Summer 2006

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING
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Promoting the technological welfare of the nation by marshalling the knowledge and insights of eminent members of the engineering profession.

The BRIDGE

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The BRIDGE
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LINKING ENGINEERING AND SOCIETY

Editor's Note

Features

NAE News and Notes

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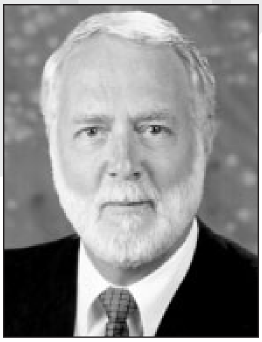
Editor's Note



G. Wayne Clough is president, Georgia Institute of Technology, and an NAE member.

Reforming Engineering Education

Nothing is more fundamental to the future of our nation's engineering enterprise than attracting talented young men and women to the pursuit of an engineering degree and providing them with an education adapted for the 21st century. Sounds simple, but neither of these can be assumed as a given. The United States is granting engineering degrees at a lower rate than in the mid-1980s, and nationally, less than 55 percent of students who undertake engineering studies complete them. Moreover, it is far from clear that engineering education is preparing our graduates to succeed in a global economy.

The stagnant number of engineers graduated each year in the United States has become more visible as competition increases for the high-tech sector of the global economy from both developed and developing nations. Although it seems obvious that graduating more engineers in a world increasingly dependent on technology should be a national priority, this turns out to be a subject of debate. Some argue that we have enough engineers based on projections of traditional engineering job opportunities for the future. Others insist that the market must be the arbiter, and until such time as the demand for engineers is clear, we should hold to our present course. Still others are calling for an increase in the number of engineers; the recent National Academies report, *Rising above the Gathering Storm*, for example, recommends doubling the number of engineering graduates.

All sides of the debate were taken up at a recent National Science Board workshop at MIT. The conclusion was that we are putting the cart before the horse by focusing only on the number of engineering graduates. Given the challenges future engineers will face, we simply cannot continue with "business as usual." It is unlikely that we can attract or retain students without making substantial improvements. By making engineering education more relevant to future needs and more interesting to a wider, more diverse group of students, we will automatically increase our numbers. For starters, if we simply raise the retention rate, we would quickly increase the number of graduates. As members of the younger generation would say, this is a "no brainer."

We must also educate engineers more broadly; this will expand their employment horizons and, in turn, justify the need for more engineering graduates. Many also believe, I among them, that engineering graduates must also take on jobs outside of engineering, including jobs in nonprofit and government policy areas where we desperately need people who can think clearly and logically and who understand technology.

The devil in the details is how we renew engineering education. The engineering curriculum is already crowded, and adding anything is difficult. We all agree that the fundamentals of engineering must be taught, but, given the imperative for change, we must begin to rethink what we casually call a university education—both out-of-class experiences and in-class learning. Out-of-class time could provide opportunities for study abroad, leadership development through real-world projects, intellectual growth through participation in music, and volunteer and club activities. Inside the classroom, we need to find places where adjustments, even small adjustments, can be made to existing courses to improve them. Perhaps more important, we need to rethink which courses are really necessary and which ones can be reduced in scope or jettisoned to free up time for new material.

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. However, even though these efforts have been impressive, they have rarely focused on the long view. NAE is encouraging more long-range thinking with the Engineer of 2020 initiative, an attempt to determine the kind of engineering education we must provide to prepare our graduates for careers two decades from now. Because large-scale changes in engineering education will take time, we must start now to change our approach to engineering education in time to produce graduates ready for 2020.

The Engineer of 2020 initiative had two phases. The first was a community-wide conversation to identify the dynamic forces at play and the aspirations and expectations that should characterize engineering in 2020. The second phase involved an educational summit to discuss how engineering education could rise to the challenge through changes in the curriculum, extracurricular options, new approaches to educational delivery, and innovative options for educational structure. Participants in the summit offered ideas for (1) the teaching of introductory courses in ways that would engage students and arouse their curiosity, (2) encouragement of a systems approach rather than the traditional piecemeal approach, (3) interdisciplinary courses, and (4) internships and cooperative experiences to supplement classroom exercises. Both phases of the 2020 initiative are described in reports that have been widely distributed and have prompted much discussion.

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. At the same time, I have heard that engineering educators in other countries are also using the Engineer of 2020 reports and similar publications to adapt their courses of study for the future. The bottom line is that time is not our friend. The longer we wait to respond, the harder it will be to make relevant changes and the more ground the competition will gain.

The papers in this edition of *The Bridge* provide a range of viewpoints and insights relevant to the tasks that lie ahead. Lisa Lattuca, Patrick Terenzini, and Fredericks Volkwein of Pennsylvania State University and George Peterson of ABET review ABET's efforts since the 1980s to provide accreditation standards to engender changes in engineering education to meet the needs of industry. Results over the past decade show that progress is being made. **Ted Kennedy** provides the perspective of an engineering consultant. He predicts that in the global economy of the future, routine aspects of engineering will be performed overseas and that U.S. engineers will need skills that distinguish them from engineers in other countries to justify their higher wages. Jackie Sullivan of the University of Colorado focuses on the educational pipeline that provides the talent. She argues passionately that the foundation for engineering education should begin with elementary school, especially if we want to attract minority and female students. She contends that engineering education should be the capstone of an integrated K–16 system.

The subject of the paper by Susan Ambrose and Marie Norman of Carnegie Mellon University is the faculty of the future. They argue that faculty will need new knowledge and skills to create and teach effective, innovative courses. According to Ambrose and Norman, faculty must focus more on how students learn and how they process information. **Zehev Tadmor** of the Technion Israel Institute of Technology describes the fusion of science and technology in emerging engineering specialties. He puts forward the idea of creating entirely new disciplines that merge science and engineering for particular fields. Finally, **Chuck Vest**, President Emeritus of MIT, advises that, although we cannot know precisely what students 15 years from now should be taught, we must focus on creating an "exciting, creative, adventurous, rigorous, demanding, and empowering" educational milieu.

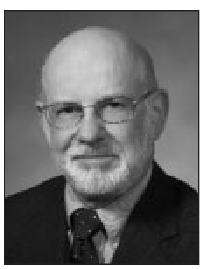
Taken together these papers provide a context and offer recommendations for shaping engineering education for the future. I hope engineering educators accept the challenge and that everyone who serves on advisory boards to engineering colleges will help stimulate discussion on their campuses. We must prepare our graduates to compete in the new world economy.

ABET EC2000 has radically changed the evaluation of undergraduate engineering programs.

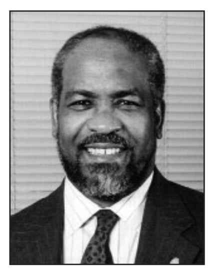
The Changing Face of Engineering Education

Lisa R. Lattuca, Patrick T. Terenzini,
J. Fredericks Volkwein, and George D. Peterson


Lisa R. Lattuca


Patrick T. Terenzini


J. Fredericks Volkwein


George D. Peterson

Most engineers today are likely to recall their undergraduate years as a period of intense mathematical and theoretical study. Until the 1940s, however, the engineering curriculum at most colleges and universities was mostly practical, with the emphasis on engineering design rather than on engineering science and mathematical applications. The field, and undergraduate education programs, changed dramatically with increased federal support for university research after World War II. As engineering schools hired faculty to teach and conduct scientific research, the number of faculty members with industry experience declined. Eventually, courses in advanced mathematics and theory replaced practical courses in machining, surveying, and drawing (Prados et al., 2005).

Lisa R. Lattuca is assistant professor and research associate, Patrick T. Terenzini is Distinguished Professor and senior scientist, and J. Fredericks Volkwein is professor and senior scientist at the Center for the Study of Higher Education, Pennsylvania State University. George D. Peterson is executive director of ABET Inc. This article is based on a presentation by George Peterson on October 10, 2005, at the NAE Annual Meeting.

The strong emphasis on technical knowledge and skills, and resulting improvements in defense-related technologies and applications, served the United States well during the war and postwar years, but, by the 1980s, economic shifts from defense to commercial applications left engineering employers dissatisfied. New graduates were technically well prepared but lacked the professional skills for success in a competitive, innovative, global marketplace. Employers complained that new hires had poor communication and teamwork skills and did not appreciate the social and nontechnical influences on engineering solutions and quality processes (McMasters, 2004; Todd et al., 1993). Several national reports recommending changes in engineering education appeared (e.g., ASEE 1987; NRC, 1985; NSB, 1986; NSF, 1989).

EC2000 emphasizes learning outcomes and accountability.

Despite a significant investment by the National Science Foundation (NSF) in engineering education, engineering schools were slow to respond to these criticisms, and deans of many colleges of engineering argued that rigid accreditation standards focused on curricular requirements and credit hours were hindering their efforts to make necessary changes. In 1992, a representative of two groups of deans of major engineering schools met with the leadership of ABET, then the Accreditation Board for Engineering and Technology, to express their concerns. Some deans suggested that a different accreditation organization was needed.

Inside ABET, members of the agency's Industry Advisory Council echoed the criticisms of members of the engineering community, and ABET's leadership responded. In 1992, the outgoing and incoming presidents of ABET jointly established an Accreditation Process Review Committee (APRC) to advise the organization on making accreditation criteria more flexible without compromising educational quality. Members of APRC were drawn from ABET and its Engineering Accreditation Commission, as well as from academia and industry. APRC identified three major barriers to change: criteria, process, and participation.

In 1994, with funding from NSF and industries represented on the ABET Industry Advisory Council, ABET sponsored three consensus-building workshops to address these concerns. More than 125 individuals, including university presidents, deans, and faculty members; industry leaders; private practitioners; professional and technical society liaisons and executive directors; state registration board members; and government researchers and regulators in technical fields participated in the workshops with ABET leaders, commissioners, and board members. Recommendations from the workshops, published in *A Vision for Change* in early 1995, became catalysts for the development of new accreditation criteria, which were circulated to the engineering community a few months later. Following a period of public comment, the ABET Board of Directors approved *Engineering Criteria 2000* (EC2000) in 1996.

The new criteria radically altered the evaluation of undergraduate engineering programs, shifting the emphasis from curricular specifications to student learning outcomes and accountability. Under EC2000, engineering programs must define program objectives to meet their constituents' needs. Rather than taking a cookie-cutter approach, the new criteria accommodate differences and innovations in programs. To ensure accountability, each engineering program is required to implement a structured, documented system for continuous improvement that actively and formally engages all of its constituents in the development, assessment, and improvement of academic offerings. Programs must publish specific goals for student learning and measure their achievement to demonstrate how well these objectives are being met. ABET was one of the first accrediting bodies to implement such a radical change in its accreditation philosophy.

Engineering Education Then and Now

To evaluate the impact of the new outcomes-based criteria on engineering graduates, ABET commissioned the Center for the Study of Higher Education at Pennsylvania State University to conduct an assessment. The study addressed two issues: (1) the impact (if any) of EC2000 on engineering students' preparation for entering their professions and (2) whether engineering programs had changed their organizational and educational policies and practices in ways consistent with the EC2000 specifications (Lattuca et al., 2006).

Following the conceptual model developed for the study (Figure 1), if EC2000 had the desired effects, one would expect to see a variety of changes rippling

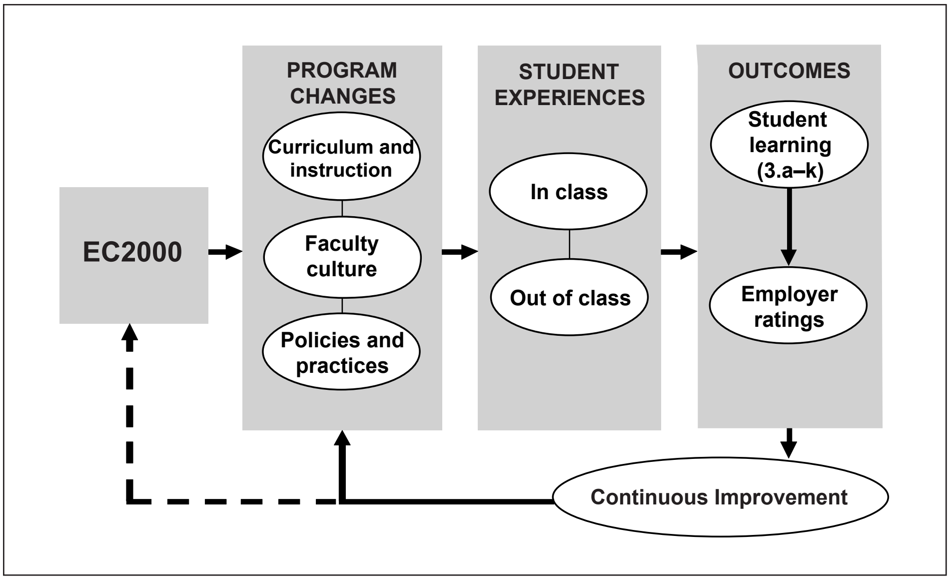


FIGURE 1 Conceptual framework for the *Engineering Change* study.

through the engineering educational process. The most immediate changes would be in engineering programs, as faculty members revised their curricula and instructional practices to promote the learning outcomes specified in EC2000 Criterion 3.a–k (Figure 2). One might also expect to see a shift in faculty culture toward greater involvement in learner-centered activities, such as outcomes assessment and professional development to improve teaching. Similarly, one might anticipate changes in administrative policies and practices, such as more emphasis on teaching and learning in hiring, promotion, and tenure decisions.

If all of the program changes were under way, the logic of the conceptual model suggested that improvements would be apparent in students' engineering education-related experiences. Like the changes in programs, the improvements would be consistent with achieving the learning outcomes specified by EC2000. Finally, such a transformation in engineering education over the past decade would be reflected in higher knowledge and skill levels among recent graduates, compared to those of their predecessors, on measures of the EC2000 outcomes.

A Précis of the Study Design and Methods

The study design for *Engineering Change* (Lattuca et al., 2006) was based on information from graduates (both pre- and post-EC2000), faculty members, program chairs, deans, and employers; the goal was to obtain a 360-degree view of changes in engineering education since the implementation of EC2000. A two-stage, disproportionate, stratified, random-sampling design ensured that sample sizes were adequate and that program disciplines, accreditation review schedules, and participation in an NSF-funded coalition during the 1990s were all taken into account. Adjustments were made to include institutions that serve historically underrepresented populations.

Data were collected from 40 colleges or schools of engineering that offer more than 200 engineering programs in aerospace, chemical, civil, computer, electrical, industrial, and mechanical engineering. Analyses were based on survey information from 1,243 faculty members (42 percent response rate), 147 program chairs (72 percent), 5,494 graduates in the class of 1994 (42 percent), 4,330 graduates of the class of 2004 (34 percent), 39 deans (98 percent), and 1,622 employers (population size and, thus, response rate unknown).

EC2000 Criterion 3.a–k

a. Apply knowledge of mathematics, science, and engineering
b. Design and conduct experiments; analyze and interpret data
c. Design a system, component, or process to meet desired needs
d. Function on multi-disciplinary teams
e. Identify, formulate, and solve engineering problems
f. Understand professional and ethical responsibility
g. Communicate effectively
h. Understand the impact of engineering solutions in a global and societal context
i. Recognize the need for, and engage in lifelong learning
j. Have knowledge of contemporary issues
k. Use modern engineering tools necessary for engineering practice

FIGURE 2 EC2000 Criterion 3.a–k learning outcomes.

By social science standards, these response rates were highly respectable, and the numbers of respondents were more than adequate for valid analyses. Statistical adjustments were made to correct for response bias by sex, NSF coalition participation, and discipline among faculty members, as well as for sex and discipline among graduates. Adjustments were also made for varying response rates among institutions. For a detailed description of the study design and methods, see Lattuca et al. (2006). The major findings are summarized below.

Changes in Programs

Curriculum and Instruction

According to program chairs and faculty members, engineering program curricula have changed considerably "over the past seven to 10 years." 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 EC2000 Criterion 3.a–k. For example, 75 percent or more of program chairs reported "some" or "significant" increases in emphasis on communication, teamwork, use of modern engineering tools, technical writing, lifelong learning, and engineering design. Similarly, more than half of the faculty respondents reported "some" or "significant" increases in their emphasis on the use of modern engineering tools, teamwork, and engineering design in courses they teach regularly.

Teaching methods 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. They also relied less on lecturing and textbook problems (Figure 3).

Faculty Culture

Faculty members reported increased involvement in the past 10 years in assessing student learning and using assessment results to guide program improvement. Program chairs, moreover, reported high levels of faculty support for assessments and related decision-support practices. More than 75 percent of program chairs estimated that either "more than half" or "almost all" of their faculty members supported efforts to ensure continuous quality improvement, and more than 60 percent of program chairs reported "moderate" to "strong" support among their colleagues for assessing student learning. Faculty members corroborated that finding. Nearly 90 percent reported being personally involved in outcomes assessment, and more than half reported "moderate" to "a great deal" of personal effort in this area. Nearly 70 percent thought their level of effort was "about right."

Another change in faculty culture included more engagement in professional development activities focused on teaching and learning. More than two-thirds of faculty respondents reported that, compared to seven to 10 years ago, they were reading more about teaching, and about half reported more frequent involvement in professional development activities, such as workshops on teaching, learning, and assessment and projects to improve engineering education. Depending on the activity, one-fifth to one-quarter of faculty members said they had increased their teaching-and-learning-related professional development efforts in the past five years.

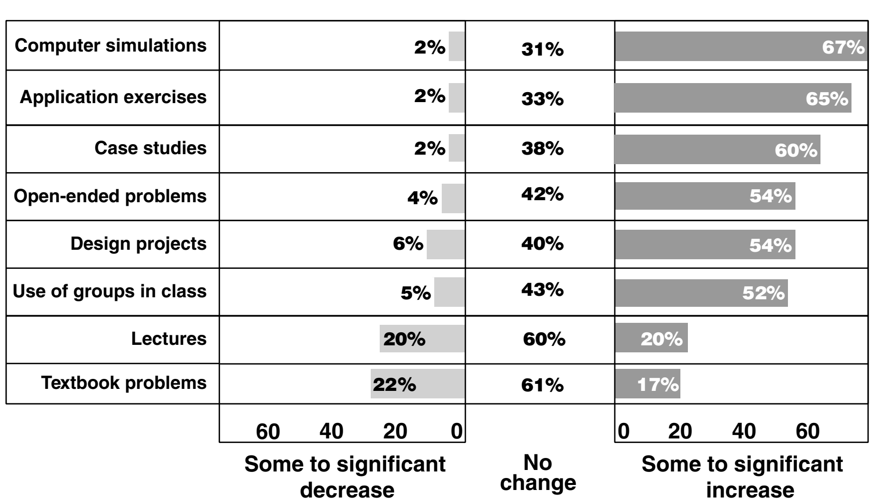


FIGURE 3 Faculty-reported changes in teaching methods.

Administrative Practices and Policies

The institutional reward system may be the single most important influence on how much time and energy faculty members devote to their teaching, research, and service. Thus, it is important to know if faculty members believe their efforts to improve teaching and undergraduate education are important considerations in decisions about promotion, tenure, and merit-based salary increases.

About half of the program chairs and faculty surveyed said they saw no change in the reward system over the past decade. Roughly 25 percent of faculty respondents said there was less emphasis on teaching since the mid-1990s; another 25 percent, however, said that the emphasis on teaching in the reward system had increased "some" or "significantly" over the same period. Faculty perceptions varied by academic rank. Senior faculty members were more likely to report an increase in emphasis on teaching in promotion and tenure decisions; untenured faculty were more likely to report less emphasis. About one-third of program chairs said the emphasis on teaching in promotion, tenure, and salary and merit decisions had increased over the past decade.

Changes in Student Experiences

According to the logic of the study's conceptual framework, changes relating to curriculum and instruction, faculty culture, and program practices and policies should be reflected in the experiences of graduates. Students who graduated in 2004 differed significantly from their predecessors in eight of 10 experiences inside and outside the classroom. The 2004 graduates reported more active engagement in their learning, more interaction with instructors, more faculty feedback on their work, more time spent studying abroad, more international travel, more involvement in engineering design competitions, and more openness in their programs to new ideas and people. Although the differences tended to be small, they persisted even after adjustments were made for an array of graduate and institutional characteristics.[1]

The 2004 graduates, however, reported experiencing a less welcoming diversity climate than their predecessors. This finding may be attributable to several factors: differences in the sex and/or racial/ethnic mix of the two cohorts, differences in awareness of diversity issues, and/or differences in the willingness to discuss and challenge prejudices or discrimination. The evidence provides no basis for evaluating these possible explanations. The 1994 and 2004 groups gave the same evaluations of their instructors' teaching skills and the number of hours spent in cooperative or internship activities.

Changes in Learning Outcomes

Given all of these changes, are recent graduates better prepared to enter the profession than their counterparts were a decade earlier? Figures 4, 5, and 6 contrast the achievement levels graduates reported on scales reflecting the Criterion 3.a–k learning outcomes.[2] For nine different measures,[3] the differences were consistent with the assumption that EC2000 is a force for change in engineering education. All differences were statistically significant ($p < .001$), ranging from +.07 to +.80 of a standard deviation (sd) (mean effect size = +.36 sd).[4] Five of the nine effect sizes exceeded .3 sd, which would be characterized as "moderate" in the social sciences.

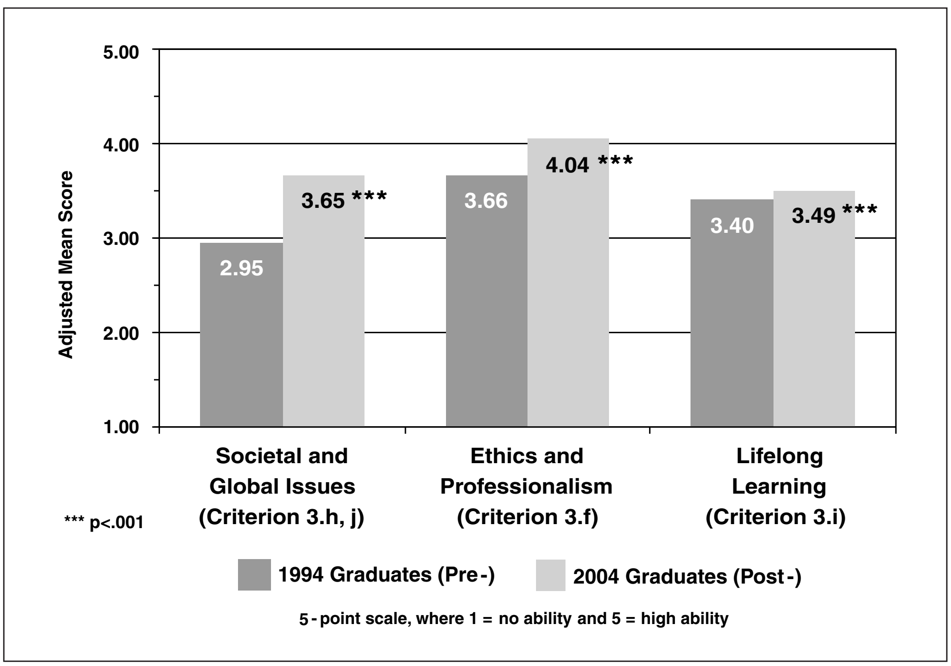


FIGURE 4 Differences in graduate-reported engineering skills (the contexts and professional skills cluster).

