing nations alike throughout the world that are investing in the necessary human capital and knowledge infrastructure. These are not simply commodities that can be conveniently outsourced or off shored to gain near-term cost savings. They are, in fact, one of our great national assets and a key to our future, assets that merit the highest priority for further investments from both government and industry.

The Knowledge Base for Engineering

Key to the ability of engineers to develop the products, systems, and services that are essential to national security, public health, and the economic competitiveness of the nation's business and industry is the knowledge base created by engineering research. The new knowledge generated through research drives technological innovation–the transformation of knowledge into products, processes, and services–which, in turn, is critical to competitiveness, long-term productivity growth, and the generation of wealth.

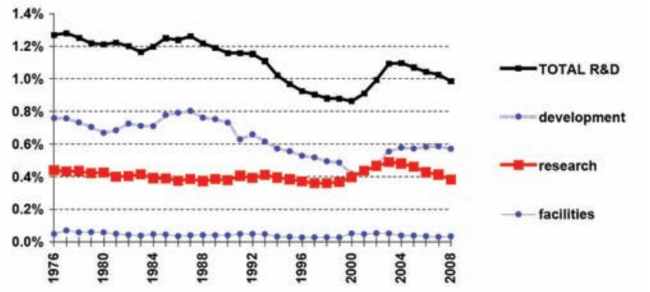
The American system of research and advanced education, relying on a partnership between universities, industry, and government, has been highly successful over the past half-century in addressing priorities such as national defense and health care. Historically, engineering research has yielded knowledge essential to translating scientific advances into technologies that affect everyday life. The products, systems, and services developed by engineers are essential to national security, public health, and the economic competitiveness of U.S. business and industry. Engineering research has resulted in the creation of technologies that have increased life expectancy, driven economic growth, and improved America's standard of living.

As a superpower with the largest and richest market in the world, the United States has consistently set the standard for technological advances, both creating innovations and absorbing innovations created elsewhere. The astounding technological achievements of the twentieth century would not have been possible without engineering, specifically engineering research, which leads to the conversion of scientific discoveries into functional, marketable, profitable products and services. Engineers take new and existing knowledge and make it useful, typically generating new knowledge in the process. Without engineering research, innovation, especially groundbreaking innovation that creates new industries and transforms old ones, simply does not happen. The United States will need robust capabilities in both fundamental and applied engineering research to address future economic, environmental, health, and security challenges. Applying technological advances to achieve global sustainability will require significant investment, creativity, and technical competence. Advances in nanotechnologies, biotechnologies, new materials, and information and communication technologies may lead to solutions to difficult environmental, health, and security challenges, but their development and application will require significant investments of money and effort in engineering research. Yet current patterns of America's investments in engineering research funding do not bode well for future U.S. capabilities in these critical fields. Among the more disturbing statistics are the following (Duderstadt, 2005):

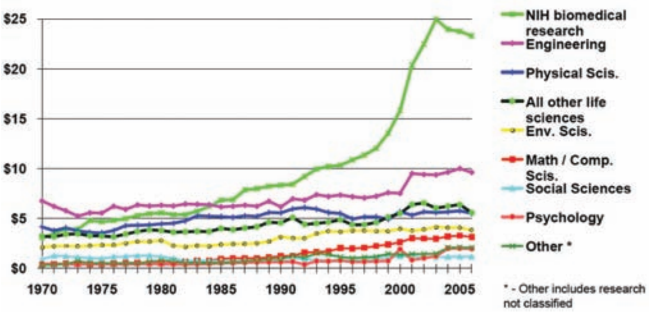
- During the last 40 years, federal support of R&D in the United States has dropped from roughly 2% to slightly less than 1% of GDP. Furthermore, since almost 60% of federal R&D is defense-related, today the federal government's support of non-defense research has declined to less than 0.3% of GDP, well below the comparable investment of many other nations. While industrial R&D has grown over this same period from 40% to now over 70% of national R&D, the bulk of the growth has been associated with highly applied product development (including clinical trials of the pharmaceutical industry).

- During the last 30 years, the federal investment in research in the physical sciences and engineering has been nearly stagnant, having grown less than 25% in constant dollars. The corresponding investment in life science research has grown over 300%. Specifically, in 1970, physical science, engineering and life science each were funded at an annual level of approximately $5 billion in 2002 dollars. Today, physical science and engineering research are funded at approximately $5 billion and $7.5 billion, respectively. The current funding for life science is about $22 billion. In fact, essentially all of the growth in the federal R&D budget during the 1990s was due to the doubling of the NIH budget. Today, what little growth does remain is primarily through highly applied development activities in defense and homeland security (Vest, 2003).

- Because of competitive pressures, much of U.S. industry has downsized its large, corporate R&D laboratories in physical sciences and engineering and reduced its already small share of funding for long-term, fundamental research. The decline in long-term industrial research is exacerbating the consequences of the current decline in federal R&D funding for long-term fundamental research in engineering and physical sciences.



Trends in federal R&D as % of GDP, FY 1976-2008
(American Association for the Advancement of Science)



Trends in federal R&D by discipline, FY 1976-2008
(American Association for the Advancement of Science)

William Broad summed up these concerns in a recent New York Times op-ed: "The US has started to lose its worldwide dominance in critical areas of science and innovation. The U.S. share of industrial patents has fallen steadily over the decades and now stands at 52%. The decline in *Physical Review* papers is down to 29%, compared to 61% in 1983. Europe and Asia are making large investments in physical science and engineering research, while the U.S. has been obsessed with biomedical research to the neglect of other areas of science" (Broad, 2005).

Engineering Education and Training

What key skills and competencies are needed by today's engineers? Certainly sufficient mastery of the basic tools of science and mathematics to address technological problems. In fact, ABET (once an abbreviation for the Accreditation Board for Engineering and Technology but now only an acronym for the accreditation agency) sets the following objective for engineering degree programs:

> "Students should gain an ability to apply knowledge of mathematics, science, and engineering; to design and conduct experiments as well as to analyze and interpret data; to function on multidisciplinary teams; and to communicate effectively."

More specifically, today's ABET's Engineering Criteria includes, among other elements, requirements which stress the importance of an engineering graduate's ability to:

* Apply knowledge of science, mathematics, and engineering
* Design and conduct experiments and analyze data
* Design a system, component, or process to meet desired needs
* Function on multi-disciplinary teams
* Identify, formulate, and solve engineering problems
* Understand professional and ethical responsibility
* Communicate effectively
* Understand the impact of engineering solutions in a global/social context
* Engage in life-long learning
* Exhibit a knowledge of contemporary issues
* Use the techniques, skills, and modern engineering tools necessary for engineering practice.

Yet, the recruiters that companies send to the campuses tend to stress narrow technical skills and achievement over such broader abilities–e.g., C++ programming, computer-aided engineering, and, oh yes, at least a 3.5 GPA. This despite the claim by their executive leadership that what they really value are broader abilities such as communication skills, a commitment to lifelong learning, an appreciation for cultural diversity, and the ability to drive change. Certainly the mismatch between the broader skills that industry leaders claim they need and the very narrow criteria imposed by their campus recruiters is driven in part by the marching orders and incentives given corporate human resources staff to deliver engineering graduates capable of immediate impact. But these broader abilities, more characteristic of a broad liberal education, while certainly essential for the executive suite, are also not usually the attributes valued by managers seeking engineering graduates capable of making immediate contributions. Hence there appears to be a mismatch between the goals of technical depth demanded by recruiters and line managers and the broader intellectual skills for engineering graduates sought by corporate leadership.

But there is also a disconnect between *engineering education* today, largely conducted much as it has been for decades; *engineering knowledge*, increasingly driven by the complexity of fields such as biology and systems science rather than the reductionism of chemistry and physics; and *engineering practice*, rapidly changing to accommodate the imperatives of phenomena such as global sourcing and a services economy. Hence it is natural to ask whether engineering education as provided today is adequate to prepare engineering students for a world of practice and citizenship that is quite different from the one that we have known.

Study after study has suggested that profound transformation is necessary in engineering education to prepare engineers for a rapidly changing world. A recent workshop hosted by the National Science Board summarized the challenges to engineering education quite well:

> "Markets have become more international and in some countries, where excellent engineers are available at one fifth the cost of a U.S. educated engineer. Supply chains are increasingly integrated across companies and nations, requiring a different set of communication and cultural skills. The speed of change means than any set of technical skills may quickly become obsolete. To prosper, U.S. engineers need to provide high value and excel at high-level design, systems integration, innovation, and leadership, developing skill sets not easily replicated by low-wage overseas engineers. In addition to analytic skills, which are well provided by the current education system, companies want engineers with passion, some systems thinking, an ability to innovate, an ability to work in multicultural environments, an ability to understand the business context of engineering, interdisciplinary skills, communication skills, leadership skills, an ability to adapt to changing conditions, and an eagerness for lifelong learning. This is a different kind of engineer from the norm that is being produced now. The current standard engineering education appears neither to provide the full set of skills that engineers are likely to need in the future nor attract the right numbers or types of people to engineering. It is time for leadership in U.S. engineering education since one of the economic battlefields of the future will be over the global redistribution of engineering talent." (NSB, 2007)

Specific Concerns about Engineering Education

<u>The Curriculum</u>: Several years ago in preparing for the centennial celebration of one of Michigan's engineering departments, a search through the university archives revealed that the engineering curricula offered a century ago was remarkably similar to today's programs. In 1898 we required students to take 130 credit hours of courses in mathematics, physics, and chemistry with a concentration in applied courses in areas such as mechanical, chemical, or electrical engineering. If one swaps the 19th-century requirement for surveying and mechanical drawing for today's courses on computers, the course titles and requirements of two curricula are almost identical–with one notable exception. Last century's curriculum allowed more opportunity for courses in the arts and humanities. Today much of this flexibility has been squeezed out by technical content overload and accreditation requirements.

Of course, the actual content of the courses themselves has changed considerably over the past century. Despite similar course titles, until WWII the engineering curriculum at most universities was quite practical, emphasizing engineering design and practical skills such as surveying and drafting and taught by faculty with experience and ongoing activity in engineering practice. However, following the great impact of science on technology during the war years, engineering education shifted curricular emphasis from practical skills to a strong foundation in science, mathematics, and the engineering sciences (e.g., thermodynamics, materials, solid and fluid mechanics). Engineering schools reflected this strong scientific nature by recruiting applied scientists with strong interests in basic research. As a result, most undergraduate engineering programs today are, in reality, programs in applied science, although they pay sufficient lip service to design, technical writing, and professional ethics to pass the muster of ABET accreditation.

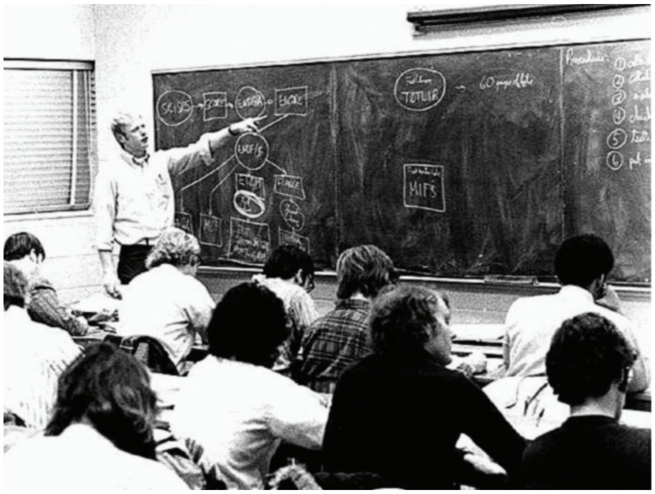
Clearly the engineering curriculum needs a major overhaul. To some degree, this will require modernizing the approaches to science and mathematics instruction, e.g., recognizing that discrete rather than continuous mathematics is the foundation of the digital age, that biology is rapidly becoming as important as physics and chemistry, and new scientific concepts and tools have made obsolete much of the traditional curriculum. Beyond these technical changes, the new engineering curriculum must reflect a broad range of concerns, including environmental, political, social, international, and legal and ethical ramifications of decisions. Although the scientific and technical courses would continue to be the core of an engineering education, the economic, political, social, and environmental context of engineering practice needs to be explicitly addressed.

<u>Depth vs. breadth</u>: Part of the problem is the way that the intellectual activities of the contemporary university are partitioned into increasingly specialized and fragmented disciplines. Perhaps reflecting the startling success of science in the 20th century, most disciplines

are reductionist in nature, focusing teaching and scholarship on increasingly narrow and specialized topics. While this produces graduates of great technical depth, it is at a certain sacrifice of a broader, more integrated education. This is particularly true in science-based disciplines such as engineering. The old saying is not far off the mark, "A Harvard graduate knows absolutely nothing about absolutely everything. An MIT graduate knows absolutely everything about absolutely nothing!"

Recalling the definition of Kodama (and Bordogna), the essence of engineering practice is the process of integrating knowledge to some purpose. Unlike the specialized analysis characterizing scientific inquiry, engineers are expected to be society's master integrators, working across many different disciplines and fields, making the connections that will lead to deeper insights and more creative solutions, and getting things done. Thus, engineering education is under increasing pressure to shift away from specialization to a more comprehensive curriculum and broader educational experience in which topics are better connected and integrated.

We must question the value of narrow specialization at a time when engineering practice and engineering systems are becoming large and more complex, and involving components and processes from widely dispersed fields. Many believe that the most important intellectual problems of our time will not be addressed through disciplinary specialization but rather through approaches capable of integrating many different areas of knowledge–through "big think" rather than "small think".


"The ubiquitous leccture is the bane of student learning!"

Pedagogical style: Unfortunately, it is increasingly clear that the science-dominated engineering curriculum has also led to an over-dependence on the pedagogical methods used in science courses–large lecture courses, rigidly defined problem assignments, highly structured laboratory courses–all of questionable utility for teaching the most important technical skills of engineering: the integration of knowledge, synthesis, design, and innovation. As a recent NSF workshop put it: "The ubiquitous lecture is the bane of true learning, especially in observation-based, hands-on fields such as engineering. The lecture-dominated system encourages a passive learning environment, a highly compartmentalized (lecture-sized) curriculum, and worst of all, instills neither the motivation nor the skills for life-long learning. Beyond that, engineering education should move away from the current dominance of classroom-based pedagogy to more active learning approaches that engage problem-solving skills and team building". Bordogna quotes the old Chinese proverb: "I hear and I forget. I see and I remember. I do and I understand" (Bordogna, 1993). Today's engineering students have all too little opportunity for discovery-oriented, interactive, and collaborative learning experiences.

The Faculty: Engineering faculties are quite different from the faculties of most professional schools since they generally have little experience or ongoing activity in professional practice. The strong research focus of many engineering schools has led to a cadre of strong engineering scientists, quite capable of generating new knowledge but relatively inexperienced in applying this knowledge in professional practice. Furthermore, engineering faculty members are judged and rewarded by criteria appropriate to science faculty, e.g., publication and grantsmanship. Indeed, professional practice is not only absent in promotion and reward criteria, but it is frequently discouraged. The faculty reward system recognizes teaching, research, and service to the profession, but it gives little recognition for developing a marketable product or process or designing an enduring piece of the nation's infrastructure. It would be hard to imagine a medical school faculty comprised only of biological scientists rather than practicing physicians or music school faculty comprised only of musicologists rather than performing artists. Yet such detachment from professional practice and experience is the norm in engineering education.

Overload: As the knowledge base in most engineering fields continues to increase exponentially, the engineering curriculum has become bloated with technical material, much of it obsolete by the time our students graduate. Even with this increasing technical content, most engineers will spend many months if not years in further workplace training before they are ready for practice. MIT professor Rosalind Williams suggests "Engineering has evolved into an open-ended 'profession of everything' where technology shades into science, art, and management, with no strong institutions to define an overarching mission. All the forces that pull engineering in different directions–toward science, toward the market, toward design, toward systems, toward socialization–add logs to the curricular logjam. Few students will want to commit themselves to an educational track that is nearly all-consuming" (Williams, 2003).

An Obstacle Course: There are other serious flaws in the current approach to engineering education. The traditional curriculum is highly sequential, built upon a pyramid of prerequisites that can quickly discourage or wash out students who fall off pace. It is plagued by intense specialization within the majors that forces students to make academic decisions early, with little recourse should they change their minds later. The ABET accreditation model requires at least 20 courses (60 credit hours) for an engineering major–almost twice that for the typical liberal arts concentration–hence restricting even further the ability of students to explore through elective courses other academic interests and giving many a feeling of isolation from the rest of the university because of the heavy workload and narrow focus of the engineering curriculum. The culture of engineering education is similar to that of the sciences, essentially functioning as a filter to separate out students experiencing academic difficulties or shifting interest–which it does remarkably and tragically well, yielding a 45% attrition rate characterized by little difference in academic abilities between those who succeed and those who withdraw from engineering programs.

There is little doubt that the current sequential approach to engineering education, in which the early years are dominated by science and mathematics courses with engineering content deferred to the upper-class years, discourages many capable students. Compounding this is the fragmentation of the current curriculum, consisting of highly specialized and generally unconnected and uncoordinated courses, whose relationship to one another and to engineering education is rarely explained. Students have little opportunity to find out what engineering is all about until late in their undergraduate studies. There is little effort to relate the curriculum to career and professional development opportunities during the early years of an engineering education. It is not unusual to find students wandering into counseling and placement offices in their senior year, still trying to find out what they are majoring in and what they can do with an engineering degree.

What Is Missing: While engineers are expected to be well grounded in the fundamentals of science and mathematics, they are also increasingly expected to acquire skills in communication, teamwork, adaptation to change, and social and environmental consciousness. A survey of CEOs conducted in the 1990s by the Business Higher Education Forum found that the qualities valued most highly in graduates beyond technical knowledge or skills were:

* The ability to communicate well
* A commitment to lifelong learning
* The ability to adapt to an increasingly diverse world
* The ability not only to adapt to change but to actually drive change

Yet the never-ending quest to include the new technical knowledge in many fields, while retaining as well much of the old, has squeezed out other important curriculum content in areas that would support these broader abilities. For example, at the University of Michigan, the humanities and social sciences component of the undergraduate curriculum has dropped to less than twenty credit hours, with as few as two credit hours of free electives in some engineering majors. In fact, one might even suggest that we have regressed over the past century, overloading our current curriculum with highly specific technical courses at the expense of broader educational opportunities for our students.

It is clear from this perspective that engineering education simply has not kept pace with the changing environment characterizing engineering practice. It is only a slight exaggeration to say that our students are currently being prepared to practice engineering in a world that existed when we, as their faculty, were trained a generation or two ago. Most are ill prepared for today's innovation-driven global marketplace.

<u>The Adequacy of an Undergraduate Degree</u>: As the growth of technical knowledge accelerates and the undergraduate engineering curriculum becomes more bloated and strained with new technical content, it becomes ever more apparent that it is simply no longer possible to regard the baccalaureate degree as sufficient for professional practice. Indeed, most undergraduate engineering programs now require 4.5 to 5 years to complete because of their pyramid of required prerequisites.

Today, engineering is one of the very few professions that requires only an undergraduate degree for professional status. Most other knowledge-intensive professions such as law, medicine, and even business administration utilize graduate programs built upon a diversity of undergraduate majors. In fact, today most undergraduates selecting majors in the liberal arts understand well that the baccalaureate degree is no longer sufficient for most careers and have already committed themselves to further graduate or professional study. Yet a baccalaureate degree in engineering is still portrayed as a "terminal degree"–a frightening term in itself!

The inadequacy of the baccalaureate degree for professional practice is becoming apparent to employers as well. There is an increasing trend to hire graduates at the master's or even Ph.D. level for technical work, while relying upon baccalaureate engineering graduates for supporting services such as sales and technical support.

We may simply have to accept the fact that it is no longer possible (if it ever was) for engineering students to learn all they need to know during their undergraduate studies. There is a growing sense that eventually engineering education will evolve into a paradigm similar to other learned professions such as law and medicine, with an undergraduate pre-engineering major followed by a practice-oriented Master of Engineering or perhaps eventually a Doctor of Engineering as the only accredited engineering degrees for professional practice. This would then be followed by a well-organized and career-long approach to continuing engineering education.

Of course, there have been many groups advocating that the first professional degree (e.g., the customary degree required for the practice of engineering) be elevated to the graduate level, including the National Academy of Engineering and the American Society of Civil Engineers, the engineering discipline most concerned with professional licensure (Kam, 2007). Furthermore, in Europe the Bologna Process aimed at unifying and standardizing higher education has called for engineering programs to accept a 3+2+2 program, in which the three-year undergraduate program would provide only a pre-engineering degree, while the first professional degree would be a two-year Master of Science, perhaps followed by some students with a doctorate requiring two more years and a dissertation. (Here we should also note that Europe adds an additional year to secondary education with considerably more rigor in science and mathematics.) It should also be noted that the Bologna 3+2+2 model is also being accepted as the standard by several Asian nations.

Yet this step to enhance the capability and prestige of engineering continues to be strongly resisted in the United States. As Schowalter notes, our engineering schools are simply not in the business of providing "pre-professional" education, despite the efforts of generations of educators to do so (Schowalter, 2003). Graduates of baccalaureate engineering programs are still hired as engineers with the expectation they will make almost immediate contributions without further training. Little wonder that the status of engineers lags behind those of other professionals with more advanced education.

<u>Lifelong Learning</u>: Neither undergraduate nor graduate engineering programs can ignore the fact that they

simply cannot provide all the necessary knowledge for graduates to remain competitive throughout their careers. Acquiring the array of technical knowledge and experience is a lifetime goal and requires a personal and institutional commitment to continual learning. An undergraduate engineering education should be viewed as only the initial launch for a career, designed to place the student in a lifetime orbit of learning (Schmitt, 1992). The primary aim should be instead to instill a strong knowledge of how to learn, while still producing competent engineers who are well grounded in engineering science and mathematics and have an understanding of design in the social context. As Peter Drucker puts it, "We are redefining what it means to be an educated person. Traditionally an educated person was someone who had a prescribed stock of formal knowledge. Increasingly an educated person will be someone who has learned how to learn and who continues to learn throughout his or her lifetime" (Drucker, 1999). Engineering schools must educate students for a lifetime of learning rather than just for their initial jobs.

A Broader Concern: In today's world of change, most graduates will find themselves frequently changing not only jobs, but entire careers several times during their lives. Even today we already find that only about fifty percent of engineering graduates will enter technical careers, and after five years, about half of these will have moved into other areas such as management, sales, or policy. Put another way, many engineering graduates of today will find themselves in engineering practice for only a relatively short period, if at all. The increasing importance of technology to our world has made some technical aspects of an engineering program an excellent preparation for many other careers and professions: business, law, medicine, consulting, and government service, to name only a few. This poses a particular challenge to engineering educators, since they still focus primarily on educating students for the engineering profession.

Roland Schmitt has suggested that today's challenge is to enlarge the very concept of the engineer to cover a wider range of human activities than ever before. Engineering educators must begin by realizing that it is their duty to educate the leaders of our society as well as to educate the professional engineer. He suggests we develop and promote a new kind of engineering education as a form of liberal education for the 21st century. This will require new objectives and new curricula, some radically different from those of today because of a radically different objective: educating not simply professional engineers but a new breed of graduates with an engineering-based, liberal education (Schmitt, 1992).

Inadequate Diversity of Engineering Education: We noted earlier in this chapter the degree to which the nation's engineering education programs fall far short of reflecting the ethnic and gender composition of today's student and faculty cohorts, much less the American population. The enrollment of women in engineering programs, after increasing substantially during the past two decades, appears to be leveling off at the 20%

Engineering students of today...

Engineering students of tomorrow...

level, even while their enrollment percentage in higher education more generally is approaching 60%. Furthermore, despite some success in increasing the number of students of color in American higher education, now above 30% in many institutions, their presence in engineering programs remains at only a fraction of this level (less than 10%). The situation is even more dire for engineering faculty, with less than 10% women and 4% minority. Beyond the loss of this very considerable human talent to the engineering profession because of the inability of educators to provide educational opportunities to these potential engineering students and faculty members, there is the broader issue of whether engineering education is upholding the long tradition of social justice and equality in American higher education.

To be sure, there are many issues here–the inadequacy of preparation in science and mathematics at the K-12 level, the financial challenges faced by many minority students that deprive them of educational opportunity, the demanding nature of engineering education, the attractiveness of other academic majors (e.g., business, law, medicine). But it is also the case that much of the challenge of achieving adequate diversity in engineering education and hence the engineering profession is self-inflicted: the stubborn determination to adhere to practices in engineering education that discriminate against diversity, the hidden–and frequently unrecognized–prejudices of a white, male establishment that continues to dominate the engineering profession (e.g., the "glass ceiling" phenomenon), and the benign neglect that all too frequently shapes institutional priorities and public policies on these issues. The professions of medicine and law have already demonstrated the ability and wisdom in achieving both gender equity and significant minority participation both in enrollments and professional practice. It is time for engineering to do the same.

Actions Taken

Engineering educators, professional societies, and federal funding agencies such as the National Science Foundation have not been insensitive to these concerns. Over the past two decades numerous efforts have been made by the engineering profession, industry, the federal government, and higher education to improve engineering education (for a more extensive summary, see Splitt, 2004 and Sheppard, 2006):

ABET: Following an extensive dialog with engineering deans, professional societies, and industry in the early 1990s, ABET significantly restructured its criteria for accreditation of undergraduate engineering education (ABET, 1995). Of particular influence was an Industry Advisory Council formed by ABET, which called for greater emphasis in the accreditation of engineering programs on the broader aspects of engineering practice, e.g., teamwork, communication skills, and an interdisciplinary understanding of the societal, ecological, financial, national, and global impacts of engineering. In particular, the ABET Industry Advisory Council urged engineering programs to provide a combination of skills, attributes, and characteristics which included "a holistic approach to achieve solutions to engineering challenges by integrating the elements of general education including human needs, culture, history and tradition, sociology, politics and government, economics and the environment"–in a sense challenging engineering schools to provide students with the elements of a truly liberal education in addition to their scientific and technological training. An excellent survey of the more recent studies has been provided in the Trilogy papers of Frank Splitt and through his efforts aimed at Systemic Engineering Education Reform (SEER) (Splitt, 2002, 2003, 2004).