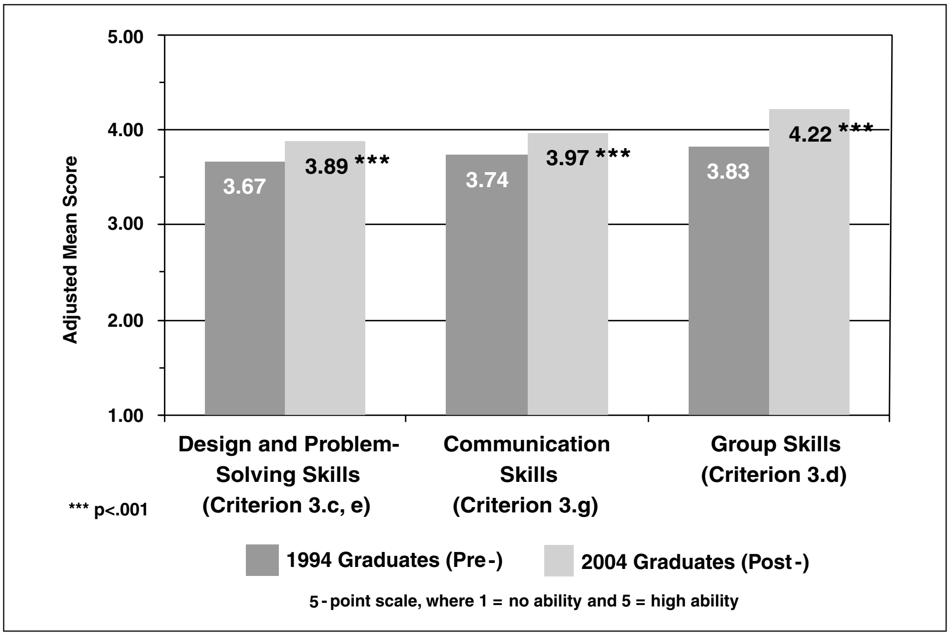


FIGURE 5 Differences in graduate-reported engineering skills (the project skills cluster).

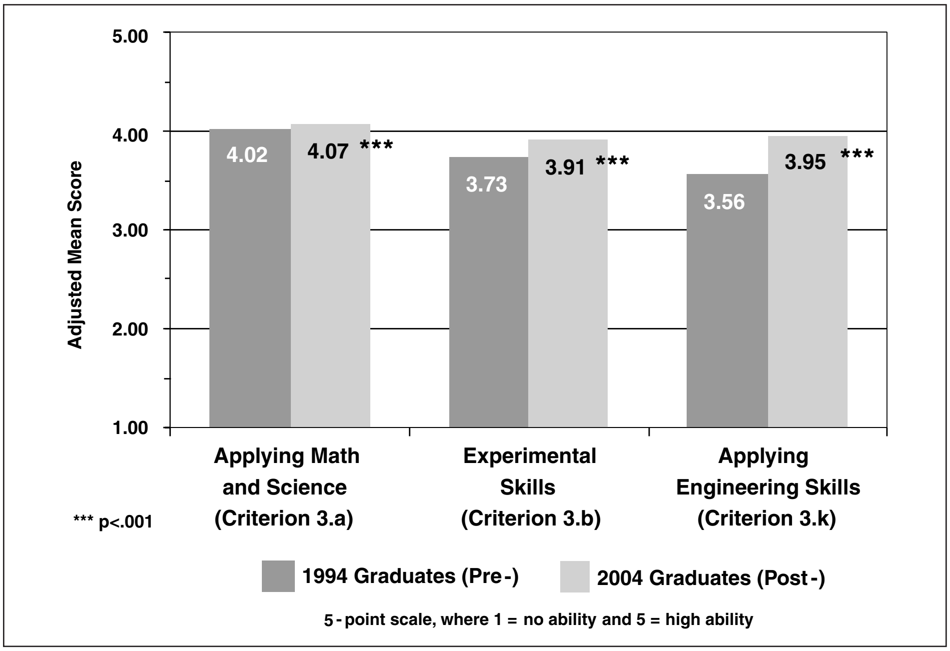


FIGURE 6 Differences in graduate-reported engineering skills (the math, science, and engineering science cluster).

The largest differences over the past decade were in five areas: awareness of societal and global issues (effect size = +.80 sd), awareness of ethics and professionalism (+.46 sd), group skills (+.47 sd), and applying engineering skills (+.47 sd). The smallest increases were in the ability to apply mathematics and sciences (+.07 sd). This last difference, although small, is noteworthy because some faculty members and others had expressed concerns that focusing on the development of the professional skills specified in EC2000 might detract from the teaching of the science, math, and engineering science skills that are the foundations of engineering. This finding not only indicates no decline, but shows a slight rise in knowledge and skills in these areas.

Linking Changes and Learning Outcomes

Multivariate statistical analyses provide moderate to strong evidence that changes in programs and student experiences were empirically linked to differences in learning. The evidence for this remained, moreover, even after controlling for a battery of students' precollege characteristics and for the characteristics of the institutions they attended. Fourteen of 16 program and faculty changes had statistically significant effects on at least one, and as many as five, student experiences, even after controlling for other factors. The most frequent and influential programmatic changes were an increase in emphasis on foundational knowledge and project skills in program curricula, less reliance on traditional pedagogies, an increase in active and collaborative pedagogies, and an increase in programmatic emphasis on assessment for improvement. Although student experiences varied, a consistent pattern emerged. The observed shifts over the past decade in program curricula, practices and policies, and faculty activities and culture related positively, at statistically significant, if sometimes small or moderate, levels, even after other factors were taken into account.

Finally, undergraduate program experiences, both inside and outside the classroom, were clearly linked to what and how much students learned. Nine of 10 measures had statistically significant, positive, and sometimes substantial influences on all nine of the measures of the EC2000 learning outcomes. The clarity of instruction, the amount of interaction with and feedback from instructors, and engagement in active and collaborative pedagogies had the strongest influence on learning.

Out-of-class experiences, however, also influenced student learning in important ways. The most important non-classroom activities were internships and cooperative education experiences, participation in design competitions, and active participation in student chapters of professional societies or associations. These non-classroom activities significantly and positively affected learning in six or more of the nine skill areas measured, although the magnitude of the effects were smaller than those of in-class experiences.

Employers' Views of Change

The 1,622 employer respondents in the study represented a wide range of geographic locations, industry types, company size, educational attainment, and engineer-evaluation experience. The employer survey asked three primary questions.

1. How important are the 11 Criterion 3 competencies for today's new hires?
2. How well prepared are today's graduates (on each of five dimensions reflecting the 11 a–k criteria)?
3. What changes have occurred over the past seven to 10 years in recent graduates' abilities?

The employer findings indicated that the EC2000 learning outcomes introduced in 1996 continue to be important to employers hiring recent graduates. Seven of 10 employers rated all 11 of the a–k criteria as at least "moderately" important, and at least six of 10 employers rated nine items as "highly important" or "essential." Moreover, employer support for the outcomes was fairly consistent across engineering fields, geographic locations, company sizes, types of business, and employer job title and educational attainment.

As shown in Figure 7, more than 90 percent of employers thought new engineering graduates were adequately or well prepared to use math, science, and technical skills, and about eight of 10 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 eight out of 10 still rated problem-solving skills as at least adequate. Barely half of employers, however, found the 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.

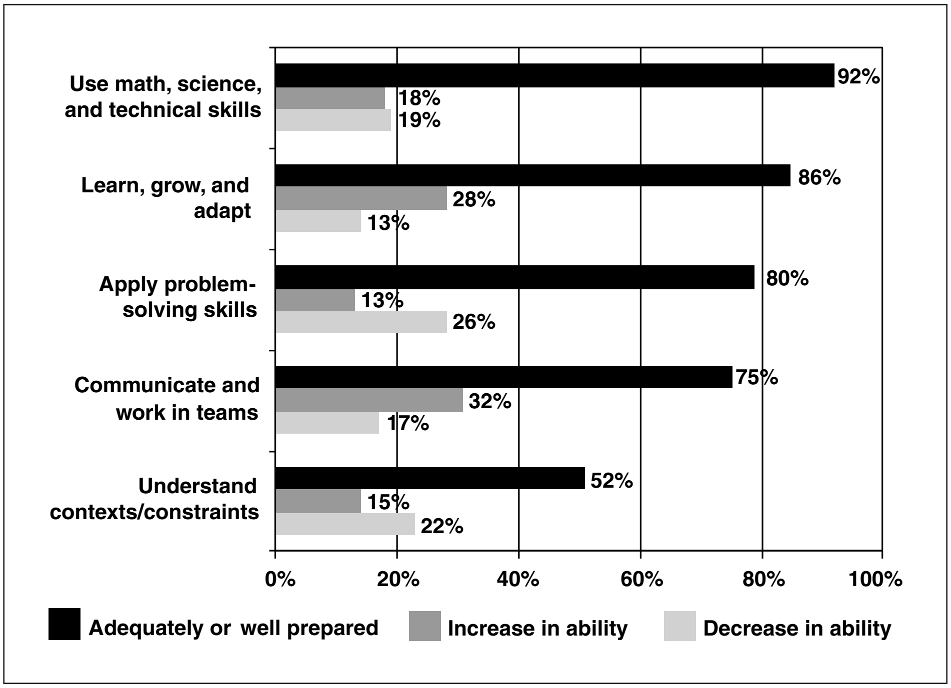


FIGURE 7 Employers' ratings of preparation and abilities of recent graduates.

Employer assessments were strikingly similar in all engineering fields, industry sectors, and geographic locations. Analyses indicate, however, that employers from larger companies that recruit nationally and hire the most engineers had more favorable assessments of preparation and changes over the past decade than employers from smaller companies that recruit locally and hire fewer engineers. This finding suggests that large national companies are seeing changes first and that some changes are just beginning to be visible to employers.

Conclusions

In the 1980s, employers expressed dissatisfaction with engineering graduates' professional skills. By the mid-1990s, ABET had implemented a new accreditation philosophy based on assessments of student learning and continuous improvement principles. Today, according to the accumulated evidence in *Engineering Change*, engineering education in the United States has changed dramatically. Engineering programs and faculty members have reengineered their curricula, teaching methods, professional development practices, program assessment and decision making, and, to some extent, their hiring, promotion, and tenure criteria.

Perhaps most important, graduates in 2004 were measurably better prepared than their counterparts of a decade ago in all of the nine learning areas assessed. The greatest increases were in understanding of societal and global issues, the ability to apply engineering skills, teamwork, and the appreciation of ethics and professional issues—all attributes U.S. engineers need to compete successfully in a competitive, global economy.

Notes

1. Analyses controlled for differences in sex, race/ethnicity, citizenship, native/transfer entry status, full-/part-time enrollment, parents' education and income, and secondary school academic achievement, as well as for institutional type, size, wealth, Carnegie Classification, EC2000 review schedule, and participation in an NSF-funded coalition.
2. Assessments are based on self-reported skill levels at the time of graduation. Although some individuals have questioned the validity of self-reports, a growing body of research in the past 30 years suggests that self-reported measures of learning and skill development are adequate proxies for objective measures of the same skills. Strauss and Terenzini (2005) provide a detailed description of the development and psychometric characteristics of the study's criterion measures and a discussion of the validity of self-reports.
3. In factor analyses, two of the 11 scales developed a priori to operationalize the a–k criteria collapsed into other scales, leaving a total of nine scales.
4. An effect size reflects the magnitude of the difference between two means after adjusting for differences in the variability of scores. The effect sizes, reported here in standard deviation (sd) units, can also be expressed as percentile-point differences. Assuming the mean skill level for 1994 graduates on any outcome marks the 50th percentile, an average increase among 2004 graduates of .2 sd is the equivalent of 8 percentile-points higher, or the 58th percentile. Other sample conversions: .4 sd = a 17 percentile-point difference; .6 = 23 percentile points; .8 = 29 percentile points, and 1.0 = 34 percentile points.

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Like it or not, the routine, repetitive aspects of engineering are priced as commodities.

The "Value-Added" Approach to Engineering Education: An Industry Perspective

Theodore C. Kennedy, founder of BE&K Inc. and an NAE member, delivered these remarks on October 10, 2005, during the NAE Annual Meeting.

Theodore C. Kennedy

I can't help but notice that I am the only speaker in this section of the program without a Ph.D. I can only assume that I am a part of the diversity initiative Bill Wulf has referred to. I'm the token B.S. degree. For those of you who have heard Bill Wulf and others talk about the declining enrollment of U.S. students in engineering, and the decline in the already anemic enrollment of women and minorities, there is little need for me to repeat either the statistics or the potential consequences.

I speak neither as a scientist nor a researcher. My business is designing and building things, things like the smokestack industries along the Gulf Coast that are all reducing production and increasing prices as a result of the hurricanes. Although I understand and agree with concerns about the declining population of Ph.D.s for both research and academia, my business, and the businesses of many engineering/construction companies like mine, is largely populated by graduates who are down a notch on the degree scale. But the issues are largely the same.

Given recent trends in business, we should really be asking why anyone thinks that enrollment wouldn't decline. In broad generalities, we might say that an aspiring engineer's mind is structured, orderly, somewhat innovative, precise, and, according to most spouses, predictable. In the past—even the recent past—many careers in engineering were also largely stable, relatively orderly, and somewhat predictable. It was not unusual for an engineer at retirement age to have only one, two, or maybe three employers listed on his résumé for an entire career.

Today, however, when young people look at the recent past—and they do—they see that stability in engineering employment is rare—even in companies with household names that prided themselves for generations on the stability of their engineering workforce. In the past, many took pride in saying they had never laid off an engineer.

Today, they frequently do. Downsizing, or "rightsizing," depending on your point of view, is a fact of life for most employers, even for the dot coms. But it is not just domestic downsizing that raises concerns among both young and older engineers. Although the projects, the contracts, and the need for engineers still exist, and are even increasing, many work-hours are now routinely shifted to lower cost engineering centers overseas where engineering firms charge a fraction of the U.S. rate. And these firms have employees with good technical educations—often obtained here in the United States. They also have adequate language skills and a seemingly never-ending supply.

Young people trying to decide on an educational path can quickly see this, and they question the value of pursuing a rigorous engineering education. In addition, women and minority students see a profession that has not welcomed them as readily as other professions, such as law, medicine, and finance.

The question, of course, is how educators and those of us in the business world can meet this challenge. If we continue to build facilities in North America, we must design and build them at competitive global prices. Neither we nor our clients can ignore the large premium we pay for a project done in the United States, even if only the detail engineering is done here. Whether we want to admit it or not, the routine, repetitive aspects of engineering have become commoditized and are being priced as a commodity, not as a profession. And that trend will not go away. Indeed, it is likely to increase. Today there are few major global engineering firms that do not have offshore engineering partners.

So, how do we become the sought-after technology center of the world? How do we move our engineering graduates up the ladder of project deliverables so that they and engineering business owners don't have to compete on a dollar-per-hour rate that will ultimately destroy our standard of living and puts us in a competition we will ultimately lose?

In personal terms, it comes down to what courses I advise my seven-year-old son to study if he wants to be an engineer, and if I want his lifestyle to be at least as good as mine. For generations, immigrants to the United States had two goals for their children: (1) to get a good education and (2) to make certain that the children would have a better life than their parents. Today, although I am not an immigrant, I have the same first goal for my son, but I am not sure he will have a better life than I have.

We have to change what we expect from engineers, and we have to turn out graduates with broader skills, interests, and abilities. With the commoditizing of basic design engineering and the migration of that function overseas, the traditional training ground for recent graduates is no longer available in the United States. Young engineers now have to move up to design leader and managerial positions much faster. The learning curve is getting steeper.

When I hire someone today, I look for different skills than I did 10 years ago. Today, it is not unusual for good candidates to have global references and experience on projects and assignments around the world. I think we must prepare our graduates for that type of career, because they aren't likely to spend their careers working in one company, or even in one country. And they must become advisors, consultants, managers, and conceptual planners much more quickly than they did a few years back.

We cannot ignore the large premium we pay for projects done in the United States.

This is true even for my business in the smokestack industries. Today, I need Georgia Tech, the University of Texas, and other educational institutions to turn out graduates who are mature and have more than professional engineering skills. I 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. I need graduates who can speak before an audience to make a point, either to me or to a client. Comfortable or not, engineers today are constantly selling—selling an idea, a concept, a study, an alternative, or just the need for a new document-control system.

Engineers must be prepared to write reports, studies, or routine business letters better than most can today. I have largely given up on teaching engineers to write succinctly, concisely, and clearly. I am tired of *cite*, *sight*, and *site* being used interchangeably. I used to send my engineers to classes, but now I have a report review team of English majors. And the situation has gotten worse with the advent of e-mail. Now we don't even write in complete sentences.

But, most important, I want employees who can analyze—analyze problems, situations, ramifications, upside and downside, near-term and long-term effects. The ability to analyze is a defining quality of new hires and of the employees I retain. I want my employees to ask the next questions: "Why is that so? Are you sure? What fact is that based on?"

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I think our legal colleagues have a better grounding in asking questions than engineers. With the increased use of the computer, we seem to have gotten lazy about asking the next question. If the printout says something is so, it must be so. Today, when I have a sticky problem or controversy, I frequently bring an attorney into the discussion—not because it's a legal matter, but because the lawyer will usually ask one or two questions to peel back another layer of the onion. Somehow, we need to incorporate this trait into engineering education.

In fact, I think we started losing our inquisitiveness when we stopped using the slide rule. With the slide rule, we got an answer, but we always had to check the rationale of the decimal point. Today the computer gives us the decimal point and three more digits, even if we're predicting next year's national debt.

Ultimately, the goal is to move our engineering deliverables up a notch on the chart. The routine and the repetitious have either gone or will go overseas, and we will soon be largely out of the detail design business as well. Today, we must manage the process—not do it.

The weaknesses in this scenario are obvious. First, I have been assuming that we can move basic engineering design functions upstream, following the path of large accounting firms that have set up business consulting divisions staffed largely by a few seasoned veterans and many young engineers and business majors with minimal experience. Whether that can work in a design context is, at least, questionable, but we must face the reality that the traditional training incubator for young engineers has largely disappeared and is moving offshore.

Second, my scenario assumes that offshore engineering firms will continue to do basic design but not migrate toward doing total project work. Given that there are still many aspects of a project that require boots on the ground before we get to the design phase, this should be more difficult to outsource. The aftermath of Katrina is a good example of this need. But with advances in computer-aided design (CAD) and laser technology, on-site vision and measurements may no longer be necessary. The need for experienced, gray-haired veterans who can head off the interferences and clashes of components has been minimized by CAD programs.

We are facing a long-term challenge. The better our technology, the less need there may be for us to do engineering design here at home. We must prepare our sons and daughters to be global engineering citizens of the world.

This will require changes in many of the engineering courses of study that we have traditionally valued. We must spend more time educating our graduates to be adaptable to the knowledge base that exists in other parts of the world. We must spend more learning time on developing inquisitive minds that can bear down on the pros and cons of a concept rather than providing calculations for a specific facet of a project.

We must all learn to translate our ideas and basic 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.

Engineers are packaged as problem solvers rather than creators and innovators addressing grand challenges.

A Call for K–16 Engineering Education

Jacquelyn F. Sullivan

Jacquelyn F. Sullivan is co-director of the Integrated Teaching and Learning Program at the University of Colorado at Boulder. This article is based on a talk given on October 10, 2005, at the NAE Annual Meeting.

The best-intentioned diversity-recruitment initiatives by engineering colleges nationwide have had little success in increasing access to the richly textured future afforded by careers in engineering. After years of focusing on increasing diversity in engineering, I am convinced that elementary school is not too early to start building the foundation for an engineering education—one that supports an informed citizenry, scaffolds an adaptive workforce, and leads to responsible innovations for our planet. A solid foundation that begins in the early, formative years would also ensure that young people and adults understand the contributions of engineers to our quality of life and would cultivate an interest in engineering in youngsters from all walks of life.

Consider the potential contributions today's young people—as tomorrow's engineers—could make toward closing our record $726 billion trade gap, if only we could interest them in our profession! Opportunities abound. The explosion of new fields, such as nanotechnology, biotechnology, and cyberinfrastructure, offers unprecedented opportunities for engineers to address significant societal challenges. And the pervasiveness and complexity of technology in our public infrastructure calls for the involvement of engineers in setting public policy—a change from the traditional, behind-the-scenes role engineers have played in the past. Increasingly, an engineer's place is in the House—and in the Senate—creating responsible, informed public policies.

As engineers, we create things, and we're proud of it. We improve society's standard of living, and we know we make a difference. But, astonishingly, most of the U.S. population is unaware of the role of engineers in medical advances, in alleviating human suffering, or even in creating the iPod that puts 10,000 tunes at our fingertips. We package engineers as problem solvers rather than creators and innovators who address the grand challenges of our time—environmental contamination, world hunger, energy dependence, and the spread of disease. Journalists report scientific achievements and engineering failures, as though engineering hasn't made profound contributions that have dramatically extended the human life span through public infrastructures. How did we let this happen?

K–16 Design Challenge

In the real world, engineers must respond to sudden changes. Yet we balk at making transformative changes in our educational system. Our educational challenge is itself a design challenge—making the "right" engineers for our nation's future. Half the U.S. population will be non-white by 2050, and engineers will increasingly serve diverse consumers (NAE, 2005). How do we attract native talent to engineering? How do we overcome the conspicuous absence of women and minority students in engineering colleges and professional practice? How do we turn around the disinterest in engineering among high school students? And, on a broader scale, how do we ensure that youngsters learn the skills they will need to thrive in a global, change-driven society?

We understand that innovative, technological breakthroughs are made at the convergence of disparate disciplines, yet we continue to draw unnatural distinctions between college-level engineering education and K–12 educational experiences that could tap into the passion of youngsters and prepare them to pursue engineering futures. Our collective challenge is to design a seamless K–16 engineering education system that integrates engineering with the liberal arts so technological literacy is considered a component of basic literacy. All engineering graduates should have excellent communication skills, and, evidenced by reading broadly and thinking deeply, a sophisticated understanding of the roles and responsibilities of engineers in our society. We must prepare tomorrow's leaders to be responsible stewards of our planet.

Making Engineering Attractive

Fewer U.S. students pursue careers in science, technology, engineering, and math (STEM) than in many other countries, where STEM studies are perceived as a path to a secure future. When we compare the participation of U.S. university students in STEM majors with the participation of students of Asian nations, such as China, Japan, and South Korea, the differences are stunning (Figure 1). Is it a coincidence that in some of these countries engineers are pervasive in top government ranks and engineering students occupy up to a third of undergraduate university seats? And, in contrast, that not one engineer can be found in the U.S. Congress?

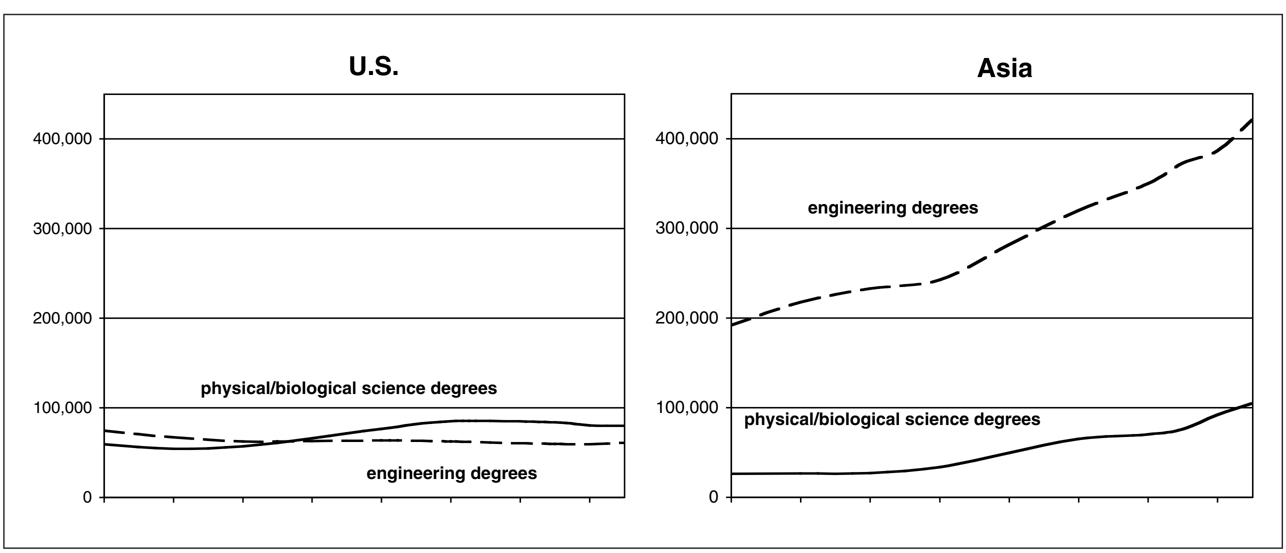

FIGURE 1 Trends in first engineering and science degrees. Adapted from NSB, 2006.

The number of engineering B.S. degrees earned by U.S. students peaked in 1985, steadily declined through 1992, and then came to rest on a decade-long plateau. The number began to climb again in 2002, but it is still lower than it was in the mid-1980s (NSB, 2006). Coupled with a dramatic increase in retirements expected in the next two decades, these numbers signal a national imperative that we attract more—and different—U.S. students to the engineering fold (NAE, 2005).

Diversity-Driven Creativity

Our entire citizenry and demographic mix should be represented in engineering. The lack of interest in engineering studies among U.S. youths is a problem—and a challenge—and a tremendous opportunity. The goal of engineering education should be the full participation of women, people of color, low-income students, and first-generation, college-bound young adults. We want and need people educated in cross-disciplinary, quantitative decision making at the helm, developing the new technologies and policies that will shape our nation's economic future and preserve the health of our planet. Our nation needs today's youngsters to be more than just users of tomorrow's technologies; we need them to be the developers of responsible technologies and products.

Although engineering is ultimately a creative endeavor, a recent poll shows that only 3 percent of U.S. adults perceive engineering as creative (Harris Interactive, 2004). Yet the goal of engineering is to *create* innovative solutions to meet the needs of people. The key word is *create*, and creativity is stimulated when design teams include contributors with diverse perspectives and life experiences.

The Gender Divide

Young women dominate the top deciles of U.S. high school graduates, yet they have a minimal presence in the engineering pipeline. Females account for only 20 percent of new B.S. engineering graduates. Even as our society becomes more technology driven, the number of women contributing to the technological revolution is shrinking. Are we content to let the best and brightest students shun our profession?

We must overcome this gender divide. Young women halfway through high school express scant interest in engineering. PSAT data for the May 2006 graduating cohort show that only 2 percent of U.S. college-bound eleventh-grade female students indicate an interest in majoring in engineering (College Board, 2004, 2006). Beyond the inequity, our profession's inability to connect with this vast reservoir of talent has economic implications.

A recent study established a quantitative link between women's representation in senior leadership and corporate financial performance (Catalyst, 2004). The 353 companies that remained in the Fortune 500 for four of five years between 1996 and 2000 boasted a higher representation of women in senior management positions than the companies that dropped off the list. It is time our engineering profession learned from this and began to leverage the full potential of our nation's diversity.

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A profound gender distinction pervades the information technology world, where the representation of women contributing to the technological revolution is shrinking. Increasingly, girls are turning away from being creators of the very technologies that shape their lives. "Boys invent things, and girls use things boys invent" (Margolis and Fisher, 2002). In 2005, only 15 percent of high school students who took advanced placement (AP) computer science exams were girls, by far the lowest percentage in any AP test. By comparison, girls made up 46 percent of the AP exam takers in calculus, 47 percent in chemistry, and 31 percent in physics (College Board, 2006). The absence of women's voices is disconcerting; a cyberspace culture designed and dominated by men alienates the sensibilities of women and represents a substantial lost opportunity.

The Public Image of Engineering

As we reflect on our slow progress in increasing diversity in the engineering workforce, it is worth pondering the relationship between diversification and the poor public image of engineering. The dominant messages—that engineering is tough and that one must *love* math *and* science to pursue engineering—are dead on arrival with girls. The Extraordinary Women Engineers Project, a coalition of engineering associations and societies, confirmed that the engineering gender divide is thriving. A needs assessment of more than

5,000 high school girls, teachers, and counselors found a profound lack of interest in engineering among mid-teen girls, who perceive engineering as a man's profession, have personally experienced little encouragement to consider engineering, and do not understand what engineering is really about (EWE, 2005).

Just think about it. How would they know? Which sitcoms highlight teams of engineers creating new products or addressing societal challenges in a stimulating and satisfying environment? Which engineering icons are empathetic role models, demonstrating that caring for humanity requires engineering solutions? The people who influence today's teenage girls are, in rank order, parents, peers, teachers/counselors, and the media. Little wonder that girls are neither encouraged nor guided toward engineering when they are steered by an adult public that perceives engineers as insensitive to societal concerns, doing little to save lives, and caring only marginally about community (Harris Interactive, 2004).

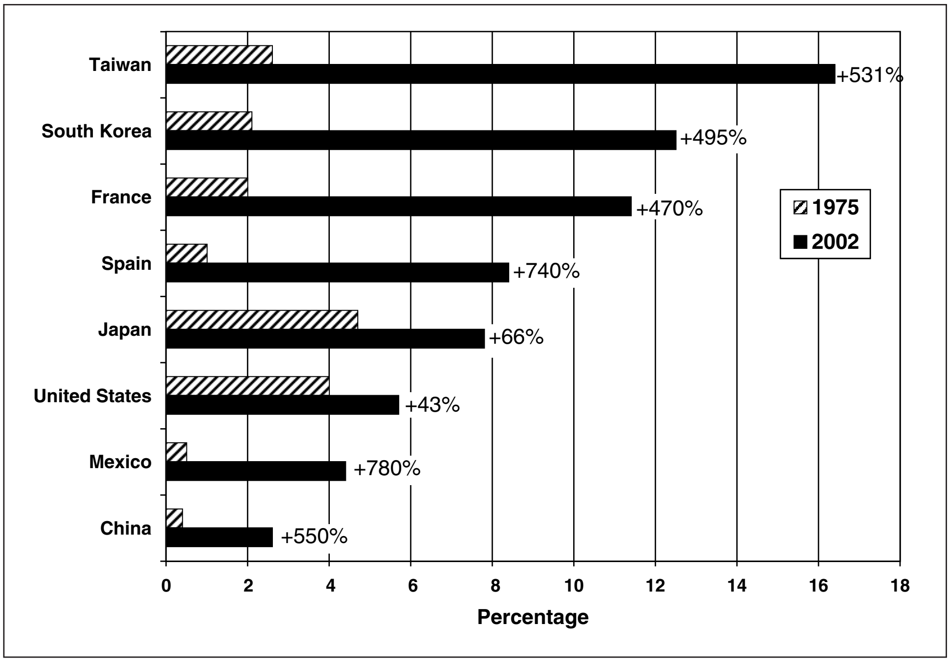

FIGURE 2 Percentage of 24-year-olds with first STEM degrees, by country and percentage change, 1975 to 2002. Adapted from NSB, 2004, 2006.

Today's engineering messages are misaligned with women's career motivators, and they do not convey the benefits or rewards of being an engineer. Our "engineering is tough" message does not resonate with young women seeking a flexible profession in which they feel they can make a difference. Clearly, we're simply not talking *with* teenage girls, and we delude ourselves if we think we are even talking *to* them.

As a creative profession, we can tackle this challenge. With National Science Foundation (NSF) funding, NAE has embarked on a public understanding of engineering study to gain insights into more effective messaging approaches. We can, and must, figure out how to market our profession to attract talented and well prepared young women.

The International Divide

One approach to probing the roots of economic competitiveness and creating better lives for a nation's citizens is to look closely at how the invention and innovation workforce is educated. If we look at a 27-year period, from 1975 to 2002, we see alarming global trends (Figure 2). The percentage of U.S. 24-year-olds who earned first STEM degrees increased by 43 percent. During this same period, the number increased astoundingly—in most cases more than quadrupled—in Taiwan, South Korea, France, Spain, Mexico, and China. The United States dropped from second among these nations (behind Japan) in 1975 to sixth in 2002.

The obvious question is: *How can our nation sustain a leadership role in innovation without STEM-proficient college graduates to fuel the technological and leadership workforce?* Who will be our inventors and creators? Or are we destined to become a lower wage service economy?

Poor High School Preparation

If we look closely at the preparation of high school students (Figure 3), we note that only slightly more than half of Hispanic and African American students even graduate, and less than one-quarter of them are prepared to succeed in college. These numbers are astonishing. In a knowledge-based economy, how can anyone attain a decent standard of living without even a high school degree? And how can the engineering profession benefit from the rich diversity of our nation if more than half of our students of color (the largest growing sector of the U.S. population) are not prepared to engage in college-level engineering education?

The latest data available on math proficiency among our nation's twelfth-grade students does not portend well for the creation of a diverse workforce. Readiness for success in college-level calculus is a known gatekeeper for success in engineering education. According to *The Nation's Report Card* (NCES, 2001), only 20 percent of U.S. Caucasian twelfth-grade students test proficient or above in mathematics; fewer than 5 percent of Hispanic or African American twelfth-grade students achieve at the proficient level (Figure 4). For our nation's 350+ engineering colleges to compete for this limited pool of qualified students is like rearranging deck chairs on the Titanic. Not only is this a compelling reason to form meaningful, outcomes-based partnerships between universities, the K–12 community, engineering societies, and engineering professionals to improve the preparation and engage the interests of American youth, it is an economic necessity.

Legitimizing Engineering Education

At the college level, fewer than 60 percent of our bright, first-year engineering

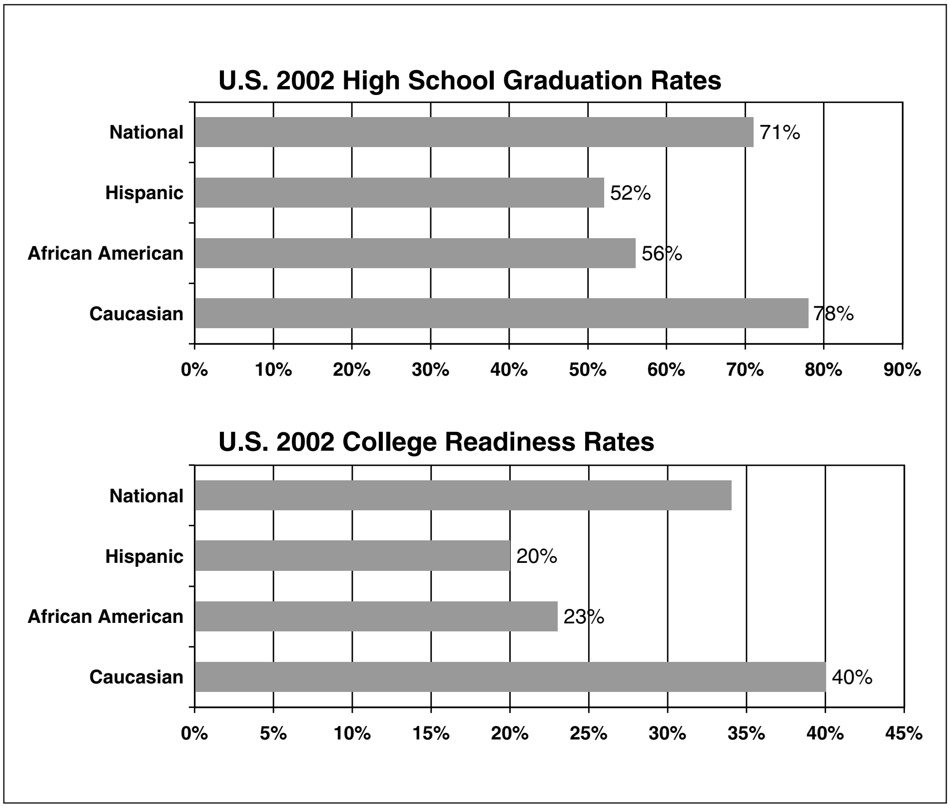

FIGURE 3 U.S. 2002 high school graduation and college-readiness rates. Adapted from Greene and Winters, 2005.

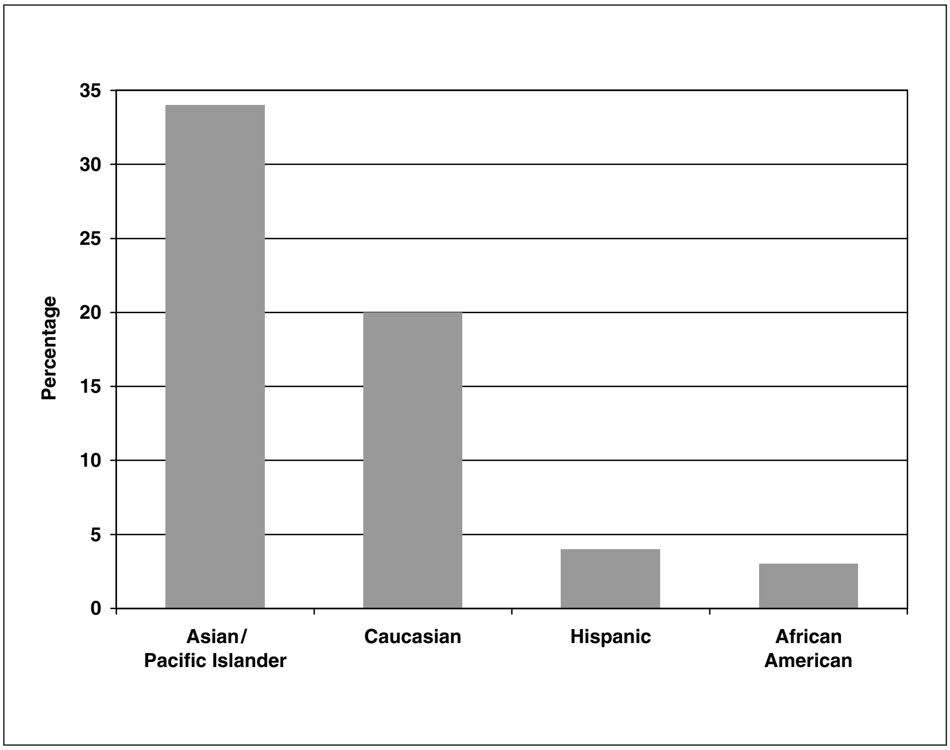

FIGURE 4 Percentage of U.S. twelfth-grade students proficient or above in mathematics. Adapted from NCES, 2001.

students graduate. Only 35 percent of college students think engineering is "worth the extra effort" (NAE, 2005)—although their peers studying medicine and law think their extra college work is worth the effort. Why not engineering? Perhaps providing pervasive K–12 engineering experiences would stimulate students to join the engineering ranks and motivate them to stay the course.

Scattered approaches to reforming engineering education have not resulted in systemic change.

Despite ABET reforms, engineering colleges have changed little in three decades. Most of us still teach the way we were taught; we have capitalized little on advances in the science of learning; we resist implementing strategies known to help retain students from underrepresented groups; and we do not take responsibility for the promotion of widespread technological literacy.

Overall, engineering curricula do not look much different than they did 30 years ago, despite a much-changed world. The challenge for today's engineering educators is to develop world citizens with highly honed critical thinking and creativity skills to support the transfer of knowledge to myriad problem contexts. To aid in that pursuit, engineering education is gaining traction as a legitimate field of research.

We now understand that educating engineers who can contribute to global engineering solutions will require changes in engineering education based on research into the most effective new educational methodologies. With advances in neuroscience and imaging, we can now apply, as never before, knowledge gleaned from the *science of learning* to engineering education.

The American Society for Engineering Education is beginning a year of dialogue on the topic of scholarship in engineering education. And, NSF now invests $10 million per year in research to create a body of knowledge to help us understand if our students are learning what we think we are teaching them. Purdue University recently created the first Department of Engineering Education in the country, followed quickly by Virginia Tech—the beginning of a trend to study engineering education and research-based connections to the K–12 community.

The passage of the No Child Left Behind (NCLB) Act in 2002 left no question that K–12 education must be driven by educational content standards and that students must master specified skills and knowledge at each grade level. Resistance from the K–12 educational community abounds, and early results are mixed, but NCLB is pushing us toward a national, standards-driven educational environment.

Massachusetts is the only state that currently has educational content standards in engineering, although standards in technology, which include engineering components, have been developed in many states. Six states—Massachusetts, Arkansas, New Hampshire, Florida, Texas, and Maryland—already mandate some high school coursework in engineering (Shuman et al., 2005). Texas even requires parental authorization for a student to *opt out* of the college track. However, in some high schools, engineering courses are relegated to the vocational-education track and are taught by former shop teachers. Unfortunately, these courses target non-college-bound students who generally do not have the academic fundamentals to pursue an engineering education.

Success Stories

Educating the Engineer of 2020 clearly laid out our challenges (NAE, 2005). We now have an undercurrent of awareness, though not yet a consensus, that the challenges facing us are so complex and daunting that tinkering at the edges of the problem will not suffice. And, we must admit that our scattered approaches to reforming engineering education have not resulted in systemic change. From what successful programs might we learn and extrapolate a way forward for K–16 engineering education?

Small High Schools

High schools with about 400 students have been able to address the plight of urban youth by drastically reducing the harmful effects of poverty. In these schools, promising achievement gains have been noted for low-income and ethnic-minority students (Cotton, 1996; Howley and Bickel, 2000). Small high schools capitalize on the body of knowledge that shows that the *quality* and *intensity* of coursework are more important in predicting college success than class ranking or SAT score. Personalized learning environments cultivate student/adult relationships that reduce student alienation and dropout rates.

A new school to watch, for both achievements and challenges relevant to the engineering community, is the Denver School of Science and Technology, a public charter school completing its second year of operation this June (*www.scienceandtech.org*). The state of Texas is considering founding 25 such schools.

Teach for America

Teach for America (TFA) is a highly selective, professional, semi-volunteer program that leverages the altruism of bright college graduates with strong leadership potential. The TFA program challenges the status quo of the regulatory, school-of-education-based approach to controlling teacher preparation and quality. Through TFA, new graduates with non-education majors are teaching in the most troubled schools.

In 2005, 7,000 new college graduates vied for 1,650 TFA openings, including 12 percent of new graduates from Yale and 8 percent from Princeton and Harvard. A recent independent program evaluation in a range of settings found that TFA teachers had outstanding educational qualifications and that they were largely successful as teachers (Decker et al., 2004). Overall, they generated a 10 percent increase in math achievement scores and maintained the current level of achievement in other subjects.

Is TFA a model program in which our profession should participate? TFA engineering teachers could increase awareness of engineering while advancing the education of the neediest students in the subjects that youngsters shy away from and for which urban schools have great difficulty recruiting teachers. Might newly graduated engineers who commit two or more years to teaching in TFA become a significant component in our campaign to shape a better future for engineering and for our country?

K–12 Engineering Outreach Corps

My personal bias is that community involvement should be an essential part of every engineering student's educational experience. Service learning brings together academic subject matter with real-world, community needs. Isn't that what engineering is all about?

If we are looking for a low-cost, high-impact approach to exposing K–12 students to the joys and creativity of engineering, let's initiate a national K–16 service-learning-based Outreach Corps. As all good teachers know, one learns best when one teaches. In this model, engineering students would connect with youngsters by teaching in K–12 classrooms.

From my own experience with such a project, I know that engineering students are highly motivated teachers of K–12 engineering material and that they can improve STEM learning (Sullivan and Zarske, 2005). Teaching-based community service promotes empathy in engineering students and can spread the word about the value of engineering to students, teachers, and parents.

An Integrated K–16 Approach

In spite of soaring U.S. college enrollments, fewer engineering degrees are awarded annually today than were awarded 19 years ago. The numbers tell us that it is not enough to harvest the brightest high school graduates; we must also *grow the talent* to fuel our profession. So, what is to be done?

A K–16 engineering "conversation" has been initiated and is picking up steam. This involves establishing long-term and skill-building relationships between engineering colleges and K–12 schools and exploiting *engineering as a vehicle for the integration of science and math* in ways that connect youngsters to the joys, challenges, and relevance of a future in engineering. Such experiences help students recognize the pervasiveness of engineering in their everyday lives and enable them to internalize engineering as a helping profession. Furthermore, early and extensive engineering experiences can prepare children and young adults to thrive in a technologically driven society—helping them to recognize the complexities of contemporary issues, engage intelligently in the discourse of our times, and make informed choices that take future generations into consideration.

Exposure to engineering may be most profound in grades 3 through 8. In these formative years, hands-on engineering experiences, conveyed through inquiry-based, design-oriented instructional methodologies, can support the learning of standards-based science and mathematics while stimulating student learning and making engineering come alive. By including engineering in early STEM learning, youngsters can begin to imagine themselves as engineers creating new products and processes for the benefit of humankind. The *TeachEngineering* digital library, a free and growing National Science Digital Library collection, provides curricular resources to support K–12 engineering initiatives with standards-based science and math curricula (Sullivan et al., 2005).