Today's ABET criteria have shifted the emphasis from dictating curriculum specifications to setting goals for student learning outcomes–a goal emulated and recommended recently for all university education by the Secretary of Education's National Commission on the Future of Higher Education (Miller, 2006). ABET has joined with several of the regional bodies that accredit higher education by requiring institutions to define and publish specific goals for student learning and then measure their achievement to demonstrate how well these objectives are being met. Today's criteria also allows greater flexibility on the part of engineering schools to innovate and experiment with new approaches to engineering education, but ensuring accountability by requiring a structured, documented system for continuous improvement that engages the faculty in the development, assessment, and improvement of academic programs. As Edward Ernst, one of the key leaders in the reform of engineering accreditation, summarized it, the new criteria "produced a consensus about what engineering education should be–what the stakeholders expect in the content of the curriculum, innovative approaches to teaching, and involvement of students." But he then went on to note that the key barrier to further reform remained the degree of change that would be necessary in engineering programs to comply with the new criteria (Ernst, 1998).

While the emphasis of the current ABET criteria on the non-technical aspects of engineering education are welcome, as is the focus on learning outcomes, there continued to be serious concerns. The cost to institutions of preparing for the accreditation process, the relative inexperience of faculty members in designing and implementing effective assessment tools, and the possible shift in accreditation emphasis away from engineering science to engineering design has been criticized (IEEE, 2006). More generally, the very existence of professional accreditation criteria at the undergraduate level continues to pose a challenge to sustaining the diversity among engineering programs necessary to serve the highly diverse needs of contemporary society. While the current standards do allow some degree of diversity and innovation, when implemented at the grass-roots levels of site visit teams, they all too frequently continue to be applied in a cookie-cutter approach to accreditation that results in a standardization that, ironically, makes American engineering education at this level even more subject to the threat of off shoring and global competition. This stands in very sharp contrast to the research-focused graduate engineering programs (M.S. and Ph.D.) conducted by our research universities, which continue to exhibit great diversity, innovation, and rigor and are clearly viewed as world class.

National Science Foundation: The National Science Foundation has an important role in science, mathematics, and engineering (STEM) education at all levels. Although relatively inactive in undergraduate education during the 1970s and early 1980s, NSF's oversight body, the National Science Board, stimulated new efforts during the 1980s and 1990s to address the challenges faced by engineering education (Neal, 1983). It has made substantial investments in curriculum improvement, laboratory instrumentation, research experiences for undergraduates (REU) and K-12 teachers and community college faculty (RET), and graduate fellowship and traineeship programs, including the multidisciplinary Integrative Graduate Education and Research Traineeships (IGERT) program, the Graduate Teaching Fellows in K-12 Education (GK-12), and NSF Graduate Research Fellowships. It has launched major initiatives including the Engineering Research Centers, Engineering Education Coalitions, and Model Institutions of Excellence. In recent years it has shifted from simply providing advice to actively enhancing engineering education by fostering the growth of a community of engineers conducting both fundamental and translational research on more effective educational practices.

More recently the NSF has launched a broader effort to create a series of national centers concerned with research on learning in science, technology, engineering, and mathematics, similar in scale to the successful Engineering Research Centers and Science and Technology Centers. These Science of Learning centers attempt to tap the rapidly emerging research from neuroscience and cognitive science on human learning to improve STEM education. Although not directly stimulated by NSF, several institutions have now established both specific faculty tracks and even academic programs in the study of engineering education, most notably Purdue's Department of Engineering Education.

Although this multiplicity of NSF programs addressed at engineering education and research has been generally viewed as effective and helpful, they have not had the intended transformative impact on engineering education or practice. Recent workshops have concluded that while the NSF investments to improve engineering education have been substantial, they have been small relative to the overall scope of the challenge. They have led to local rather than systematic change in the perceptions, education, and quality of American engineering (NSB, 2007).

National Academies: The National Academy of Engineering has also been an important force for change. Throughout the past decade the NAE has launched an array of workshops, studies, and symposia designed to focus attention on the need for change. The NAE has established a Center for the Advancement of Scholarship in Engineering Education and supported NAE Fellows in Engineering Education to stimulate research at the forefront of engineering education. And through the generosity of a donor, the NAE has established the $500,000 Gordon Prize to recognize contributions to engineering education.

One of the most important recent efforts of the NAE has been the Engineer of 2020 study, chaired by Georgia Tech President Wayne Clough, which conducted a two-phase effort to stimulate change in engineering education. In the first phase the study group developed several provocative scenarios of engineering practice and challenges two decades hence, followed by a second phase to recommend possible changes in engineering education to address these futures. Among these recommendations were the following:

* The BS degree should be considered as a pre-engineering or "engineer in training" degree.
* Engineering programs should be accredited at both the BS and MS levels, so that the MS degree can be recognized as the engineering "professional" degree.
* Institutions should take advantage of the flexibility in the current ABET accreditation criteria–in theory, at least, if not always in practice–in developing innovative curricula.
* Students should be introduced to the "essence" of engineering early in their undergraduate careers.
* Colleges and universities should endorse research in engineering education as a valued and rewarded activity for engineering faculty and should develop new standards for faculty qualifications.
* In addition to producing engineers who have been taught the advances in core knowledge and are capable of defining and solving problems in the short term, institutions must teach students how to be lifelong learners.
* Engineering educators should introduce interdisciplinary learning in the undergraduate curriculum and explore the use of case studies of engineering successes and failures as a learning tool.
* Four-year schools should accept the responsibility of working with local community colleges to achieve workable articulation with their 2-year engineering programs.
* Institutions should encourage domestic students to obtain the MS and/or PhD degrees.
* The engineering education establishment should participate in efforts to improve the public's understanding of engineering and technology literacy.
* The NSF should collect or assist collection of data on program approach and student outcomes for engineering departments/schools so prospective freshman can better understand the "marketplace" of available engineering baccalaureate programs.

Results Achieved

In assessing progress to date, Wayne Clough concludes,

> "The good news is that the majority of U.S. engineering colleges have been working for some time to improve engineering education through NSF Education Coalitions and in collaboration with ABET. I have visited a number of campuses in the past two years and have been encouraged to see that many engineering educators have taken the message of the Engineer of 2020 initiative to heart and are seriously reexamining their educational offerings to adapt them to meeting future needs. However, even though these efforts have been impressive, they have rarely focused on the long view" (Clough, 2005).

Recent studies have confirmed this progress (Lattuca, 2005). According to surveys of program chairs and faculty members, engineering program curricula have changed considerably over the past decade. Although few programs have relaxed their emphasis on foundational skills in mathematics, science, and engineering science, both program chairs and faculty members reported increased emphasis on nearly all of the professional skills and knowledge sets associated with ABET criteria. Teaching methods have also changed substantially. One-half to two-thirds of faculty respondents said they increased "some" or "significantly" their use of active learning approaches, such as group work, design projects, case studies, and application exercises. Students who graduated in 2004 differed significantly from their predecessors in 80% of the experiences inside and outside the classroom.

Furthermore, surveys found that more than 90% of employers thought new engineering graduates were adequately or well prepared to use math, science, and technical skills, and about 80% gave recent graduates passing marks on their ability to solve problems and to learn, grow, and adapt. Three of four employers assessed graduates' teamwork and communication skills as at least adequate. Moreover, these employers reported modest improvements in the past decade in teamwork and communication skills, as well as in the ability to learn and adapt to changing technologies and society. Employers perceived no change in technical skills in math and science, but some noted a modest decline in problem-solving skills, although 80% still rated problem-solving skills as at least adequate. Barely half of employers, however, found graduates' understanding of organizational, cultural, and environmental contexts and constraints to be adequate. Moreover, skills in this area, according to employers, appeared to have declined somewhat over the past decade (Lattuca, 2005).

The Challenge Remains

There have been dozens of conferences and reports, major programs such as the NSF Engineering Coalitions and Systemic Initiatives efforts, and hundreds of efforts by individual engineering schools. Over the past decade there have been numerous innovative approaches to transforming engineering education to serve a rapidly changing world. Some involved major federal investment, such as the NSF Engineering Education Coalitions and Research Experience for Undergraduates and K-12 Teachers. Others such as the new Olin School of Engineering were created with major private support. Still others involved major commitments by colleges and universities such as MIT, Drexel, RPI, Georgia Tech, and Purdue. Furthermore there have been important efforts to break the cycle of periodic calls for reform in engineering education and instead adopt a more disciplined approach to continuous improvement and innovation, relying on fundamental educational research and creating a community of scholars to study engineering education (Lohmann, 2005).

Despite these efforts and the progress in engineering education they have stimulated, we continue to provide a form of engineering education, which, while familiar from our own educational experiences, is increasingly inadequate to respond to the changing needs of a profession–not to mention a society–that has moved far beyond the educational experiences we provide our students.

Who is holding back change? Certainly constituencies such as the professional societies, the National Academy of Engineering, ABET, and the National Science Foundation have recognized the need for change and launched important efforts aimed at better aligning engineering with the changing needs of society. Yet, quite frankly, although well intentioned, most of these steps have been largely at the margin, leaving both the fundamental character and the imperative challenges of engineering largely unscathed.

Industry is a bit more ambivalent. Although they wax eloquently about the need for more broadly educated engineering graduates, better able to adapt to the new demands of the global economy, they still tell their campus recruiters to stress traditional technical skills and academic records. Furthermore, while professional societies and educators alike recognize the inadequacy of an undergraduate engineering degree, the employer market continues to resist upgrading the degree requirements to the graduate level or making an adequate investment in the continuing education and training of their engineering staff, particularly when the alternative of off-shoring engineering services to cheaper foreign providers provides such cost advantages.

What about the academy? To be sure, change is sometimes a four-letter word on university campuses. It is sometimes said that universities change one grave at a time. Judging from a comparison of today's course of study with the engineering curriculum of a century ago, even this may be too optimistic for engineering education. In fact, most engineering educators are ill-informed about new pedagogies based on learning research in areas such as cognitive science. They also tend to be very conservative with regard to pedagogy, curriculum, and institutional attitudes, most comfortable in teaching in the way that they learned years earlier. This conservatism produces a degree of stability (perhaps inflexibility is a more apt term) that results in a relatively slow response to external pressures.

It is certainly the case that in some areas, American engineering education is clearly unrivalled, for example, in the strength of its graduate programs. The flow of international students into our graduate programs provides ample evidence that the research skills, intellectual curiosity, and innovative approaches characterizing graduate engineering education in our nation's research universities, particularly at the Ph.D. level, are still viewed as world-class and well worth the additional investment and compensation. Yet, are other aspects of engineering education sufficiently world-class to produce practicing engineers capable of adding value and meriting rewards several times the capacity of engineers in other nations? Perhaps in some of our more innovative undergraduate programs, such as the Olin College of Engineering, Harvey Mudd, RPI, Caltech, or MIT. But certainly not across the full spectrum of engineering education in America.

Returning again to the observations of Rosalind Williams: "The most obsolete institutional container is that of the 'engineering school.' Its raison d'être is to educate students for engineering, defined as a distinctive profession with its own well-defined identity. As this professional identity dissipates in a process of expansive disintegration, engineering schools will have to evolve or else find another mission. The segregation of engineering education served its purpose in the 19th century, by allowing an alternative form of education to develop. Now this segregation defeats the purposes both of engineering education and of higher education, at once marginalizing engineering and depriving the rest of higher education of its benefits" (Williams, 2003).

Of course, it is important to recognize that the challenge facing engineering education is very much one of systems design, since great diversity among students, educational programs, and engineering roles and capabilities will be necessary to address the diversity of the needs of our nation and the world. While the very large engineering schools at major research universities tend to dominate the headlines, there are hundreds of smaller programs, many in technology-focused institutions, which provide unique and highly innovative educational experiences. The nation needs many different types of engineers, ranging from master engineers at the top of the profession capable of unusual creativity and innovation in product design, systems integration, entrepreneurial efforts, and technology management, to graduate-level engineering scientists capable of fundamental research, to graduates with engineering or engineering technology backgrounds for broader roles such as marketing, sales, and management, to baccalaureate graduates with strong science and technology educations who will move into senior leadership positions in business and government. Such diversity in American engineering practice and education should be encouraged and sustained.

Concluding Remarks

Wayne Clough leaves us with the key challenge: In the past, changes in the engineering profession and engineering education have followed changes in technology and society. Disciplines were added and curricula were created to meet the critical challenges in society and to provide the engineers, knowledge base, and professional skills required to integrate new developments into our economy. Today's landscape is little different; society continually changes, and engineering eventually must adapt to remain relevant. But we must ask if it serves the nation well to permit the engineering profession and engineering education to lag changes in technology and society, especially as these occur at a faster and faster pace. Rather, should the engineering profession anticipate needed advances and prepare for a future where it will provide more benefit to humankind? Likewise, should engineering education evolve to do the same? (Clough, 2005)

Among the important questions raised by Clough's NAE Engineer of 2020 study, one group stands out:

> Can the engineering profession play a role in shaping its own future? Can a future be created where engineering has a broadly recognized image that

> celebrates the exciting roles that engineering and engineers play in addressing societal and technical challenges? How can engineers best be educated to be leaders, able to balance the gains afforded by new technologies with the vulnerabilities created by their byproducts without compromising the well-being of society and humanity?

Clearly today our nation's prosperity and security depend on engineering and technology. Considering the magnitude and complexity of the challenges ahead in energy, security, health care, the environment, and economic competitiveness, we simply do not have the option of continuing to conduct business as usual. We must change how we prioritize, fund, and conduct research; how we attract, educate, and train engineers and scientists; how we consider and implement policies and legal structures that affect engineering practice; and how we maximize contributions from institutions engaged in technological innovation and workforce development (e.g., corporations, universities, and federal agencies).

Yet current trends in research investment and workforce development provide early warning signs that the United States could fall behind other nations, both in its capacity for technological innovation and in the quality of its engineering workforce. Unless the United States maintains its capacity for technological innovation, as well as its ability to create the best and brightest engineers and scientists from home or abroad, the economic benefits of technological advances may not accrue to Americans. Change must become the order of the day.

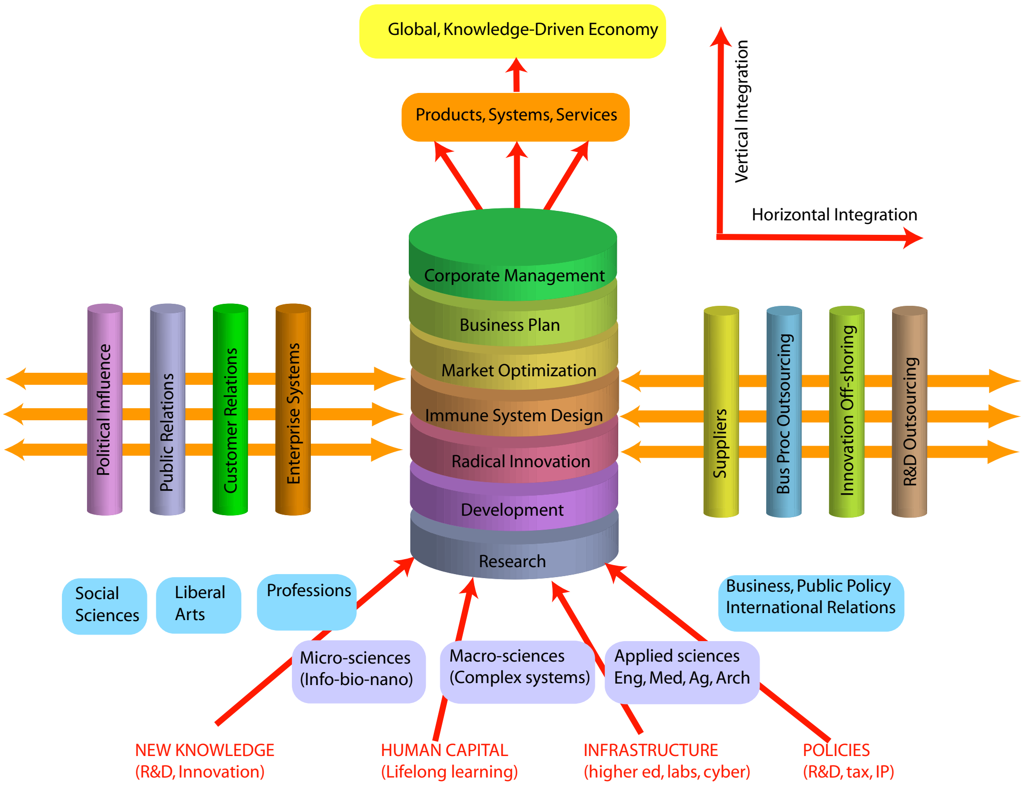
Chapter 4

Engineering Tomorrow: Needs, Objectives, and Vision

Today more than ever the nation's prosperity and security depend on technological innovation and hence upon engineering. The United States will need robust capabilities in engineering practice, research, and education to address future economic, environmental, health, and security challenges. To capitalize on opportunities created by scientific discoveries, the nation must have engineers who can invent new products and services, create new industries and jobs, and generate new wealth. It must generate the new knowledge through engineering research so essential to leadership in technological innovation. And it must educate engineers capable of adapting to the imperatives of an intensely competitive global economy.

The Changing Nature of 21st Century Engineering Practice

The changing demands on engineering practice by the global, knowledge-driven economy are perhaps best illustrated by the example of global sourcing. Traditionally, engineering practice has added value through a vertical process, moving linearly through a sequence of activities such as R&D, product development, manufacturing, sales and marketing, and management to develop products, systems, and services. This was built on a strong educational foundation of science, mathematics, and engineering sciences. Today, however, the global economy tends to function hori-



21st Century Engineering

zontally. The elements of adding value through products, systems, and services are disaggregated and then distributed throughout the world–off shored or globally sourced–to wherever and whoever can accomplish these tasks at highest quality and lowest cost.

Although the outsourcing paradigm has been used for many years in manufacturing, to shift the manufacturing of commodity or sub-assembly products to low-cost regions such as Latin America or Asia, more recently the software industry and now other high-tech companies are shifting engineering services off-shore to low-cost high-tech centers such as Bangalore and Shanghai. Although global sourcing was initially used for more routine functions such as call centers or simple software systems, the improving engineering skills of off-shore providers are allowing the off-shoring of more sophisticated services including engineering design, R&D, and even innovation.

Hence the major challenge to American engineering today is how to transform its value proposition, shifting away from routine, repetitive aspects of engineering that have indeed become commodities appropriate for off-shoring, and developing the competency to move up the value-chain to higher-order activities. The horizontal nature of global sourcing suggests one possibility, since the disaggregation and reaggregation of product design and services across global networks require not only broad intellectual span but also strong capability in systems design, integration, and management. Furthermore, even the elements of the vertical stack of engineering functions are changing rapidly to include activities such as radical innovation, immune (i.e., self-healing) design, applications testing to enable market optimization, and financial planning. Needless to say, these also will require a quite different form of education and training than is now provided to engineering students.

Global sourcing is also driving rapid change in the nature of business organizations, in which the traditional approach of creating large, multinational corporations both to capture market share and to protect intellectual assets and reduce financial risk is being challenged by very small, nimble, innovative, and highly entrepreneurial enterprises. A recent IBM conference on global innovation notes that these companies take advantage of the increasingly strong character of global networks that allow simultaneous collaboration and competition to generate value. They take advantage of the decomposition of business enterprise into component parts, understanding well what their core competencies are, and then develop the partnerships–the strategic alliances–necessary for the global development of products and services. In a more abstract sense, these highly flexible configurations achieve high resilience. Engineers in these small, networked companies identify less with their role as employees than with the broader network of colleagues sharing their interests and expertise (IBM, 2006).

Hence, adopting an optimistic view of global sourcing, it seems clear that market pressures will likely drive off shore the kind of engineering activities that are more easily commoditized, forcing U.S. engineers–and U.S. engineering educators–to elevate substantially the sophistication and value of their activities by placing a premium on creativity, innovation, and entrepreneurship necessary to retain American leadership in engineering. This in turn could enhance the value and prestige of American engineering–if the engineering profession and engineering educators respond appropriately to the challenge.

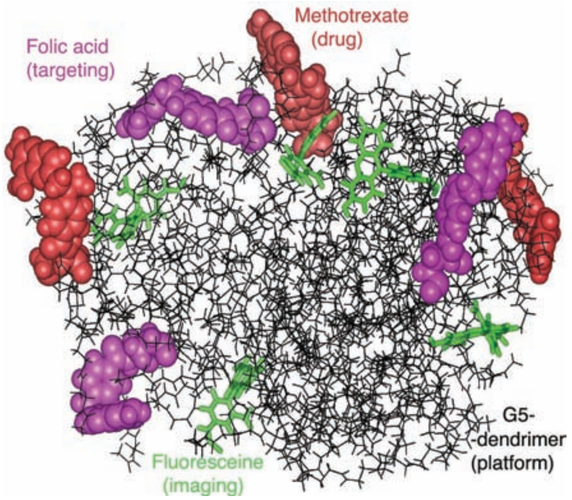
More generally, the forces driving such change in our world–globalization, exponentiating technologies, shifting demographics, and a host of global challenges–require revolutionary changes in the engineering profession. Clearly the skills required of engineers in such knowledge networks are profoundly different than those imparted by the typical engineering curriculum or the training and experience provided in the engineering departments of most large corporations today. To be sure, a strong foundation in science and mathematics remains important–although even this will change significantly, as our discussion of engineering education later in this chapter will suggest. However, engineers need the capacity to function in a global economy. As Kennedy notes, "Businesses need graduates who know something about working with others–not just teamwork, which is a given–but a basic understanding that our culture is not the only one around! We must prepare engineers to be global citizens. They must learn to translate ideas and plans into reality for cultures that may not look, sound, or dress the way we do. Unless we can do that, a large part of our engineering business will soon leave our shores" (Kennedy, 2006). They need a global awareness. To add high value, tomorrow's engineers must have diverse skills enabling them to serve as advisors, consultants, managers, and conceptual planners much more like learned professionals such as lawyers and physicians rather than engineering employees.

To understand better the skills and competencies required for 21st-century engineers, consider the possible careers for engineers suggested by Bordogna:

* Sustainable development: avoiding environmental harm; energy / materials efficiency
* Life cycle / infrastructure creation and renewal
* Micro / nanotechnology / microelectromechanical systems
* Mega systems
* Smart systems
* Multimedia and computer-communications
* Living systems engineering
* Management of technological innovation
* Enterprise transformation

(Bordogna, 1995). These also suggest that the skill set for next generation engineers must broaden significantly.

There are three particular competencies that are particularly important and deserve further comment. First is the *ability to innovate*, which is strongly dependent upon the engineer's capacity to synthesize and create. Here one might observe that the professions that have dominated the late twentieth century have been those that manage knowledge and wealth, professions such as law, business, and politics. Yet today there are signs that our society is increasingly valuing activities that actually create new knowledge and wealth, professions such as art, music, architecture, and engineering. The tools of creation are expanding rapidly in both scope and power. Today, we have the capacity literally to create objects atom by atom. We are developing the capacity to create new life-forms through the tools of molecular biology and genetic engineering. We are now creating new intellectual life-forms through artificial intelligence and virtual reality. Hence the most significant role of the engineer of the future will be innovation through the creation of new products, processes, and service–a role that stresses synthesis over analysis. Tomorrow's engineers must have the capacity to produce concurrent discovery and innovation, key to both economic prosperity and social well being in a knowledge-driven world.



Bionanotechnology: engineering at the molecular level

A second essential competency is the *integration of knowledge* across an increasingly broad intellectual span. Focusing on one or even several of the traditional technical disciplines of engineering will simply not be sufficient to address the complexity of the needs of tomorrow's society. Instead one must heed the warning of E. O. Wilson: "Most of the issues that vex humanity daily cannot be solved without integrating knowledge from the natural sciences with that of the social sciences and humanities. Only fluency across the boundaries will provide a clear view of the world as it really is, not as seen through the lens of ideologies and religious dogmas or commanded by myopic response to immediate needs". He refers to this capacity to integrate knowledge across many disciplines as *consilience*, and this will become an increasingly important trait of successful engineers. In fact, one might even suggest that the American engineer of the 21st century should strive to become a polymath, one who is knowledgeable in many fields, (and in the arts and sciences in particular), much like others in our history who have made unusually important contributions to society through technology (e.g., Leonardo Da Vinci).

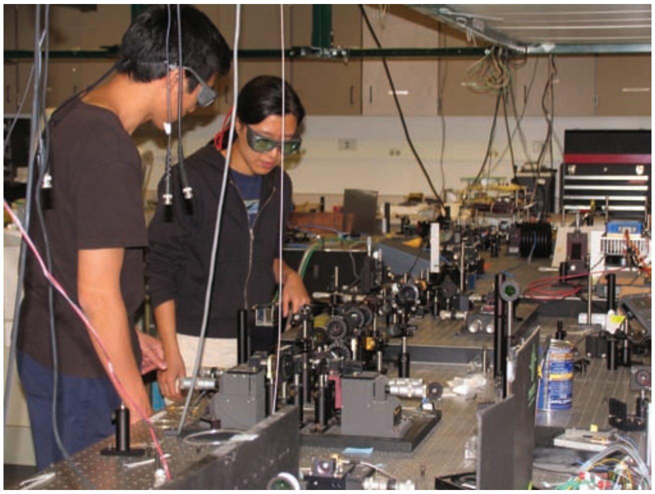
Third, it is important to stress the importance of a *global perspective* for engineering practice. Key is not only a deep understanding of global markets and organizations, but the capacity to work in multidisciplinary teams characterized by high cultural diversity, while exhibiting the nimbleness and mobility to address rapidly changing global challenges and opportunities.