Conclusion

We are facing both great challenges and great opportunities. It is critical to our nation's health that we make bold, coherent K–16 engineering choices and bring engineering out of the shadows. As long as it remains a "stealth profession," the excitement of engineering will continue to be one of the best kept secrets on the planet. It's up to us to make engineering visible and relevant in the lives of K–12 students, teachers, counselors, and parents.

As we face increasing competition from low-wage, high-human-capital communities across the globe (and as wealth, thankfully, spreads and the global standard of living increases as never before), we must design engineering education to capitalize on an interrelated K–16 system. As my favorite professor once said, "It is our choices . . . that show what we truly are, far more than our abilities" (Rowling, 1999). We know what is possible. Our challenge is to *make the possible probable* for our educational system and our profession.

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When it comes to teaching, most faculty members enter the academy as "well intentioned gifted amateurs."

Preparing Engineering Faculty as Educators

Susan A. Ambrose

Marie Norman

Susan A. Ambrose and
Marie Norman

In *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, the authors ask, "What will or should engineering education be like today, or in the near future, to prepare the next generation of students for effective engagement in the engineering profession of 2020?" (NAE, 2005). To answer this question, we must look to engineering faculty—those who design the educational environment.

When engineering faculty members enter the academy, many—through no fault of their own—are not fully prepared for their role as educators. Although graduate schools have begun to focus more attention on developing teaching skills, the main focus continues to be on creating researchers. As a result, when most faculty members enter the academy, they are, as Kuh and associates note (2005), "well intentioned gifted amateurs" when it comes to teaching.

Furthermore, it has become increasingly clear that teaching and learning involve complex, interrelated intellectual, social, and emotional processes. Thanks to research in social psychology, the cognitive sciences, and education, we now know much more than we did 20 years ago about how cognition,

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motivation, and intellectual development affect learning and teaching. Unfortunately, universities have not successfully transmitted this information to faculty.

In this paper, we raise three questions germane to the task of preparing engineering faculty to educate students effectively. Our intention is to call attention to relevant findings from recent research to underscore the complexity and sophistication necessary for effective teaching and to argue for more recognition of teaching in the academic reward structure.

Overview

To improve engineering education, we must address three questions:

1. Is there a consensus among engineering faculty and administrators that faculty members need better preparation for their role as educators?
2. If so, what do they need to know, do, or understand to function more effectively?
3. How would academic institutions have to change for faculty to function more effectively as educators?

In this paper, we focus primarily on the second question. We address the first and third questions only briefly.

> *Improvements must begin with faculty members, the people on the "front lines" of education.*

Recognition of the Need for Change (Question 1)

Students would probably call this first question a "no-brainer." Over the past decade or two, leaders in the engineering community have identified shortcomings in engineering education and called for reform (ASEE Engineering Deans Council and Corporate Roundtable, 1994; NAE, 2004, 2005; NRC, 1995, 1999; NSF, 1995, 1996). In 1994, the Engineering Deans Council and Corporate Roundtable of the American Society for Engineering Education stated that, although engineering education has served the nation well, "there is broad recognition that it must change to meet new challenges." In 1995, the National Science Foundation (NSF) echoed this sentiment, and the National Research Council (NRC) Board of Engineering Education reinforced it: "In many areas, major change in the engineering education system is indeed necessary if it is to meet the needs of the nation and world in the coming century."

Organizations like NSF and the National Academy of Engineering (NAE) have led efforts to improve engineering education. An increasing number of centers at universities and elsewhere around the country (e.g., the NAE Center for the Advancement of Scholarship on Engineering Education) are researching issues in engineering education and implementing educational innovations. Similarly, the seven NSF-funded engineering education coalitions of the 1990s were charged with "stimulat[ing] bold, innovative, and comprehensive models of systemic reform of undergraduate engineering education." In fact, these initiatives have "produced significant reforms that have reinvigorated undergraduate engineering curricula . . . " (Foundation Coalition, 2006). Workshops on engineering education have focused specifically on preparing future faculty as effective educators, and prizes like the prestigious NAE Bernard M. Gordon Prize for Innovation in Engineering and Technology Education are now well established (NAE, 2006).

The question of whether engineering education should be improved and whether engineering faculty need better preparation, in other words, has been answered at the highest levels of the profession. Furthermore, a commitment of time and resources has been made toward meeting this goal. The larger question—*how* to prepare engineering faculty—remains to be answered.

Necessary Changes (Question 2)

Improving engineering education must begin with faculty members, the people on the "front lines" of education. At a minimum, they must (1) understand their students as intellectual-social-emotional beings, (2) understand basic principles of learning, and (3) understand the components of effective course design.

Understanding Students

Teaching requires complex human interaction. Students, like faculty, are social-emotional-intellectual beings, and all of these dimensions impact learning. Engineering faculty do not have to be social psychologists, cognitive scientists, or cultural anthropologists, but to design effective courses and implement effective classroom pedagogy, they must have a general understanding of the most relevant research findings.

First, educators must acknowledge the profound cognitive and emotional shifts experienced by 18- to 22-year-old college students. In a seminal work, *How College Affects Students*, Pascarella and Terenzini (1991) provide a synthesis of research on the influence of college on student development. They discuss not only learning and cognitive development, but also personal growth and changes, including changes in identity; relationships; cultural, aesthetic, and intellectual values; educational and occupational goals; political and social attitudes; and moral principles. The growth college students experience in a variety of ways every day impacts everything they do, and the better faculty members understand this, the better they can design learning experiences that can help students evolve into professionals. A few examples from four different areas of development highlight the types of information that can deepen our understanding of students as learners.

Intellectual Development

Ample research has been done in the past 50 years on how approaches to knowledge develop over time (Baxter-Magolda, 1992; Belenky et al., 1986; Perry, 1998).[1] Perry, for example, describes four stages of intellectual development. In the first stage, students have a dualistic view of the world; they perceive knowledge as clear and absolute and questions as having right and wrong answers. Students with a dualistic view believe that faculty know the right answers and that their role as students is to learn these answers. In the second stage, students recognize that there are multiple perspectives, but they may also believe that all opinions are equally valid or invalid. This is certainly not where we want our students to be at the end of four years!

As students gain greater maturity and experience and become more sophisticated intellectually, they reach the third stage, which Perry (1998) calls contextual relativism. At this stage "right and wrong, adequate and inadequate, appropriate and inappropriate can exist within a specific context and are judged by 'rules of adequacy' that are determined by expertise . . ." By the last stage of intellectual development, students are able to make decisions and understand the consequences of those decisions. At this stage, they have the ability, and the courage, to take and defend a position.

This brief description of Perry's work cannot capture the complexity of intellectual development, but it provides a context for thinking about how intellectual development impacts learning and teaching and raises a number of questions for educators. For example, if a first- or second-year undergraduate has difficulty with ambiguous or unstructured problems, should we push him or her to the next cognitive level, or will that happen naturally as the student matures? Can we assume that seniors have the ability to generate meaning and make choices among legitimate alternatives? Is it realistic to expect such intellectual growth in the four years of undergraduate education? If not, what are reasonable goals and expectations? The answers to these and other questions impact the way we design courses and the way we teach.

New knowledge is filtered through existing knowledge, whether or not it is accurate.

Intellectual Preparation

In addition to students' intellectual development, we would do well to focus on their intellectual preparation. We know that new knowledge is filtered through and interpreted according to existing knowledge, whether or not that knowledge is accurate (NRC, 2000). Consequently, we must assess students' prior knowledge and skills, correct inaccuracies, and identify gaps in their understanding or abilities in order for new knowledge and skills to have a strong foundation. We must assess not only *declarative knowledge* (i.e., knowledge that defines or describes), but also *procedural knowledge* (i.e., knowledge of how to use or apply) and *contextual knowledge* (i.e., knowledge of when to access and use certain principles, concepts, or procedures) (NRC, 2000).

The level of a student's knowledge or skills when he or she enters an engineering class depends to a large degree on what was learned in high school. Thus, it is important for engineering faculty to pay attention to what is happening in the schools that produce engineering students.

Given the increasing importance of high-stakes testing as a result of recent initiatives, such as the No Child Left Behind Act, and given the popularity of advanced

[1] For a synopsis, see Felder and Brent (2004).

placement (AP) courses in high schools, it is reasonable to question the depth of students' understanding. Do they enter college with a deep understanding of relevant material, or is their knowledge base superficial and fragile? Can they recognize when skills they have learned are applicable to new contexts, or do they only recognize their applicability in the context in which they were acquired? Finally, can they apply those skills appropriately? All of these questions warrant further exploration.

The childhood experiences of students differ markedly from those of their professors.

Generational Issues

A third body of information developed from studies of the "millennial" generation has identified traits that can be both advantageous and challenging to educators (Howe and Strauss, 2000, 2003). For example, many millennial students have older parents who are better educated than previous generations of parents. In addition, many students come from smaller families, in which parents have more time and resources to devote to each child. Some have called millenials the most protected generation ever, from prenatal classes and vitamins through childhoods with infant car seats, bicycle helmets, poison hotlines, childproof pill caps, and so on. Millennials have also lived highly scheduled and busy lives; structured play dates and after-school programs left them little free time. As a colleague likes to say, these young people are used to eating a sandwich in the car while doing homework on their way from soccer practice to piano lessons while listening to music on their iPods and text messaging with their cell phones! Current college students comprise "the most supervised and scheduled child generation ever" (Howe and Strauss, 2000).

What impact does growing up this way have on student attitudes, values, and behaviors? How do their experiences—which differ markedly from the childhood experiences of most of their professors—affect their interactions with faculty and their overall learning? Although it may be too soon to understand such complex sociological dynamics, we must start asking the questions now.

Cultural Issues

Faculty must understand not only generational culture, but also larger issues of cultural diversity among students. International students, for example, who constitute an increasingly large group on many campuses, come from a wide range of cultural and educational backgrounds. Their perspectives offer exciting pedagogical possibilities, as well as significant challenges. Communication skills, both written and oral, are an obvious area of concern, but less obvious cultural issues can also have profound effects on classroom dynamics, and thus on learning. The following examples represent just two of the many cultural differences that can affect interactions and perceptions in the classroom.

Differences in cultural and educational background can influence conversational styles, such as conventions regarding turn-taking during discussions; interruption techniques; pacing, pitch, and volume; and the number of people involved in a discussion at any given time. In the conversational style typical of certain cultures (Japan and Korea, for example), participation in discussions is orderly and characterized by polite turn-taking and deference to hierarchy. Linguist Deborah Tannen (1984) calls this "high-considerateness style." In the conversational style typical of other cultures (Latin America and the Middle East, for example), discussions are characterized by fast pace and high volume, frequent interruptions, and overlapping speech—"high-involvement style." Steinbach (1996) illustrates the difference between these two styles via a sports analogy. He compares high-consideration style to bowling; every player waits his turn, and only one player participates at a given time. He compares high-involvement style to rugby, which is characterized by loose rules and a great deal of movement. Rugby play does not stop when a player is tackled.

From an instructor's perspective, having students from both stylistic groups in one classroom can create particular challenges. Who will talk? Who will not? How do students perceive one another or the teacher? As instructors, how can we mediate and encourage a constructive level of participation for all? These questions become more complex when we consider that these are only two of many conversational styles and that there are many variations within and between cultures and contexts.

Many other cultural variations affect teaching and learning. In the United States, for example, students are generally expected to ask questions, indicate areas of confusion, and ask for examples to support their understanding. In some cases, students are encouraged to debate their peers, challenge their professors' ideas, and so on. Students who come from cultures where they are expected to maintain a respectful silence in class may be unaccustomed to asking professors for clarification or elaboration and may consider such behavior either disrespectful or personally embarrassing. Such cultural differences can lead to misunderstandings. If students do not volunteer questions, instructors may wrongly assume they understand the material. If they do not volunteer answers, instructors may wrongly assume they do not understand the material.

It may not be reasonable to expect faculty to learn all of the cultural differences that influence student thinking and behavior, but they must at least be aware of how differently students from diverse cultures can conceive faculty and student roles, conversational approaches, and the purpose of education. The better faculty understand the issues that impact classroom dynamics and student learning, the better they will be able to devise effective teaching strategies.

Understanding the Learning Process

In addition to understanding students better, we need a more thorough picture of how learning takes place. Educators today have the advantage of sophisticated research in the cognitive sciences and education to help them understand the learning process and design better instruction. Although we cannot do justice to the rich literature on learning here, two brief examples can suggest how engineering faculty might think about and foster student learning.

Organizing Information Effectively

Prior knowledge is the lens through which everyone views new information. If that lens is inaccurate, incomplete, or naïve, it can interfere with or distort the integration of incoming information (Clement, 1982; Minstrell, 1989; NRC, 2000). Research on cognition also indicates that the way this knowledge is *organized* determines its accessibility and use.

Students—like professors—create mental models that guide the retrieval and use of information; these models in turn shape further learning (diSessa, 1982; Holyoak, 1984; NRC, 2000). Effective mental models (clear causal relationships, accurately and logically categorized information, and evident relationships among concepts) enable students to retrieve information and apply relevant skills. Flawed or incomplete mental models lead to flawed and incomplete retrieval and application.

The challenge for faculty is to help students learn to organize knowledge the way experts do—"around core concepts or 'big ideas' that guide their thinking about their domains" (NRC, 2000). Core principles and concepts must be connected mentally to relevant pieces of information, and disconnected information and inaccurate links must be identified and corrected. In other words, to improve learning, engineering faculty must (1) assess (and sometimes correct) students' prior knowledge and (2) help students develop cognitive models for organizing prior and new information effectively. By making these goals explicit in the design of courses and classroom pedagogy, faculty can help students gain a deeper conceptual understanding of the material and thus enable the transfer of knowledge and skills to new situations.

Building Metacognitive Skills

To develop proficiency in an area of knowledge, learners must be able to select, monitor, evaluate, and adjust their learning strategies. In other words, students must become conscious of their thinking processes. This is called metacognition (Matlin, 1989; Nelson, 1992).

One way engineering faculty can help students do this is to "model" the way they, as experts in the field, construct intellectual problems, formulate questions, weigh alternatives, consider implications, and so on. An instructor might, for example, "talk through" a problem, identifying and putting into words the internal dialogue in which he or she naturally engages. This, of course, requires that the instructor become conscious of processes that have become so natural they may be barely conscious. By making "unconscious

Educators today can draw on sophisticated research in the cognitive sciences and education.

competence" conscious, the instructor (1) becomes more aware of the multiple subtasks and skills required to solve even simple problems, (2) helps students identify and address gaps in their understanding, and (3) models the metacognitive skills students are expected to develop.

Understanding Effective Course Design

Aside from a more conscious consideration of the learning process, instructors need a systematic approach to designing courses. Early in their careers, they often simply teach the way they remember being taught or adapt a colleague's course for their own purposes. They may also design courses based on a list of topics they think are important, rather than on learning objectives that indicate their expectations for student performance. If they do not clearly identify learning objectives, the activities they plan (lectures, discussions, in-class activities, etc.) may not actually teach the skills and knowledge they want their students to learn. At the same time, if assessments (exams, assignments, etc.) are considered an ex post facto means of measuring student performance, they cannot be used constructively to enhance learning.

Successful course design begins with asking who students are and using this knowledge to help design instruction. Designing effective courses involves three key components: (1) articulation of course objectives; (2) the creation of instructional/learning activities; and (3) the design of assessments. An instruction-design triangle (Figure 1), a simple illustration of a complex process, can provide a framework for thinking about teaching and support effective course design.

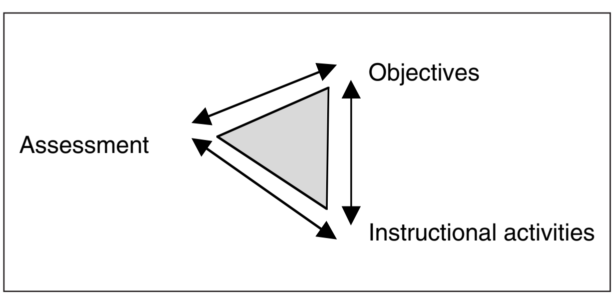

FIGURE 1 The instruction-design triangle.

Objectives refer to the knowledge, skills, values, and attitudes an instructor wants students to acquire by the end of the course. For example, an instructor might want students to be able to apply basic circuit laws to analyze simple circuits that include resistors and capacitors or to build Karnaugh maps and develop Boolean expressions. An explicit statement of these objectives, using active verbs and focusing on demonstrable skills, serves several purposes. First, it makes students aware of the goal of the course and the discrete skills and bodies of knowledge they must acquire to get there. Second, the identification of learning objectives helps the instructor design appropriate assessments and instructional activities that will help students realize those objectives.

Instructional activities include contexts and activities that encourage active engagement in learning. Research on cognition clearly indicates that students learn best by doing—by identifying types of data, formulating problems, discussing alternatives, weighing options, choosing among formulas and tools, justifying decisions, and so on. They do not learn as well passively. Successful instructional activities must be closely aligned with learning objectives, thus enabling students to practice the skills they are expected to master.

Assessments characterize the tasks and contexts that enable students to practice, demonstrate, and extend their knowledge and skills. Effective assessments provide both faculty and students with timely, systematic feedback on individual and group performance. Optimally, assessments not only measure student achievement (at the end of a learning experience), but also enhance student learning throughout the learning experience by enabling them to revisit concepts or practice their skills. Like instructional activities, assessments must be closely aligned with learning objectives so that the skills and knowledge students are working to achieve are reinforced simultaneously at multiple levels.

Each component of the triangle is directly connected to the other two; the relationships between them are direct and bi-directional. That is, each component should influence and guide the development and implementation of the others. The learning objectives guide what is assessed, and what is assessed guides the development and implementation of instructional activities. Many educational researchers agree that a close alignment of these three elements results in deeper and more meaningful learning (Gipps, 1999; Pellegrino et al., 1999; Snow and Mandinach, 1991; Stiggins, 1997).

Conditions Necessary for Change (Question 3)

For engineering faculty to become more effective educators, they must acquire skills and knowledge about students, learning, and effective instruction. At the same time, they must prepare students to function in a rapidly changing world. Students must understand global issues, function in interdisciplinary and cross-cultural contexts, engage comfortably with diversity, work effectively in teams, have strong written, oral, and visual communication skills, incorporate ethics into their professional lives, and so on. The only way students will be competent in these skills is if they are embedded in courses and curriculum in the context of engineering. In other words, faculty must change not only how they teach, but also what they teach. They must be committed to ongoing reevaluations of course designs as students change, the world changes, and our knowledge of learning evolves.

Clearly, this is asking a lot of faculty, whose time and energy are already stretched thin. In our experience, young engineering faculty genuinely *want* to improve their course design and teaching skills. However, because of overwhelming pressure to write grants and publish, along with committee responsibilities and other demands on their time, they often give teaching short shrift. The will is there, but the time, resources, and rewards are not.

Thus, improving engineering education will require not only a commitment on the part of faculty, but also significant support, resources, and recognition on the part of the university. First, engineering faculty members will need help to access the types of information discussed in this paper and support in adapting their courses to align with what we know about students, the learning process, and the changing world students will enter. Second, and perhaps most important, administrators must recognize the complexity and sophistication of good teaching, acknowledge the time and effort required to teach well, provide the resources necessary to prepare faculty appropriately, and give high-quality teaching greater recognition in the academic reward structure.

Conclusion

We can now review the three questions we initially posed. First, is there a widely perceived need for reforming engineering education? The answer is a resounding yes. Second, what would the necessary changes entail? We have provided a brief glimpse into the knowledge and skills necessary to create and teach effective, innovative courses. We hope we have conveyed that teaching is a complex process, learning is an even more complex process, and the human beings involved in teaching and learning are the most complex of all. Educating students is challenging, exciting, frustrating, unpredictable, and satisfying, often all at the same time.

Third, what are the necessary conditions for change at the institutional level? Faculty deserve to be better equipped to meet all of their responsibilities, and students have a right to expect their education to prepare them to function as effective engineers. If we expect engineering faculty to move from "well intentioned gifted amateurs" to expert teachers, we must recognize that expertise requires a large body of well organized knowledge and deliberate practice. Developing teaching expertise takes commitment, time, focused resources, and recognition in the reward structure. We know the conditions required for meaningful change in engineering education. The final question is: Will we provide them?

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Science and technology are becoming a single entity and igniting a new scitech *revolution.*

Redefining Engineering Disciplines for the Twenty-First Century

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Zehev Tadmor

All engineering disciplines derive from military engineering,[1] which was formalized in eighteenth-century France through the creation of technical institutes (Figure 1). Inspired by the French Revolution and the "century of light," the first institute, the École Polytechnique, was established in Paris in 1794 (Bugliarello, 1991; Tadmor, 2003). The concurrent industrial revolution,[2] and the so-called second industrial revolution associated with the rise of the steel, chemical, and electrical industries (Nybom, 2003), were driving forces behind the proliferation of the technical institute/university model that led to the establishment of a host of polytechniques in Europe, the Technische Hochshule in Germany, and institutes of technology in the United States (Rensselaer Polytechnic Institute, 1824; Massachusetts Institute of Technology [MIT], 1861; Stevens Institute of Technology, 1870; Georgia Institute of Technology, 1885; California Institute of Technology, 1891; Carnegie Mellon University, 1900) and elsewhere. These early institutes, which focused mostly on the industrial arts, began by teaching civil engineering and then gradually introduced other engineering disciplines.

Creation of Modern Engineering Disciplines

During the first quarter of the twentieth century, a new educational philosophy emerged that transformed engineering education from high-level, vocational, trade school-like training in current industrial practices into a

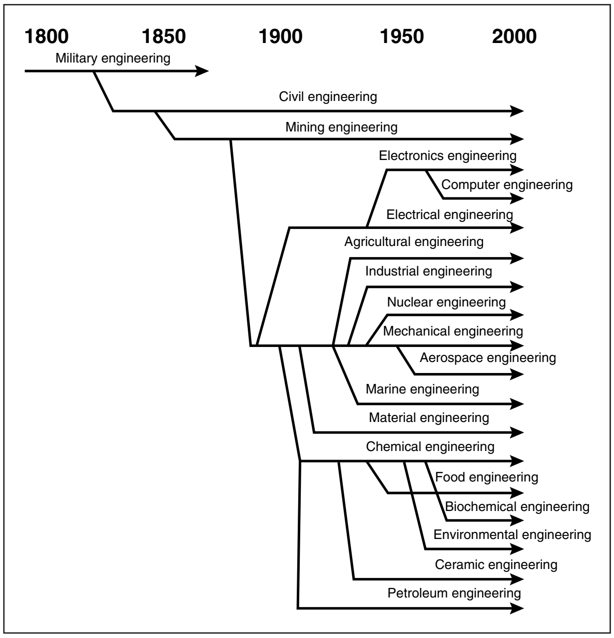

FIGURE1 A schematic approximation of the historical evolution of engineering disciplines.

discipline firmly rooted in the sciences. One of the leaders who championed this transformation was Karl Taylor Compton, president of MIT, who made it the theme of his inaugural address in 1930 (Compton, 1930):

> *I hope, therefore, that increasing attention in the Institute may be given to the fundamental sciences; that they may achieve as never before the spirit and results of research; that all courses of instruction may be examined carefully to see where training in details has been unduly emphasized at the expense of the more powerful training in all-embracing fundamental principles. Without any change of purpose or any radical change in operation, I feel that significant progress can thus be made.*

As Compton foresaw, the movement toward fundamental principles became the dominant trend in engineering education throughout the century. Triggered by phenomenal successes in the natural sciences, which have expanded mankind's understanding and horizons beyond all expectations, the scientific method was also applied to engineering. The movement gained momentum after World War II, when engineering curricula were gradually purged of vocationalism and were augmented by fundamental science studies. The impact of this change was so profound that it can be considered a revolution in engineering education. Indeed, the "science revolution" is the hallmark of engineering education in the twentieth century.

This profound restructuring of engineering education led to the formulation of engineering sciences, which still constitute the core curricula of engineering education in all disciplines. Thus, graduating engineers are no longer simply proficient in current engineering practices. They have been instilled with a solid engineering science foundation that enables them to cope with fast-changing technologies. In parallel, the engineering professoriate, whose main goal throughout much of the twentieth century was to create the engineering sciences using "tough quantitative and mathematical tools," imparted "academic, scientific respectability" to the profession (Simon, 1969).

An inevitable by-product of the science revolution was that engineering design, because it did not have a formalized, quantitative, teachable core body of knowledge, was largely eliminated from engineering curricula. Instead, engineers were expected to learn design on the job. Indeed, the development of a formalized approach to engineering design remains an open challenge to the engineering professoriate.

Fusion of Science and Technology

Historically, the scientific revolution preceded the industrial-technological revolution by about two centuries. Until the end of the nineteenth century, the two movements ran on parallel tracks with little interaction between them. Their objectives were different, and they were led by different kinds of people. The objective of the industrial movement was to develop new technologies and improve old ones; this movement was led by craftsmen, artisans, and visionary entrepreneurs, such as James Watt and other inventors.[3] The objective of the scientific movement was to understand nature and was led by philosophers and scientists.

At the beginning of the twentieth century, the two revolutions began to converge, reinforcing and catalyzing each other.[4] By the end of the century, they had effectively fused into a single entity, igniting a new science-technology (*scitech*) revolution, with more profound consequences for the human condition than either of the revolutions that preceded it. The scitech revolution is the cause, source, and alma mater of all high technology, globalization, and the subsequent explosive developments in worldwide economics. Scitech has blurred the distinction between basic and applied research, obliterated the classical linear innovation model (whereby it was assumed that the fruits of basic research lead in a linear fashion to industrial application), and shortened the time from invention to application. Scitech mandated multidisciplinarity in leading-edge research on the micro, nano, molecular, atomic, and even subatomic levels, and it made the research university the wellspring of technological innovation.

If the hallmark of engineering education in the twentieth century was the science revolution, which led to curricula designed to teach engineers[5] science-based, all-embracing, fundamental principles, we must ask ourselves how the ongoing fusion of science and technology, and the consequent scitech revolution, will affect engineering disciplines in the twenty-first century. If science and technology are indeed fused into a new entity, doesn't this blur the distinction between engineering and science? Perhaps we should no longer be talking about applying scientific methods to engineering, but rather inventing new curricula in which there is *no separation* between science and engineering.

In other words, perhaps we should reconsider engineering curricula in the most fundamental way and create entirely novel science-engineering (*scieng*) or engineering-science (*engsci*) curricula.[6] From this perspective, the twenty-first century could herald the next revolution in engineering education. The dictionary definition of the *engsci engineer* or *scigineer* could be "a person who uses scientific knowledge and microscopic building blocks to create products, materials, and processes that are useful to man."

Molecular Engineering: A Case in Point

In May 2002, an international workshop, Touchstones of Polymer Processing, was held at the Polymer Processing Institute, New Jersey Institute of Technology. Leading researchers in the field examined long-term trends of their profession and concluded that the relatively new discipline of polymer processing and engineering, which had split off from chemical engineering in the United States and mechanical engineering in Europe, rather than converging into a well defined, separate engineering discipline as had been expected, was, in fact, diverging into a broad, multidisciplinary activity (PPI, 2002). Of course, the divergence of disciplinary research into multidisciplinary approaches is characteristic of most engineering disciplines, but polymer processing, a latecomer as an engineering discipline, had diverged before it had a chance to converge into a separate, well defined entity.

As polymer processing becomes increasingly multidisciplinary, and looking from "inside the profession out," the participants concluded that the name macromolecular engineering and science (MMES) described the current character of the profession better than polymer processing.[7] Moreover, MMES is, in fact, part of a broader scene. On the fundamental level, the boundaries of MMES merge with molecular biology, complex fluids, polymer chemistry, polymer physics, chemical engineering, and other disciplines. At the research university level, this could lead to the creation of an entirely new engsci or scieng undergraduate curriculum called molecular engineering.

As shown in Figure 2, the molecular engineering curriculum could branch out in the junior year into three separate engsci disciplines: chemical molecular engineering (formerly chemical engineering), macromolecular engineering (formerly polymer engineering and science and polymer processing), and biomacromolecular engineering (formerly biochemical engineering and biotechnology).

A scieng or engsci curriculum would require five years of study, rather than the current four, and would lead directly to an M.S. degree. The philosophy of engsci curricula would be radically different from current engineering curricula. The engsci point of view, perspective, and mind-set would lead from the molecular toward the macroscopic, and not the other way around. The latter begins by examining a macroscopic process, analyzing it, and, if need be, looking all the way down to the molecular scale, whereas the former begins with a process on the molecular scale and examines its macroscopic

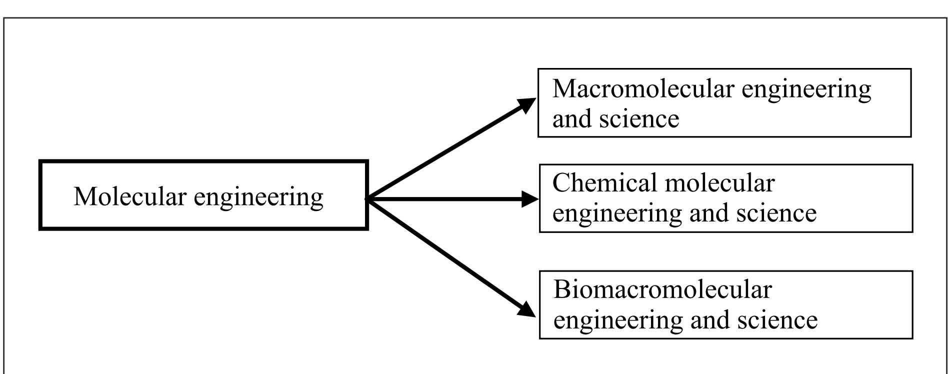

FIGURE 2 The new engsci discipline of molecular engineering, which breaks up in the junior year into three separate engsci disciplines.

implications and consequences. This bottom-up perspective would lead not only to a more in-depth understanding of processes, but also to fresh insights and the application and production of a multitude of novel artifacts that serve useful purposes.

A follow-up to the Touchstones Workshop, held in Leeds, United Kingdom, was supported by the Center for Advanced Engineering Fibers and Films at Clemson University and the National Science Foundation (NSF). At this workshop, the first steps were taken toward constructing an engsci curriculum and exploring the possibility of multi-university implementation. The workshop participants formulated a first draft of a curriculum for molecular engineering designed to educate engineers who consider molecular issues before designing a process or product and then use molecular information to increase the accuracy of the design (CAEFF, 2003).

The workshop participants concluded that educating students to view problems from the molecular level first would require restructuring and reordering many existing courses, as well as developing a number of new courses. Thus, additional funding would be required to formulate the discipline in detail and implement it, even as a multi-university effort. To this end, proposals have been and are being submitted to NSF and other agencies to fund course development and program implementation.

Conclusion

It is important to remember that a revolutionary redefinition of engineering disciplines into engsci, scieng, or scigineering disciplines at the research university level will not mean that conventional engineers in chemical, electrical, mechanical, and other fields of engineering are no longer needed. In fact, they continue to be crucial for current industrial needs, and colleges and other institutions of higher education must continue to educate them. Research universities, however, could focus on educating scigineers, who would be equipped with the knowledge and skills to shape and contend with the industries of the twenty-first century.

In the author's judgment, considering the explosion of knowledge in all relevant fields, it is no longer possible to educate engineers in just four years. The time has come to implement a five-year curriculum at all research universities, and perhaps at other institutions as well (Augustine, 1994; Tadmor et al., 1987). The M.S. degree should be an engineer's first professional degree, and certainly the first degree of an engsci graduate.

Acknowledgements

The author thanks Professors Dan Edie, Costas G. Gogos, and Ellad B. Tadmor and the members of the organizing committee of the Touchstones Workshop and the Leeds follow-up workshop for their reviews and comments.

Notes

1. *The Encyclopedia Britannica* of 1779 defines *engineer* as "one in the military art, an able expert man who by perfect knowledge in mathematics, delineates upon paper or makes upon the ground all sorts of facts and other works for offense and defense."
2. In 1769, James Watt patented a steam engine with a separate condenser, which vastly improved the Thomas Newcomen machine and thus helped launch the industrial revolution.
3. Eli Whitney, Samuel Morse, Alexander Graham Bell, William Henry Perkins, Guglielmo Marconi, Thomas Edison, George Eastman, Leo Baekeland, Charles Goodyear, John Wesley Hyatt, Orville and Wilbur Wright, and Nicola Tesla are among the inventors who catalyzed the industrial revolution.
4. Historians of technology consider GE Laboratories, established in 1900, the first laboratory where science was systematically applied for the promotion of technology. During World War II, the interaction was greatly accelerated by the application of science to the war effort, yielding important developments, such as radar, synthetic rubber, and, of course, the atomic bomb. This experience convinced the government that "science is power" and is thus worthy of public support. The recommendations in Vannevar Bush's famous report to the president, *Science: The Endless Frontier* (1945), which was submitted shortly after the war, were enthusiastically accepted and implemented. This led to the creation of the National Science Foundation (NSF), which signaled the beginning of massive support for science that continues to the present day.
5. The current *Webster's Dictionary* definition of *engineer* is "(a) a member of the military group devoted to engineering work; (b) a designer and builder of engines; (c) a person who is trained in or follows a profession in a branch of engineering." *Engineering* is defined as "(a) the art of managing engines; (b) a science by which the properties of matter and the sources of energy are made useful to man."
6. Prof. Ellad B. Tadmor, who reviewed this paper, suggested

that just as Disney coined the term "imagineering," we could adopt the word "scigineering."

7. In 1997, "Interdisciplinary Macromolecular Science and Engineering" (MMES), a workshop cosponsored by NSF and the U.S. Department of Energy, had arrived at similar conclusions—that at the interface between macromolecular science, chemistry, physics, and biology, a new field of MMES is emerging that "requires a new kind of polymer processing."

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Engineering educators must tap into students' passion, curiosity, engagement, and dreams.

Educating Engineers for 2020 and Beyond

Charles M. Vest is President Emeritus, Massachusetts Institute of Technology, and an NAE member. This article is based on a talk given on October 10, 2005, at the NAE Annual Meeting.

Charles M. Vest

When I look back over my 35-plus years as an engineering educator, I realize that many things have changed remarkably, but others seem not to have changed at all. Issues that have been with us for the past 35 years include: how to make the freshman year more exciting; how to communicate what engineers actually do; how to improve the writing and communication skills of engineering graduates; how to bring the richness of American diversity into the engineering workforce; how to give students a basic understanding of business processes; and how to get students to think about professional ethics and social responsibility. But for the most part, things have changed in astounding ways. We have moved from slide rules to calculators to PCs to wireless laptops. Just think of all that implies.

Looking ahead to 2020, about 15 years, and setting goals should be a "piece of cake." But to gain some perspective, look back about 15 years, and think about what was *not* going on in 1990. There was no World Wide Web. Cell phones and wireless communication were in the embryonic stage. The big challenge was the inability of the American manufacturing sector to compete in world markets; Japan was about to bury us economically. The human genome had not been sequenced. There were no carbon nanotubes. Buckminster Fullerines had been around for about five years. We hadn't even begun to inflate the dot-com bubble, let alone watch it burst. And terrorism was something that happened in other parts of the world.

So predicting the future, or even setting meaningful goals, is risky, even on a scale of a mere 15 years. Years ago, I read that Gerard O'Neil of Princeton made a study of predictions of the future and found one simple constant—we always underestimate the rate of technological change and overestimate the rate of social change (O'Neil, 1981). That is an important lesson for engineering educators. We educate and train the men and women who drive technological change, but we sometimes forget that they must work in a developing social, economic, and political context.

Opportunity and Challenge

I envy the next generation of engineering students because this is the most exciting period in human history for science and engineering. Exponential advances in knowledge, instrumentation, communication, and computational capabilities have created mind-boggling possibilities, and students are cutting across traditional disciplinary boundaries in unprecedented ways. Indeed, the distinction between science and engineering in some domains has been blurred to extinction, which raises some serious issues for engineering education.

As we think about the challenges ahead, it is important to remember that students are driven by passion, curiosity, engagement, and dreams. Although we cannot know exactly what they should be taught, we can focus on the environment in which they learn and the forces, ideas, inspirations, and empowering situations to which they are exposed. Despite our best efforts to plan their education, however, to a large extent we simply wind them up, step back, and watch the amazing things they do.

In the long run, making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details. In fact, that is my primary message.

Globalization

When we look to engineering in 2020 and beyond, we have to ask basic questions about future engineers—who they will be, what they will do, where they will do it, why they will do it, and what this implies for engineering education in the United States and elsewhere. In the future, American engineers will constitute a smaller and smaller fraction of the profession, as more and more engineers are educated and work in other nations, especially in Asia and South Asia. In the future, all engineers will practice in national settings and in global corporations, including corporations with headquarters in the United States. They will see engineering as an exciting career, a personal upward path, and a way to affect local economic well-being.

Universities around the world, especially in Asia and South Asia, are becoming increasingly utilitarian, focusing on advancing economies and cutting-edge research. I am reminded of a two-day meeting at Harvard six or seven years ago of a delegation of presidents of American universities and the presidents of seven Chinese universities that had been chosen to be developed into world-class research universities. Among the Americans were a Renaissance scholar, an economist, a political scientist, a linguist, a mechanical engineer, and, I believe, a lawyer. Among the Chinese university presidents were six physicists and one engineer who had become a computer scientist. I tell this story to illustrate the tectonic changes taking place in the way engineers are being produced and in where engineering and research and development (R&D) are being done.

We can only thrive on brainpower, organization, and innovation.

From the U.S. perspective, globalization is not a choice, but a reality. To compete in world markets in the so-called knowledge age, we cannot depend on geography, natural resources, cheap labor, or military might. We can only thrive on brainpower, organization, and innovation. Even agriculture, the one area in which the United States has traditionally been the low-cost producer, is undergoing a revolution that depends on information technology and biotechnology, that is, brainpower and innovation.

To succeed, we 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. We must also continue to bring new products and services to market faster and better than anyone else, and we must design, produce, and deliver to serve world markets. We must recognize that there are natural global flows in industry, that, the manufacture of many goods will inevitably move from country to country according to their state of development. Manufacturing may start in the United States, then move to Taiwan, then to Korea, and then to China or India. These megashifts will occur faster and faster and will pose enormous challenges to our nation.

Our companies already know this, but it often seems that the public and the body politick are still largely in denial of this reality—a very dangerous situation. If we continue to deny the realities of globalization or, worse yet, retreat into protectionism, then we won't do the very things that will enable us to lead and benefit from this brave new world.

Meeting these challenges will require an accelerated commitment to engineering research and education. Research universities and their engineering schools will have to do many things simultaneously: advance the frontiers of fundamental science and technology; advance interdisciplinary work and learning; develop a new, broad approach to engineering systems; focus on technologies that address the most important problems facing the world; and recognize the global nature of all things technological.

We mustn't deny the realities of globalization or retreat into protectionism.

Scale and Complexity

There are two frontiers of engineering, each of which has to do with scale and each of which is associated with increasing complexity. One frontier has to do with smaller and smaller spatial scales and faster and faster time scales, the world of so-called bio/nano/info. This frontier, which has to do with the melding of physical, life, and information sciences, offers stunning, unexplored possibilities, and natural forces of this frontier compel faculty and students to work across traditional disciplinary boundaries. This frontier meets the criterion of inspiring and exciting students. And out of this world will come products and processes that will drive a new round of entrepreneurship based on things you can drop on your toe and feel—real products that meet the real needs of real people.

The other frontier has to do with larger and larger systems of great complexity and, generally, of great importance to society. This is the world of energy, environment, food, manufacturing, product development, logistics, and communications. This frontier addresses some of the most daunting challenges to the future of the world. If we do our jobs right, these challenges will also resonate with our students.

New Systems Engineering

I first heard the term "systems engineering" as a graduate student in a seminar about the Vanguard missile—the United States' first, ill-fated attempt to counter Sputnik by putting a grapefruit-sized satellite into space. An embarrassing number of Vanguards started to climb and then blew up, which Soviet Premier Nikita Khrushchev found amusing. In fact, the Vanguard rocket was assembled from excellent components, but it was designed with insufficient knowledge of how the components would interface with each other. As a result, heat, electrical fields, and so on, played havoc with them. The system needed to be engineered. I found this very interesting, but then, like most students of that era, I pursued a career in engineering science.

Today, many of our colleagues believe we should develop a new field of systems engineering and that it should be central to engineering education in the decades ahead. In 1998, MIT established an Engineering Systems Division, which reflected a growing awareness of the social and intellectual importance of complex engineered systems. At the time, a large number of faculty members in the School of Engineering and other schools at MIT were already engaged in research on engineering systems, and MIT had launched some important educational initiatives at the master's and doctoral levels. The Engineering Systems Division, which provides administrative and programmatic coherence for these activities, is intended to stimulate further development.

MIT, of course, is famous for spearheading "engineering science," which revolutionized engineering in the post-World War II era. In fact, in my view, the pivotal moment in MIT's history was when President Karl Compton realized that we could not be a great engineering institution if we did not also have great science. This realization started the institution on a path that ultimately led to the engineering science revolution.

Another pivotal moment in MIT's history occurred half a century ago when a faculty commission (headed by Warren K. Lewis) considering the nature of our educational programs told us we had to develop strong programs in the humanities and social sciences (Committee on Educational Survey, 1949). Perhaps that set us on a path toward the twenty-first-century view of engineering systems, which surely are not based solely on physics and chemistry. Engineers of today and tomorrow must be prepared to conceive and direct projects of enormous complexity that require a highly integrative view of engineering systems.

Academics led the way in engineering science, but I don't think we have led the way in systems engineering. In fact, as we observe developments in industry, government, and society, we are asking what in the world we should teach our students. We need to establish a proper intellectual framework within which to study, understand, and develop large, complex engineered systems. As Wm. A. Wulf (2004) has warned us, we work every day with systems so complex that we cannot know all of their possible end states. Under those circumstances, how can we ensure that they are safe, reliable, and resilient? In other words, how can we practice engineering?

Something exciting is happening, however, and it comes none too soon. Biologists and neuroscientists are suddenly rediscovering the full glory and immense complexity of even the simplest living systems. Engineers and computer scientists are suddenly as indispensable to research in the life sciences as the most brilliant reductionist biologists. The language in the life sciences today is about circuits, networks, and pathways.

It also is fascinating to participate in discussions of the role of science and biology in R&D on homeland security, or, more generally, on antiterrorism, which I think of as the "Mother of All Systems Problems." Designing systematic strategies to protect against terrorism has about as much in common with protecting ourselves from the Soviet threat of just a few years ago as it does with strategizing against eighteenth-century British troops marching toward us in orderly file.

Here's another example of systems engineering. Consider what IBM vice president for research, Paul Horn, is thinking about these days. His company and his industry, which produce the ultimate fruit of the engineering science revolution (i.e., computers), are morphing into a new services sector—financial services, manufacturing services, McDonald's hamburger services. Paul Horn (2005) is asking himself if a services science is about to emerge. If a new discipline does appear, it will be a subset of the new systems engineering.

An even greater, and ultimately more important, systems problem than homeland security is the "sustainable development" of human societies on this system of ultimate complexity and fragility we call Earth. In Europe, sustainable development, ill defined though it may be, is part of the everyday thinking of industry and politicians and a common element in political rhetoric—and rhetoric is a start. I am troubled that it barely appears on the radar screen in U.S. politics. Nevertheless, sustainable development must be on our agenda for preparing future engineers.

In Europe, sustainable development is part of everyday thinking in industry and politics.

I believe energy is the key, the sine qua non, to sustainable development, but I fear that we risk becoming a "can't do" nation with respect to innovation rather than continuing in the great American "can do" tradition. The federal government has underinvested in engineering and physical sciences, and only nibbled around the edges of long-term energy supply and distribution problems. As a result, we have marginalized the field from the perspective of many bright young men and women. It seems to me that we are in a situation similar to the one we faced in the 1980s when our historically dominant manufacturing sector had become fat, sassy, and then, suddenly, uncompetitive.

We need to recharge corporate entrepreneurial and academic R&D, as well as our curricula in energy. We need to make energy an exciting, well supported, dynamic field that attracts the best and brightest young men and women and gives them opportunities to contribute and to innovate. We made this transition in manufacturing, design, and product development after being knocked down by the Japanese, and we can do it now in the domain of energy, environment, and sustainability. But the federal government and industry must kick start the change.

Delivery and Pedagogy

So far, I have suggested that engineering students prepared for 2020 and beyond must be excited by their freshman year; must have an understanding of what engineers actually do; must write and communicate well; must appreciate and draw on the richness of American diversity; must think clearly about ethics and social responsibility; must be adept at product development and high-quality manufacturing; must know how to merge the physical, life, and information sciences when working at the micro- and nanoscales; and must know how to conceive, design, and operate engineering systems of great complexity. They must also work within a framework of sustainable development, be creative and innovative, understand business and organizations, and be prepared to live and work as global citizens. That is a tall order . . . perhaps even an impossible order.

Information technology is more or less the paper and pencil of the twenty-first century.

But is it really? I meet kids in the hallways of MIT (and I am sure the same would be true at other universities) who can do all of these things—and more. So we must keep our sights high. But how are we going to accomplish all this teaching and learning? What has stayed constant, and what needs to be changed?