The Knowledge Base for Engineering

Engineering research is founded on a disciplined approach to problem solving and the application of sophisticated modeling, design, and testing tools to solve problems. For instance, fundamental engineering research led to the creation of finite element methods of stress analysis, which have provided sophisticated computational tools used by mechanical and structural engineers in a vast array of applications. Engineering researchers have also made significant progress in using molecular dynamics to measure time more precisely, a critical enabling technology for faster computers, global positioning systems, wireless communications, and many other products in common use. Many other technologies are based on the results of fundamental engineering research, mostly conducted at universities (Duderstadt, 2005).

Broadly speaking, the most daunting challenges facing the nation in health care delivery, energy production and distribution, environmental remediation and sustainability, national and homeland security, communications, and transportation pose complex systems challenges that require parallel advances in knowledge in multiple disciplines of engineering and science and collaboration and cross-fertilization among disciplines. In fact, both basic and applied engineering research will be critical to the design and development of processes and systems on which every major sector of the U.S. economy depends. Both forms of research will be essential to meeting the challenges and taking advantage of the opportunities that lie ahead.

As Vest notes, engineering research is evolving along two trajectories. One frontier is characterized by smaller and smaller sizes and faster and faster time scales–the world of info-, bio-, and nanotechnology. Here the physical sciences, life science, and information sciences are converging, creating disruptive technologies that evolve exponentially (Moore’s law). Working at this level requires engineers to master new forms of engineering science based on disciplines such as quantum mechanics, genomics and proteomics, and abstract mathematics. At the other extreme are larger and larger systems of great complexity such as energy, environment, infrastructure, urban systems, and global systems–addressing some of the most daunting challenges to our future survival. While academic research continues to lead the way in the engineering sciences characterizing microscopic technology, the engineering research needed to address large-scale systems has traditionally been the focus of industry and government (e.g., the corporate and national laboratories) (Vest, 2005).



Engineering research: from the microscopic...

To the macroscopic...

Engineering research has been changing rapidly. Information technology will be a part of every product and process in the future, and discrete mathematics, rather than continuous mathematics, is the language of information technology. Biological materials and processes are a bit behind information technology in terms of their impact on engineering practice, but they are catching up fast. Biology and chemistry, organic chemistry and molecular biology in particular, have become just as important as physics and chemistry. The walls surrounding the traditional disciplinary silos in which engineering research is conducted and funded are crumbling, as contemporary challenges require true multidisciplinary collaboration.

The new areas of research will require entirely new disciplines and methodologies, e.g., living systems engineering, nanotechnology, quantum technology, mega-infrastructure, global systems, intelligent systems, and knowledge services. Fortunately, the evolution of powerful new tools will facilitate engineering research in these fields. Prominent among them is rapidly evolving cyberinfrastructure–the hardware, software, systems, people, and policies that yield the information and communications technologies critical to address research in these new fields. For example, hardware is now evolving from terascale (10^{12}) to petascale (10^{15}) over the next several years. Within another decade processing speeds and storage are likely to be at the exascale level (10^{18}). Furthermore, open-source, open-content, and open-learning paradigms in which educational resources are put in the public domain (e.g., MIT's OpenCourseWare initiative), Google's massive digitization of library materials, and the development of the open-source tools for scholarship and learning could well achieve the long-sought goal of universal access to all recorded knowledge and learning opportunities within a generation. Storage is becoming operationally infinite–imagine the Library of Congress on your iPod (or iPhone) within a decade. Networks are moving toward TB/s for research, GB/s for the home, and 100 MB/s wireless (over local areas several miles in extent). Microchips with sensors, wireless connectivity, and even GPS systems will soon be the size of dust grains–or as some put it, "an IP on every cockroach"–allowing sensor networks of unimaginable complexity and extent (Atkins, 2003; Reed, 2006).

The availability of such technology will stimulate new research paradigms such as the complete digital simulation of physical phenomena, semantic data repositories enabling deeper searches, infinite recall, digital convergence of multimedia, always on peer-to-peer collaboration assisted by AI-enabled agents, and continuous awareness by smart sensors and telemetry. And, of course, new types of intelligence may emerge. In fact, if we think of the Internet not simply as hardware but rather as a tightly connected community of millions–and eventually billions–of human collaborators, we are already seeing new forms of intelligence such as wikis, flash mobs, and virtual worlds.

Beyond the explosion of scientific knowledge and rapid evolution of new technologies, there are new knowledge paradigms important to contemporary engineering involving activities such as creativity, innovation, and entrepreneurship. Recent studies have clearly identified the importance of innovation: the process of creating new knowledge and applying it to things that are new and different, to quote Drucker (COC, 2004, RAGS, 2005, Bordogna, 2006). But innovation depends upon the discovery of new knowledge, both through the curiosity-driven activities of scientific research and the more social-need-driven research of engineers. Its impact depends upon entrepreneurs, who have the capacity to understand the nature and potential of innovations, the creativity to assemble human and financial capital to build organizations capable of utilizing them to create value, and the courage to take the risks to take them into the marketplace.

Discovery, innovation, and entrepreneurship are the backbone of 21st century progress and also the primary ingredients for Schumpeter's economic theory of creative destruction, as new companies devour the old, resulting in the ecosystem of a vibrant economy. Yet as Bordogna points out, the blurring of discovery, learning, and innovation are bringing together scientists and engineers, educators, and entrepreneurs to work across many different disciplines, fields, and economic sectors to achieve more creative solutions and add even greater value in a economic transformation process he terms "creative transformation" (Bordogna, 2006). Key in this process are the role of partnerships among academe, business, and government to speed the transformation of new knowledge into new products, systems, and services, producing new jobs, creating wealth, and serving society. Yet here our nation faces challenges.

To pursue open, collaborative innovation, companies must find ways to tap into the potential of people around the globe. This may mean managing R&D less as a discrete department and more as a supply chain, where the best ideas from around the world are exchanged dynamically (Palmisano, 2005). This implies that rather than building expensive new research facilities in merging markets, a greater priority might be establishing "sensing hubs" to seek out new ideas and innovation components, as well as ready receivers for the company's existing ideas.

In the postwar period, governmental policies shielded huge sectors of engineering practice–defense contracting, highway construction, communication–from direct market pressures. Government patronage made academics less tightly linked to industrial concerns and perspectives. With the end of the Cold War in 1990, government support for research in science and engineering began to level off in most areas (biology being the major exception) both in corporations and in universities. Since then, university-based engineers have sought to revitalize their links with industry as sources of research support and as employers of their graduates. Yet today industry still provides less than 10% of the funding for campus-based engineering research.

Industrial support for corporate engineering research has been strongly market oriented. As government support has flattened, industry has begun to take a more "value-received perspective" in regard to research investments. They have to be justified in terms of the bottom line, and the short-term bottom line at that. Some corporate labs have become mission oriented; others have disappeared. As investment in research has diminished or scattered, consulting has become less important as a bridge between universities and industries. Instead, businesses have found that they can get the benefit of good research ideas by investing in and eventually buying up small companies, which pay more attention to marketability, timeliness, and productivity than university labs.

Yet despite some efforts to offshore R&D, many companies are continuing to rely heavily on universities to perform much of the basic engineering research that undergirds new product and system development. In a sense, the research programs of engineering faculty members are becoming increasingly critical to sustaining the long-term research that enables the new knowledge created through scientific discovery to be applied to the needs of our society–research that used to be an important focus of large central industrial research laboratories, but now has been relegated to the campuses of research universities. As an increasingly important element of the American technological innovation system, such university-based engineering research will require new paradigms, e.g., for the conduct of large-scale, multidisciplinary team research, in the relationship between industry and higher education, and in new technology transfer mechanisms to transfer this new engineering knowledge into the marketplace.

Engineering Education

With only 8% of the world's engineering workforce, clearly the United States cannot compete quantitatively in the production of engineering graduates with emerging economies characterized by large populations such as China and India. Rather, the goal of American engineering schools and industry training programs should be to focus more on quality, producing engineers capable of adding exceptional value through innovation, entrepreneurial skills, and global competence. Clearly this will require a very major transformation in engineering education.

The skill set required for contemporary engineering practice is changing rapidly and will continue to do so even more in the years ahead. Beyond a strong foundation in fundamentals such as science, mathematics, and engineering sciences, engineers require broader skills such as those suggested by Bordogna (2003):

* Engineering science (analysis)
* Systems integration (synthesis)
* Problem formulation as well as problem solving
* Engineering design
* The ability to realize products
* Facility with intelligent technology to enhance creative opportunity
* Ability to manage complexity and uncertainty
* Teamwork (sensitivity in interpersonal relationships)
* Language and multicultural understanding
* Ability to advocate and influence
* Entrepreneurship and decision making
* Knowledge integration, education, and mentoring

Rosalind Williams suggests even more fundamental changes in the engineering skill set. She suggests that the strong focus on physical sciences such as physics and chemistry, usually reduced to the application of a few fundamental principles such as the laws of motion or thermodynamics, will be displaced by a more complex and highly interdisciplinary foundation in which information-rich sciences such as biology and social sciences must be blended with the traditional tools of physical science and mathematics. Information technology is already having a major impact on engineering practice, with analytical tools such as symbolic mathematics software and computer-aided design shifting the emphasis from analysis (which computers are very good at) to synthesis (design and innovation). As Williams notes, "most engineering departments are becoming, to a greater or lesser extent, departments of applied-information technology. In the form of a common digital language, technology dissolves the familiar boundaries of engineering" (Williams, 2003).

The engineering curriculum will become more balanced, with less emphasis on "reductionist" science (e.g., physics) and more emphasis on "information-rich" science (e.g., biology); less emphasis on analysis and more emphasis on synthesis; merging and cross-pollinating creative disciplines (art, music, architecture) with engineering activities such as design and innovation. Several years ago a faculty committee at Caltech developed a brief list of the topics they believed should be included in an undergraduate science and engineering education. The breadth of subjects is quite striking:

* conservation laws
* biochemistry
* scalar wave equation
* genetics
* dynamical systems
* evolution
* cell biology
* physical forces
* geochemistry
* atmospheric chemistry
* quantum mechanics
* discrete mathematics
* logic and probability
* chemical bonding
* information theory
* electrical circuits
* statistical mechanics
* thermodynamics
* chemical equilibrium
* condensed matter
* systems engineering
* complexity
* collective properties
* chaotic systems
* neurobiology

Quite a contrast with today's engineering curriculum. Quite a challenge. And clearly impossible, at least within the current undergraduate engineering degree constraints.

Beyond science, mathematics, and engineering science, the undergraduate curriculum must also change substantially to provide students with the broader skills necessary to be successful in a rapidly changing global society. As we noted before, employers increasingly seek social and cultural skills such as the ability to communicate, to function in an increasingly diverse environment, to be committed to and capable of lifelong learning, and to not only adapt to but actually drive change. As we will suggest later in Chapter 6, these are also the goals of a liberal education, something that today's overburdened engineering curricula has great difficulty in accommodating.

To achieve the necessary transformation in engineering, changes are needed at every level of our national education infrastructure, from K-12 education capable to providing the fundamental skills in science, mathematics, and written and oral communication; undergraduate education that introduces engineering as a discipline within the context of a broad liberal education; graduate-level professional degrees that provide an accredited route into the engineering profession; doctoral education that enables the conduct of fundamental research and discovery that fuels innovation; and a more strategic approach to lifelong learning necessary both to enable engineers to track the rapidly expanding knowledge base and broaden their own capacity for leadership. To summarize the challenge for

21st-century engineering education, we need to redefine undergraduate engineering as a liberal education, providing depth and disciplinary expertise required for professional practice at the graduate level, and augmenting the doctoral degree beyond research capability with the skills necessary for innovation, entrepreneurship, and leadership. And, as with other learned professions such as medicine and law, we must recognize that this will be a never-ending challenge, requiring continual innovation, improvement, and occasionally radical transformation.

Discovery-Based Learning

Clearly this will require that engineering education shift increasingly away from the lecture-laboratory approach of the sciences to more active learning experiences that engage problem-solving skills, team building, creativity, design, and innovation. Engineering faculty must create discovery-oriented learning environments that capitalize on the full power of new communication, information, and visualization technologies (NSB, 2007). But these concerns are neither novel nor unique to engineering education. Psychologists and cognitive scientists have known for decades that the most effective learning occurs through the active discovery and application of knowledge, not through mere study and contemplation. From John Dewey to Jean Piaget to Seymour Papert, we have ample evidence that most students learn best through "constructionist" learning. Hence it is long past time that we ripped engineering education out of the lecture hall and place it instead in the discovery environment of the laboratory, the design studio, or the experiential environment of practice.

Engineering schools have powerful evidence of the effectiveness of such constructionist learning through the numerous research, design, and competitive projects students undertake (Prince, 2004). Followup studies of student achievement following participation in projects such as the solar car race or autonomous vehicle competition reveal that student academic performance improves very significantly with such experiences, even though students may temporarily take reduced course loads to accommodate such demanding activities.

The last major revolution in engineering education occurred in the years following World War II when the earlier undergraduate curriculum based upon the mastery of practical engineering tools (e.g., surveying, drafting, design) was rebuilt upon a strong scientific base, adopting both the pedagogical methods and the faculty reward structure of the sciences. Today many believe that we need to reverse this trend of the past half-century to re-introduce practice into the curriculum (Lumancusa, 2006). More generally, discovery-based or constructionist learning in engineering education might benefit more from an experiential approach, involving oncampus activities such as design or systems integration, perhaps in studios rather than classrooms or laboratories, and assisted (rather than led) by faculty with both experience and active involvement in engineering practice. In a sense, this would involve turning the curriculum inside out, putting engineering experience at the core and wrapping about it the engineering sciences enabling problem solving (Jamieson, 2007). This could

Engineering students tend to learn better through projects such as the World Solar Car Race.

Another example of active student learning: fleet of autonomous dirigibles that exhibit flocking behavior...

be augmented with extracurricular experiences such as co-operative education, internships, study abroad, service learning, and team experiences such as the solar car race or autonomous vehicle competition. Here one might also consider powerful new immersive computer technologies to simulate the environments for engineering practice, e.g., virtual reality environments such as Second Life and gaming environments such as the World of Warcraft. In fact the U.S. military has made great strides in utilizing modeling, simulation, immersive and virtual learning environment in quite sophisticated training (Institute for Creative Technologies, 2007) that might be adapted for engineering education.

It should be noted that making experiential learning the core of professional education has been adopted by other professions such as medicine, law, and business. Medical students are now placed in the clinical environment their first year, taking patient histories, accompanying doctors on their rounds, to build an early sense of what being a physician is all about, even as they are beginning to acquire the necessary scientific knowledge for the practice of medicine. Similarly, the use of moot courts and law clinics provide such experiences for law students, while service learning and business plan development projects serve this role in business administration. Educators should strive to create such immersive experiences for engineering students in an effort to teach them not only "how to do", but more important, "how to be" (Brown, 2005).

The Plug and Play Generation

On a deeper level, technology is forcing us to rethink the notions of literacy: From literacy in the oral tradition, to the written word, to the images of film and then television, to the computer and multimedia. Of course there are many other forms of literacy: art, poetry, mathematics, science itself, etc. But more significantly, the real transformation is from literacy as "read only, listening, and viewing" to composition in first rhetoric, then writing, and now in multimedia (Daley, 2003).

The traditional classroom paradigm is being challenged today, not so much by professors, who have by and large optimized their teaching effort and their time commitments to a lecture format, but by our students. Today's students have been born into a digital world and are comfortable with these technologies in ways that their elders (and their teachers) will never be. Members of today's digital generation of students have spent their entire lives immersed in robust, visual, electronic media–video games, home computers, cell phones, instant messaging, MySpace, and Second Life. Unlike those of us who were raised in an era of passive, broadcast media such as radio and television, today's students expect–indeed, demand–interaction. They approach learning as a "plug-and-play" experience. They are unaccustomed and unwilling to learn sequentially–to read the manual. Instead they are inclined to plunge in and learn through participation and experimentation. Although this type of learning is far different from the sequential, pyramidal approach of the traditional college curriculum, it may be far more effective for this generation, particularly when provided through a media-rich environment.

The plug-and-play generation in a computer camp.

John Seely Brown and his colleagues at Xerox PARC have studied the learning habits of the plug-and-play generation and identified several interesting characteristics of their learning process (Brown, 2000). First, today's students like to do several things at once–they "multitask", performing several tasks simultaneously at a computer such as website browsing and e-mail while listening to music or talking on a cellular phone. Although their attention span appears short, as they jump from one activity to another, they appear to learn just as effectively as earlier generations. They have mastered the skill of rapid context switching, a key to functioning in our rapid-paced world.

Furthermore, it is clear that they have also mastered a broader range of literacy skills, augmenting traditional verbal communication skills with visual images and hypertext links. They are particularly adept at navigating through complex arrays of information, acquiring the knowledge resources they seek and building sophisticated networks of learning resources. Some observers suggest that this may lead to problems later in life as the digital generation sacrifices qualities such as patience and tranquility. But, of course, patience and tranquility have never been characteristics of the young. Asked about their elders concerns, the typical response of the digital generation is: "Get over it!"

Indeed, there is even research that suggests the presence of a physiological difference between the brains of the "digital generation" and those of us from 20th Century generations. More specifically, it has been known that early exposure of infants and young children to various stimulation can actually affect their neurological development–the evolution of their neutral networks. Children raised in a media-rich, interactive environment tend to think and learn differently because they are physiologically different from us. Their brains are wired in different ways. Our styles of learning are not theirs.

Student-Faculty Learning Teams

Today's students are active learners. They construct their own knowledge structures and learning environments through interaction and collaboration. Their approach to learning is highly nonlinear rather than following the sequential structure of the typical university curriculum. They are adept at multitasking and context switching. And they are challenging the faculty to shift their instructional efforts from the development and presentation of content, which is more readily accessible through the web and open-content efforts such as the Open CourseWare initiative of MIT, and instead become like mentors and consultants to student learning (Duderstadt, 2005).

Some cognitive scientists have concluded that perhaps the best approach in these technology-rich environments is to turn the students loose, letting them define their own learning environments. New pedagogies, such as peer-to-peer learning and content development and the use of massively multi-layer gaming ("virtual worlds") as a simulation tool, are rapidly replacing faculty teaching as the dominant educational process on several technology-rich campuses. There is not yet a consensus among the faculty as to where they are headed, but there is strong agreement that the "net" generation is both challenging and changing the learning process in very fundamental ways.

Student-faculty learning teams

In these new learning paradigms, the word "student" becomes largely obsolete, because it describes the passive role of absorbing content selected and conveyed by teachers. Instead we should probably begin to refer to the clients of the 21st-century university as active learners, since they will increasingly demand responsibility for their own learning experiences and outcomes. Furthermore, our students will seek less to learn about (after all, in many ways they are more sophisticated at knowledge navigation in the digital age than their teachers) and instead seek to "learn to be" by looking for opportunities to experience the excitement and challenge of engineering practice (Brown, 2006).

In a similar sense, the concept of a teacher as one who develops and presents knowledge to largely passive students may become obsolete. Today, faculty members who have become experts in certain subfields are expected to identify the key knowledge content for a course based on their area of interest, to organize and then present the material, generally in a lecture format, in this course. Frequently, others, including graduate teaching assistants and professional staff, are assigned the role of working directly with students, helping them to learn, and providing them with guidance and counseling. In a future increasingly dominated by sophisticated educational commodities and hyperlearning experiences, the role of the faculty member will shift. In these new paradigms the role of the faculty member becomes that of nurturing and guiding active learning, not of identifying and presenting content. That is, they will be expected to inspire, motivate, manage, and coach students.

There will be strong pressures on universities to shift away from being faculty-centered institutions in which faculty determine what to teach, whom to teach, how to teach, and where and when to teach. Instead universities will likely evolve into learner-centered institutions, in which learners have far more options and control over what, how, when, where, and with whom they learn. This should not be surprising. In our increasingly democratic, market-driven world, the concerns of individuals, or customers, or clients have become the focus of most successful organizations.

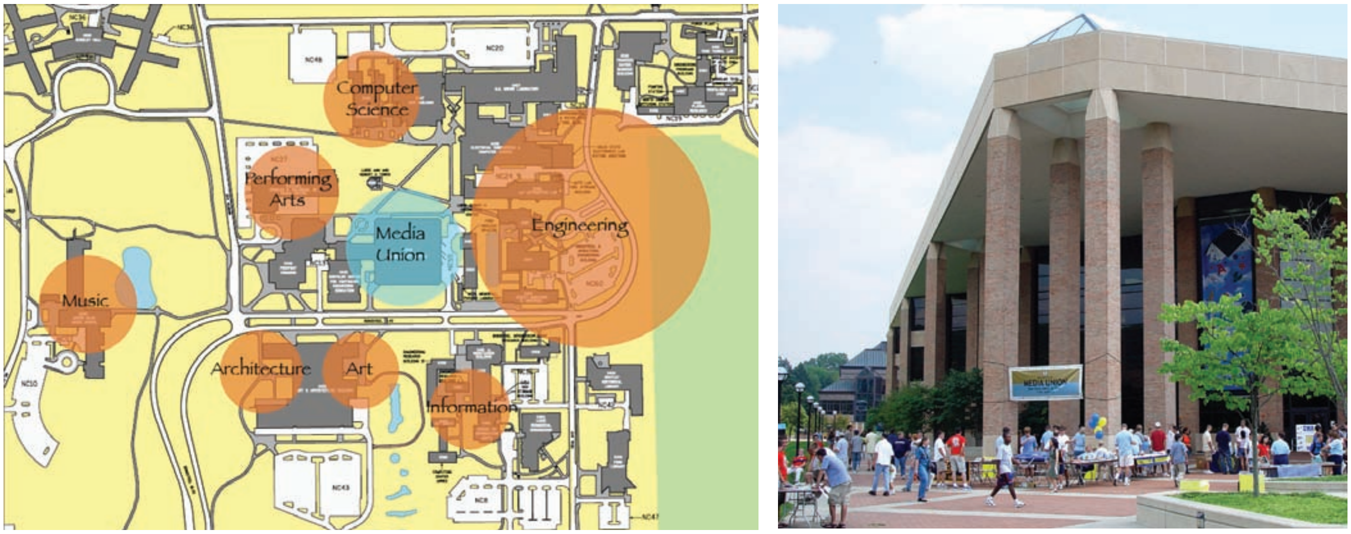
Synthesis, Design, Creativity, Innovation, …and Entrepreneurship

The development of skills in synthesis and creativity, so essential to engineering design and technological innovation, is a particular challenge to engineering schools, which have long stressed instead scientific analysis and problem solving. While universities are experienced in teaching the skills of analysis, we have far less understanding of the intellectual activities associated with creativity. In fact, the current disciplinary culture of our campuses sometimes discriminates against those who are truly creative, those who do not fit well into our stereotypes of students and faculty.

Several universities have introduced multidisciplinary design institutes (e.g., Stanford, Michigan), bringing together faculty and students from fields such as engineering, law, medicine, and business, with faculty from the behavioral sciences and arts to share experience, research, and educational pedagogies. Some engineering programs have been created (e.g., Olin College) or transformed (e.g., RPI, Purdue, Harvey Mudd) to permeate the engineering curriculum at all levels with design experience through project or studio-based activities.

The increasing value a knowledge-driven society places upon creativity and innovation suggests we might even speculate that the university of the 21st-century should also shift its intellectual focus and priority from the preservation or transmission of knowledge to the processes of creativity and innovation themselves. Such a paradigm shift would require that the university organize itself quite differently, stressing forms of pedagogy and extracurricular experiences to nurture and teach the art and skill of creation. This would probably imply a shift away from highly specialized disciplines and degree programs to programs placing more emphasis on synthesizing and integrating knowledge to enable creativity and innovation. An example of just such approach is the Renaissance Campus project at the University of Michigan, in which those academic programs stressing creativity and synthesis over study and analysis have been co-located on a single campus (the university's North Campus) and augmented by facilities which encourage collaboration among the disciplines. At Michigan this includes the schools of art, design, architecture, music, theater, dance, computer science, information, and, of course, engineering, with major integration spaces such as the Arthur Miller Theatre, the Student Commons, and the Media Union co-located in the midst of the academic programs where students and faculty come together in multidisciplinary teams to create and innovate.

Beyond synthesis, creativity, and design, tomorrow's engineers must acquire skills in innovation and entrepreneurship. Innovation involves much more than mastering newly emerging science and technology. It involves the creativity to understand how to take this knowledge to the next stage into the marketplace and to serve society. As Richard Miller, president of Olin College, puts it, "Engineers in the next generation must take ownership for the process or commercialization of technology and not simply leave this to the business community. This doesn't mean that the need to add an MBA to their list of accomplishments, but they at least need to know the vocabulary and questions that MBAs bring to the table. Ultimately, I believe the country would almost always be better off with the final decision maker having an engineering background." An appropriate spokesman indeed, since Olin College of Engineering represent a very important experiment



The Renaissance Campus of the University of Michigan and the associated Media Union

of a radical new approach to engineering education, utilizing project-based learning and embracing an educational philosophy that emphasizes both entrepreneurship and humanities in addition to a solid technical education (enabled by partnerships with nearby Babson College of Business and Wellesley College). Its method of instruction has more in common with a liberal arts college, where the focus is on learning how to learn rather than with a standard engineering curriculum. Again to quote Miller, "How can you possibly provide everything they need in their knapsack of education to sustain them in their 40-year career? Those days are over. Learning the skill of how to learn is more important than trying to fill every possible cup of knowledge in every possible discipline." Olin has crafted an educational approach with the objectives of providing its students with skills in teamwork, communication, creativity and design, entrepreneurial thinking, self-directed and agile learning skills, as well as technical competence.

More broadly, Bordogna suggests that the key for both today's engineering students and tomorrow's entrepreneurs is to think both strategically and holistically, able to read patterns and trends from a larger context to envision the future (Bordogna, 2006). As he notes, "If technological innovation is at the heart of progress, the engine turning the world's economic axis, then we need to understand the skills that foster the capacity for risk taking, for imagination, and a tolerance for unfamiliar and uncertain territory. Engineers will have to become effective collaborators, innovators, risk takers, and communicators, working across shifting boundaries and embracing diversity. We must teach them to think against the grain; swim upstream; violate the norm."