One constant is the need for a sound basis in science, engineering principles, and analytical capabilities. In my view, a strong grounding in the fundamentals is still the most important thing we provide. I am so old-fashioned I still believe that masterfully conceived, well delivered lectures are wonderful teaching and learning experiences. They still have their place . . . at least they better have, because at MIT we just built a magnificent, whacky, inspirational, and expensive building designed by Frank Gehry, and—by golly—it has classrooms and lecture halls in it (among other things).

But even I admit there is a good deal of truth in what my extraordinary friend, Murray Gell-Mann, likes to say: "We need to move from the sage on the stage to the guide on the side." Studio teaching, team projects, open-ended problem solving, experiential learning, engagement in research, and the philosophy of CDIO (conceive/design/implement/operate) should be integral elements of engineering education.

Two obvious things have changed: we now have information technology, and we have the MTV generation, Generation X, and beyond. So I suppose we should provide deep learning through instant gratification. It sounds oxymoronic to me, but it seems to be happening! Actually, our Frank Gehry building is about something like that.

Before I turn to the role of information technology in educating the engineer of 2020, I want to relate an interesting incident. A few years ago, two dedicated MIT alums, Alex and Britt d'Arbeloff, gave a very generous endowment, the d'Arbeloff Fund for Excellence in Education, which was inspired by their desire to understand and capitalize on the role of information technology in teaching and learning on a residential campus. We celebrated the establishment of the fund with an intense, day-long, interactive forum on teaching that brought together a large number of our most innovative and talented teachers and a wide range of students.

At the end of that very exciting day, we all looked at each other and realized that nobody had actually talked about computers. Even though information technology is a powerful reality, an indispensable, rapidly developing, empowering tool, computers do not contain the essence of teaching and learning, which are deeply human activities. So we have to keep our means and ends straight.

Information technology is more or less the paper and pencil of the twenty-first century. For engineering students of 2020, it should be like the air they breathe—simply there to be used, a means, not an end. The Internet, World Wide Web, and computers can do two things for engineering schools. First, they can send information outward, beyond the campus boundary. And second, they can bring the external world to the campus. By sending information out, we can teach, or, better yet, provide teaching materials to teachers and learners all over the world. By bringing the world in, we can enrich learning, exploration, and discovery for our students.

Information technology can also create learning communities across time and distance. It can access, display, store, and manipulate unfathomable amounts of information: text, images, video, and sound. It can provide design tools and sophisticated simulations.

In addition, information technology can burn up a lot of money. To reduce the amount, we should take advantage of what the Internet and Web do best—create open environments and share resources and intellectual property across institutions. The goal of MIT's OpenCourseWare initiative is to make the basic teaching materials for 2,000 MIT courses available on the Web to teachers and learners everywhere, at any time, free of charge. And even more amazing forms of educational sharing are coming. My remarkable colleague Jesus del Alamo, for example, has established a program called iLab that allows experiments to be run via the Web. He is installing PCs in under-resourced African universities that enable students to log on and operate sophisticated and expensive experimental equipment that is physically located at MIT.

OpenCourseWare and iLab are prime examples of a snowballing global movement toward open resources for education and for scholarly materials emanating initially from the United States and fueled largely by thoughtful support from the Mellon Foundation and the Hewlett Foundation. I think educational openness and global sharing emanating from the United States is a very good exercise in public diplomacy; it contributes to the global common good in new and recognized ways. Our nation needs this at this moment in its history.

In my view, openness is creating a global meta-university, a transcendent, accessible, empowering, dynamic, communally constructed framework of Web-based open materials and platforms on which much of higher education worldwide can be either constructed or enhanced. Like the computer operating system LINUX, knowledge creation and teaching at each university will be elevated by the efforts of individuals and groups all over the world. It will rapidly adapt to the changing learning styles of students who have grown up in a computationally rich environment. But the biggest potential winners are clearly in developing nations.

Danger of Complacency

In the past 15 years, the number of engineering and computer science B.S. degrees granted in the United States dropped from about 110,000 to a low of 88,000, although it has recently rebounded to about 109,000 (NSB, 2006). We must double and redouble our efforts to make our engineering schools and our profession attractive and fully engaging for women and for currently under-involved minorities. We need equity and full participation in our engineering workforce, our faculties, and our leadership.

In this global knowledge age—with its serious problems and great opportunities—we need the best and brightest to enter engineering schools. And we need a larger percentage of them to earn Ph.D.s in areas of engineering that can lead to innovations that will keep us free, secure, healthy, and thriving within a vibrant economy.

We all know the statistical trends. The United States awards about 220,000 first degrees in science and engineering. China awards almost the same number, about 350,000 first degrees in science and engineering, having grown by almost 120 percent in the past decade. In 2002, Asian countries awarded 635,700 first engineering degrees, European countries awarded 369,700, and North America awarded 122,400.

The United States annually awards about 19,480 doctoral degrees in science and engineering, a number that has remained essentially constant for a decade. China today awards more than 7,500 doctoral degrees annually in science and engineering, an astounding 420 percent increase in one decade.

Statistics are important, but, in my view, the global challenge in engineering technology and innovation leadership is cultural. In Asia today, science and engineering "rule" for young people. These are hot, exciting, and respected fields. In Asian countries, engineering and science are understood to be the path of upward mobility for individuals and for nations. These countries are hungry, and they are not ashamed to learn all they can from the very best the world has to offer and then try to improve on it—nor would we want it any other way. They understand competition, and they are learning rapidly about innovation. The United States is still the clear world leader in science and technology, but of all the enemies our country faces, complacency is the one I fear the most.

In Asia today, science and engineering "rule" for young people.

We may be beginning to shake off our national complacency, however. Last fall, the National Academies' Committee on Prospering in the Global Economy of the Twenty-First Century released its report, *Rising Above the Gathering Storm: Energizing and Employing America for a*

Brighter Economic Future (NRC, 2006). This report outlines a federal agenda to improve K–12 science and mathematics education, strengthen our commitment to long-term basic research, and make the United States the best place in the world to study, do research, and innovate. The Council on Competitiveness framework document, *Innovate America* (2004), preceded this report. Building on these and other national studies, the president of the United States, in his 2006 State of the Union Address, proposed an American Competitiveness Initiative to begin building momentum for a science, education, and innovation agenda (DPC and OSTP, 2006). Hopefully, Congress will convert these urgent agendas into strong, well-funded programs.

Conclusion

As I said earlier, my primary advice regarding engineering education is that making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details. As we develop the concept of a new curriculum and new pedagogy and try to attract and interest students in nanoscale science, large complex systems, product development, sustainability, and business realities, we must resist the temptation to crowd the humanities, arts, and social sciences out of the curriculum. The point of my referring to the meeting of American and Chinese university presidents was to demonstrate the integral role of these subjects in U.S. engineering education. In this respect, we are different from much of the rest of the world. I believe the humanities, arts, and social sciences are essential to the creative, explorative, open-minded environment and spirit necessary to educate the engineer of 2020.

American research universities, with their integration of learning, discovery, and doing, can still provide the best environment for educating engineers…if we support, sustain, and challenge them. They must retain their fundamental rigor and discipline but also provide opportunities for as many undergraduates as possible to participate in research teams, perform challenging work in industry, and gain substantive professional experience in other countries.

My secret desire, which I hope will play out on the timescale of the next 15 years or so, is that cognitive neuroscience will catch up with information technology and give us a deeper understanding of the nature of experiential learning—a real science of learning. Then we might see a quantum leap, a true transformation in education. In the meantime, we must see to it that the best and brightest young American men and women become our students and, therefore, become the engineers of 2020 and beyond. We simply cannot afford to fail.

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NAE News and Notes

NAE Newsmakers

Sigma Xi, the scientific research society, has announced the establishment of the **George Bugliarello Prize** to be awarded for a superior interdisciplinary essay, review of research, or analytical article published in *American Scientist*. The $5,000 prize, to be awarded biennially, is endowed by the Greenwall Foundation of New York in honor of **George Bugliarello**, University Professor and President Emeritus of Polytechnic University, past president of Sigma Xi, NAE foreign secretary, and interim editor in chief of *The Bridge*. According to Peter Blair, executive director of Sigma Xi, the prize "reflects our esteem for him as a leader, scholar, administrator, teacher, articulate visionary, and companion in zealous research." The purpose of the prize is to inspire thoughtful discourse about how technology and engineering can advance human society and the health of our planet.

The University of Colorado at Boulder honored several distinguished engineering alumni at the 41st annual Engineering Awards Banquet on April 21. **Subrata K. Chakrabarti**, president, Offshore Structure Analysis Inc., was recognized in the private practice category for his successful career in the engineering of marine structures, including storage tanks, submarines, wave basins, piers, and for the design and installation of concrete piers for the new Tacoma Narrows Bridge.

Esther M. Conwell, professor of physics and chemistry, University of Rochester, has been named the recipient of the **Susan B. Anthony Lifetime Achievement Award** by the Anthony Center for Women's Leadership at the University of Rochester. The award is presented annually to an alumna, trustee, faculty member, or administrator who has served as a model for other women, demonstrated strong leadership qualities, and attained personal and professional success. Dr. Conwell's work in semiconductor physics has earned her international recognition.

Robert Q. Fugate, senior scientist for atmospheric compensation, Air Force Research Laboratory, AFRL/DES, Starfire Optical Range, was awarded the **Air Force Outstanding Civilian Career Service Award** at a ceremony marking his retirement after 35 years of federal service. Dr. Fugate was honored for his accomplishments and contributions to the Air Force.

NAE Foregin Associate **Herbert Gleiter**, professor, Institute of Nanotechnology, Research Center Karlsruhe, received the **Humboldt Medal**, the highest award of the Alexander von Humboldt Foundation, at the Symposium for Humboldt Research Awardees in March 2006. The medal was presented by Professor Wolfgang Fruehwald, president of the foundation. Dr. Gleiter was honored for his contributions to international scientific collaboration and his many years of service as a member of the Selection Committee for Research Awards of the Alexander von Humboldt Foundation.

Gerard J. Holzmann, principal computer scientist, Jet Propulsion Laboratory, was one of four computer scientists recognized by the Association for Computing Machinery (ACM) for contributions to the development of techniques for powerful formal verification tools for hardware and software systems. The four honorees received ACM's **Paris Kanellakis Theory and Practice Award**.

Pradman P. Kaul, chairman and CEO, Hughes Network Systems Inc., was named **Executive of the Year** by the Tech Council of Maryland (TCM) at the annual dinner and awards celebration on April 5. The TCM Tech Awards are presented to outstanding technology companies and executives who have contributed to their companies and communities. Criteria for the Executive of the Year award include outstanding leadership, integral contributions to the firm's growth and/or profitability, successful outcomes of calculated risks, and leadership in the Maryland technology community.

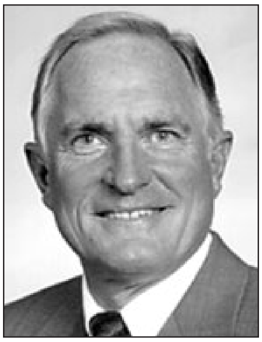
Chain T. Liu, senior corporate fellow, Metals and Ceramics Division, Materials Science Section, Alloying Behavior and Design Group, Oak Ridge National Laboratory, has been elected a **member of the Chinese Academy of Engineering**. Every two years the Chinese Academy elects several foreign scholars who have made significant contributions to engineering and technology in China.

Ponisseril Somasundaran, director, NSF/IUCR Center for Surfactants and La Von Duddleson Krumb

Professor, School of Engineering and Applied Science, Columbia University, is the recipient of the **Mineral Industry Education Award** of 2006 from the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME). Established in 1960, the award is given for distinguished contributions to the advancement of mineral industry education. Dr. Somasundaran was honored for "outstanding scholarly achievements in surface sciences, innovative teaching, and tireless efforts to inspire students in their pursuit of excellence."

The International Information Systems Security Certification Consortium (ISC)2(R) announced that **Willis H. Ware**, computer scientist and advisor to the federal government, and Corporate Research Staff Emeritus, The RAND Corporation, is the recipient of the **2005 Harold F. Tipton Award**. Dr. Ware was honored for his distinguished career in information security.

NAE Officers and Councillors Elected; Vice President and Councillors Complete Service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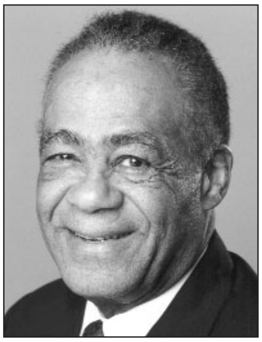
Maxine L. Savitz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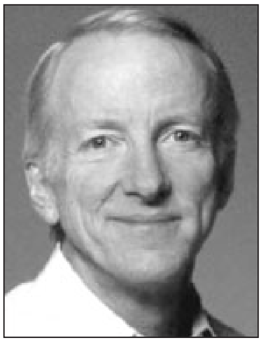
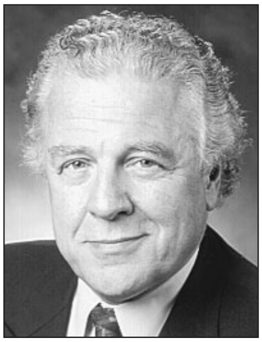

Robert F. Sproull


Sheila E. Widnall


Ruth M. Davis


Michael P. Ramage


Paul Torgersen

The results of the spring 2006 election of NAE officers and councillors are in. **Craig R. Barrett**, chairman of the board of Intel Corporation, was reelected to a two-year term as NAE chair. **Maxine L. Savitz**, retired general manager for technology partnerships of Honeywell Inc. (previously AlliedSignal), was elected to a four-year term as NAE vice president.

John Brooks Slaughter, president and chief executive officer, National Action Council for Minorities in Engineering, was reelected to a second three-year term as councillor. Newly elected councillors are **William F. Banholzer**, corporate vice president and chief technology officer, Dow Chemical Company; **Thomas F. Budinger**, professor, Departments of Bioengineering and Electrical Engineering and Computer Sciences, University of California, Berkeley, and head, Department of Nuclear Medicine and Functional Imaging, E.O. Lawrence Berkeley National Laboratory; and **Robert F. Sproull**, vice president and Sun Fellow, Sun Microsystems Inc. All terms begin July 1, 2006.

On June 30, 2006, **Sheila E. Widnall**, Institute Professor at Massachusetts Institute of Technology, will have completed eight consecutive years of service as vice president, the maximum allowed under the NAE bylaws. **Ruth M. Davis**, president and chief executive officer of Pymatuning Group Inc.; **Michael P. Ramage**, retired executive vice president of ExxonMobil Research and Engineering Company; and **Paul Torgersen**, John W. Hancock Jr. Chair and President Emeritus of Virginia Polytechnic Institute and State University, will have completed six consecutive years of service as councillors, the maximum allowed under the bylaws. Dr. Widnall, Dr. Davis, Dr. Ramage, and Dr. Torgersen were recognized for their distinguished service and other contributions to NAE at a dinner in May attended by other council members and NAE staff.

2006 Draper and Gordon Prize Recipients Honored

NAE President **Wm. A. Wulf** hosted the NAE annual awards dinner and presentation ceremony on February 21 to honor engineers whose professional accomplishments have improved lives and changed the world. The recipients of the **2006 Charles Stark Draper Prize** and **Bernard M. Gordon Prize** received their awards before an audience of more than 300 guests at a formal dinner at historic Union Station in Washington, D.C. The prizes were presented by Vincent Vitto of the Charles Stark Draper Laboratory, Inc., **Bernard M. Gordon**, founder of NeuroLogica, Inc., and NAE Council Chairman **Craig R. Barrett**.

Charles Stark Draper Prize

Willard S. Boyle and **George E. Smith** were awarded the Charles Stark Draper Prize "for the invention of the charge-coupled device (CCD), a light-sensitive component at the heart of digital cameras and other widely used imaging technologies." The $500,000 award is given annually to an engineer(s) whose accomplishments have significantly benefited society.

At Bell Laboratories in 1969, Boyle and Smith were searching for a way to configure semiconductors to store data to compete with new magnetic bubble memory technologies. "We were always coming up with new ideas, but most of them didn't work," joked Boyle. One day, however, they sketched out the design of the CCD, and soon researchers at Bell Laboratories and other companies were abuzz about the tiny, simple device. Boyle and Smith's invention became the first practical solid-state imaging device.

"Because they are small, accurate, and reliable, CCDs have found many applications as imaging devices," said Smith. In fact, they have become ubiquitous components in electronics, such as digital cameras, video cameras, and scanners. They are also essential in many medical imaging devices, such as the tiny cameras used to perform diagnostic procedures and surgical instruments that enable surgeons to perform procedures with smaller incisions. Because CCDs are much more sensitive than photographic film, they are now used in space telescopes and remote sensing cameras. The spectacular images transmitted by the Hubble Space Telescope, the Mars rovers (*Spirit and Opportunity*), and the many surveillance satellites circling Earth are all possible because of electronics that incorporate the rugged, energy-efficient CCD.

The CCD has a flat array of semiconductor capacitors that detect photons. Each capacitor holds an electrical charge proportional to the intensity of the light striking it. The device is extremely sensitive because it can hold this discrete, isolated charge and then move it without circuitry interconnects to a single output detector. The electronic readout can then be digitized and displayed and analyzed by a computer.

Willard Boyle was inducted into NAE in 1974. From 1953 to 1979, he led Bell Laboratories research in optical and satellite communications, digital and quantum electronics, computing, and radio astronomy. Boyle was also a member of the scientific team that helped NASA select the site for the first Apollo landing on the moon in 1969. He now resides in Nova Scotia, Canada.

George E. Smith, an NAE member since 1983, was a researcher at Bell Laboratories from 1959 to 1986. For much of this time, he led research on novel lasers and other semiconductor devices. He continues to reside in New Jersey.

The Draper Prize was established in 1988 and endowed by the Charles Stark Draper Laboratory Inc., Cambridge, Massachusetts, to honor the memory of "Doc" Draper, the "father of inertial navigation," and to increase public understanding of the contributions of engineering and technology to our quality of life.

Bernard M. Gordon Prize

Jens Jorgensen, John S. Lamancusa, Lueny Morell, Allen L. Soyster, and José Zayas-Castro were awarded the Bernard M. Gordon Prize, a $500,000 award presented annually in recognition of innovation in engineering and technology education. The recipients this year were cited for "creating the Learning Factory, where multidisciplinary student teams develop engineering leadership skills by working with industry to solve real-world problems."

The Learning Factory was developed to educate engineering students to translate engineering theory into practice and manage projects independently. In this innovative undergraduate program, students tackle real problems in industry, such as designing a collapsible crutch, turning coal ash into paving material, and producing a mechanism that adjusts the position of car seatbacks safely. Multidisciplinary teams of students define and characterize a problem, build a solution prototype, write a business proposal, and make presentations of their idea. "Learning Factory students see firsthand the importance of teamwork, effective communication, and engineering ethics," says NAE President Wm. A. Wulf. "Mastering such qualities is essential for engineers to become leaders in a dynamic workplace."

The Learning Factory began as a coalition between three universities, Sandia National Laboratories, and 36 industrial partners that shared a desire to give students firsthand experience in design, manufacturing, and business. Created in 1994 as a Manufacturing Engineering Education Partnership (MEEP), the Learning Factory was funded by a National Science Foundation/ Defense Advanced Research Projects Agency grant.

Within three years, the university partners—Pennsylvania State University, the University of Puerto Rico-Mayagüez (UPRM), and the University of Washington (UW)—successfully integrated the Learning Factory into their institutions and curricula. Since then, Learning Factory concepts and course materials have been adapted by other departments in these institutions and adopted by other universities in the United States and Latin America. To date, more than 10,000 students have created more than 1,200 Learning Factory design projects with more than 200 industry partners.

Jens Jorgenson, Professor Emeritus of Mechanical Engineering at UW, led facilities development at all three partner universities and directed the Learning Factory at UW until his retirement in 2000.

John S. Lamancusa, professor of mechanical engineering and director of the Learning Factory at Pennsylvania State University, was a principal investigator who designed the product-realization curriculum, the product-dissection course, and the facilities for Penn State's Learning Factory.

Lueny Morell, director of university relations for Latin America for Hewlett Packard Company and former professor of chemical engineering at UPRM, led the development of the Learning Factory curriculum at UPRM and continues to conduct dissemination workshops and assessments. More than 35 Learning Factory workshops have been offered in the United States and abroad since 1998.

Allen L. Soyster, now professor and dean of the College of Engineering at Northeastern University, was head of the Department of Industrial Engineering at Penn State. He headed the administration of the MEEP, was responsible for assembling the Learning Factory faculty and staff, and established the industry advisory board for the program.

José Zayas-Castro, professor and chair of industrial and management systems engineering at the University of South Florida (USF), established the Learning Factory at UPRM and has adapted Learning Factory concepts to other U.S. universities. In 1999, Zayas-Castro implemented the Entrepreneurial Manufacturing Innovation Learning

Experience Program at the University of Missouri at Columbia. At USF, he has redesigned the capstone project to include aspects of Learning Factory activities.

The Gordon Prize, established in 2001 by NAE member Bernard M. Gordon and endowed by the Gordon Foundation, is given in recognition of the creation of new modalities and experiments in education that help educate engineering leaders.

To learn more about the NAE Awards Program, visit *www.nae.edu*.

Draper Prize Acceptance Remarks

Wm. A. Wulf, George E. Smith, Willard S. Boyle, and Craig Barrett.

These remarks were delivered by Willard Boyle on February 21, 2006.

George and I are much honored to receive the Draper Prize. We thank Dr. Wulf and the staff of NAE for this wonderful occasion, and we thank our nominators and sponsors for putting our name before the Draper Prize Committee as inventors of the charge-coupled device (CCD). And, of course, we thank the committee for choosing us over what we are certain were other deserving submissions.

First I want to say a little about how and why the CCD was born. George and I originated the concept of the CCD about 35 years ago. At that time, we used to have frequent brainstorming sessions trying to invent useful devices. None of the devices amounted to anything until one session, about an hour long, produced the CCD. It literally appeared out of thin air as a diagram on the blackboard, and almost immediately, it had the feel of a good idea. In a few weeks, we had the models laboratory make a model, and it worked. Even though it was only a three-bit device, it established that the concept was sound. What a wonderful surprise!

It is not entirely true that it just popped out of thin air. In the lab next door, a group was working on a brand new technology called magnetic bubbles. I am certain that our thinking was influenced by that technology.

Our boss at that time was Jack Morton, who was vice president of device development at Bell Labs. He was enthralled by bubbles! So much so that he would call us frequently and ask if there were any new ideas for devices in the semiconductor group. He would then say that the bubble group had just received three new patents!

Incidentally, Jack Morton was one of the 24 founding members of NAE. He was not a man to be ignored. He was a hands-on manager if there ever was one, and he could make you feel that it was time to start looking in the help-wanted ads if he were displeased. With that kind of prodding, it is not surprising that George and I had a particularly brilliant brainstorming session and the CCD was born.