The Global Engineer

Of comparable importance is developing an educational paradigm capable of producing truly global engineers, capable of practice in an increasingly complex, interconnected, and rapidly changing world. Beyond an understanding of the workings of the global economy, engineers need the ability both to understand and work with other cultures, to work effectively in multinational teams, to communicate across nations and peoples, and to appreciate the great challenges facing our world–sustainability, poverty, security, public health. A recent year-long study coordinated by Technical University of Darmstadt and sponsored by Continental AG examined this from the perspective of a group of leading universities from around the world. Beyond the traditional approaches, e.g., coursework in international studies, second language proficiency, and international experience, they suggested several more substantive steps to achieving such global competence (Continental, 2006):

- Engineering programs should incorporate knowledge of the fundamentals and dynamics of globalization, as well as opportunities to become immersed in study, work, or research abroad.

- Transnational mobility for engineering students, researchers, and professionals needs to become a priority. Barriers to studying, working, conducting research, and attending international meetings need to be removed and incentives expanded.

- Global engineering excellence depends critically on a mutual commitment to partnerships, especially those that link engineering education to professional practice. Industry must take the lead in developing opportunities for students to practice engineering in a global context, whether through on-site employment, virtual involvement in global engineering projects, or other experiential opportunities.

- Since the phenomenon of global engineering is still emerging, there is a need for research on both global organizational processes and management methods-i.e., global sourcing-and how they will affect engineering practice and hence education.

An increasing number of companies already are searching for engineers with foreign-language abilities and industry experience in global management and team-oriented skills. Universities are responding with efforts to provide students with international experiences through study abroad or internships with transnational companies. (Carlson, 2007)

Traditional study abroad programs are frequently incompatible with the sequential technical curriculum characterizing engineering education. Several institutions have developed highly structured and effective approaches to integration of overseas experiences with the technical, cultural, and practice-based characteristics of global engineering, among them the team project approach of Worcester Polytechnic Institute, the integrated approach of Purdue's GEARE program, and the global clinic approach of Harvey Mudd. Global institutional partnerships utilizing information and communications technology have also been effective for bringing together students from various nations in joint educational experiences. But clearly more effort is needed to develop new paradigms and activities for global engineering.

Lifelong Learning

From this perspective, it becomes clear that our educational perspective must broaden from educating the young to preparing our students for a lifetime of education. Just as in other majors, engineering students should be encouraged early in their studies to think more expansively about career options and lifetime goals, to consider the grand challenges facing our world, which will require engineers of exceptional skill, creativity, innovation, and global understanding. The list of "grand challenges" suggested in Chapter 2 provides a good starting point–global sustainability, infrastructure, energy, global poverty and health, and the knowledge economy–but students should be challenged to consider the importance of addressing these and other great challenges facing our society to stimulate both their commitment to their college education and to future careers.

To reinforce the idea that engineering education should become life-long, perhaps we need to consider a step system of engineering education objectives that would be mastered through formal programs, workplace training, and practice experience in phases during a professional career. In fact, one might even consider a new set of credentials that would add value to engineers as they meet each educational objective, commanding more responsibility and earning more compensation with each step up the ladder. Parenthetically, this might provide a far more constructive role for accreditation agencies such as ABET rather than focusing their attention upon undergraduate education.

This would also be consistent with contemporary employment practices in which few engineers will experience a career within a single corporation or organization. It is estimated that today's college students will have over four jobs before the age of 30, and over ten jobs before they are 40. In fact, many engineering graduates will work for small high-tech companies or consulting services companies, moving from organization to organization and role to role frequently. To adapt to this new work environment, engineering graduates must accept the personal responsibility for their lifelong learning through acquiring effective self-learning skills. Employers, in turn, must recognize the importance of investment in furthering the knowledge base and skills of their engineering staff, and accept this responsibility as a necessary investment in their future technological and innovation capability.

The Renaissance Engineer

It has been said that engineering is the engine of innovation. If so, then science is its fuel. As Bordogna observes, "Engineers stand at the fulcrum of scientific and technological change, creating new knowledge, artifacts and systems; stimulating economic development; creating wealth and jobs; sharpening the nation's competitive edge; raising our prospects for more productive and satisfying lives; caring for the environment; and strengthening our national security." (Bordogna, 2006) He goes on to conclude that "Engineering education is at the very heart of these issues. Demands are increasing for a holistic breed of engineers–graduates with the skill to work across intellectual, social, and cultural boundaries."

Perhaps what is most missing in the current engineering education curriculum, crammed as it is increasingly with demanding technical material, is the opportunity for a truly liberal education, designed to enable young students to develop the deeper intellectual skills necessary to adapt to a world characterized by continual change. Here we should heed Samuel C. Florman's call for the model of a "renaissance engineer", engineering graduates capable of a broad range of activities from technology to management to public service. Florman suggests that "If we want to develop renaissance engineers, multi-talented men and women who will participate in the highest councils, we cannot educate them in vocational schools–even scientifically distinguished vocational schools–which is what many of our engineering colleges are becoming" (Florman, 2001).

Beyond breadth–the ability to master consilience–Wayne Clough suggests that we should also emphasize leadership as the basis for engineering education. We have noted earlier that the absence of engineers from either the leadership roles of business and government or the major debates over the issues of our times poses a major threat to society in an increasingly technological world. Here engineering schools would intentionally add to their educational programs experiences that enhance the sociability and understanding of cultural issues, augmented as well by leadership courses and internships. Of particular value here are service learning experiences, now commonly utilized as an important part of undergraduate education in other disciplines and many MBA programs. Such leadership in service activities provide an important experience for graduates, particularly those intending to pursue engineering careers. Working on behalf of others emphasizes that to be a good leader one also has to be a good team player. Often the best leadership is the example set in helping others.

Diversity must become not only a characteristic but also a predominant strength of American engineering.

A Diverse Engineering Workforce

Finally, it is critical that our engineering education programs build programs capable of attracting and preparing a diverse cadre of engineering graduates that faithfully reflect the rapidly changing nature of the American population. A distinguishing characteristic and great strength of American higher education has been its growing commitment over time to serve all segments of our pluralistic society. Higher education's broadening inclusion of talented students and faculty of diverse ethnic, racial, economic, social, political, national, and religions background has allowed our academic institutions to draw on a broader and deeper pool of talent, experience, and ideas than more exclusive counterparts in other places and times. Clearly such a commitment is even more important today, since tapping the talent pool of an increasingly diverse population will be essential to meeting the human capital needs of the engineering profession. Moreover, in a world of diverse cultures ever more tightly interconnected and interdependent, such diversity is absolutely essential. As Bill Wulf notes, "In any creative profession, what comes out is a function of the life experiences of the people who do it. Sans diversity, we limit the set of life experiences that are applied, and as a result we pay an opportunity cost in products not built, in designs not considered, in constraints not understood, in processes not invented." Engineering educators must accept the personal and institutional responsibility to achieve such diversity in their programs as the cornerstone of the future vitality and relevance of the engineering workforce in an ever more diverse nation.

The Hazards of Predicting the Future

Clearly the science and engineering knowledge base is growing at an exponential pace with profound implications for engineering practice and education. In some fields such as nanotechnology or bioengineering the knowledge doubling time is as short as five years, enough to make a student's education obsolete even before graduation! Yet it is also the case, that despite this explosion of new knowledge, we frequently overestimate the near-term impact of technological change, while greatly under estimating its impact over the longer term. Part of the reason is that we tend to extrapolate what we know today to predict a future that may be dramatically different than we can imagine because of disruptive technologies. But predicting future trends in engineering and technology is hazardous for another reason. The near-term impact of engineering is usually constrained by the rate of social change, since technological change occurs with a social, economic, and political context. However, once technology begins to reshape culture, e.g., the Internet or wireless communication, society can change very significantly.

Here it is important to recognize that the technologies–info-bio-nano–that are driving such disruptive change are characterized by exponential evolution, increasing in power by 100 to 1,000 fold each decade. If these technologies continue to evolve at this pace over the next several decades almost any imagined future is possible, as well as some we cannot even imagine. Neural implants capable of linking the human mind directly with the Internet–e.g., fiber to the forehead? These already exist at an early stage. The emergence of a new type of super intelligence? Again, this is already occurring as billions of people begin to interact over the Internet with robust access to the recorded knowledge of human history (think Google or Wikipedia). The capacity to modify humankind through genetic engineering or superhuman prosthesis? Clearly within the grasp of biomedical research. Comprehensive brain scans that allow the downloading of a human mind into cyberinfrastructure? Perhaps...representing the next stage of evolution of the human species (Kurzweil, 2005).

Although the future becomes more uncertain as the pace of technological evolution continues to accelerate, there is one feature that we can predict with some confidence. Engineering practice, research, and education will change both rapidly and dramatically. It would be most unwise to simply extrapolate the rather slow pace of change in these activities characterizing the 20th century to understand the challenges we must face. As Williams suggests, the engineering profession will almost certainly continue to multiply into an even more diverse array of roles and levels since the engagement with rapidly evolving technology rapidly outgrows the existing enterprise. "What engineers are being asked to learn keeps expanding along with the scope and complexity of the hybrid. Engineering has evolved into an open-ended profession of everything in a world where technology shades into science, art, and management, with no strong institutions to define an overarching mission" (Williams, 2003). This multiplicity must be understood, accepted, and accommodated by the forms taken by engineering practice, research, and education in the future.

Perhaps Joe Bordogna summarizes it best when he observes that:

> "The challenge requires a transformation–a continuing revolution, if you will–in engineering education. Our engineering education must go beyond the best to confront the new global realities. We need a model of engineering education suitable to a new world in which change and complexity are the rule, a world continuously transformed by new knowledge and the technology it makes possible, a world

linked globally, where differences and divisions that have not been integrated can have immediate and large-scale consequences. We must understand how to produce the right engineers for our times and our future. Only then can engineering careers become a promising and appealing choice for more of our young people." (Bordogna, 2003)

Chapter 5

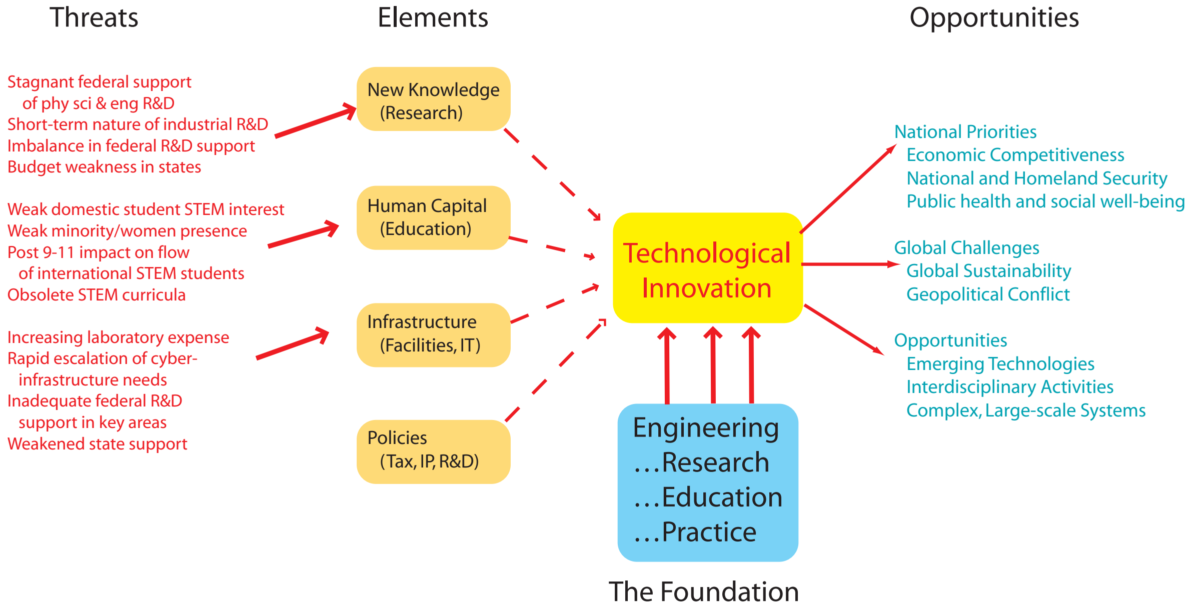
How Far Do We Have To Go? A Gap Analysis

Clearly the challenges facing our rapidly changing world are immense and require the skills of talented engineers, both to address existing needs and to provide the innovative products, systems, and services necessary for prosperity, security, and social well being in the future. Yet these will require very significant changes in engineering–in its practice, its supporting knowledge base, and its education and training. Here many questions must be addressed. For example, what is necessary to provide engineers with the skills, knowledge, tools, learning opportunities, prestige, and influence to address the challenges of a 21st-century world? American engineers face the challenge of providing sufficient value added through their engineering activities to maintain a standard of living significantly higher than that characterizing those parts of the world where engineering services are now being outsourced. And, of course, this is a moving target, since while much of today's off-shoring of engineering involves routine, repetitive services, it is clear that the commitment of other nations to education in science and engineering, the strong work ethic and rising quality of their engineering talent, and the rapidly expanding size of their engineering workforce–particularly in Asia–will allow global sourcing to move rapidly up the value chain to research and development product design, and innovation.

The Gap Analysis

Engineering Practice

Engineering practice is changing rapidly. The United States is part of a global economy driven increasingly by technological innovation and hence engineering. Multinational corporations manage their technology

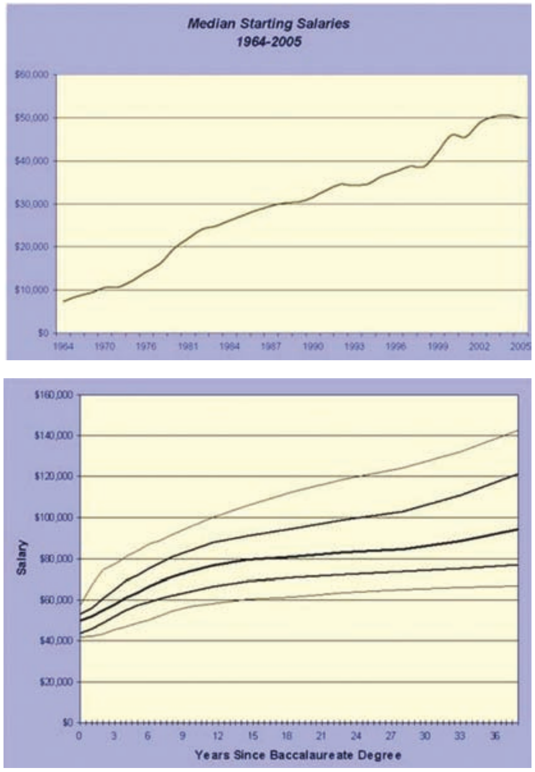


The Challenges to American Innovation

activities to take advantage of the most capable, most creative, and most cost-efficient engineering and scientific talent, wherever they find it. Smaller U.S. firms without global resources are facing stiff competition from foreign companies with access to talented scientists and engineers–many of them trained in the United States with technical skills rivaling the best U.S. graduates. Relentless competition is driving a faster pace of innovation, shorter product life cycles, lower prices, and higher quality than ever before.

In a global economy increasingly driven by technological innovation and the creation of new business, the role of the engineer as innovator and entrepreneur becomes ever more important. Unlike the 20th century, when the large systems engineering projects characterizing the defense industry set the pace for engineering practice, today most of the excitement is in small business development within collaborative-competitive global networks. While many corporations still require a large engineering workforce for product development and manufacturing, others are pushing their engineering activities off-shore to take advantage both of lower labor costs and the rapidly increasing engineering sophistication of nations in Asia making major commitments to science and engineering education for large populations. Clearly American engineers face the challenge of elevating their activities to a higher level of sophistication and value added if they are to be competitive in the global economy.

The prestige of the profession of engineering in our nation requires particular attention, since most Americans tend to view engineers as employees of industry or government rather than learned professionals such as physicians and lawyers. We tend to portray engineers as problem solvers rather than creators and innovators who address the grand challenges of our time–environmental sustainability, world hunger, energy dependence, and the spread of disease. Journalists report scientific achievements and engineering failures, ignoring the profound contributions that engineers have made to dramatically extending the human life span through public infrastructures (Wulf, 2003). How did we let this happen? To some degree the lack of prestige of the engineering profession reflects its continued reliance on undergraduate programs. But it also is due to the tendencies of many companies to treat engineers as commodities, similar to other white-collar employees subject to lay-offs or off-shoring whenever near-term financial pressures arise. Like most professions, compensation reveals the value the marketplace places on engineers. While starting salaries are attractive, at least when compared to most of those received by other baccalaureate majors, compensation flattens off in later years for engineers, falling far behind those of lawyers, physicians, and business executive officers. Clearly for engineering to play the role it must in the future of our nation, the prestige and influence of the engineering profession needs to be significantly enhanced.



Engineering salaries not only lag those of other professions such as business and law but tend to level off after a decade or so in practice.

Of course there continues to be debate over whether the United States faces a shortage of scientists and engineers, and such arguments threaten to undermine the necessary national investments in research and STEM education. While there is little doubt that there has been a decline of interest in these fields, particularly at the graduate level, by top students who instead seek the rewards, prestige, and security of other learned professions such as medicine, law, and business administration, economists tend to argue that in a global economy, the needs for scientists and engineers are being met either by immigrants or outsourcing and off shoring research and engineering services (Wadha, 2006; Teitelbaum, 2007). Of course, this ignores the vulnerability of our national economy and security to a disruption of overseas talent, such as that which occurred following the 9-11 attacks. It also ignores the needs of the defense and intelligence sector, where security clearances require U.S. citizenship. Finally, such narrow assessments also ignore the importance of getting more individuals with science and engineering backgrounds into key leadership positions in business and government, similar to their leadership roles in Europe and Asia where the importance of technology to economic and public policy seems better understood. Just as it would be foolish to limit undergraduate majors in economics because we have too many economists, such assessments of the national need for scientists and engineers usually ignore the fact that the nation desperately needs more leaders with these backgrounds if it is to face the challenges of an increasingly technology-driven world.

As suggested by Lynn and Salzman, the United States must also develop strategies that are less focused on competitive advantage and become more focused on collaborative efforts that leverage increasing global capabilities (Lynn, 2006). In fact, learning how to achieve "collaborative advantage" will replace the 20th-century goal of "competitive advantage" for most companies. For example, as other nations build strong capabilities in engineering research and development, the United States must abandon its goals of scientific and technological hegemony in all areas. Rather it should adopt the philosophy of the Press Report of the National Academies (Press, 1995) by seeking leadership only in those areas of highest national priority and seeking only to be among the leaders in other areas, i.e., "ready to pounce" should the need arise. Key in all activities will be a greater reliance on collaboration with scientists and engineers in other nations.

Yet it is also essential that through both public policy and corporate leadership our nation resist the bandwagon trend to outsource and off shore a dominant amount of our technological activity. It is increasingly clear that economic prosperity, national security, and social well being require a high degree of technological competence as the key to innovation. Short-sighted business leadership more driven by near-term profits or investor pressures toward excessive outsourcing of technological competence will almost certain lead in the long term to financial failure and national vulnerability in an increasingly technology-dependent society.

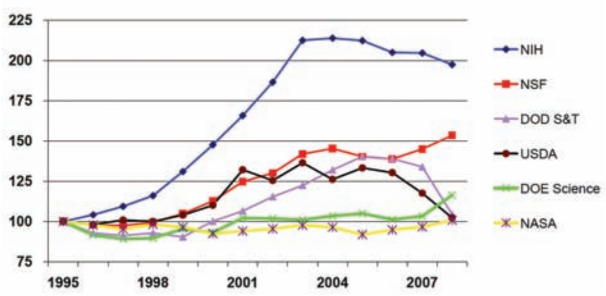
The Engineering Knowledge Base

Key to the nation's prosperity and security in a global, knowledge-driven economy will be its leadership in technological innovation, which, in turn, requires global leadership in engineering research and education. Technological innovation will also be essential in addressing future challenges such as the health care needs of an aging population, homeland security, and global sustainability while exploiting new opportunities presented by rapidly evolving technologies such as info, bio, and nano technology.

While our American culture, based upon a highly diverse population, democratic values, and free-market practices, provides an unusually fertile environment for technological innovation, history has shown that significant federal investment is needed to produce the essential ingredients necessary for innovation to flourish: new knowledge (research), human capital (education), infrastructure (e.g., physical, cyber), and policies (e.g., tax, property).

Even though current measures of technological leadership–percentage of gross domestic product invested in R&D, absolute numbers of researchers, labor productivity, and high-technology production and exports–still favor the United States, a closer look at the engineering research and education enterprise and the age and makeup of the technical workforce reveals several interrelated trends indicating that the United States may have difficulty maintaining its global leadership in technological innovation over the long term. The funding trend is on a collision course with the changing nature of technological innovation, which is becoming increasingly dependent on interdisciplinary, systems-oriented research. These well-documented trends include: (1) a large and growing imbalance in federal research funding between the engineering and physical sciences on the one hand and biomedical and life sciences on the other; (2) increased emphasis on applied R&D in industry and government-funded research at the expense of fundamental long-term research; (3) erosion of the engineering research infrastructure due to inadequate investment over many years; (4) declining interest of American students in science, engineering, and other technical fields; and (5) growing uncertainty about the ability of the United States to attract and retain gifted science and engineering students from abroad at a time when foreign nationals account for a large, and productive, component of the U.S. R&D workforce.

Numerous recent studies (COSEPUP 1998-2003, Vest 2003, Augustine 2005) have warned that federal investment in basic engineering research and engineering education, key to technological innovation, has been stagnant for the past three decades, raising the question of whether the current level of federal investment is adequate to meet the challenge of an increasingly competitive, knowledge-driven, global economy. Although federal support of engineering research and education is provided by numerous federal mission agencies (e.g., DOD, DOE, NASA), the National Science Foundation plays a particularly significant role in linking basic engineering research and education to fundamental scientific discoveries in the physical, natural, and social sciences. There are also increasing concerns that the relatively modest funding of the NSF Engineering Directorate is inadequate to enable NSF to play a significant leadership role in creating the new knowledge, human capital, and infrastructure necessary to sustain the nation's objectives of global leadership in innovation.

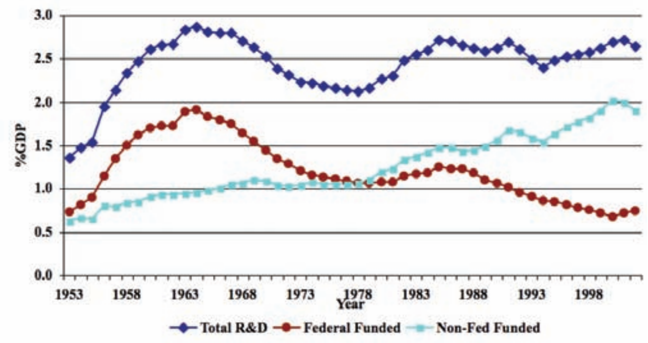


Trends in federal R&D by federal agencies, FY1995-2008 (American Association for the Advancement of Science)

Current federal R&D priorities have led to a situation today in which over 65% of all federal support of academic research flows to the biomedical sciences. Beyond its impact on faculty priorities and student interest, there is some evidence that this imbalance in federal research support is also distorting university funding and capital expansion priorities, thereby eroding even further support for programs in physical science and engineering essential to technological innovation. Most engineering research and education is conducted in public universities, already under great strain from state budget cuts. Without enhanced federal support, the ability of these programs to contribute to the nation's capacity for technological innovation could be seriously threatened by inadequate state support.

One result of the stagnation of federal investment in engineering research has been the deterioration of the engineering research infrastructure at many schools of engineering. Only a few research universities have facilities adequate for advanced engineering research that can support increasingly systems-oriented, interdisciplinary technological innovation. Too many engineering schools operate in old facilities, with laboratory equipment dating from before the invention of the transistor, let alone the personal computer. These institutions do not have the sophisticated laboratories, cyberinfrastructure, or instrumentation necessary for today's technological leadership. Research in many fields of engineering requires sophisticated, expensive equipment and instruments that rapidly depreciate. Effective research in many areas of microelectronics, bioengineering, and materials science requires Class 10 and Class 100 clean rooms and precision instruments; costs for these can exceed $100 million. Research and education in emerging fields, such as quantum computing, as well as established fields, such as nuclear engineering, are suffering for want of resources for the development and/or maintenance of facilities. In fact, it will take billions of dollars to update facilities at hundreds of engineering schools nationwide. This investment, however, would create geographically dispersed, world-class research facilities that would make engineering attractive to more students (at home and from abroad), stimulate cooperation, and maybe competition, among research groups working on related problems, and provide a locus for networks of researchers and clusters of industry across the nation.

Over the past several decades a similar imbalance has arisen in which industrial R&D (primarily applied research and development) now dwarfs federal R&D,



The changing balance of U.S. R&D expenditures

raising a serious concern about whether sufficient applications-driven basic research is being conducted to translate new scientific discoveries into innovative products, processes, and services that address national priorities.

The imbalance in federal funding for research, combined with a shift in funding by industry and federal mission agencies from long-term basic research to short-term applied research, raises concerns about the level of support for long-term, fundamental engineering research. The market conditions that once supported industrial investment in basic research at AT&T, IBM, RCA, General Electric, and other giants of corporate America no longer hold. Because of competitive pressures, U.S. industry has downsized its large, corporate R&D laboratories and reduced its already small share of funding for long-term, fundamental research. Although industry currently accounts for almost three-quarters of the nation's R&D expenditures, its focus is primarily on short-term applied research and product development. In some industries, such as consumer electronics, even product development is increasingly being outsourced to foreign contractors (Engardio, 2005). Consequently, federal investment in long-term research in universities and national laboratories has become increasingly important to sustaining the nation's technological strength. But just as industry has greatly reduced its investment in long-term engineering research, engineering-intensive mission agencies have also shifted their focus to short-term research.

Our nation's leadership in science, engineering, and technological innovation has been due, in part, to the capacity of our universities and industry to attract outstanding students, scientists, and engineers from around the world. Cumbersome immigration policies implemented in the wake of 9-11, along with international reaction to U.S. foreign policy are threatening the ability of the nation's universities and industry to attract and retain the top engineering and scientific talent from around the world, key to its innovation capacity. As other nations invest in their knowledge infrastructure-universities, research laboratories, high tech industry–an increasing number of students, scientists, and engineers are finding attractive career opportunities in their home countries and no longer have the desire to immigrate to America.

To meet the demands of global competition, other countries are investing heavily in the foundations of modern innovation systems, including research facilities and infrastructure and strong technical workforces (NSB, 2003). Some of the innovations that emerge from these investments will be driven by local market demands, but many will be developed for export markets. As other countries develop markets for technology-laden goods and international competition intensifies, it will become increasingly difficult for the United States to maintain a globally superior innovation system. Only by increasing its investment in engineering research and education can the United States retain its competitive advantage in high-value, technology-intensive products and services, thereby encouraging multinational companies to keep their R&D activities in this country.

Engineering Education

Despite the profound changes occurring today in engineering practice and engineering science and technology, we continue to educate and train engineers much as we have for the past several decades. In the curricula of our engineering schools we still stress analytical skills involving scientific and mathematical analysis to solve well-defined problems rather than the broader skills of engineering design, systems integration, and innovation. Bowing to industry and student pressure, we continue to pretend that one can become an engineer with only a four-year undergraduate education, despite the fact that the curriculum has become overloaded, pushing aside the opportunities for the broader type of liberal education required to address the changing nature of engineering practice. A recent summit meeting on the status of mechanical engineering education in the United States concluded that the primary emphasis of engineering programs on scientific fundamentals has led to "a weak link to engineering practice and a lack of emphasis on industrial innovation and the commercialization of technology. Engineering education must be transformed to embrace both fundamentals and practice; both the procedural knowledge of the problem-solving engineer as well as the declarative knowledge of the applied scientist" (Ulsoy, 2007).

So what should we stress as the core competencies of the education of American engineers as we aim to enhance their value-added and hence their value in the global marketplace? More intensive technical training? Perhaps not. Rather we should strive for broader intellectual span, consilience, building on the unusual breadth of American universities. This should be combined with strong skills in knowledge integration, synthesis, innovation, communication, and teamwork.

Engineering students should gain both the capacity and the commitment for lifelong learning, since the technology treadmill is accelerating, and those relying on old skills and past learning will quickly fall off. But even broader skills and abilities are necessary, including the social skills of relating to different cultures, functioning in a global enterprise, and thriving in a world of ever-accelerating change. In a sense, we must shift from emphasizing the mastery of technical content to mastering the process of learning, since the shelf life of the content learned early in college will erode rapidly. Experiential learning will become increasingly important, whether in the laboratory, the design studio, or through internships. Global awareness will place a higher premium on international experiences such as study-abroad programs. And, perhaps as important as anything, we must infuse in our students a new spirit of adventure, in which risk-taking and innovation are seen as an integral part of engineering practice, and where bold solutions are sought to the major challenges facing our world.

Finally we must make engineering education, engineering practice, and the profession of engineering itself more attractive to young people. Today students sense both the narrowness of engineering education and the commodity nature of engineering careers. Why do they prefer professions such as business and law? Not because they find these subjects intellectually stimulating, but because they open doors to further opportunities rather than close down options as an engineering education is perceived to do. We must instead reshape engineering education as the route to creativity and innovation, developing the capacity to understand and control those technological forces driving change in our world. Students need to understand that engineering has become the most important profession in addressing the grand challenges of our time–promoting global sustainability, addressing world health and poverty, and stimulating a new spirit of adventure, exploration, and hope for the future.

Hence to attract the best students, we must strive to create undergraduate engineers who are sufficiently well-balanced to serve a much broader range of student career options than simply professional practice.

Numerous workshops on engineering education have identified possible actions for the near term (e.g., Ulsoy, 2007; NSF, 2007):

- Dropping some of the existing traditional engineering curriculum in favor of material related to soft skills such as communication, leadership, and entrepreneurship.
- Embedding social and global context, leadership, and other broader skills as themes throughout the curriculum.
- Developing broader skills through extracurricular activities.
- Postponing preparation for the engineering profession to the graduate level in order to provide more curriculum (and hence abandoning the practice of ABET accreditation at the undergraduate level).

Yet any such actions will encounter strong opposition. Of course the engineering faculties will immediately insist that the engineering curriculum is already overloaded with necessary material and that removing anything would water down undergraduate programs. Worth noting here, again, is the fact that most engineering faculty members are engineering scientists engaged in research rather than professional practice and sometimes give short shift to broadening the education to include material and develop skills important to the profession. Furthermore such actions will require substantial investment in resources, faculty effort, and, if professional education is shifted to the graduate level, additional expenditures by students and parents. Many universities today tend to view engineering education as a cash cow, much like business administration, and they have been reluctant to make the investments necessary to facilitate change. Most engineering faculty are already on a treadmill, under pressure to teach larger classes, to generate more research funding to support not only their laboratories and graduate students but even part of their own salaries, and to be a good university citizens by participating in the myriad faculty committees and governance characterizing the contemporary university. Furthermore both the lockstep nature of the engineering curriculum and restrictive university policies frequently prevent engineering students from participating in the broader array of educational opportunities available to other students such as study abroad, programs restricted to majors (music, art, business), and an array of extracurricular activities.

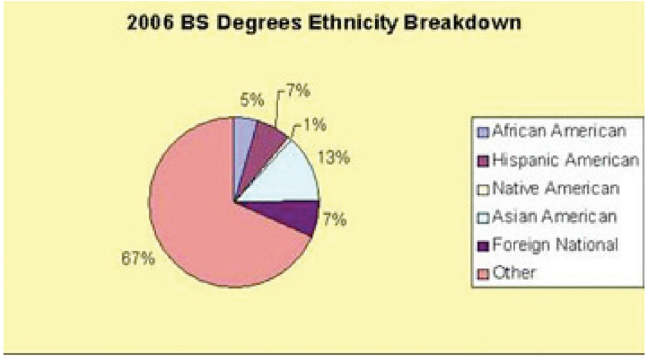
Yet another barrier to innovation in engineering education is the dearth of rewards and recognition of achievement in this activity. Most engineering schools are located in research universities, where faculty rewards such as compensation, promotion, and tenure are determined more by research reputation and grantsmanship than contributions to engineering education. Although the National Academy of Engineering has recently created the Bernard M. Gordon Prize for innovation in engineering education, most awards from academic institutions and engineering societies fall far short in prestige of the peer recognition provided by honors such as election to membership in the National Academy itself. In fact, one of the most significant actions that might be taken by the National Academy of Engineering is to recognize extraordinary achievement and leadership in *engineering education* as a criterion sufficient for membership and to create a new section for such members.

Employers also present a challenge, since they will likely resist anything that extends engineering education, making it more expensive. Unlike medicine, where licensure requirements were utilized by the profession to overcome resistance to cost, industry is likely to turn, at least initially, to further outsourcing of engineering services and off shoring of engineering jobs should the domestic supply become more expensive–at least until greater value-added can be demonstrated. Furthermore they will continue to seek baccalaureate graduates with narrowly defined skills capable of immediate implementation in preference to more broadly educated graduates capable of eventually rising to leadership positions. So too, students and parents are likely to resist the increased costs of an expanded engineering education paradigm, particularly if it requires graduate education for the professional degree–although ironically many are already bearing the additional cost burden of the 4.5 to 5 years it takes to complete today's engineering degree programs.

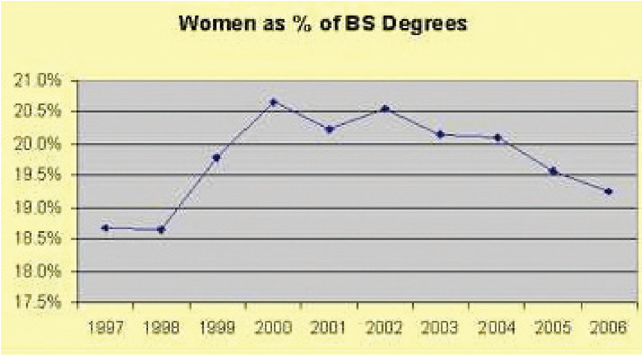
But the strongest resistance to change is likely to come from the profession itself. Engineers are usually a conservative lot, frequently moored to the past, and will insist that the traditions of engineering practice are not only well established but also time-tested and successful (ignoring the implications of engineering's increasing globally competitive character). They will complain that significant dislocation will occur from any major restructuring of the nature and requirements for professional practice, even with grandfathering clauses. While some disciplines such as civil and mechanical engineering may be more receptive, others such as electrical and computer engineering, which tend to downplay the importance of licensure, will see little advantage to such restructuring. Furthermore, many are likely to raise concerns about the impact such restructuring would have on student interest in engineering majors, particularly among women and minority students, already badly underrepresented in the engineering workforce.

To be sure, an important key to any strategy for strengthening U.S. engineering capacity will be attracting into science and engineering careers an increasing number of women and underrepresented minorities. This will require both a major new commitment and more effective strategies for diversifying the nation's science and engineering workforce. We also must make a concerted effort to re-establish the United States as a destination for talented students, scientists, and engineers from around the world. In particular, our immigration policies need a major overhaul to give far higher priority to immigrants with advanced education and skills who can contribute at a very high level to our knowledge economy rather than simply opening our borders to low skill workers willing to assume American jobs at wages too low for domestic workers. While acknowledging the importance of homeland security in the wake of the 9-11 attacks, we also need to once again encourage visits and collaboration between American scientists and colleagues from abroad through more rational visa policies.

Yet here the challenges will be great. An increasing number of Americans oppose the traditional approaches to achieving diversity such as affirmative action or opportunity programs based upon race or gender. Voters are taking aim through referenda at an earlier generation's commitment to civil rights. Courts are pondering cases that challenge programs based on race or gender. Despite a landmark decision by the U.S. Supreme Court in 2003 involving the University of Michigan that stressed the importance of diversity in higher education, there remain reasons for great concern (Duderstadt, 2007). The Court ruled that "Student body diversity is a compelling state interest that can justify the use of race in university admission. When race-based action is necessary to further a compelling governmental interest, such action does not violate the constitutional guarantee of equal protection so long as the narrow-tailoring requirement is also satisfied." Yet in the aftermath of this decision, many successful programs aimed at extending opportunity and participation of underrepresented groups have been discontinued as institutions have chosen to accept a very conservative and restrictive interpretation of the Supreme Court decision as the safest course. This retrenchment has been accelerated by efforts in numerous states (including Michigan) to pass referenda banning the use of race or gender in public institutions, an effort that could eventually reach the federal level and seriously hinder existing affirmative action programs aimed at diversifying educational and career opportunities in fields such as engineering.



Clearly we are falling short of addressing adequately the need for a diverse engineering workforce.



Similar constraints hinder the ability to attract talented engineers and scientists from abroad. Unlike most other nations, current U.S. immigration policy favors family relationships over education level and technical skills. Although there are currently efforts underway to reform immigration policy to better address the human resource needs of the nation in these critical fields, these modifications face an uphill battle in an intensely political environment.

Today we are still falling far short of preparing engineering graduates for practicing–and leading–in a change-driven, knowledge-intensive, global society that will characterize the decades ahead. Few would disagree that the current undergraduate curriculum emphasis on engineering science continues to produce graduates with strong technical skills. But much more is needed not only for engineering practice but for the many other careers likely to attract engineers. Furthermore, many of our best and brightest students tend to turn away from the current narrowly defined engineering curriculum, despite their strong interest in science, mathematics, and technology. The sad fact is that all too many students–and members of the public more broadly–continue to see engineering as more a trade or even a commodity service than a learned profession of immense importance to an increasingly technology dependent world.

Part of the challenge here is encouraging far more experimentation in engineering education and then facilitating the propagation of successful models. As mentioned in Chapter 1, the Flexner Report of 1910 was so influential in transforming medical education because it could point to the successful models such as Johns Hopkins University, which required a baccalaureate education for admission and introduced laboratory and teaching-hospital paradigms to medical education and training. The high visibility given to this model by Flexner led to its rapid adoption as the dominant form of medical education and led to the closure of hundreds of didactic-based medical schools.

It is also the case that in large engineering schools, significant change such as the introduction of more research opportunities for undergraduates or engineering project teams requires substantial investment in faculty time and resources. Hence it is not surprising that much of the innovation in engineering education occurs in smaller programs where the resource requirements associated with change are considerably less–albeit frequently significant relative to the resource base of these programs.

For example, Olin College of Engineering is pioneering a project-based approach, with a heavy emphasis on design, innovation, entrepreneurship, and other aspects of engineering education, coordinated with nearby Babson College of Business to provide the necessary business background. Similarly, the Naval Postgraduate School's graduate engineering programs for mid-level career military officers provide an important model for continuing education. Stanford's tutored off-campus master's program and the National Technological University have provided important models of highly effective distance learning. And the University of Southern California's Institute for Creative Technologies is actively exploring the use of sophisticated simulating and gaming environments for learning. Yet today there are few comprehensive models one can point to as the possible futures for engineering education.

While recent efforts taken to improve engineering education by groups such as ABET are moving in the right direction with their stress on learning outcomes rather than simply resource input, many question their impact on innovation in engineering education. To be sure, the new engineering accreditation criteria were designed to encourage greater innovation. Yet such goals can only be achieved if evaluation teams can rise above simple bean counting demanded by rigid criteria, an aspiration that many deans feel they fail to achieve. Many contend that the current accreditation process continues to discourage radical departure from the status quo. This is particularly ironic in view of the fact that such a rigid approach to standardization flies in the face of one of the great strengths of American higher education, its very diversity, and in an ever-flattening world, makes American engineering and practice even more susceptible to off shoring.

Here it is also important to heed the warnings of academic leaders such as former Harvard president Derek Bok on the dangers of imposing vocational goals on undergraduate majors (Bok, 2006). One might well make the argument that the accreditation of professional (or pre-professional) is antithetical to the purposes of a liberal education and should be avoided at the undergraduate level. In reality, professional accreditation agencies such as ABET are simply not qualified to evaluate or accredit the broader objectives of undergraduate education, a task more appropriate for regional institution-level accreditation groups.

In summary, then, it is clear that entirely new paradigms for engineering education are needed:

* To respond to the incredible pace of intellectual change (e.g., from reductionism to complexity, from analysis to synthesis, from disciplinary to multidisciplinary, from local to global.

* To permeate engineering education with new levels of innovation and continuous improvement informed by scholarly research and based upon evidence-based guidance from validated practices.

* To provide engineering students with the ability to adapt to new technologies (e.g., from the microscopic level of info-bio-nano to the macroscopic level of megacities and global systems).

* To 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.

* To prepare engineering graduates for a lifetime

of continuous learning, while enabling them to enjoy the prestige and influence of other learned professions.

* To reflect in its diversity, quality, and rigor the characteristics necessary to serve a 21st century nation and world.

* To infuse in our students a new spirit of adventure, in which risk-taking and innovation are seen as an integral part of engineering practice, and where bold solutions are sought to the major challenges and opportunities facing our world.

Why Is Change So Slow? And What Can We Do About It?

Change in engineering has proceeded at glacial speed for many decades despite study after study and the efforts of many individuals and groups (e.g., ABET, NAE, and NSF). There are many barriers to change. Considerable resistance comes from American industry, which tends to hire most engineers for narrow technology-based services rather than for substantive leadership roles. All too many companies continue to prefer to hire engineers on the cheap, utilizing them as commodities, much like assembly-line workers, with narrow roles, preferring to replace them through younger hires or off-shoring rather than investing in more advanced degrees.

Resistance to change also comes from university faculty, where the status quo is frequently and strongly defended as the best option. Engineering educators tend to be particularly conservative with regard to pedagogy, curriculum, and institutional attitudes. This conservatism produces a degree of stability (perhaps rigor mortis is a more apt term) that results in a relatively slow response to external pressures. The great diversity of engineering disciplines and roles has created a chaotic array of professional and disciplinary societies for engineering that, in turn, generates a cacophony of conflicting objectives that paralyze any coordinated effort to drive change.

Furthermore today's industrial strategies, educational programs, and government policies are increasingly out-of-date for supporting the key needs of an innovation-driven nation, e.g., generating new knowledge (research), human capital (education), building infrastructure, and putting into place policies that encourage innovation and entrepreneurs. As a result, there are signs that the United States' leadership in engineering research, education, and practice, and consequently capacity for technological innovation is declining relative to other nations.

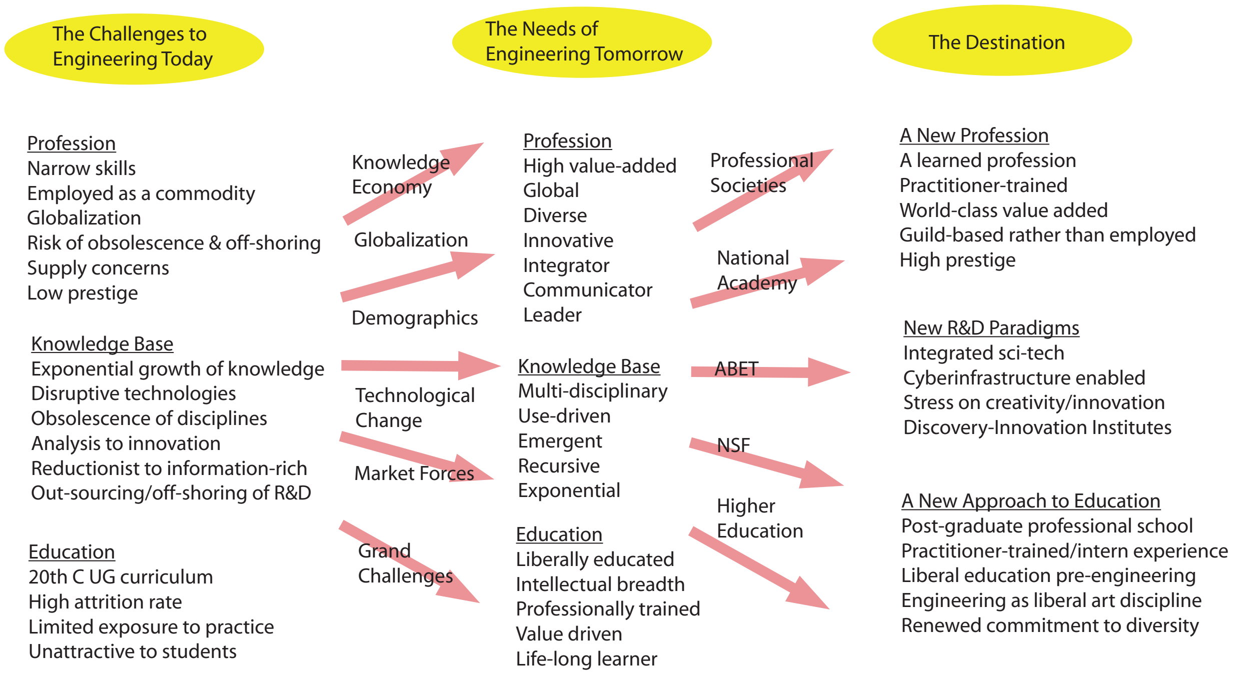
The stakes are high and the time is short. Other nations are making strategic commitments to challenge America's long-standing leadership in technology and innovation. Many enlightened leaders of business and industry are beginning to question whether a blind commitment to further outsourcing and off shoring could leave their company–and their nation–behind with an empty cupboard for technological competence and world-class innovation. Students are beginning to seriously question whether an engineering education is worth the effort and the expense when the projected compensation is so low compared to that of other professions (business, law, medicine) and the risk of obsolescence or off shoring so high. In fact, what is really at stake is the continued existence of American engineering as a world-class asset of this nation.

Yet we face a dilemma: To produce higher value in a hypercompetitive global economy, U.S. engineers clearly need a broader and more integrative undergraduate education, followed by a practice-based professional education at the post-baccalaurate level, and augmented throughout their career with lifelong learning opportunities. Yet they also face a marketplace governed by a business model that seeks the cheapest talent that will accomplish a given short-range goal. Hence the key question: How do we motivate U.S. (or global) companies to pay more for better educated engineers? Can practice-based professional education increase the value of American engineering sufficiently to justify the investment of time and resources? And what will happen to those American engineers without this advanced education? Will they face the inevitability of their jobs eventually being off shored through global sourcing? Could it be that the future of American engineering will become similar to other exportable services: that most routine engineering services and engineering jobs will eventually be off shored, leaving behind a small cadre of well-educated “master engineers” managing global engineering systems to address complex engineering challenges?

Hence our challenge is to overcome this resistance to change and provide recommendations that can comprise a roadmap to a future of engineering more aligned with the imperatives and challenges faced by our world.

Chapter 6

A Roadmap to 21st Century Engineering



A roadmap to 21st century engineering

We finally turn our attention to developing the roadmap that will take us to a vision of engineering practice, research, and education appropriate for a 21st-century world. Here we set out as our destination the following objectives:

1. To establish engineering practice as a true learned profession, similar in rigor, intellectual breadth, preparation, stature, and influence to law and medicine, with an 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 the 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 degree for an increasingly technology-driven and dependent society of the century ahead.

5. To achieve far greater diversity among the participants in engineering, the roles of engineers needed by our nation, and the programs engaged in preparing them for professional practice.

In this chapter we explore these destinations and suggest strategies for achieving them.

As we have suggested in earlier chapters, the stage for these objectives has been set by several conclusions:

1. In a global, knowledge-driven economy, technological innovation–the transformation of knowledge into products, processes, and services–is critical to competitiveness, long-term productivity, economic 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.

2. To compete with talented engineers in other nations 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.

3. 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 outstanding students. Of particular importance is greatly enhancing the role of engineers both in influencing public policy and popular perceptions and as participants in leadership roles in government and business.

4. 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 provide 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, architecture), requiring a broad liberal arts baccalaureate education as a prerequisite for professional education at the graduate level.

However, the resistance to such transformations will be considerable. Industry will continue to seek low–cost engineering talent. Educators will defend the status quo, as they tend to do in most fields. And the great diversity of engineering disciplines and roles will continue to generate a cacophony of conflicting objectives that prevents change. Yet while the views of industry leaders, educators, and professional groups should be considered, it is essential to recognize that American engineering must be transformed if it is to be responsive to the changing needs of a nation, a world, and, of course, prospective and practicing engineers.

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.

A century ago the American Medical Association and the American Bar Association exerted strong political influence at the state and federal level to elevate the educational and licensing requirements for their professions. Yet in contrast with medicine and law, engineering is characterized by numerous disciplines and roles, many of which have their own professional societies. While there are broader organizations such as the National Society of Professional Engineers, the American Association of Engineering Societies, ABET, and the National Academy of Engineering, none has the influence to unite engineers behind a concerted and coordinated effort to break the stranglehold of employers and achieve radical transformation–at least yet.

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.

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, re–create) 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. Although many think of the concept of guild in medieval terms such as craftsmen and apprenticeships, today there are many examples of modern guilds in the learned professions. The practice of law and medicine is sustained by strong laws at the state and federal level that dictate both educational requirements and practice requirements. Similarly, the guilds for actors and writers are enabled by strong laws governing intellectual property. And business guilds such as real estate brokers are sustained by standard business practices such as pricing (e.g., a commission of 6% of the sales price of homes).

While engineering does have some elements of these modern guilds, the great diversity of engineering roles, professional organizations, and clients (employers) prevent 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, engineer-

A sometimes confusing cloud of engineering professional and disciplinary societies

ing 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 language:

* Engineers: from *employees* to *professionals*
* Market: from *employers* to *clients*
* Society: from *occupation* to *profession*

Actually, some of this may already be happening through the rapid evolution of the globally integrated company. The need to build more flexible and responsible organizations, capable of making rapid decisions about how to build, buy, or partner for world class capability is leading to enterprises characterized by aggregations of specialized entities with complementary interests and deep specialization. As a recent IBM study suggests, such a "collaborative, contribution-based environment could shift the role of the business enterprise to one of orchestration and facilitation of these activities, much like medieval guilds." Professionals such as engineers could move freely and frequently among projects and employers–rather clients–to apply their skills (IBM, 2006).

Next Steps (Guilds)

1. Build on the important work of Sheppard, Sullivan, and others engaged in the Carnegie Foundation's project on the professions to understand how the current profession of engineering aligns with (or differs from) the six "common places" of learned professions (see p. 73; Shulman, 1998).

2. Empower (or create) an umbrella organization across all disciplinary and professional engineering organizations (NSPE?, AAES?) with power and influence comparable to the professional organizations governing law (ABA) and medicine (AMA).

3. Enhance the visibility, prestige, recognition, and influence of members of the National Academy of Engineering from industry and government both within their own organizations, the scientific and engineering community, and the American public.

4. Working closely with the National Academy of Engineering, develop a new level of engineering licensing as a pre-requisite for the awarding of professional-practice-based degrees such as

the M. Eng. and D. Eng. Such licensing would be both national in scope and generic across all engineering disciplines and would eventually encompass continuing engineering education.

Expanding the 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, 2005).

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). We summarize the most important of these recommendations below:

Rebalancing the R&D Portfolio: 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.

Re–establishing Research As a Priority for Industry: Long-term basic engineering research should again become a priority for American industry. The federal government should design and implement tax incentives and other policies to stimulate industry investment in long-term engineering research (e.g., tax credits to support private sector investment in university-industry collaborative research).

Strengthening the Links Among Industry and Research Universities: Sustaining the nation's leadership in technological innovation requires far more robust ties between American industry and research universities. Recommended actions include: major new joint initiatives such as the Discovery Innovation Institutes (proposed below and funded through a combination of federal, state, industry, and university support); federal efforts to streamline and standardize intellectual property and technology transfer policies across all of American higher education to better enable the transfer of new knowledge into the marketplace; programs to support industry scientists and engineers as visiting "professors of practice" on engineering and science faculties; and the placement of advanced graduate and postdoctoral students in corporate R&D laboratories. Such actions should be funded through a combination of tax incentives, federal grants, and industry support.