Little could we have guessed that 35 years later we would be standing here being honored with the Draper Prize.

Gordon Prize Acceptance Remarks

Wm. A. Wulf, José Zayas-Castro, Allen Soyster, Lueny Morell, Jens Jorgensen, John Lamancusa, Bernard Gordon, and Craig Barrett.

These remarks were delivered by John Lamancusa on February 21, 2006.

It is my great privilege to accept the Gordon Prize for Innovation in Engineering Education on behalf of the Learning Factory team. Thinking back on the 12-year journey that has brought us to this place, I am reminded of the man who walked into a doctor's office and asked if he could get in without an appointment. The receptionist kindly checked her book and said that he was in luck and could see the doctor right away. The doctor entered and asked "So, what seems to be the problem?" to which the man replied, "Doctor, I think I'm a moth." The doctor said "I'm sorry I can't help you, but there is a psychiatrist just down the street." The man said "I know, that's where I was headed, but your light was on."

There have been many lights on in the last 12 years that drew us in many unexpected and wonderful directions. The brightest of these has been the National Science Foundation's (NSF) efforts to reestablish the importance of engineering education. In my opinion, the greatest and most subtle impact of the NSF effort has been to convince a growing number of engineering faculty that devoting their passion and creativity to education is a worthwhile and scholarly pursuit. I would also like to thank the National Academy of Engineering for their recent Engineer of 2020 report, which we hope will be a catalyst for future passion and creativity.

Now a bit about the Learning Factory team. We were blessed with a visionary leader and manager, Al Soyster, who has a tremendous knack for recognizing opportunities, assembling and empowering the right team, and holding that team's feet to the fire when necessary. José, Jens, and I were in charge of local operations at each of our universities, and we have the singed feet to prove it. Lueny was the driving force behind our assessment and outreach activities, as well as our emotional heart and chief joke teller. In addition to these principals, there were many unsung faculty, staff, and industry partners at the three universities and at Sandia National Laboratories, several of whom are here tonight. I ask them now to stand and be recognized.

So what did we do? We listened well—to the voices of our students and our industry partners, who told us that there is a gap between what we teach and the practice of engineering. We borrowed well—from many other universities that are doing wonderful things. We rediscovered that the best way to teach is not to lecture but to put students in situations where they can gain first-hand experience. For this, we created places where future engineers could get dirty, tinker, develop judgment, leadership, and common sense—where they could make mistakes and learn from them. "An early stumble saves a later fall."

We believe that the primary job of faculty is to coach more and lecture less. We believe that the highest calling of engineers is to design, build, and sell things that help people. We did not invent anything really new, but we were able to make all of this work at a large research university and keep it working long after the grant money was gone.

In the words of Al Soyster:

> *It was always great to see our students collaborating with faculty and industry mentors in the completion of their senior design projects. For the students, the Learning Factory experience both validated their choice of an engineering major and provided a gateway to real-world challenges of working together to actually make something. For our faculty, the Learning Factory validated that ordinary professors can accomplish the extraordinary when united as a dedicated team. To do this, our partners from Mayaguez taught us, by example, that attitude is everything.*

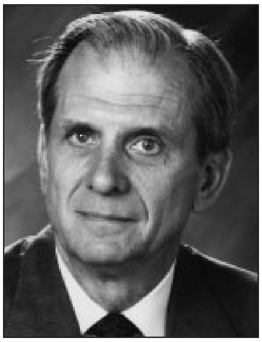
We could not have accomplished this without our 200 industry partners, exemplified by companies such as Boeing and Hewlett Packard that look beyond the next quarter's stock price. I would like to thank my dean, David Wormley, for his unwavering financial and moral support. Most important, I must acknowledge the support and sacrifice of our spouses: Julie, Mari, Waldy, Glenda, and Sharon. Thank you for putting up with all of those late nights and all of our trips to exotic places that you weren't invited to—places like Prague, Puerto Rico, Pittsburgh . . .

This journey has been the most rewarding thing I have done in my career. It has been an honor and a privilege to work with these special people, whose friendship and respect I will always treasure.

Finally, thanks to **Bernard Gordon** and the selection committee for their relentless pursuit of innovation in engineering education. We are humbled to be in the elite company of the previous award winners and will do our best to honor the trust you have placed in us.

In closing, I am reminded of the words of a very wise lady—my mother—who is with us tonight. At times like these, she would say: "Whenever you pat yourself on the back, make sure you do it low enough." So, on behalf of my compadres, and before someone pats me off the stage, adios, good night, and thanks for keeping the lights on.

Report of the Home Secretary



W. Dale Compton

Colleagues:

In his December 6, 2005, newsletter, Dr. Wulf discussed the difference between the distribution of Academy members specified by the NAE Council and the actual distribution of members. As it now stands, 45 percent are from business, 45 percent are from academia, and 10 percent are from the "other" sector. The desired distribution is 50 percent, 40 percent, and 10 percent, respectively, and the difference has actually increased since 2002.

Upon the recommendation of the Membership Policy Committee, the council has considered this matter in detail. Based on observations from past elections, the Council found that (1) the percentage of nominees from business who were ultimately elected was higher than the percentage of nominees from academia and (2) the number of nominees from business was significantly lower than the number from academia. The Council concluded that, once nominated, nominees from business have a good probability of being elected. The Council then determined that the best way to address this issue is to increase the number of nominations from business. To encourage these nominations, the Council has taken the following actions.

First, the formula used to determine the allocation of slots for peer committees has been changed to encourage an increase in the number of business nominees. The current formula can be found by going to *www.naeelections.org* and choosing the second item under the General Info tab.

Second, each section is being asked to create a search committee whose membership is largely distinct from that of the peer committee. The committee that submits replacement names for the peer committees (i.e., the section chair, the section vice chair, and the chair of the peer committee from the previous election) will also submit nominations for members of the search committees. Search committee members will serve three-year terms on a rotating basis. The membership on these committees will be approved by the Council following review by the president and home secretary.

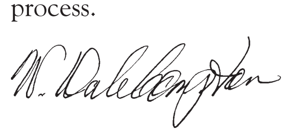
Because the NAE Articles of Organization and Bylaws specify that the vice chair of the peer committee will exercise principal oversight of the search, one member of each search committee will serve as committee executive and report to the vice chair of the peer committee.

Third, every year the vice chair of each peer committee will submit a written report to the vice chair of the Committee on Membership describing the committee's experience with the search process for the just-completed election. The vice chair of the Committee on Membership will report annually to the NAE Council on the overall search process, and the Council will specify the overall emphasis for the search process for the next year.

For the 2007 and 2008 elections, the emphasis will be on increasing the number of nominations from business. In future years, the focus might be on underrepresented minorities, evolving technical areas, or small business.

For the time being, the Council expects that the membership of the search committees will be influenced by the overall imbalance in NAE membership. Thus, if a section has few business members, the search committee for that section should have a significant number of members from business to focus attention on potential new members from business and industry.

Because the search process for candidates for nomination for the 2007 election is already under way, not all of these changes will be activated immediately. All peer committees have been asked to form search committees, but full implementation will not take place until the beginning of the 2008 election process.



W. Dale Compton
Home Secretary

Report of the Foreign Secretary


George Bugliarello

Since my report in the last issue of *The Bridge*, the first Indo-U.S. Frontiers of Engineering (FOE) Symposium, hosted by Dr. Sanjay G. Dhande, director of the Indian Institute of Technology Kanpur, was held on March 1–4 in Agra, India. Like other bilateral FOE symposia, the Indo-U.S. meeting brought together a select group of young engineers from each country to learn about cutting-edge research and become acquainted with each other. The Agra symposium focused on four themes: (1) nanotechnology; (2) research opportunities and challenges in the wireless domain; (3) national disaster simulation and mitigation; and (4) the interface of engineering with biology and medicine. The meeting was co-chaired by Dr. Sanjay Mittal of the Indian Institute of Technology, Kanpur, and NAE member **Subra Suresh** of the Massachusetts Institute of Technology. NAE President **Wm. A. Wulf**, Executive Officer **Lance Davis**, and I attended. At the end of the workshop, the participants were received in New Delhi by the president of India, Dr. A.P.J. Abdul Kalam, a famous engineer and the "father" of the Indian rocket program. President Kalam spoke on the direction of Indian technological development and entertained questions from the group.

The usefulness and popularity of bilateral FOE symposia have led to requests from several other countries for similar programs with NAE. Although these ideas are welcome, they require commitments of personnel and financial resources that can be difficult for NAE to sustain at this time.

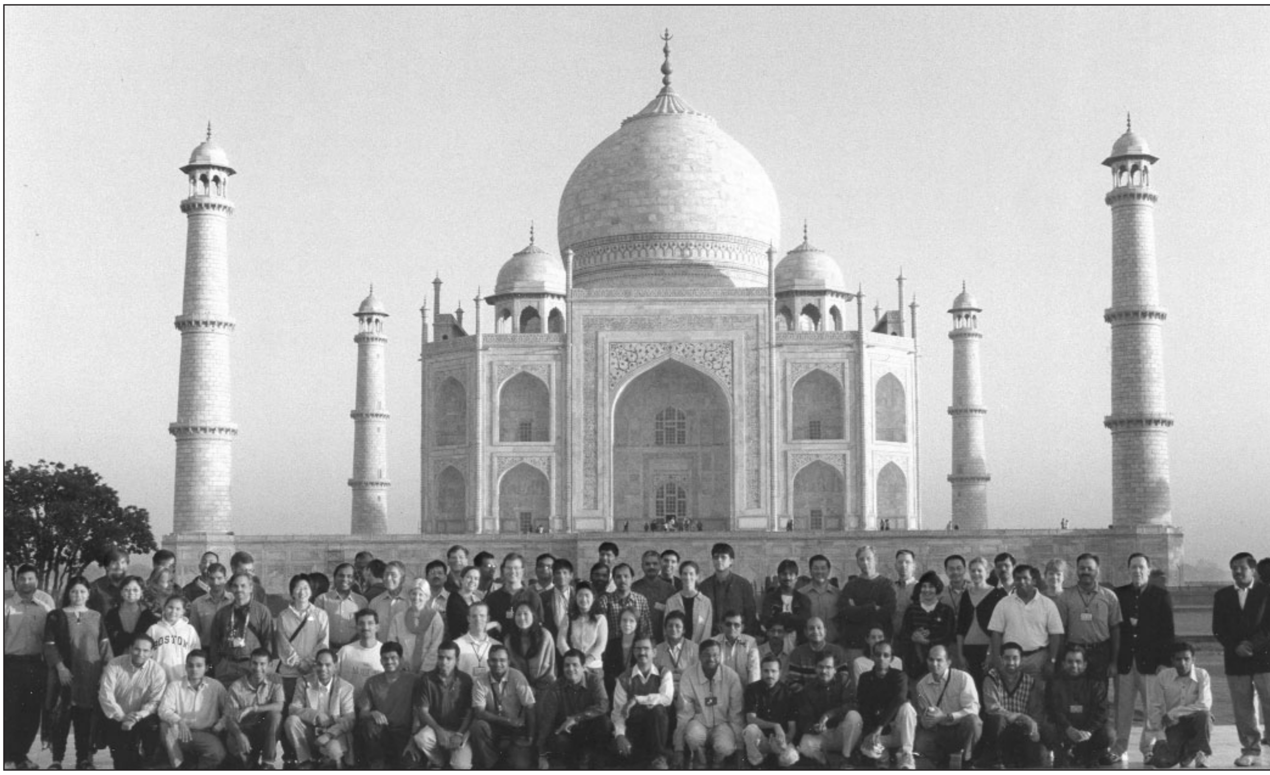
NAE's cooperation with the Mexican and Canadian Academies and FUMEC (the U.S.-Mexico Foundation for Science) in the area of automotive electronics continues. Progress thus far and future activities were discussed at a meeting at NAE in March. Automotive electronics will also be a theme of the annual meeting of the Canadian National Academy of Engineering in June.

President Wulf's invitation for suggestions from NAE members on developing or strengthening connections between NAE and academies and scientific organizations in other countries generated a gratifying number of positive responses. We are in the process of determining how to coordinate efforts to enhance our international outreach. One of the areas in which those who have expressed interest can be immediately helpful is in identifying potentially influential Foreign Associate candidates, particularly from countries that are underrepresented or not represented at all in our current roster. Home Secretary **Dale Compton** and I are working on forming a very small ad hoc committee to discuss how the process of electing Foreign Associates can be improved. The recently formed International Affairs Committee of the NAE Council is providing advice and assistance (members include **William F. Ballhaus Jr.**, **William L. Friend**, **Siegfried S. Hecker**, **M. Elisabeth Paté-Cornell**, and **George Bugliarello** [chair]).

I would like to thank all NAE members and foreign associates who have shared their ideas and expressed their willingness to become involved in these international efforts.

George Bugliarello
Foreign Secretary

First Indo-U.S. Frontiers of Engineering Symposium Held in Agra, India



Indo-U.S. Frontiers of Engineering participants visited the Taj Mahal on the first day of the meeting.

With the first Indo-U.S. Frontiers of Engineering Symposium on March 1–4, in Agra, India, NAE added a third bilateral meeting to the Frontiers of Engineering portfolio. The symposium was planned by NAE and the Indian Institute of Technology Kanpur (IITK) and sponsored by the Indo-U.S. Science and Technology Forum (IUSSTF). NAE member **Subra Suresh**, head of the Department of Materials Science and Engineering and Ford Professor of Engineering at the Massachusetts Institute of Technology, was U.S. co-chair. Professor Sanjay Mittal, professor in the Department of Aerospace Engineering at IITK, was Indian co-chair.

Like other bilateral FOE symposia, this meeting brought together approximately 60 engineers, ages 30 to 45, from U.S. and Indian universities, companies, and government laboratories for a three-day meeting to discuss leading-edge developments in four engineering fields: nanotechnology, wireless communication, natural disaster simulation and mitigation, and the interface between engineering and biology and medicine. The topics were selected for their timeliness and relevance to both countries.

The four talks at the session on nanotechnology provided a broad overview of nanotech and nanoscience. Speakers focused on (1) new paradigms of efficient fabrication on meso-scales; (2) the challenges of functionalizing nanotechnology through system integration that spans different scales and physical domains; (3) hurdles and approaches to the commercialization of nanotechnology; and (4) societal, ethical, environmental, and health issues related to nanotechnology. In a concluding summary, the organizers of the session emphasized that the initial "roll-out" of nanotechnology will be mostly improving current products rather than introducing entirely new products ("re-evolution" rather than "revolution"). They also pointed out that, although the economic effects of nanotechnology can be anticipated, the societal and environmental effects cannot. Finally, they noted, nanotechnology presents unique opportunities for interdisciplinary activities involving engineering, biology, physics, chemistry, social sciences, and public policy.

The second session was on wireless communication. Explosive global growth in this industry has catalyzed research that has advanced the understanding of many fundamental issues, such as channel capacity, interference mitigation, and coding theory for fading channels. The presentations covered the state of the art in four areas: (1) physical-layer research (capacity, spectral efficiency, opportunistic communications, and multiple-input multiple-output [MIMO] communication); (2) interference management techniques that can mitigate limits on energy and degrees of freedom, with a special emphasis on network coding; (3) challenges in wireless resource allocation (quality of service, scheduling algorithms, cross-layer design, and radio resource management); and (4) the impact of recent developments (3G services; integration of GPS, Wi-Fi, and Bluetooth with the handset; efficient architectures for mobile multimedia; and advances in video compression technology) on multimedia streaming and digital video broadcasts to handsets. The presentations gave the listeners an idea of the tremendous variety and global scale of research on wireless communications.

The December 2004 tsunami and Hurricane Katrina provided a timely context for the session on natural disaster simulation and mitigation. In an introduction, the organizers pointed out that extensive loss of life, injuries, and property damage caused by natural disasters are expected to increase as populations increase in urban areas, coastal zones, and other vulnerable regions. The presentations focused on the simulation, observation, detection, prediction, warning, and mitigation of hurricanes/cyclones, floods, tsunamis, and earthquakes. Each talk was focused on a single aspect for each type of natural disaster. The presentation on hurricanes was focused on coupled atmosphere-wave-ocean modeling, the next-generation of high-resolution prediction models enabled by increases in computer power, and other advances. The presentations on floods and tsunamis were focused on observation, detection, and warning, for example, X-band radars linked through a distributed, collaborative, adaptive sensing network for floods, and the coupling of data from deep-sea pressure transducers and simulation databases or linear shallow-water wave theory for detecting tsunamis. The presentation on earthquakes was focused primarily on experimental simulation and structural mitigation. The session concluded with a panel discussion highlighting interrelationships among the four types of natural disaster and identifying key areas for future engineering research.

The last session was on the interface between engineering and biology and medicine. As more is learned about molecular interactions at the genomic, proteomic, and metabolic levels, researchers are coming closer to understanding the inherent design principles of biological systems. The application of engineering principles to living systems may lead to the understanding of novel design principles and create opportunities for applying biological systems to engineering applications. The four talks in this session focused on: (1) a standard experimental platform made possible by advances in synthetic biology; the platform can be used for designing and wiring genetic networks using engineering principles; (2) how technologies to (a) assess a substantial fraction of genetic variation in a large number of individuals, with and without a disease of interest, and (b) identify the differences could lead to the discovery of common genetic variants that provide modest protection from common diseases; (3) the use of a mathematical framework based on machine learning and systems

President of India Dr. A.P.J. Abdul Kalam, an aeronautical engineer, met with the Indo-U.S. FOE participants at the Presidential Palace in Delhi.

biology to integrate information and develop decision-support systems for exploring hypotheses, designing experiments, and learning from successes and failures to design properties in drugs; and (4) the development of a novel biosensor, the suspended microchannel resonator, for detecting biomarkers for cancer and measuring single cells for diagnosing diseases, such as malaria.

Dinner addresses were given by Fazir Chand Kohli, former chair of Tata Consultancy Services, India's premier information technology organization, and **Wm. A. Wulf**, president of NAE. Kohli, known as the father of the Indian software industry, spoke about the need to increase literacy and improve access to technology in rural areas of India. However, he cautioned that automation should not be implemented too quickly so as not to increase unemployment in this nation of a billion people. India's greatest resource, he said, is its intelligent, ingenious, and hard-working people. On the second evening, President Wulf focused on the need for reform in U.S. visa policies for short-term visits by Indian scientists and engineers. He cited several recent cases of eminent Indian scientists and engineers whose visa applications were either delayed or denied, thereby putting at risk the good relations between the U.S. and Indian science and engineering communities.

A visit to the Taj Mahal and royal city of Fatehpur Sikri near Agra on Sunday afternoon was followed by an audience with the president of India, Dr. A.P.J. Abdul Kalam, at the Presidential Palace in Delhi. Dr. Kalam spent about 30 minutes answering questions and discussing topics of interest, such as nanotechnology, biotechnology, and energy. Following the meeting, there was a reception and an opportunity to stroll through the beautiful palace gardens.

IUSSTF, the symposium sponsor, is an autonomous, nonprofit society that promotes Indo-U.S. bilateral collaborations in science, technology, engineering, and biomedical research. The society was established in 2000 under an agreement between the governments of India and the United States, which both provide funding for the organization. The next Indo-U.S. Frontiers of Engineering Symposium will be held in March or June 2008 in the United States.

For information about FOE symposia or to nominate an outstanding engineer to participate in a future symposium, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

Technology for a Quieter America

On May 1 and 2, 2006, members of the NAE Committee on Technology for a Quieter America met at the National Academies to kick off a 30-month study on the development and deployment of technologies to alleviate the negative hearing and health effects of noise in workplaces, communities, and homes. The steering committee, chaired by **George Maling**, includes Robert Bernhard, Robert Bruce, Beth Cooper, Patricia Davies, Carl Hanson, Robert Hellweg, Gerald Lauchle, **Richard Lyon**, and Ian Waitz. Consultants to the project include NAE members **Leo Beranek**, **Stephen Crandall**, **Ken Eldred**, and **William Lang**.

Based on the results of a preliminary workshop in September 2005 and the expertise of committee members, nine areas of interest have been identified: cost-benefit analyses of noise-control technologies; impacts of noise on the competitiveness of U.S. products; industry demand for and education for noise-control specialists; new technologies; engineering controls and common descriptors for hazardous noise; improved metrics for community noise; public information on the benefits of low-noise products and the adverse effects of excessive noise; coordination of activities by federal and state agencies; and providing assistance to state and local noise-control programs.

Energy Futures and Air Pollution in Urban China and the United States

A joint U.S.-Chinese committee on energy futures and air pollution is conducting a study on urban energy use, policies, and air pollution in both countries. The overall goal of the study is to assist Chinese cities in addressing air-pollution challenges based on U.S experience. In October 2005, a group of committee members from both countries visited two cities in China, Huainan and Dalian. In March 2006, a similar group completed a two-week tour of the Pittsburgh and Los Angeles areas. The purpose of the trips was (1) to provide a historical context for experiences with urban air pollution and increasing energy consumption and (2) to explore institutional frameworks for managing air quality.

Huainan and Dalian were selected for the study because the challenges they face are reminiscent of the challenges faced by Pittsburgh and Los Angeles. Huainan, in Anhui Province, is a coal-rich industrial city hoping to position itself as an energy base for cities in neighboring Jiangsu Province, including Nanjing and Shanghai. Dalian, in Liaoning Province, an important seaport for northeast Asia, is a modern coastal city with rapidly increasing personal-vehicle traffic. The joint committee met with the mayors, representatives of local environmental-protection bureaus and other government agencies, local professors and researchers, and representatives of local utilities and industries in both cities.

In Pittsburgh, the joint committee, accompanied by a delegation from Huainan, visited the Allegheny County Health Department, the U.S. Department of Energy National Energy and Technology Laboratory, Carnegie Mellon University, Bellefield Boiler Plant, FirstEnergy Bruce Mansfield Power Plant, U.S. Steel Clairton Works, the Heinz Plant, and ALCOSAN. In addition, the committee was welcomed by Allegheny County Chief Executive Dan Onorato during a reception at the Heinz History Center. In the Los Angeles area, the committee, accompanied by a delegation from Dalian, visited the Air Resources Board El Monte Office, the South Coast Air Quality Management District, the Port of Long Beach, the BP refinery, the Southeast Resource Recovery Facility, and laboratories at the University of California, Irvine.

The committee hopes to draw lessons from the experiences of Pittsburgh and Los Angeles in assessing the benefits and costs of options for meeting the dual challenges of continuing coal consumption and a rapid increase in the number of private vehicles, at the same time meeting the needs of a rapidly growing economy and addressing environmental and public health concerns. The committee will also identify areas for continued cooperation between the United States and China. The report will be published in early 2007.

This joint project by NAE, the National Research Council, the Chinese Academy of Engineering, and the Chinese Academy of Sciences is funded by the National Academies.