Rebuilding the Infrastructure for Engineering Research: Federal and state governments and industry (through tax incentives) should invest more resources in upgrading and expanding laboratories, equipment, information technologies, and other infrastructure needs of research universities to ensure that the national capacity to conduct world-class engineering research is sufficient to address the technical challenges that lie ahead. Geographically dispersed, world-class research facilities will have the added benefit of making engineering attractive to more students (at home and from abroad), will stimulate a competition of ideas as multiple research groups interact on related problems, and will encourage the emergence of networks of researchers and clusters of industry across the nation.

Enhancing the Diversity of American Engineering: All participants and stakeholders in the engineering community (industry, government, 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 very significant increase in investment from both public and private sources, increasing diversity is clearly essential to sustaining the U.S. scientific and engineering workforce.

Enhancing the Flow of Graduate Scientists and Engineers: The nation should secure an adequate flow of next-generation scientists and engineers through a major federal fellowship-traineeship program in key strategic areas (e.g., energy, info-nano-bio, knowledge services), similar to that created by the National Defense Education Act.

Building Stronger Interest in Engineering Careers: Working closely with industry, professional engineering societies, higher education, and perhaps K-12, the nation should take steps to improve the attractiveness of engineering careers. Possibilities include: upgrading the engineering degree required for professional practice to the graduate level (e.g., M. Eng., D. Eng.); adopting corporate compensation policies for senior engineers comparable to those for senior executives; using tax incentives to encourage industry to make a firm commitment to lifelong learning opportunities for its scientists and engineers to enable them to stay ahead of technological obsolescence.

Implementing More Strategic Immigration Policies: 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.

Similar recommendations have appeared in many reports such as the National Academies' *Rising Above the Gathering Storm* and the Council on Competitiveness's *National Innovation Initiative* (Augustine, 2005; Council on Competitiveness, 2005). The concerns raised by leaders of industry, higher education, and the scientific community have stimulated the federal government to launch two major efforts aimed at sustaining U.S. capacity for innovation and entrepreneurial activities: the administration's *American Competitiveness Initiative* and Congress's *America COMPETES Act* (the latter being 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.

Clearly U.S. leadership in innovation will require such commitments and investments of funds and energy by the private sector, federal and state governments, and colleges and universities. But the NAE Committee on Engineering Research concluded that something more is needed if the United States is to maintain its leadership in technological innovation: a bold, transformative initiative, similar in character and scope to initiatives undertaken in response to other difficult challenges (e.g., the Land Grant Acts, the G.I. Bill, and the government–university research partnerships). America must reshape engineering research, education, and practice to respond to challenges in global markets, national security, energy sustainability, and public health. The changes suggested by the NAE Committee were not only technological, but also cultural, affecting the structure of organizations and relationships between institutional sectors of the country: the federal government, the states, industry, foundations, and academia.

To this end, we strongly support one final recommendation made by the NAE Committee on Engineering Research as an important element of our roadmap for transforming American engineering: the creation of Discovery Innovation Institutes on the campuses of America's research universities (Duderstadt, 2005).

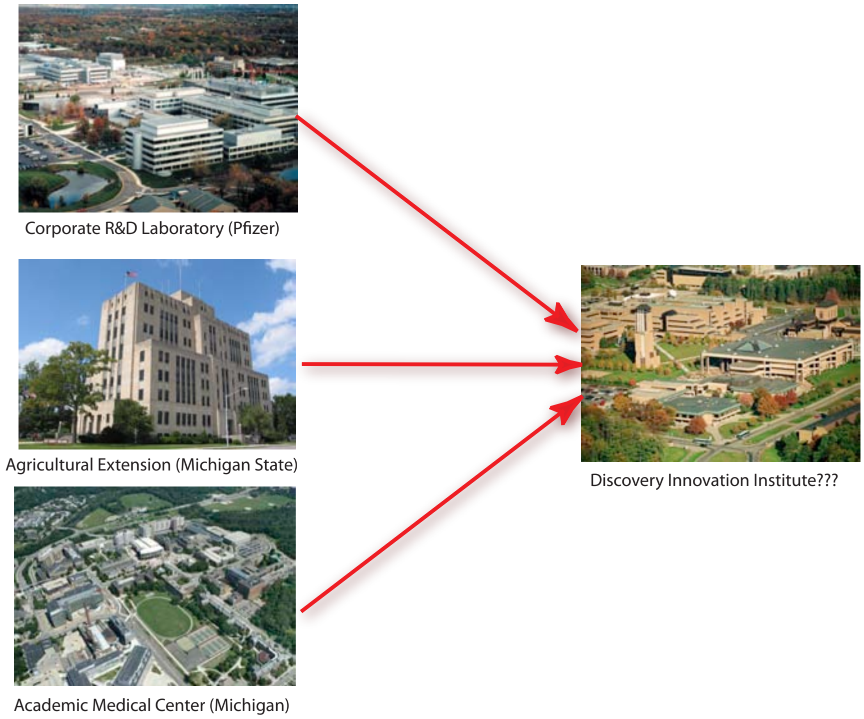
Proposal 2: The federal government, in close collaboration with industry, higher education, and the states, should launch a large number of Discovery Innovation Institutes at American research universities with the mission of linking fundamental scientific discoveries with technological innovation to build the knowledge base essential for new products, processes, and services to meet the needs of society.

One of the most critical–and today most neglected–elements of the innovation process is the long-term research required to transform new knowledge generated by fundamental scientific investigation into innovative products, processes, and services required by society. In years past this applications-driven basic research, sometimes referred to as *Pasteur's Quadrant,* was a primary concern both of major corporate R&D laboratories and campus-based programs such as engineering schools (Stokes, 1997). 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 research has largely disappeared both from the corporate setting and from the campuses, putting at risk the discovery-innovation process in the United States.

Research universities are critical to generating new knowledge, building new infrastructure, and educating innovators and entrepreneurs. The Land-Grant Acts of the 19th century and the G.I. Bill and government–university research partnerships of the 20th century showed how federal action can catalyze fundamental change in higher education. In the past, universities dealt primarily with issues and problems that could be solved either by a disciplinary approach or by a multidisciplinary approach among science and engineering disciplines (e.g., NSF's Engineering Research Centers). To meet future challenges, however, universities will need a new approach that includes schools of business, social sciences, law, and humanities, as well as schools of science, engineering, and medicine. Solving the complex systems challenges ahead will require the efforts of all of these disciplines.

To this end, *Discovery Innovation Institutes* represent a new paradigm aimed at linking fundamental scientific discoveries with technological innovations to create products, processes, and services to meet the needs of society. These new centers would be created through a partnership, very much in the same spirit as the earlier land-grant acts, involving the federal government, the states, industry, and higher education. These campus-based research centers would amount to "miniature Bell Laboratories", capable of conducting the long-term research necessary to convert basic scientific discoveries into the innovative products, processes, services, and systems needed to sustain national prosperity and security in an increasingly competitive world. But the mission and impact of these Discovery Innovation Institutes would be far broader, since they would also stimulate the building of the infrastructure, the interdisciplinary linkages, and the educational programs capable of producing not simply the knowledge needed for innovation, but the engineers, scientists, innovators, and entrepreneurs necessary to sustain this nation's leadership in innovation.

Discovery Innovation Institutes would be operationally similar to corporate R&D laboratories since they would link fundamental discoveries with the long-term engineering research necessary to yield innovative products, services, and systems. Their responsiveness to societal priorities would be similar to the agricultural experiment stations and extension services that stimulated modern agriculture in the last century. And like academic medical centers, they would bring together research, education, and practice. Beyond developing new technologies, they would educate the next generation of engineers while stimulating significant commercial activity as clusters of startup firms, private research organizations, suppliers, and other complementary groups and businesses located nearby, stimulating regional economic development.



Operationally, Discovery Innovation Institutes would be similar to corporate R&D laboratories, agricultural extension services, and academic medical centers.

The Discovery Innovation Institutes would have the following characteristics:

<u>Partnership</u>: The federal government would provide the core support for the Discovery Innovation Institutes on a long-term basis (perhaps a decade or more, with possible renewal). States would contribute to the institutes through cost-sharing requirements (perhaps through the provision of capital facilities). Industry would be partners, both providing staff to work alongside university faculty and students in the centers and through direct financial support. The universities would commit to providing the policy framework (e.g., transparent and efficient intellectual property policies, faculty appointment flexibility, skillful financial management) and necessary additional investments (e.g., in physical facilities and cyberinfrastructure) necessary for the Discovery Innovation Institutes to achieve their mission.

<u>Interdisciplinary Character</u>: Although most Discovery Innovation Institutes would involve engineering schools (just as the agricultural experiment stations involved schools of agriculture), the centers would require strong linkages with other academic programs where fundamental new knowledge is being generated through curiosity-driven research as well as other disciplines critical to the innovation process (e.g., business schools, medical schools, and other professional programs). These campus-based centers would also attract both the participation and possible philanthropy of established innovators and entrepreneurs.

<u>Education</u>: Engineering schools and other disciplines related to the centers would be stimulated to restructure their organization, research activities, and educational programs to reflect the interdisciplinary team approaches necessary for

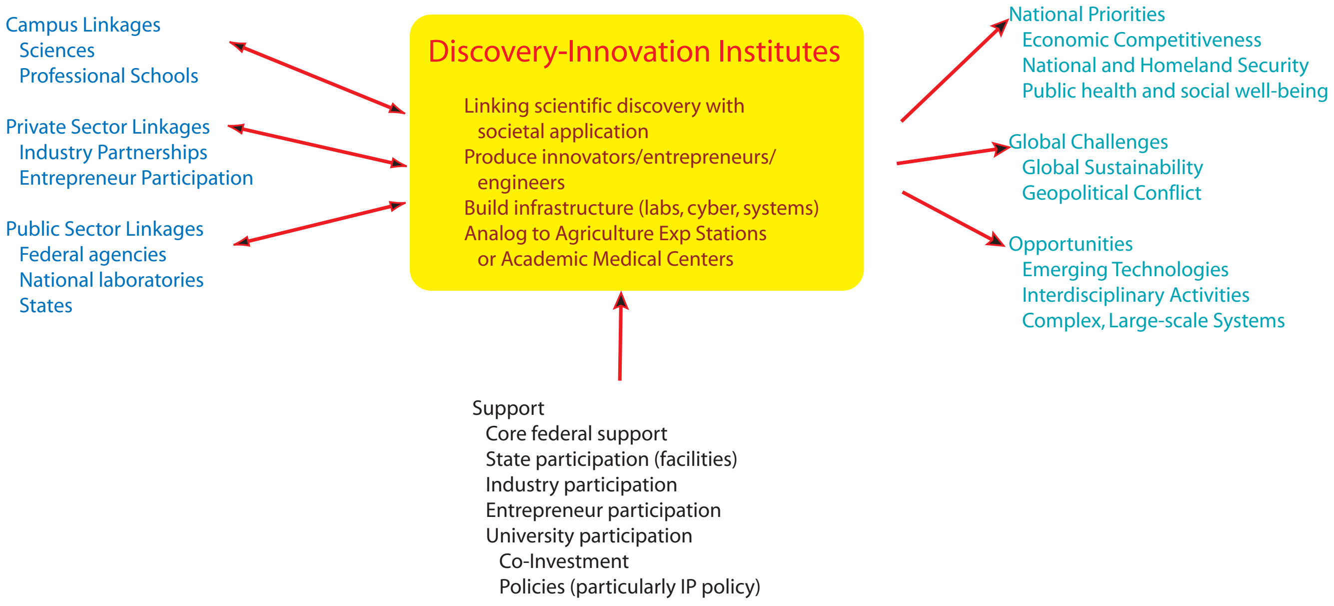
> research aimed at converting new knowledge into innovative products, process, services, and systems while producing graduates with the skills necessary for innovation.

At the federal level, the Discovery Innovation Institutes should be jointly funded by agencies with responsibilities for basic research and missions that address major national priorities (e.g., NSF, NIH, DOE, NASA, DOD, DHS, DOT, DOC, and EPA). States would contribute to the institutes (perhaps by providing capital facilities). Industry would provide challenging research problems, large-scale systems capability, and real-life market knowledge, as well as staff who would work with university faculty and students in the institutes. Industry would also fund student internships and provide direct financial support for facilities and equipment (or share its facilities and equipment). Universities would commit to providing a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure). Finally, the venture capital and investment community would contribute expertise in licensing, spin-off companies, and other avenues of commercialization.

This initiative would stimulate and support a very wide range of Discovery Innovation Institutes, depending on the capacity and regional characteristics of a university or consortium and on national priorities. Some centers would enter into partnerships directly with particular federal agencies or national laboratories to address fairly specific technical challenges, but most would address broad national priorities that would require relationships with several federal agencies. Awards would be made based on (1) programs that favor fundamental research driven by innovation in a focused area; (2) strong industry commitment; (3) multidisciplinary participation; and (4) national need. Periodic reviews would ensure that the institutes remain productive and continue to progress on both short- and long-term deliverables.

Discovery Innovation Institutes could take many forms, as suggested by the examples below:

* Institutes linking engineering with the physical sciences, social sciences, environmental sciences, and business programs to address the urgent national challenge of developing sustainable en-



A possible strucure for Discovery Innovation Institutes ergy sources, including, for instance, the production, storage, distribution, and uses of hydrogen–based fuels for transportation.

* Institutes linking engineering with the creative arts (visual and performing arts, architecture, and design) and the cognitive sciences (psychology, neuroscience) to conduct research on the innovation process per se.

* Institutes linking engineering systems research with business schools, medical schools, schools of education, and the social and behavioral sciences to address issues associated with the knowledge-services sector of the economy.

* Institutes linking engineering with social sciences and professional schools to conduct research on communication networks to determine capacity, identify bottlenecks, estimate extensibility, and define performance characteristics of complex systems that comprise terrestrial, wired, wireless, and satellite subnets, as well as the legal, ethical, political, and social issues raised by the universal accessibility of information.

* Institutes linking engineering, business, and public policy programs with biomedical sciences programs to develop drugs, medical procedures, protocols, and policies to address the health care needs and complex societal choices for an aging population.

Using as models the earlier Land Grant Acts or the level of applications-driven basic research in industry during earlier periods, the NAE Committee on Engineering Research proposed that total federal support of these Discovery Innovation Institutes should build to a level of $5 billion to $10 billion a year to have the necessary impact on the nation’s capacity for innovation. Although federal and state budgets are severely constrained at this time, the growing national public understanding of the critical need for public investment in research to sustain national security and prosperity would give this program the necessary priority. The level of investment and commitment would be analogous to the investments in the late nineteenth century that created and sustained the agricultural experiment stations, which endure to this day and have had incalculable benefits for agriculture and the nation as a whole. We expect similar results from Discovery Innovation Institutes.

Next Steps (Discovery Innovation Institutes)

1. Modify the current language authorizing the creation of discovery–innovation institutes in current Congressional legislation, i.e., the Senate bills introduced in both 2006 (S. 2197 Protecting America’s Competitive Edge through Energy Act) and 2007 (S. 771 The America COMPETES Act), to conform more accurately to the recommendations of the National Academy of Engineering report, which recommended these be co-located with research university campuses rather than restricted to national laboratories.

2. Direct the National Science Foundation to host a series of workshops to better refine the discovery–innovation institute concept as a multi–federal agency effort that would eventually be funded at the suggested level of $5 billion/year.

3. Launch the first wave of federally funded discovery innovation institutes in the critical area of energy research (see an example of such a network provided in Appendix C).

Transforming Engineering Education

The challenges we face in transforming engineering education can be summarized by quoting from a recent bulletin for Princeton’s program in engineering and applied science:

> “For too long traditional engineering education has been characterized by narrow, discipline-specific approaches and methods, an inflexible curriculum focused exclusively on educating engineers (as opposed to all students), an emphasis on individual effort rather than team projects, and little appreciation for technology’s societal context. Engineering education has not generally emphasized communication and leadership skills, often hampering engineers’ effectiveness in applying solutions. Engineering is perceived by the larger community to be

> specialized and inaccessible, and engineers are often seen as a largely homogenous group, set apart from their classmates in the humanities, social sciences, and natural sciences. Given these perceptions, few women and minorities participate in engineering, and non–engineering students are rarely drawn to engineering courses" (Princeton, 2004).

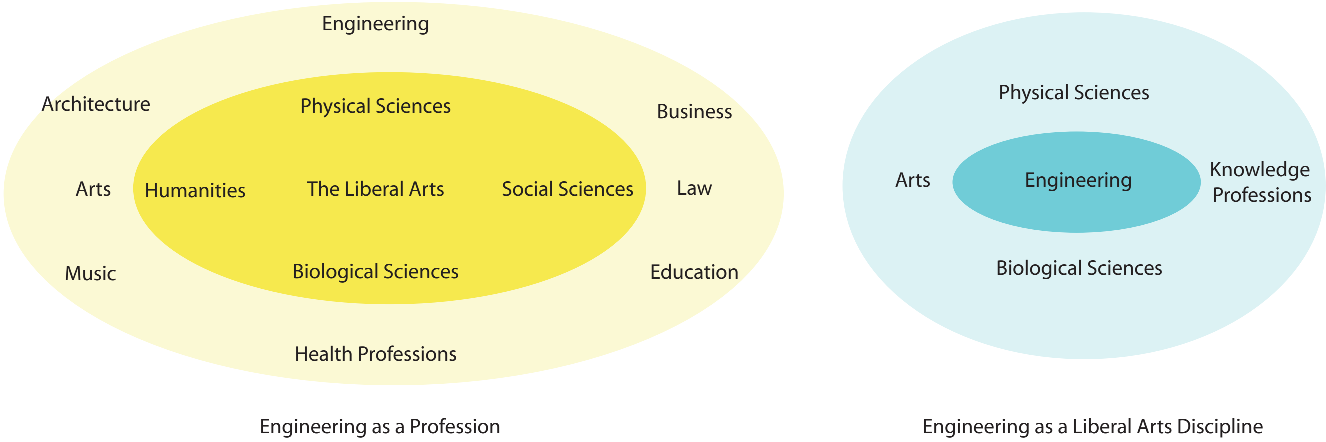
Many nations are investing heavily in developing their engineering workforce within cultures in which science and engineering are regarded as exciting, respected fields by young people and as routes to leadership roles in business and government–in contrast to the relatively low popularity and influence 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 four 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, and 4) to include the academic discipline of engineering (or more broadly technology) in a 21st-century liberal arts canon suitable for all undergraduate students. 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.

A century ago, at the time of the Flexner Report, both law and medicine required only a brief period of



The separation of engineering as a profession and a discipline college-level study beyond a secondary education for practice. However the growing knowledge and practice demands of these professions soon strengthened the requirements for entry to a baccalaureate degree followed by three or four years of professional education and training, which have lengthened still further in medicine to requirements for additional training through internships, residencies, and postdoctoral study. Yet despite the explosion of the scientific and technical knowledge base and the rapidly changing character of engineering practice, engineering education continues today to be focused at the undergraduate level.

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 two- or three-year, practice-focused degree programs (e.g., M. Eng. or D. Eng.). 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.

Yet here we face the formidable problem since we have few existing models to build upon in the way that Abraham Flexner utilized Johns Hopkins University as his model for the future of medical education. Instead most of our existing engineering schools are heavily discipline-based, providing the science, mathematics, and engineering science instruction that undergird engineering, but with little of the professional training and experience that professional schools in other disciplines provide (e.g., moot courts or clinical rounds).

As we have noted earlier, most engineering faculty today are, in reality, engineering scientists, focusing their professional activities on research rather than professional practice. Little of the pedagogy used in engineering schools has immediate connection to engineering practice and instead is based on the lecture and laboratory paradigms characterizing the sciences. While there are important efforts to push engineering education out of the lecture hall and into experiential learning, these are usually based on laboratory-based instruction (perhaps augmented by student research opportunities), design studios (more similar to those of architecture studios than the skunkworks characterizing engineering practice), and student projects (e.g., the solar car competition). We really have no analog to teaching hospitals or law clinics. As a result, today's engineering students must depend on summer employment, cooperative education, and early employment to provide their first exposure to engineering practice and training.

So how might such a true professional school be designed? Garner and Shulman stress that professions, almost by definition, consist of individuals who are given a certain amount of prestige, influence, and autonomy in return for performing a set of services in a disinterested way (Shulman, 1998, 2005). They are more driven by community interest than personal interest. They suggest that the primary characteristics of all professions are:

- A commitment to serve in the interests of clients in particular and the welfare of society in general
- A body of theory or specialized knowledge with its own principles of growth and reorganization
- A specialized set of professional skills, practices, and performances.
- The developed capacity to render judgments with integrity under conditions of both technical and ethical uncertainty.
- An organized approach to learning from experience both as individuals and collectively and thus of growing new knowledge from the contexts of practice;
- The development of a professional community responsible for the oversight and monitoring of

> quality in both practice and professional education.

As Sullivan notes, three educational elements are required for entry into a profession:

1. The first is focused on the cognitive demands of the academy, weighing academic credentials over practical competence.
2. The second links academic preparation to practice through clinical and practical training.
3. Finally, there is the shaping of the future practitioner as a member of a specific community of practice, integrating learned competence with educated conscience.

The professional school serves as almost an apprenticeship where faculty, themselves experienced and continually involved in professional practice, "initiate and guide beginning students into the mysteries of their guild" (Sullivan, 2005). Although students obtain the knowledge base necessary to practice the profession–e.g., the concepts, skills, and traditions–through formal education, they are expected to remain current with the growth and changes in the knowledge important to their profession through further education throughout their careers.

Of course, each profession is characterized by unique educational experiences–what Shulman terms "signature pedagogies"–that instruct novices how to think, perform, and act with integrity. The Socratic method used in law schools, coupled with moot court experiences and law clinics, introduces law students to the styles of thinking and conduct of the legal profession. Medical schools have increasingly shifted away from didactic methods–even for the instruction in the medical sciences–and instead depend on both clinical and laboratory experiences to train physicians (Shulman, 2005).

Here part of the challenge we face in designing true engineering professional schools is to identify and develop an appropriate signature pedagogy for engineering education. The lecture and laboratory methods used in scientific disciplines seem quite inadequate for this purpose. Furthermore, while design studios, student projects, and student research experiences are useful tools to stimulate learning, they fall short of what will be required to educate the professional engineer of the future.

Speculating a bit about the structure of such schools, it seems clear that they would have to exist at the graduate level, requiring a B.S./B.A. in science, mathematics, or "pre-engineering". Here, while an undergraduate major in the discipline of engineering, such as those currently taught in our engineering schools, might be an appropriate pre-engineering program, many of today's undergraduate engineering programs are overly specialized, much like the B.B.A. in business administration, and do not allow a sufficiently broad liberal education at the undergraduate level to support lifelong professional practice and continued learning in engineering. Since the nature of engineering practice is quite different from the problem-solving and research activities of the scientist, some thought needs to be given to the metrics one would use in admitting students to a professional engineering program. Here we are likely seeking something quite different than simply aptitude in science and mathematics. Instead we need to find a better predictor of success in activities such as synthesis, design, innovation, systems integration, and entrepreneurial activities. In fact, medical schools are increasingly admitting students from the humanities and social sciences to M.D. programs to produce more broadly educated and capable physicians, and engineering professional schools might do the same (albeit with strong science and mathematics backgrounds).

A new paradigm for an engineering professional school?

The M.Eng. 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, a more extended program 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 possibly students, if designed properly, the value provided by the additional years of study invested in a graduate professional degree in engineering would far 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).

There are several possibilities for clinical experience in engineering practice, along the lines of the teaching hospital or law clinic. While sophisticated intern experiences in industry are certainly a possibility–if carefully designed and monitored by the faculty–it may be desirable to create specific opportunities more closely related to campus-based activities. Here the Discovery Innovation Institutes mentioned earlier in this chapter would be one attractive possibility. Another would involve the creation of captive, for-profit engineering consulting or services companies, managed by professional engineers and staffed by student interns.

While the level and rigor of education and training we are suggesting for this new practice-based graduate degree are similar to those of medicine and law, it is also important to point out several differences. Law and medicine are “point of service” professions, based heavily upon professional services provided to individuals (e.g., clinical care or legal defense). Engineering practice is one or more degrees removed, since it provides technology (products, systems) that, in turn, provides the services.

Furthermore, while it is tempting to contrast the proposed professional practice degree with undergraduate engineering education using the analog of the contrast between the M.D. and the allied health professions (e.g., nursing, public health), perhaps a more accurate comparison is found in business education. Here, the undergraduate B.B.A. is regarded as a degree primarily suited for non-executive roles, e.g., accounting, sales, and marketing, while the graduate M.B.A. is identified as the degree appropriate for executive leadership.

Finally, a very strong involvement of the engineering profession in the design, accreditation, and support of these new professional schools would be essential. Organizations such as the National Society of Professional Engineers, the American Association of Engineering Societies, the National Academy of Engineering, the American Society for Engineering Education, and, of course, ABET would be key players.

There are several models of such professional engineering education we might look to for guidance. Many engineering schools already have developed professionally oriented masters programs, substituting a project work or an internship in place of a research thesis. Some have also developed specific M.Eng. programs for industry, working closely with particular companies to address particular needs of practicing engineers. Here Stanford’s tutored Internet instruction paradigm, Michigan’s global engineering program with General Motors, and Johns Hopkins programs for the defense industry are examples.

Perhaps the most highly developed practice-based engineering professional program is MIT’s David H. Koch School of Chemical Engineering Practice. Founded over 75 years ago, the MIT Practice School utilizes a carefully constructed internship program to introduce professional training and experience that requires intense effort on several industry projects at an advanced technical level within engineering teams working closely with company personnel and management. Here it is important to stress that unlike cooperative education, the students are not employees of particular companies but rather organized into teams of consultants, working closely with an MIT station director in the company, an approach particularly well suited to building the guild culture proposed earlier in this chapter for the engineering profession. The Koch Chemical Engineering Practice School not only provides experience in applying technical skills but also develop communication, leadership, and other professional skills. The program is demanding, involving problem definition, resource management, and extensive interaction with company personnel. It leads to the M.S.CEP (Master of Science in Chemical Engineering Practice).

These practice-oriented masters programs could provide a useful basis for developing post-graduate engineering professional schools. In fact, one might imagine the creation of institutes within or connected to existing colleges of engineering to conduct such professional M.Eng. and D.Eng. programs, staffed primarily by senior engineers–"professors of practice"–with considerable professional experience (including retired industry leaders) operating in an environment free from the usual academic constraints of tenure-track faculty.

Next Steps (Professional Schools)

1. Build engineering professional schools as a coordinated effort involving current professional development graduate programs for practicing engineers (e.g., Stanford's Center for Professional Development, Georgia Tech's Center for Distance learning, Michigan's Center for Professional Development, Johns Hopkins' Engineering programs for Professionals).

2. Commission the National Academy of Engineering to convene a blue ribbon commission of members drawn from industry and government to develop the content for both two–year and three-year professional degree programs in engineering, assisted by educators, and involving close cooperation with organizations such as NSPE, AAES, and ASEE.

3. Seek support from key foundations to enable the launch of "green–field" experiments to build new professional schools of engineering similar to the undergraduate experiment of Olin College.

4. Explore engineering analogs to the academic medical center by combining the creation of a Discovery Innovation Institute and a closely affiliated engineering professional school with existing engineering schools (i.e., including undergraduate and graduate engineering degree programs). (See Appendix C for an example.)

5. Infuse more professional content into existing engineering programs by encouraging engineering schools to appoint to their faculties engineers with distinguished careers in industry and government as Professors of Practice, similar to those at leading institutions such as MIT and Stanford

If the professional elements of an engineering education were shifted to a true post-graduate professional school, it 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 professional practice.

Here we propose that the discipline of engineering would be taught by existing engineering schools through both degree programs at the undergraduate and graduate level and 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 investigation (e.g., see Vincenti, 1990). Furthermore, in the near term 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 challenged. Although science and engineering are heavily based on laboratory methods, in fact they are usually taught through 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, 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 might consider adopting 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.

Yet as any engineering dean will quickly note, a significant shift from the lecture paradigm to more research or experiential learning through undergraduate research experiences, team design projects, or internships will require a substantial investment of faculty time and financial resources. Since many engineering programs are already struggling with faculties overloaded by undergraduate engineering enrollments, burdensome research administration obligations, and stagnant or declining budgets, both the time and dollars required for major transformation from the current lecture-based mode are in short supply.

The ever narrower specialization among engineering majors is driven largely by the reductionist approach of scientific analysis rather than the highly integrative character of engineering synthesis. While this may be appropriate for 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.

But there is an even more important transformation in engineering education that simply must occur. It is useful to step back and consider more carefully the fundamental purposes of a college education. At the core of these considerations is 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." Or, in the more flamboyant terms of Emerson, "Colleges have their indispensable office, to teach elements. But they can only serve us when they aim not to drill but to create; when they gather from afar every ray of various genius to their hospitable halls, and by the concentrated fires, set the hearts of their youth on flame."

Today the purpose of the liberal arts in a college education can be found enshrined in the introduction to most college bulletins, for example:

> "Liberal arts education aims to train a broadly based, highly disciplined intelligence without specifying in advance what that intelligence will be used for. In many parts of the world, a student's entry into higher education coincides with the choice of a field or profession, and the function of education is to provide training for this profession. A liberal arts approach differs from that model in at least three ways. First, it regards college as a phase of explo-

> ration, a place for the exercise of curiosity and the discovery of new interests and abilities, not the development of interests fully determined in advance. Second, though it permits (even requires) a measure of focus, liberal arts education aims at a significant breadth of preparation, storing the mind with various knowledge and training it in various modes of inquiry rather than building strength in one form alone.
>
> "Third and most fundamentally, liberal arts education does not aim to train a student in the particulars of a given career. Instead its goal is to develop deep skills that people can bring to bear in whatever work they eventually choose. These skills include but are not confined to: the ability to subject the world to active and continuing curiosity and to ask interesting questions; the ability to set a newly-noticed fact in a larger field of information, to amass relevant knowledge from a variety of sources and bring it to bear in thoughtful, discerning ways; the ability to subject an object of inquiry to sustained and disciplined analysis, and where needed, to more than one mode of analysis; the ability to link and integrate frames of reference, creating perceptions that were not available through a single lens; the ability to express one's thoughts precisely and persuasively; the ability to take the initiative and mobilize one's intelligence without waiting for instructions from others; the ability to work with others in such a way as to construct the larger vision no one could produce on his own; the sense of oneself as a member of a larger community, local and global, and the sense that one's powers are to be used for the larger good" (Yale, 2003).

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. As provost Linda Katehi of University of Illinois states it, "The goal of an engineering education should be to teach our students how to learn rather than what to know" (Katehi, 2007).

In our proposal one would define engineering as a discipline suitable both for undergraduate majors and for students in other majors 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., M. Eng., Ph.D.). Students wishing 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 soon require further education and training to remain relevant. Other undergraduates 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.). Clearly this greater diversity of engineering programs would require a more sophisticated effort to get meaningful information out to prospective students to enable them to make wise decisions about their future studies.

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 and instead 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 also 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. And 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 (Ohland, 2007), 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 (such as those Olin College has developed for students at Wellesley and Brandeis) provide 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 premed students.

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.

One further opportunity would be enabled by broadening the undergraduate preparation for engineering careers: it would provide a more strategic alignment with a possible national commitment to 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."

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 (Miller, 2006).

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 off shoring 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 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.

Next Steps (Engineering Education)

1. Ask the National Academy of Engineering to re–evaluate the appropriateness in today's world of the recommendations made 40 years ago by the ASEE Report on "The Goals of Engineering Education" (1968) in response to a request by the ECPD, i.e.,
   * The first professional degree in engineering should be the Master of Engineering degree, awarded on completion of an integrated program of at least five years. The first four years would concentrate on the common engineering core, with specialization occurring in the fourth year.
   * The credits required for a pre-engineering bachelor's degree should be reduced by 15%.
   * ECPD (today ABET) should gradually shift their accrediting activity away from the bachelor's degree to the master's degree.
   * The accreditation of discipline–based degree programs should be replaced by accreditation of the engineering unit as a whole. (Here reflecting the view of many ASEE leaders that discipline-based undergraduate curricula be replaced by undesignated curricula, patterned after the "engineering science" model of the 1955 Grinter Report, with disciplinary specialization in a fifth year master's program.)

2. Utilize the work of Sheppard and Sullivan (Carnegie Foundation) to develop a taxonomy of engineering programs and institutions (e.g., undergraduate professional degrees, engineering and applied science, design-innovation based, engineering management, liberal arts based (B.A.), etc.). (Sheppard, 2008)

3. Stimulate more activity in the scholarship of engineering education and learning, encouraging investment in research and the adoption of evidence-based approaches to innovation and continuous improvement while providing recognition to engineering educators of great distinction through honors such as election to the National Academy of Engineering (establishing a new section of the NAE devoted to engineering education).

4. Transform the current faculty paradigm, based primarily on the scholarly requirements of the physical sciences, to accommodate in addition "professors of practice", analogous to the clinical faculty of medical schools or performance faculty of the performing and visual arts, who stress professional practice rather than basic research

in their activities and pedagogy.

5. With the support of both federal agencies (particularly NSF but also mission agencies such as DOD, DOE, and NASA), foundations, and industry, encourage the exploration of more radical experiments in engineering education similar to those at Olin College or the Cambridge-MIT Institute (design-innovation), RPI (studio-based), Caltech (multidisciplinary with the sciences), and Princeton (B.A. engineering programs for leadership roles). The engineering accreditation process and accreditation teams would not be allowed to constrain or interfere with such experiments.

6. Through a series of federally-, foundation-, and industry-funded experiments, explore the development of a series of educational programs (steps) designed to provide lifelong learning opportunities for practicing engineers (e.g., integrating the goals and methods of undergraduate education, graduate professional education, continuing education, workplace learning, and professional development).

This brings us to a broader proposal for a 21st-century college education:

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 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. In the history of education, the seven liberal arts comprised two groups of studies: the *trivium* and the *quadrivium*. Studies in the trivium involved grammar, dialectic (logic), and rhetoric; and studies in the quadrivium involved arithmetic, music, geometry, and astronomy. These liberal arts made up the core curriculum of the medieval universities. 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 society. It once emphasized the education of elites in the classics; but, with the rise of science and humanities during the Age of Enlightenment, the scope and meaning of “liberal arts” expanded to include them. 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.

William Wulf reminds us of another important belief of Thomas Jefferson: one cannot have a democracy without informed citizens. But here Wulf warns that today we have a society profoundly dependent upon technology, profoundly dependent on engineers who produce that technology, and profoundly ignorant of technology: “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 at least technology–should be added to the set of liberal arts disciplines, much as the natural sciences were added to the trivium and quadrivium 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.

Next Steps (Engineering in the Liberal Arts Canon)

1. Ask the National Science Foundation, working through the National Academy of Engineering, to launch an effort to identify and establish the intellectual core of a engineering-technology "distribution" requirement for liberal arts majors.

2. Ask the NSF to fund a series of coordinated efforts at the campus level to develop, implement, and assess such a sequence in various institutional types (e.g., liberal arts colleges, comprehensive universities, research universities).

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.

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 consisted with the American population.

A recent study by the National Science Board stated the challenge well:

"The future strength of the US S&E workforce is imperiled by two long-term trends:

1) Global competition for STEM talent is intensifying, such that the U.S. may not be able to rely on the international labor market for still unmet skill needs.
2) The number of native-born STEM graduates entering the workforce is likely to decline unless the nation intervenes to improve success in educating STEM students from all demographic groups, especially those that have been under-represented in science and engineering careers.

Since an increasingly large share of the workforce will consist of women, underrepresented minorities, and persons with disabilities, groups persistently underrepresented in STEM careers, this is where we must turn our attention" (NSB, 2003).

The National Academy of Engineering went further by recommending:

"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)

Yet, in view of the increasing challenges through the courts or referenda to the traditional mechanisms used to achieve diversity–e.g., affirmative action and equal opportunity programs based on race or gender–new approaches must be found. To this end, it is important to recognize that most institutions (universities, corporations, government) are actually biased against diversity since they usually circle the wagons to protect the status quo. Hence efforts to enhance diversity are, in reality, exercises in fundamental institutional change. And in this sense, achieving diversity requires both strong commitment and active leadership from the top of the organization–engaging, listening, and learning from under-represented communities–and eventually

Key to the future of engineering education: diversity and innovation

picking up the flag and leading the troops into battle. It also requires a highly strategic approach, investing in what is found to work, and either fixing or abandoning efforts that fail.

It is important to note the successful efforts of several technical colleges (MIT, Caltech, RPI) achieving substantial gains in the enrollment of women (respectively 44%, 37%, and 31% women in all programs), through concerted outreach efforts that are sensitive to interests in fields such as life sciences, biomedical, and environmental engineering and the desire for more flexibility and breadth in undergraduate majors that enable the broader career interests of women students. This provides evidence that significant progress can be made, at least for highly selective programs with strong reputations for academic quality.

Richard Atkinson suggests that in today's political climate, it may require as well an entirely different philosophy of social inclusion. It is clearly the case that today many believe that despite the importance of diversity, racial or gender preferences are contrary to American values of individual rights and the color- and gender-blindness that animated the Civil Rights Act of 1964 (Atkinson, 2005). He suggests that we need to adopt a new strategy that recognizes the continuing corrosive force of racial and gender inequality but does not stop there. We need a strategy grounded in the broad American tradition of opportunity, because opportunity is a value that all Americans understand and support. We need a strategy that makes it clear that our society has a stake in ensuring that every American has an opportunity to succeed–and that every American, in turn, has a stake in equality of opportunities and social justice in our nation.

To that end, let us return to an important theme that has run throughout this report: the growing recognition that in an age of knowledge in a global economy, educated people, the knowledge they produce, and the innovation and entrepreneurial skills they possess have become the keys to economic prosperity, social well-being, and national security. Moreover, education, knowledge, innovation, and entrepreneurial skills have also become the primary determinants of one's personal standard of living and quality of life. Hence one could well make the case that democratic societies–and their governments and institutions at all levels–must accept the responsibility to provide all of their citizens with the educational and training opportunities they need as a *civil right*. This was one of the animating themes of the recent National Commission on the Future of Higher Education in America (Miller, 2006) and it could well provide the framework for a new, concerted, and stragetic effort to diversify the opportunities for and participation in engineering careers that would address the needs of the nation.

Next Steps (Diversity)

1. Working closely with organizations such as NACME, inventory and assess the vulnerability of various institutional, state-based, and federal programs aimed at enhancing the diversity of engineering education and the engineering workforce to the current legal and political environment.

2. Through learning outcome and professional achievement measures, assess the effectiveness of current engineering program admission criteria (e.g., standardized test scores such as the SAT and ACT, advanced placement courses, secondary school grade-point and graduation rank measures) in predicting both academic performance and career success, with broadening admission criteria to enable a more diverse student body.

3. Ask the NSF, working closely with the Department of Education, to launch a study of the implications of a national commitment to lifelong learning as a civil right for all Americans for engineering education and practice. (Refer to the study papers for the work of the National Commission on the Future of Higher Education in America (Miller, 2006) for a more detailed description of such a strategy.)

4. Ask the National Science Foundation, the National Academy of Engineering, and higher education organizations to inventory those best practices of engineering programs and organizations that have been particularly successful in achieving diversity (students, faculty, employees, leadership) based on gender, race, and ethnic characteristics and develop effective methods for communicating and propagating these approaches.

5. Ask the National Science Foundation or the National Academy of Engineering to conduct a comprehensive survey of the success of engineering organizations in industry, government, and education in achieving diversity, including an assessment of goals, programs, and investments in these efforts, and then provide a publicly available comparison and rating of these efforts.

The Future of Engineering Schools

Some consideration should be given to the implications of this proposed separation of *engineering as a discipline* from *engineering as a profession* for existing engineering schools and faculties. Of course this would clearly benefit liberal arts colleges and community colleges across the country, since the presence of graduate engineering professional schools would enable them to offer undergraduate degree programs with an appropriate emphasis on science, mathematics, and perhaps "engineering as a liberal art", as an appropriate preparation for further study in engineering as a profession. It would also relieve the pressure on engineering schools to seek accreditation for all of their undergraduate programs, providing more opportunity for experimentation and innovation in the development of new areas (e.g., info-bio-nanotechnologies, quantum engineering, or global systems engineering). Furthermore it would provide students with the flexibility necessary to obtain a broader education that better prepares them for lives and careers in a rapidly changing global society. One might well find the emergence of entirely new disciplines and professions combining skills and competencies such as creativity-innovation-entrepreneur, global-systems-integrator, and engineering-business-law–statesman.

But these steps would likely also threaten some engineering schools, since they might find enrollments in existing discipline-based degree programs (e.g., mechanical engineering, electrical engineering, etc.) declining as students choose broader majors in preparation for further professional study in engineering (or other professions such as business, medicine, or law). Should engineering (or technology) become part of the general education requirements of an undergraduate education, engineering faculty might find themselves with new instructional commitments much like those assumed by the physical sciences and mathematics. And those engineering programs offering more technology-focused undergraduate programs might be threatened by an emphasis on broader, liberal-arts based engineering programs promoted as the favored route to leadership roles in engineering practice.

Yet it is also increasingly clear that the current paradigm for engineering education may no longer be a viable option. Engineering schools must realize that they no longer compete just with those institutions listed in the annual rankings of U.S. News & World Report. Rather, just as engineering practice has become a truly global enterprise, so too must engineering education. If the graduates of American engineering schools are unable to add sufficient value added to enable world-class practice, management, or leadership, these roles will rapidly be off shored to other competent, willing, and hardworking engineers elsewhere, taking with them the demand for engineering education in this country .

Although major structural transformation of engineering schools would be required to accommodate a new articulation between engineering as a profession and engineering as a discipline, there could be many approaches. Some engineering schools, particularly those in research universities, could decide that the disciplinary focus was their real core competency rather than vocational training and hence evolve more toward programs in engineering and applied science, stressing an engineering science undergraduate focus and research and graduate education as the faculty's strength. Other schools might choose to evolve toward more practice-oriented programs, adding "professors of practice" and developing programs akin to MIT's chemical engineering practice school as the first steps toward building a true graduate professional school.

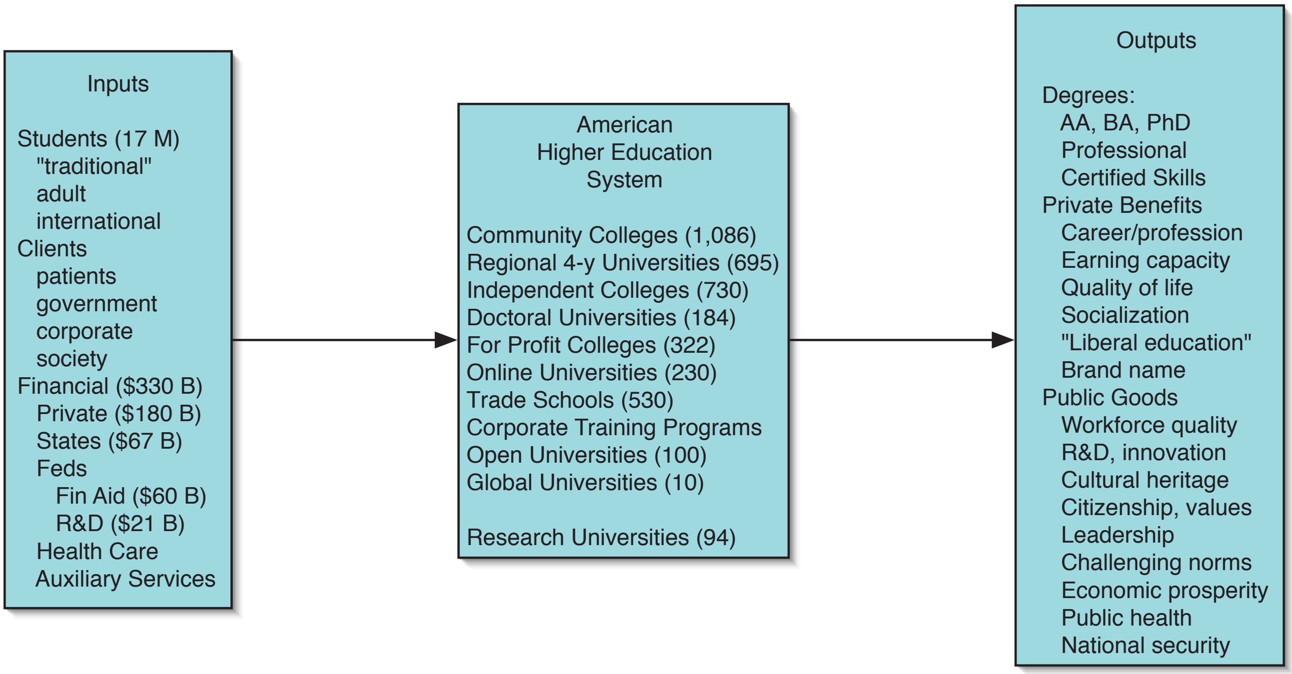
Still others might adopt a hybrid approach, spanning both engineering education and research as a discipline and building an affiliated professional school stressing training and practice, much as one finds in today's academic medical center. A more complete discussion of this very broad approach, which taps the synergies between fundamental education and research in engineering science and professional training and practice, is provided in appendix B.

A Systemic Approach to Engineering Education

One of the greatest challenges to transforming engineering education to better respond to the needs of the nation in an ever-flattening world is to address this from a systems focus, since no single institution or program can span the full spectrum of diverse engineering needs. Indeed, the great strength of the American higher education system arises from its extraordinary diversity.

It is important to stress once again the importance of preserving–and indeed enhancing–the great diversity characterizing engineering education in America, ranging from highly practical engineering technology programs to a broader array of diverse baccalaureate engineering degree programs to advanced graduate programs aimed at preparing the engineering scientists necessary to sustain our nation's leadership in technological innovation. All are valued, and all are needed by a technological nation with highly diverse needs. This implies that any "Flexner report" on engineering must adopt a strong systems perspective, designing an education, research, and practice enterprise capable of serving an ever more diverse nation in an increasingly competitive global economy rather than defining a monolithic profession of engineering. The objective is to build a highly diverse and innovation ecosystem of engineering education–of institutional types, including research universities, technology institutes, undergraduate colleges, community colleges, specialized training programs, and lifelong professional programs; and of academic programs, including undergraduate engineering disciplines, pre-engineering programs, design–based master's degrees, research M.S./Ph.D. degree programs, and graduate practice-based professional degrees.

But this recognition also implies major responsi-



Higher education in the United States as a system

bilities for America's engineering programs to carefully consider and define their unique roles and missions and then take appropriate strategic actions to achieve quality and rigor in these activities. Many programs will continue to conduct ABET-accredited engineering programs at the undergraduate level, perhaps augmented by traditional M.S. and Ph.D. programs. Others may choose to stress a particular engineering role, such as the strong emphasis on design and innovation at schools such as RPI and Purdue, or the focus on educating engineering scientists for research or teaching careers at Caltech, UC Berkeley, and Stanford, or the emphasis on technology management characterizing programs at MIT and Georgia Tech. To these, one must add the great contributions of both community colleges and liberal arts colleges to engineering, since these education-focused institutions produce many of the students who go on to major in university-based engineering programs at the undergraduate and graduate level.

It is clearly very important to encourage far more innovation and experimentation in developing new approaches to engineering education, such as the project–based experiential learning at Olin College, the liberal arts approach to engineering at Princeton and Yale, or the Internet-based professional M.Eng. programs developed to address the specific needs of particular industry by many universities including Stanford, Michigan, and Johns Hopkins.

Yet it is also the case that the prestige, influence, and impact of the profession is likely to be determined by the pinnacle of professional practice, much as the highest level of medical training and practice determines the nature of the broader allied health care professions. For this reason, we believe it particularly important to explore the new paradigms suggested for post-baccalaureate professional education.

As noted earlier, it is important both to recognize and support the efforts of research on engineering education pedagogy as key to the continuous improvement and innovation necessary to enable engineering education to keep pace with the evolving nature of engineering practice driven by a rapidly changing world. In fact, rigorous scholarship in engineering education research may be the most effective long-term mechanism for achieving the necessary systemic transformation of both engineering education and engineering practice.

Concluding Remarks

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, similar in character and scope to initiatives undertaken in response to earlier times of change and challenge (e.g., the Land Grant Acts, the G.I. Bill, and the government-university research partnership) will be necessary for the nation to maintain its leadership in technological innovation. The United States will have to reshape its engineering research, education, and practice to respond to challenges in global markets, national security, energy sustainability, and public health. The changes we envision are not only technological, but also cultural. They will affect the structure of organizations and relationships between institutional sectors of the country. This task cannot be accomplished by any one sector of society. The federal government, states, industry, foundations, and academia must all be involved.

Sometimes a crisis is necessary to dislodge an organization from the complacency arising 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 should serve as a wakeup call in the same way that the outsourcing of blue–collar manufacturing jobs did 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 U.S., 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.

William Wulf, former president of the National Academy of Engineering, conveyed the urgency of this effort in his 2003 address to the National Academy: "We have studied engineering reform to death. While there are differences among the reports, the differences are not great. Let's get on with it! It is urgent that we do so!" He then went on to observe: "I honestly don't know the answer, but I have a hypothesis–namely, that most do not believe change is necessary. They are following the time-tested adage—'if it ain't broke, don't fix it.'"

Well, American engineering is broken, at least when measured against the emerging technology capabilities of the rest of the world. Otherwise it would not be outsourced and off-shored. We can no longer afford simply chipping away at the edges of fundamental transformation of the engineering profession and its preparation. *Radical transformation will require radical actions!*

Chapter 7

So ... How Do We Get This Done?

With the destination of our roadmapping effort now established, we turn to the challenging task of getting from here to there, from the current 20th-century paradigm for engineering practice, research, and education in America to a new paradigm appropriate for a 21st-century world. But here we immediately encounter a very serious dilemma. We have suggested 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. This will require new paradigms for engineering research that better link scientific discovery with innovation. It will also require American engineers to achieve a much higher level of education, particularly in professional activities such as design, systems integration, and global engineering practice. And it will require very considerable investment and great commitment on the part of individuals and institutions.

Yet, resistance to such transformation will be considerable. Industry will continue to seek low-cost engineering talent, with narrow roles, vulnerable to layoffs or replacement by off-shored engineering services at the slight threat of financial pressure. Educators will defend the status quo. 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.

More specifically, all of the actions we have proposed will require increased investment and hence raise the cost (and price) of American engineering. Since current global business practices seek the lowest-cost engineering services of acceptable quality, there is a very real possibility that such efforts could trigger even more out sourcing of engineering services and off shoring of engineering jobs, eroding even further this nation's domestic technological capacity.

Hence the key question is how to motivate the United States and its global industries to accept a higher cost for higher-quality engineering services and more capable engineers. Would a more influential engineering profession, involving a far more extensive process for professional education, really increase the value of American engineers sufficiently to compete in the global marketplace for engineering services? Even if the answer is yes, would the effort to raise the bar for engineering quality in this nation simply drive the remainder of more routine engineering services to off shore providers, except for a very small cadre of "master engineers" who would manage such "global supply chains" of engineering, technology, and innovation?

Let us consider several approaches to this dilemma.

Option 1: Benign Neglect

One approach is to simply continue the status quo, accepting the current global market realities, reacting as best as one can to new requirements such as the need for global engineers, and wait until conditions deteriorate sufficiently to stimulate bolder action. Of course if the current trends continue, such as the off shoring of engineering jobs in preference to hiring less experienced (and more expensive) young American engineers or inadequate investment in R&D, students will continue to turn away from engineering careers, and our domestic capacity for technological innovation will continue to deteriorate. Hence what could be at stake in this approach of benign neglect is the erosion not simply of American innovation and economic competitiveness, but perhaps even the leadership of the engineering profession itself as young people see more attractive career options in more highly compensated and secure professions such as law, business administration, and medicine.