CASEE Builds Communities for Educational Innovations

The Center for the Advancement of Scholarship on Engineering Education (CASEE) has recently been engaged in two activities to encourage discussions between engineering educators and experts in nonengineering fields. First, a series of roundtable discussions was held on developing an engineering education research agenda. In addition, a targeted meeting was held on improving the diffusion of curricular innovations.

The Engineering Education Research Colloquies are funded by the National Science Foundation and led by a multi-institutional team headquartered at Purdue University. The goal of these discussions is to identify research topics to guide the efforts of faculty, funding agencies, and policy makers working to advance research on engineering education. CASEE was intimately involved in the planning and execution of three discussions:

- In September 2005, faculty members in engineering, cognitive science, and education disciplines met in Washington, D.C., to develop an initial framework for articulating fundamental themes for engineering education research and to develop a road map of the most pressing research questions.
- In October 2005, a gathering in conjunction with the CASEE Annual Meeting in Indianapolis, Indiana, brought together 65 faculty members (more than three-fourths of whom had participated in the first meeting) to develop a road map for engineering education research.
- An extension to the second meeting was held in February 2006 in Chicago, Illinois, to refine research themes and begin fleshing out three documents: (1) a report to engineering faculty and research foundations; (2) an executive-summary report to engineering deans and industry representatives; and (3) a short, policy-oriented document for policy makers.

The results of the Engineering Education Research Colloquies series will be made public in June 2006 at the annual meeting of the American Society for Engineering Education.

On April 26 and 27, 2006, CASEE, working in collaboration with the American Sociological Association (ASA), brought together nine engineering faculty members and nine researchers in sociology to explore how interactions might improve the acceptance and diffusion of curricular and instructional innovations. Workshop attendees participated in one of three groups addressing underlying questions, such as how new knowledge, curriculum, and pedagogical practices gain legitimacy; the identification of impediments and facilitators of change that can be modeled; identification of hypotheses to be tested; and clarification of what we need to know from research and practice to answer these questions. The results of the meeting will be documented in a monograph issued jointly by CASEE and ASA, to be distributed to deans of engineering, deans of arts and sciences, and professional associations.

New CASEE Scholar in Residence


Lynette Osborne

Beginning on July 3, 2006, Lynette Osborne will be an ExxonMobil Scholar in Residence at the National Academy of Engineering (NAE). She received her B.A. in psychology from California State University, Chico, her M.A. in sociology from Old Dominion University, and her Ph.D. in sociology from Purdue University. Lynette's dissertation was on the classroom climate in engineering education with a focus on peer culture and student-centered teaching techniques. At NAE, Lynette's primary research will focus on the effects of self-reflection by faculty on instruction. She will also develop a guide to proposal writing and project management for NSF education projects.

Calendar of Meetings and Events

May 8–9	Convocation of Professional Engineering Societies
June 8	NAE Finance and Budget Committee Conference Call
	NAE Awards Committee Conference Call
June 13	Bernard M. Gordon Prize Committee Conference Call
June 14	NRC Executive Committee Meeting
June 15	NAE Regional Meeting Pennsylvania State University
June 20	NAE Audit Committee Meeting
July 11	NAE Nominating Committee Meeting
July 18	NRC Executive Committee Meeting
July 24–28	Engineering Education Leadership Institute Meeting Chicago, Illinois
July 25	Charles Stark Draper Prize Committee Meeting
July 26	Fritz J. and Dolores H. Russ Prize Committee Meeting
August 2–3	NAE Council Meeting Woods Hole, Massachusetts
August 4–5	NRC Governing Board Meeting Woods Hole, Massachusetts
September 12	NRC Executive Committee Meeting
September 14	Bernard M. Gordon Prize Committee Meeting
September 21–23	12th U.S. Frontiers of Engineering Symposium Dearborn, Michigan

All meetings are held in the National Academies buildings, Washington, D.C., unless otherwise noted. For information about regional meetings, contact Sonja Atkinson at *satkinso@nae.edu* or (202) 334-3677.

In Memoriam

HUBERT I. AARONSON, 81, R.F. Mehl University Professor Emeritus, Department of Materials Science and Engineering, Carnegie Mellon University, died on December 13, 2005. Dr. Aaronson was elected to NAE in 1997 for contributions to the understanding of diffusional phase transformation in commercial steels.

NORMAN A. GJOSTEIN, 74, retired director, Manufacturing and Materials Laboratory, Ford Motor Company, died on April 5, 2006. Dr. Gjostein was elected to NAE in 1990 for contributions to the technology of surfaces and interfaces and for technical leadership in the application of advanced materials to ground vehicles.

WILLIAM R. GOULD, 86, Chairman Emeritus, Southern California Edison Company, died on March 11, 2006. Dr. Gould was elected to NAE in 1973 for his contributions to the development of fossil-fuel and nuclear power, siting, environmental impact, and water desalinization.

EDWARD G. JEFFERSON, 84, retired chairman and CEO, E.I. du Pont de Nemours & Company, died on February 9, 2006. Dr. Jefferson was elected to NAE in 1986 for contributions to university-industry cooperation in science and engineering and for creative direction of one of the largest industrial organizations in the world.

JAMES M. LAFFERTY, 89, retired manager, Power Electronics Laboratory, GE Corporate Research and Development, died on March 26, 2006. Dr. Lafferty was elected to NAE in 1981 for contributions as an individual and as a manager to ultra-high vacuum technology, vacuum switching devices, and electric vehicles.

I. HARRY MANDIL, 86, founding partner and board member, MPR Associates Inc., died on April 27, 2006. Dr. Mandil was elected to NAE in 1998 for the design and development of materials for naval and commercial nuclear reactors.

HERBERT JOHN SHAW, 87, Professor Emeritus, Department of Applied Physics, Stanford University, Ginzton Laboratory, died on January 19, 2006. Dr. Shaw was elected to NAE in 1986 for leadership in the development of theory and design procedures for acoustic-surface-wave devices and applications of optical fibers.

WARREN E. STEWART, 81, Professor Emeritus of Chemical Engineering, University of Wisconsin-Madison, died on March 27, 2006. Dr. Stewart was elected to NAE in 1992 for his research in chemical engineering and the application of advanced mathematical and numerical methods.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <*http://www.nap.edu*> or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Basic Research in Information Science and Technology for Air Force Needs. The U.S. Air Force is developing new force capabilities for which advances in information science and technology (IS&T) will be essential. As a consequence, the Air Force must refocus its IS&T basic research program. The Air Force Office of Scientific Research (AFOSR) asked the National Research Council to conduct a study to develop a plan for IS&T-related programs in the AFOSR Mathematics and Space Science Directorate. This report includes an assessment of basic research needs for Air Force systems and communications, software, information management and integration, and human interactions with IS&T systems. The report also provides recommendations for priorities for basic IS&T research and an analysis of funding mechanisms.

NAE members on the study committee were **Ruzena K. Bajcsy**, Director Emeritus of the Center for Information Technology, University of California, Berkeley; **Elwyn R. Berlekamp**, professor of mathematics, University of California, Berkeley; **Philip A. Bernstein**, senior researcher, Microsoft Corporation; **Roger W. Brockett**, An Wang Professor of Electrical Engineering and Computer Science, Harvard University; and **Ronald W. Schafer**, HP Fellow, Hewlett-Packard Laboratories. Paper, $28.25.

Protection, Control, and Accounting of Nuclear Materials: International Challenges and National Programs: Workshop Summary. The National Academies and Russian Academy of Sciences convened a workshop in 2003 for sharing best practices in nuclear materials protection, control, and accounting (MPC&A). Topics included the status and application of remote monitoring technologies, personnel issues, and national and international safeguards. The goals of the workshop were to identify areas in which the United States and Russia could promote best practices in MPC&A globally and expand U.S.-Russian cooperation on nuclear nonproliferation. This workshop summary is based on the papers and outcomes of workshop discussions.

NAE member **John P. Holdren**, Teresa and John Heinz Professor of Environmental Policy, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, chaired the study committee. **John Ahearne**, director, Ethics Program, Sigma Xi, The Scientific Research Society; and **Siegfried S. Hecker**, senior fellow, Los Alamos National Laboratory, were members of the committee. Paper, $18.00.

Innovating for Profit in Russia: Summary of a Workshop. The National Academies and Russian Academy of Sciences hosted an interacademy workshop in Yekaterinburg, Russia, in October 2004 to explore opportunities for industrial innovation in the Urals region of Russia. Workshop presenters focused on the establishment of cooperative business partnerships (based on "market pull") between Russian companies and Russian research organizations (particularly in closed nuclear cities) and companies with international research centers. The workshop presentations and discussions are summarized in this volume.

NAE member **Alvin W. Trivelpiece**, retired director, Oak Ridge National Laboratory, and retired president, Lockheed Martin Energy Research Corporation, chaired the study committee. Paper, $18.00.

Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana. In the past 50 years, coastal Louisiana has suffered catastrophic land loss caused by both natural changes and human activity. The loss of coastal wetlands has increased the vulnerability of the area to storm damage and increased the risk to lives, property, and economies—as Hurricanes Katrina and Rita recently demonstrated. This review of a proposed restoration plan developed by the U.S. Army Corps of Engineers and the state of Louisiana concludes that, even though the individual projects are scientifically sound, large-scale projects and a comprehensive approach will be necessary to address land loss over such a large area. More important, the study concludes that restoration should be guided by a detailed map of the future landscape of coastal Louisiana based on agreed-upon goals for the region and the nation.

NAE member **Robert G. Dean**, graduate research professor, Department of Coastal and Oceanographic Engineering, University of Florida, was a member of the study committee. Paper, $40.00.

Strengthening Long-Term Nuclear Security: Protecting Weapon-Usable Material in Russia. Published in 2005, this report highlights obstacles to the transition of a program to ensure the security of 600 tons of weapon-usable nuclear material at a level of international acceptability from a U.S.-Russian cooperative program to a Russian-directed, Russian-funded program. Overcoming these obstacles will require a strong commitment on several levels of the Russian government to material protection, control, and accounting systems (MPC&A). Facilities where weapon-usable material is located must be provided with adequate resources for upgrading and maintaining MPC&A systems. In addition, technical security systems being installed through the cooperative program must be fully embraced by Russian managers and specialists. The report recommends the establishment of a 10-year indigenization fund of about $500 million to be provided by Russia and its G-8 partners as a mechanism for gradually shifting the financial burden of MPC&A to the Russian government.

NAE members on the study committee were **John F. Ahearne**, director, Ethics Program, Sigma Xi, The Scientific Research Society; and **Richard A. Meserve**, president, Carnegie Institution of Washington. Paper, $31.50.

Midsize Facilities: Infrastructure for Materials Research. Most of the instruments used for materials research are too complex and expensive for individual investigators to own, operate, and maintain. Consequently, instruments have become increasingly consolidated into multi-user, small and midsized research facilities located at many sites around the country. The proliferation of these facilities has elicited calls for best principles for their operation. With support from the U.S. Department of Energy and the National Science Foundation, the National Academies conducted a study to characterize ways of optimizing investments in the infrastructures of materials research facilities, especially midsized facilities. The report also includes a discussion of the capabilities of midsized facilities, the challenges they face, and the adequacy of current investment levels.

NAE member **David R. Clarke**, professor of materials, University of California, Santa Barbara, was a member of the study committee. Paper, $32.00.

Asking the Right Questions about Electronic Voting. High-profile problems in recent elections have elicited calls for using electronic information technology in the voting process to head off problems in the future. Electronic voting, however, is not as straightforward as has been suggested in the emotional public debate. Many election officials believe electronic voting systems can lead to better administered and less expensive elections, but a number of concerns have been raised about security and other aspects of these systems. To address these concerns, the National Science Foundation asked the National Research Council to investigate the problems and benefits of electronic voting systems. This report provides an extensive list of questions that must be addressed by election officials, policy makers, and the public about the use of electronic information technology. The report also provides a number of conclusions to put these questions in perspective.

NAE member **Thomas B. Sheridan**, Ford Professor of Engineering and Applied Psychology Emeritus, Massachusetts Institute of Technology, was a member of the study committee. Paper, $29.00.

Principal-Investigator-Led Missions in the Space Sciences. Principal-investigator-led (PI-led) missions are an important aspect of NASA's space science enterprise. NASA requested that the National Research Council explore issues related to cost and scheduling, the selection process, relationships among PI-led team members, and opportunities for knowledge transfer to new PIs. This report includes a discussion of the evolution and current status of the concept of PI-led missions, the effects of certain practices on performance, and steps to ensure future success. The study was conducted in collaboration with the National Academy of Public Administration.

NAE member **Alan M. Title**, Senior Fellow, Lockheed Martin Advanced Technology Center, was a member of the study committee. Paper, $18.00.

Priorities in Space Science Enabled by Nuclear Power and Propulsion. Because of inherent limitations in photovoltaic and chemical propulsion systems, in 2003, NASA began a research program (named Project Prometheus in 2004) to develop nuclear power and propulsion systems for the exploration of the solar system. To help NASA determine appropriate missions with a nuclear power and propulsion capability, the National Research Council (NRC) was asked to provide an independent assessment of potential missions that could be enabled by operational space nuclear systems. This report identifies space science objectives and missions in astronomy and astrophysics, solar system exploration, and solar and space physics for 2015 and beyond. The report is based on, but does not reprioritize, the findings of previous NRC decadal surveys in those three areas.

NAE member **William A. Anders**, retired chairman, General Dynamics Corporation, was a member of the study committee. Papers, $63.00.

Review of NASA Plans for the International Space Station. In January 2004, President Bush announced a policy to promote the human and robotic exploration of space. In June 2004, the President's Commission on Implementation of United States Space Exploration Policy issued a report recommending, among other things, that the National Aeronautics and Space Administration (NASA) ask the National Academies to reevaluate its space-science priorities to take advantage of the new initiative. Congress also directed the National Academies to conduct a thorough review of NASA's proposed science agenda. The first study, *Science in NASA's Vision for Space Exploration*, was published in February 2005. This second report, focused on NASA's plans for the International Space Station (ISS), provides advice on programmatic issues NASA is likely to face as it updates its plans for using the ISS. The report also identifies research and test-bed activities that must be performed on the ISS to ensure that exploration objectives can be met.

NAE member **James P. Bagian**, director, National Center for Patient Safety, Veterans Health Administration, was a member of the study committee. Paper, $18.00.

Measuring and Sustaining the New Economy: Software, Growth, and the Future of the U.S Economy. Report of a Symposium. Since the mid-1990s, the United States has experienced an unprecedented upsurge in economic productivity, and continued technological change in communications, computing, and information management promise further gains in productivity. This phenomenon is often referred to as the New Economy. The National Academies Board on Science, Technology, and Economic Policy (STEP) convened a series of workshops and commissioned papers to explore the New Economy, including the workshop covered in this volume, Software, Growth, and the Future of the U.S. Economy. The workshop brought together academic experts and industry representatives from leading companies, such as Google and General Motors, to participate in a high-level discussion of the role of software in increased productivity; the unique qualities of software; the measurement of software in national and business accounts; the implications of moving the U.S. software industry offshore; and related policy issues.

NAE member **William J. Spencer**, Chairman Emeritus of SEMATECH, was a member of the oversight committee. Paper, $46.00.

Proceedings from the Workshop on Biomedical Materials at the Edge: Challenges in the Convergence of Technologies. Recent advances in biomedical materials technology could lead to revolutionary changes in clinical medicine. These advances are possible because of a convergence of technologies based on a wide range of scientific discoveries. This convergence, however, presents challenges as well as opportunities. A workshop was held under the auspices of the National Research Council Roundtable on Biomedical Engineering Materials and Applications to identify these challenges and ways to overcome them. This report and accompanying CD provides a summary and proceedings of the workshop, including discussions of the context for new biomedical materials and three emerging technologies: stem cells as biomaterials; biomolecular materials composites; and supermolecular/nanoscale engineering and design.

NAE member **Robert M. Nerem**, Parker H. Petit Professor and director, Institute for Bioengineering and Bioscience, Georgia Institute of Technology, is a member of the Roundtable. Free PDF is available online at: *http://www.nap.edu/catalog/11639.html.*

Aeronautics Innovation: NASA's Challenges and Opportunities. The National Aeronautics and Space Administration (NASA), a global leader in aeronautics research and development, has led the way in aviation safety and emissions, propulsion technology, and many other areas. The agency's Aeronautics Research Mission Directorate (ARMD) has played a vital role in the U.S. aeronautics industry. In recent years, the leaders of ARMD and experts outside the agency have been looking for ways to speed up the development of innovative uses of ARMD's research results. But the directorate faces management challenges that have made it difficult, sometimes impossible, for such applications to succeed. This new report from the National Research Council offers guidance on managing the transfer of technology to external users, as well as implementing flexible personnel and financial-management practices. The report also identifies problems arising from uncertainties about the future direction of ARMD and several years of federal budget cuts.

NAE member **Meyer J. Benzakein**, chair, Aerospace Engineering Department, Ohio State University, chaired the study committee. Other NAE members on the study committee were **Henry McDonald**, Sim Center, University of Tennessee at Chattanooga; **Duncan T. Moore**, professor, Institute of Optics, University of Rochester; and **Alan Schriesheim**, Director Emeritus, Argonne National Laboratory. Paper, $18.00.

C4ISR for Future Naval Strike Groups. The U.S. Navy has proposed a new structure for its strike forces to improve its deterrence and rapid-response functions. A key aspect of this structure is flexible, adaptive command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) systems. To assist the Navy in the development of this capability, the National Research Council was asked to conduct a study of C4ISR systems for carrier, expeditionary, and missile defense groups and for expeditionary strike forces. This report provides an assessment of C4ISR capabilities for each type of strike group, recommendations for C4ISR architecture for major combat operations, promising trends in technology, and organizational changes to support the recommended architecture.

NAE members on the study committee were **Richard E. Blahut**, Henry Magnuski Professor and head, Department of Electrical and Computer Engineering, University of Illinois; **Archie R. Clemins**, president, Caribou Technologies Inc.; **Barry M. Horowitz**, professor of systems engineering, University of Virginia; and **John R. Stenbit**, retired executive vice president, TRW Inc. Paper, $58.50.

Identification of Promising Naval Aviation Science and Technology Opportunities. The U.S. Department of Defense is working toward the transformation of the armed forces to meet future military challenges. According to the Naval Power 21 documents, which detail what transformation will entail for the U.S. Navy and Marine Corps, many new war-fighting concepts will be necessary. The Office of Naval Research (ONR) requested that the National Research Council conduct a study to identify science and technology opportunities for new naval aviation capabilities to support transformation. This report provides an assessment of the implications of transformation for naval aviation, an analysis of some capabilities that would make significant contributions toward realizing those concepts, and an assessment of key technologies in which ONR could invest to achieve seven key capabilities: multispectral defense; unmanned air operations; hypersonic weapons delivery; fast-kill weapons; heavy-lift air transport; intelligent combat information management; and omniscient intelligence.

NAE members on the study committee were **Earl H. Dowell**, William Holland Hall Professor and Dean Emeritus, Edmund T. Pratt Jr. School of Engineering, Duke University; **Joseph B. Reagan**, retired vice president and general manager, Lockheed Martin Missiles and Space Company; **Lyle H. Schwartz**, retired director, Air Force Office of Scientific Research; and **William A. Sirignano**, Henry Samueli Endowed Chair in Mechanical and Aerospace Engineering, University of California-Irvine. Paper, $18.00

Improving the Regulation and Management of Low-Activity Radioactive Wastes. Hospitals, utilities, research institutions, and defense installations where nuclear materials are used produce large amounts of waste that contain small amounts of radioactive material (so-called low-activity waste [LAW]). Millions of cubic feet of LAW are also produced every year by non-nuclear enterprises, such as mining and water-treatment facilities. Although LAW presents much less of a radiation hazard than spent nuclear fuel or high-level radioactive waste, it can cause health risks if it is not controlled properly. Current regulations are based primarily on the type of industry that produces the waste (i.e., its origin) rather than risk. This report by the National Research Council concludes that LAW should be regulated and managed according to the degree of risk involved in its treatment, storage, and disposal. The authoring committee proposes a risk-informed approach for regulating and managing all types of LAW in the United States and explains how this approach could be implemented gradually. Based on established principles for risk-informed decision making, current risk-informed initiatives by waste regulators in the United States and abroad, solutions available under current regulatory authorities, and remedies through new legislation when necessary, the proposed approach combines scientific risk assessment with public values and perceptions. The focus throughout is on the hazardous properties of the waste in question and comparisons of the hazards from LAW and other waste materials.

NAE members on the study committee were **Wm. H. Arnold**, retired general manager, Advanced Energy Systems Division, Westinghouse Electric Corporation; and **Maurice C. Fuerstenau**, Emeritus Professor of Metallurgy, University of Nevada. Paper, $38.00.

Reusability of Facemasks During an Influenza Pandemic: Facing the Flu. In the event of an influenza pandemic, public health officials will have to use many different measures to reduce the impact. If effective vaccines and antiviral medications do not exist or are not available in adequate quantities, respirators and medical masks could help prevent or slow transmission of the disease. The U.S. Department of Health and Human Services requested that an Institute of Medicine committee examine the potential reuse of medical masks and N95 respirators. Over a period of three months, during which the committee held two meetings, reviewed information from manufacturers, and reviewed a large body of technical literature, the committee concluded that very little is known about the potential for disinfecting and reusing either medical masks or respirators. Fundamental research on the epidemiology of influenza and on the material properties of medical masks and respirators will be necessary before methods of disinfection and reuse can be developed. However, based on the expertise of committee members, the committee describes in detail a method of use that might allow for the extended use of N95 respirators.

NAE member **Frank E. Karasz**, Silvio O. Conte Distinguished Professor, University of Massachusetts, was a member of the study committee. Paper, $26.50.

State and Federal Standards for Mobile Source Emissions. Emissions from mobile sources (e.g., cars and light- and heavy-duty trucks, diesel-powered cranes, bulldozers, and tractors) and equipment powered by small gasoline engines (e.g., lawn mowers) contribute significantly to air pollution in the United States. Because it is not clear whether the states or the federal government is responsible for establishing mobile-source emissions standards, Congress called on the Environmental Protection Agency (EPA) to commission an independent study of the practices and procedures by which California has developed separate emissions standards from the federal government and by which other states have adopted the California standards. This report provides an assessment of the scientific and technical procedures used by states to develop or adopt statewide emissions standards and a comparison of those policies and practices with those used by EPA. It also assesses the impacts of state emissions standards on compliance costs and emissions. The report concludes that, despite substantial progress in reducing emissions from mobile sources nationwide, federal air-quality standards are needed in many parts of the country. The report also concludes that California should continue its pioneering role in setting emissions standards for cars, trucks, and off-road equipment.

NAE member **Karl J. Springer**, retired vice president for automotive products and emissions research, Southwest Research Institute, was a member of the study committee. Paper, $42.00.

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