Option 2: Evolution (Education and Persuasion)

A more proactive approach would involve the launch of a major outreach and education campaign aimed at convincing American industry, government, and the public of the importance of sustaining and enhancing domestic engineering capacity through additional investments in engineering education and research to raise the value-added by American engineers, as reflected in enhanced prestige and compensation for the engineering profession. Here one would stress the dangers to both American competitiveness and national security by the accelerating tendency to off shore both engineering jobs and competence, driven by short-term financial pressures and the emergence of transnational corporations with declining interest in regional or national consequences. Such an effort would also stress the importance of STEM education at all levels as key to knowledgeable citizenship in an increasingly technological world. Both the federal administration's American Competitiveness Initiative and Congress's America COMPETES Act provide an unusual opportunity to address these concerns.

In parallel with this effort would be the launch of a number of experiments to create models of possible futures for engineering practice, research, and education. Examples might include a federally supported effort to create several Discovery-Innovation Institutes and privately supported post-graduate professional schools of engineering (similar to recent experiments such as Olin College of Engineering).

Such an effort would require broad leadership, e.g., through groups such as the National Academy of Engineering, the engineering professional societies, and business groups such as the Council on Competitiveness and National Business Roundtable. It would also require sustained commitment and substantial investment, perhaps from key foundations with strong interests in science and engineering. This would also require loosening somewhat the existing constraints (such as accreditation) to encourage far more innovation and risk-taking in engineering research and education.

A key role: the National Academy of Engineering

Option 3: Revolution (Politics and Cartels)

Here engineering professional societies would emulate the efforts of the medical and law professions (through the American Medical Association and American Bar Association) to seek legislation at the state and federal level to create a regulatory environment sufficient to empower the engineering profession. The goal would be to create through regulatory activities governing licensing and practice more of a guild-like culture in engineering, in which engineers like other learned professionals would increasingly identify more with their professional standards than their particular employment.

Of course there are some significant differences between engineering and more regulated professions such as medicine and law. For example, while law involves rather routine skills, it depends on significant cultural factors and precedents that limit the ability to outsource legal services. Medical practice has a high technical skill level more comparable to engineering with relatively few cultural constraints; yet it also is characterized by an urgency and personal character that again limits the outsourcing of most practice (with the exception of diagnostic evaluations). Business administration like law also involves more routine skills, characterized by relatively little urgency or cultural constraints. Yet the financial responsibilities of business executives create a highly compensated marketplace for business talent, unlike that for engineering services.

As we noted earlier, there is also a serious question as to whether the diverse array of engineering professional and disciplinary societies could be sufficiently corralled to agree on a unified agenda. Revolutions are launched by the proletariat, and it is difficult to see what would excite the rank and file of the engineering workforce to this level.

Option 4: Punctuated Evolution and Spontaneous Emergence

Finally, one might simply take an opportunistic approach by keeping an eye out for possible tipping points that would drive–or at least allow–fundamental transformation of existing paradigms for engineering practice, research, and education, much as rapid climate changes drove occasional bursts of simultaneous co-evolution of biological species on Planet Earth. One example would be cyberinfrastructure, which is rapidly changing the very nature of scientific and engineering work. As NSF Director Arden Bement stresses, "These revolutionary technologies have helped us scan the research frontier at velocities that are orders of magnitude faster than ever before. These tools are not simply faster–they are also fundamentally superior. They have raised the level of complexity we can understand and harness. That capability is growing at a breathtaking pace." (Bement, 2007)

Another example would be the rapid evolution of open education resources such as the MIT's OpenCourseWare project or the Google Book Scan library consortium, which could well lead to the very rapid propagation of effectively universal access to knowledge and learning tools, bypassing traditional professional education and certification organizations to empower the amateur (Brown, 2005).

Finally, the rapidly changing nature of the global, knowledge economy, with its stress on innovation, flexibility, and rapid transformation might lead to new business structures. For example, enterprises might essentially become an aggregation of specialized entities with complementary interests–expanding, contracting, and reconfiguring themselves in a way that best adapt to or even anticipates market dynamics. Paradoxically, these super-flexible configurations may prove even more stable over time. Self-organizing and self-aggregating entities are often much more adaptable in the face of disruption (think of flocks of birds or schools of fish). For knowledge workers such as engineers in particular, a form of 21st-century guild could emerge to facilitate accreditation, skills development, and reputation management. Individual knowledge workers may one day command "agents" who seek out and negotiate short-term opportunities and effectively manage career paths on their behalf (IBM, 2006).

Epilogue

In summary, 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 21st-century engineering.

Perhaps, as Frank Splitt suggests, we could simply heed the advice of Thomas Paine:

> Perhaps the sentiments contained in the following pages, are not sufficiently fashionable to procure them general favour; a long habit of not thinking a thing wrong, gives it a superficial appearance of being right, and raises at first a formidable outcry in defense of custom. But the tumult soon subsides. Time makes more converts than reason (Paine, *Common Sense*, 1776).

Those with most at stake: future generations of engineers

Yet, unfortunately, the challenges of our changing world move ahead at a rapid pace despite our tendency toward procrastination. The future–indeed, the very survival–of American engineering demands the exploration of new paradigms of practice, research, and education today.

Appendix A

A Summary of Suggested Next Steps

The Profession

1. (Guild) Build on the important work of Sheppard, Sullivan, and others engaged in the Carnegie Foundation's project on the professions to understand how the current profession of engineering aligns with (or differs from) the six "common places" of learned professions (Shulman, 1998).

2. (Guild) Empower (or create) an umbrella organization across all disciplinary and professional engineering organizations (NSPE?, AAES?) with power and influence comparable to the professional organizations governing law (ABA) and medicine (AMA).

3. (Guild) Enhance the visibility, prestige, recognition, and influence of members of the National Academy of Engineering from industry and government both within their own organizations, the scientific and engineering community, and the American public.

4. (Guild) Working closely with the National Academy of Engineering, develop a new level of engineering licensing as a pre-requisite for the awarding of professional practice-based degrees such as the M. Eng. and D. Eng. Such licensing would be both national in scope and generic across all engineering disciplines and would eventually encompass continuing engineering education.

5. (Professional Schools) Commission the National Academy of Engineering to convene a blue ribbon commission of members drawn from industry and government to develop the content for both two-year and three-year professional degree programs in engineering, assisted by educators, and involving close cooperation with organizations such as NSPE, AAES, and ASEE.

6. (Engineering Education) Ask the National Academy of Engineering to re–evaluate the appropriateness in today's world of the recommendations made 40 years ago by the ASEE Report on "The Goals of Engineering Education" (1968) in response to a request by the ECPD, i.e.,

* The first professional degree in engineering should be the Master of Engineering degree, awarded on completion of an integrated program of at least five years. The first four years would concentrate on the common engineering core, with specialization occurring in the fourth year.

* The credits required for a pre-engineering bachelor's degree should be reduced by 15%.

* ECPD (today ABET) should gradually shift their accrediting activity away from the bachelor's degree to the master's degree.

* The accreditation of discipline–based degree programs should be replaced by accreditation of the engineering unit as a whole. (Here reflecting the view of many ASEE leaders that discipline-based undergraduate curricula be replaced by undesignated curricula, patterned after the "engineering science" model of the 1955 Grinter Report, with disciplinary specialization in a fifth year master's program.)

7. (Engineering Education) Stimulate more activity in the scholarship of engineering education and

learning, encouraging investment in research and the adoption of evidence-based approaches to innovation and continuous improvement while providing recognition to engineering educators of great distinction through honors such as election to the National Academy of Engineering (establishing a new section of the NAE devoted to engineering education).

8. (Engineering Education) Through a series of federally-, foundation-, and industry-funded experiments, explore the development of a series of educational programs (steps) designed to provide lifelong learning opportunities for practicing engineers (e.g., integrating the goals and methods of undergraduate education, graduate professional education, continuing education, workplace learning, and professional development).

9. (Diversity) Working closely with organizations such as NACME, inventory and assess the vulnerability of various institutional, state-based, and federal programs aimed at enhancing the diversity of engineering education and the engineering workforce to the current legal and political environment.

Government

1. (Research) Modify the current language authorizing the creation of discovery–innovation institutes in current Congressional legislation, i.e., the Senate bills introduced in both 2006 (S. 2197 Protecting America's Competitive Edge through Energy Act) and 2007 (S. 771 The American COMPETES Act), to conform more accurately to the recommendations of the National Academy of Engineering report, which recommended these be co-located with research university campuses rather than restricted to national laboratories.

2. (Research) Direct the National Science Foundation to host a series of workshops to better refine the discovery–innovation institute concept as a multi–federal agency effort that would eventually be funded at the suggested level of $5 billion/year.

3. (Research) Launch the first wave of federally funded discovery innovation institutes in the critical area of energy research (see an example of such a network provided in Appendix C).

4. (Engineering Education) With the support of both federal agencies (particularly NSF but also mission agencies such as DOD, DOE, and NASA), foundations, and industry, encourage the exploration of more radical experiments in engineering education similar to those at Olin College or the Cambridge-MIT Institute (design-innovation), RPI (studio-based), Caltech (multidisciplinary with the sciences), and Princeton (B.A. engineering programs for leadership roles). The engineering accreditation process and accreditation teams would not be allowed to constrain or interfere with such experiments.

5. (Engineering Education) Through a series of federally-, foundation-, and industry-funded experiments, explore the development of a series of educational programs (steps) designed to provide lifelong learning opportunities for practicing engineers (e.g., integrating the goals and methods of undergraduate education, graduate professional education, continuing education, workplace learning, and professional development).

6. (Engineering Education) Ask the National Science Foundation, working through the National Academy of Engineering, to launch an effort to identify and establish the intellectual core of a engineering-technology "distribution" requirement for liberal arts majors.

7. (Engineering Education) Ask the NSF to fund a series of coordinated efforts at the campus level to develop, implement, and assess such a sequence in various institutional types (e.g., liberal arts colleges, comprehensive universities, research universities).

8. (Diversity) Ask the National Science Foundation, the National Academy of Engineering, and higher education organizations to inventory those best practices of engineering programs and organizations that have been particularly successful in achieving diversity (students, faculty, employees, leadership) based on gender, race, and ethnic characteristics and develop effective methods for communicating and propagating these approaches.

9. (Diversity) Ask the National Science Foundation or the National Academy of Engineering to conduct a comprehensive survey of the success of engineering organizations in the industry, government, and education in achieving diversity, including an assessment of goals, programs, and investments in these efforts, and then provide a publicly available comparison and rating of these efforts.

10. (Diversity) Ask the NSF, working closely with the Department of Education, to launch a study of the implications of a national commitment to lifelong learning as a civil right for all Americans for engineering education and practice. (Refer to the study papers for the work of the National Commission on the Future of Higher Education in America for a more detailed description of such a strategy).

Higher Education

1. (Professional Schools) Build engineering professional schools as a coordinated effort involving current professional development graduate programs for practicing engineers (e.g., Stanford's Center for Professional Development, Georgia Tech's Center for Distance learning, Michigan's Center for Professional Development, Johns Hopkins' Engineering Programs for Professionals).

2. (Professional Schools) Seek support from key foundations to enable the launch of "green–field" experiments to build new professional schools of engineering similar to the undergraduate experiment of Olin College.

3. (Professional Schools) Explore engineering analogs to the academic medical center by combining the creation of a Discovery Innovation Institute and a closely affiliated engineering professional school with existing engineering schools (i.e., including undergraduate and graduate engineering degree programs). (See Appendix B for an example.)

4. (Engineering Education) Infuse more professional content into existing engineering programs by encouraging engineering schools to appoint to their faculties engineers with distinguished careers in industry and government as Professors of Practice, similar to those at leading institutions such as MIT and Stanford.

5. (Engineering Education) Stimulate more activity in the scholarship of engineering education and learning, encouraging investment in research and the adoption of evidence-based approaches to innovation and continuous improvement while providing recognition to engineering educators of great distinction through honors such as election to the National Academy of Engineering (establishing a new section of the NAE devoted to engineering education).

6. (Engineering Education) Transform the current faculty paradigm, based primarily on the scholarly requirements of the physical sciences, to accommodate in addition "professors of practice", analogous to the clinical faculty of medical schools or performance faculty of the performing and visual arts, who stress professional practice rather than basic research in their activities and pedagogy.

7. (Engineering Education) With the support of both federal agencies (particularly NSF but also mission agencies such as DOD, DOE, and NASA), foundations, and industry, encourage the exploration of more radical experiments in engineer-

ing education similar to those at Olin College or the Cambridge-MIT Institute (design-innovation), RPI (studio-based), Caltech (multidisciplinary with the sciences), and Princeton (B.A. engineering programs for leadership roles). The engineering accreditation process and accreditation teams would not be allowed to constrain or interfere with such experiments.

8. (Engineering Education) Through a series of federally-, foundation-, and industry-funded experiments, explore the development of a series of educational programs (steps) designed to provide lifelong learning opportunities for practicing engineers (e.g., integrating the goals and methods of undergraduate education, graduate professional education, continuing education, workplace learning, and professional development).

9. (Diversity) Through learning outcome and professional achievement measures, assess the effectiveness of current engineering program admission criteria (e.g., standardized test scores such as the SAT and ACT, advanced placement courses, secondary school grade-point and graduation rank measures) in predicting both academic performance and career success, with broadening admission criteria to enable a more diverse student body.

Appendix B

A Possible Model for an "Academic Engineering Center"

Perhaps the best model for a comprehensive approach to creating an "academic engineering center" spanning the full spectrum of engineering education, research, and professional practice is the academic medical center. These remarkable organizations exploit the synergies of combining medical education, research, and practice. They provide educational programs ranging from undergraduate ("pre-med") programs to graduate and post-graduate training in the health professions to graduate research degrees (M.S. and Ph.D.) to advanced postdoctoral and clinical training. Their research activities range from the most fundamental investigations in genomics and proteomics to translational research with strong clinical applications. Their service activities are similarly broad, from operating large health maintenance organizations to providing medical care at the most sophisticated level to public health policy and civic education. By gathering all of these activities under the umbrella of the academic medical center, one achieves enormous synergies both intellectually (connecting fundamental research with translational research and clinical practice), but also financial management (supporting education and scholarship in part from clinical income). More generally, such an organization takes advantage of the American research university's core competency in building academic programs characterized by an unusual combination of quality, breadth, and capacity in order to achieve maximum impact on society. The constellation of activities conducted by the contemporary academic medical center is illustrated by the figure on p. 105.

So how might one emulate such a model in engineering? Actually many large engineering schools already exhibit many of these characteristics. Their educational programs span the range from undergraduate engineering degrees to graduate research programs (M.S. and Ph.D.) to continuing education for practicing engineers. They conduct many types of research, from fundamental scientific investigations in emerging fields such as nanotechnology and quantum physics to highly applied systems research on topics such as global energy sustainability and civic infrastructure. Many engineering schools have robust technology transfer activities, spinning off intellectual property through licensing and startup companies. They maintain strong relationships with industry and affiliations with peer engineering programs around the world.

Yet the model we suggest would go further, by adding true post-graduate professional schools of the type discussed in Chapter 6, staffed by practice-focused faculty and providing degree programs more along the lines of medicine and law. One could imagine service organizations analogous to teaching hospitals and clinics perhaps through affiliated engineering services companies, discovery innovation institutes, or a more tightly coupled network of spinoff and startup companies providing both experience in engineering practice for students and outlets for innovation and entrepreneurial activities on the part of faculty and research staff. And underpinning such a comprehensive academic engineering center would be a new financial model that augments traditional university and government support of teaching and scholarship with the income derived from engineering services, intellectual property, and equity holdings in spinoff activities. This is illustrated both in the figure on p. 106.

Academic Medical Center

Education

Biomedical Sciences
Health Professions Training
Residencies
Postdoctoral Training
Continuing Education

Degrees
…M.D., Ph.D., M.P.H.,...
Postgraduate Certification

Research

Basic Research
Clinical Research
Clinical Trials
Translational Research

Publications
Patents
New Clinical Procedures

Organizations

Teaching Hospitals
Research Centers
Technology Transfer Offices

Clinical Care
Spinoff Companies
Intellectual Property Licensing

"Academic Engineering Center"

Education

Undergraduate
Graduate
Professional
Continuing

Degrees
…B.S., B.A.
…M.S., Ph.D.
…M.Eng., D. Eng..

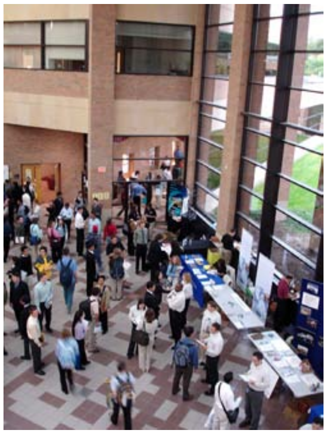
Research

Basic Research
Applied Research
Systems Development

Publications
Patents
Consulting
Systems, Products

Organizations

Academic programs
Research labs, centers, institutes
Practice Schools and Internships
Discovery-Innovation Centers
Captive Eng Services Companies
Practice Schools
Spinoff Companies



Appendix C

The Great Lakes Energy Network: An Example of Discovery Innovation Institutes

The United States economy, our national security, and the well-being of our citizens are dependent upon the availability of clean, affordable, flexible, and sustainable energy resources. Yet our current energy infrastructure, heavily dependent upon fossil fuels, is unsustainable. Global oil production is expected to peak within the next several decades. While there are substantial reserves of coal and tar sands, the mining, processing, and burning of these fossil fuels poses increasingly unacceptable risk to both humankind and the environment, particularly within the context of global climate change. Furthermore, the security of our nation is threatened by our reliance on foreign energy imports from unstable regions of the world. Clearly energy independence must become among the highest priorities of the federal government if it is to meet its responsibilities for national security, economic prosperity, and social well-being.

Unfortunately, current federal energy strategies, policies, and investments seem woefully inadequate when balanced against the urgency, complexity, and scale of the challenges in building a sustainable energy infrastructure for the nation. The severity of the looming energy crisis facing the United States, viewed within the context of the federal R&D effort characterizing other national priorities such as health care ($30 B/y) and defense ($80 B/y), would suggest a federal energy R&D effort on the order of $40 to $50 B/y, roughly ten times the current federal effort. Furthermore, much of this energy R&D investment should be channeled through new research paradigms characterized by an intimate partnership among multiple participants–federal agencies, research universities, established industry, entrepreneurs, and the investment community, more capable of rapid transfer of highly innovative technologies into the marketplace

To this end, we propose the implementation of an entirely new research paradigm recently proposed by a blue ribbon task force of the National Academy of Engineering: a national network of multidisciplinary discovery-innovation institutes (DIIs) capable of linking fundamental scientific discoveries with technological innovations to create the products, processes, and services needed by society and funded by a consortium of federal and state governments, industry, foundations, venture capital and investing communities, and universities. Because of the unique vulnerability of the energy intensive manufacturing, agricultural, and transportation industries in the Great Lakes states, we propose the launch of this new effort by creating the Great Lakes Energy Research Network, an integrated network of five energy discovery-innovation institutes, each focused on a different research theme (e.g., transportation, biofuels, electrical power, renewables, conservation) located adjacent to a leading research university in the region.

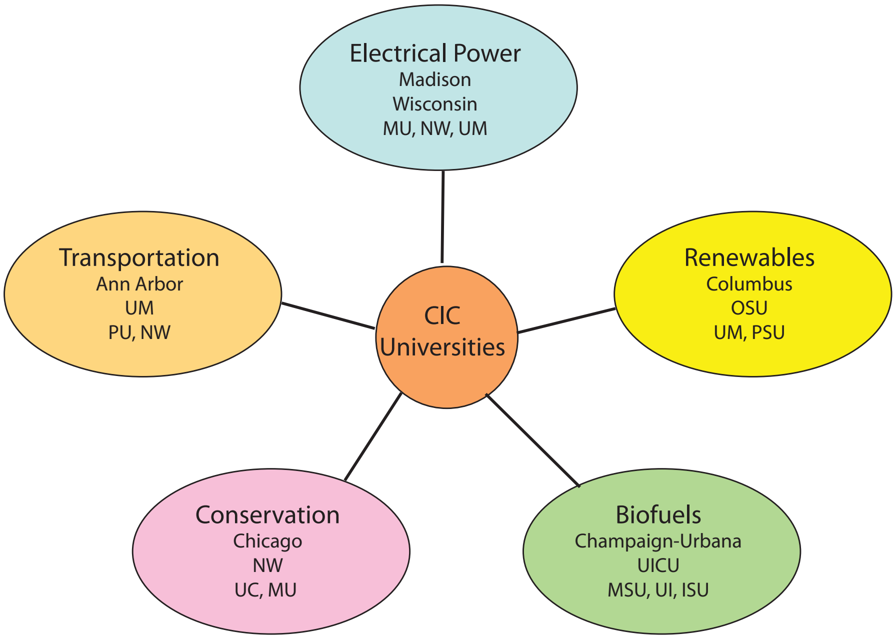
Each DII center would have core support from multiple federal agencies at a level growing to $250 million per year (i.e., $1.25 B/y in total), with significant additional funding from state, industry, foundation, and university sources. Each DII would have numerous participants and affiliates from industry, federal and state agencies, and other research universities from around the nation. Although each individual DII center would be managed as a federally funded R&D Center by a lead research university, the integrated Great Lakes En ergy Research Network would be managed collectively by the Committee on Institutional Cooperation (CIC, aka the Big Ten) university consortium with strong industrial participation.

To illustrate the approach, we have given one example of a possible network of energy DIIs based at CIC institutions, with typical inter-CIC linkages and broader affiliations.

Here it is important to understand that the Great Lakes Energy Research network would be characterized not only by the novel research paradigm of discovery-innovation institutes, but perhaps even more by its highly integrated character as a research network. Undergirded by powerful information and communications technology (much of it developed by the CIC university consortium itself), and overlaid by a network of virtual organizations involving scientists, engineers, industrial management, and federal participants, the Great Lakes Energy Research Network would provide a powerful test-bed for the new types of research organizations enabled by rapidly evolving cyberinfrastructure (Atkins, 2005).

The proposed Great Lakes Energy Research Network would nucleate activities from government, academia, large and small business, and the investment community, marking the beginning of a knowledge revolution that will augment the manufacturing and transportation industries of the Great Lakes region. It would also begin to move the federal government toward more progressive energy policies and new research paradigms that will lead to an integrated approach to address the nation's challenge of sustaining energy infrastructure.

But perhaps equally significant, the Great Lakes Energy Research Network is proposed as the first step toward the National Academy vision of a national network of discovery-innovation institutes addressing the major challenges facing our nation in the years ahead.



A possible configuration of a Great Lakes Energy Network

Appendix D

Author Biography

Dr. James J. Duderstadt is President Emeritus and University Professor of Science and Engineering at the University of Michigan. Dr. Duderstadt received his baccalaureate degree in electrical engineering with highest honors from Yale University in 1964 and his doctorate in engineering science and physics from the California Institute of Technology in 1967. After a year as an Atomic Energy Commission Postdoctoral Fellow at Caltech, he joined the faculty of the University of Michigan in 1968 in the Department of Nuclear Engineering. Dr. Duderstadt became Dean of the College of Engineering in 1981 and Provost and Vice President for Academic Affairs in 1986. He was appointed as President of the University of Michigan in 1988, and served in this role until July, 1996. He currently holds a university-wide faculty appointment as University Professor of Science and Engineering, directing the University's program in Science, Technology, and Public Policy, and chairing the Michigan Energy Research Council coordinating energy research on the campus.

Dr. Duderstadt's teaching and research interests have spanned a wide range of subjects in science, mathematics, and engineering, including work in areas such as nuclear fission reactors, thermonuclear fusion, high-powered lasers, computer simulation, information technology, and policy development in areas such as science, engineering, and education. During his career, Dr. Duderstadt has received numerous national awards for his research, teaching, and service activities, including the E. O. Lawrence Award for excellence in nuclear research, the Arthur Holly Compton Prize for outstanding teaching, the Reginald Wilson Award for national leadership in achieving diversity, and the National Medal of Technology for exemplary service to the nation. He has been elected to numerous honorific societies including the National Academy of Engineering, the American Academy of Arts and Science, Phi Beta Kappa, and Tau Beta Pi.

Dr. Duderstadt has served on and/or chaired numerous public and private boards. These include the National Science Board; the Executive Council of the National Academy of Engineering; the Committee on Science, Engineering, and Public Policy of the National Academy of Sciences; the Nuclear Energy Research Advisory Committee of the Department of Energy, the Big Ten Athletic Conference; the University of Michigan Hospitals, Unisys, and CMS Energy. He currently serves on or chairs several major national study commissions in areas including federal science policy, higher education, information technology, and energy sciences, including NSF's Advisory Committee on Cyberinfrastructure, the National Commission on the Future of Higher Education in America, the Association of Governing Board's Task Force on the State of the University Presidency, the Intelligence Science Board, and the Executive Board of the American Association for the Advancement of Science.

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Index


ISSUES
Information Technology and the Research University
The BRIDGE
In Search of Global Engineering Excellence
EDUCATING THE ENGINEER OF 2020
THE ENGINEER OF 2020
Journal of Engineering Education
ENGINEERING RESEARCH AND AMERICA'S FUTURE
INNOVATE AMERICA
Global Innovation Outlook 2.0
National Science Board
The Science and Engineering Workforce Realizing America's Potential
RISING ABOVE THE GATHERING STORM
ISSUES
Information Technology and the Research University
NSF's Cyberinfrastructure Vision for 21st Century Discovery
The U.S. Scientific and Technical Workforce
American Competitiveness Initiative
Leading the World in Innovation
The Vital Center
The Leadership Imperative
The World Is Flat
A Brief History of the Twenty-First Century
Thomas L. Friedman
A TEST OF LEADERSHIP