ENGINEERING RESEARCH AND AMERICA'S FUTURE

MEETING THE CHALLENGES OF A GLOBAL ECONOMY

NATIONAL ACADEMY OF ENGINEERING
OF THE NATIONAL ACADEMIES

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Committee to Assess the Capacity of the U.S. Engineering Research Enterprise

NATIONAL ACADEMY OF ENGINEERING
OF THE NATIONAL ACADEMIES

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PREFACE

Leadership in innovation is essential to U.S. prosperity and security. In a global, knowledge-driven economy, technological innovation—the transformation of new knowledge into products, processes, and services of value to society—is critical to competitiveness, long-term productivity growth, and an improved quality of life. Preeminence in technological innovation depends on a wide array of factors, one of which is leadership in engineering research, education, and practice. A three-decade-long decline in the share of federal investment in research and development (R&D) devoted to engineering and a perceived erosion of basic, long-term engineering research capability in U.S. industry and federal laboratories have raised serious questions about the long-term health of engineering research in the United States.

To assess and document the current state of the U.S. engineering research enterprise and to raise awareness of the critical role of engineering research in maintaining U.S. technological leadership, the National Academy of Engineering (NAE) initiated the current study. The focus of the study is primarily on academic research because of its importance to long-term basic engineering research and to educating future engineers and engineering researchers. The study is based on the opinions and judgments of a 15-member committee of experts from industry and universities. The committee's deliberations were informed by testimony from key decision makers and policy makers in the federal government, as well as a detailed review of many recent studies on national R&D policy, investment patterns, needs, and shortcomings.

Reports by the President's Council of Advisors on Science and Technology, National Science Board, U.S. Department of Energy Science Advisory Board, Council on Competitiveness, National Research Council, and others have consistently emphasized the importance of basic research in engineering and physical sciences and expressed concerns about the adequacy of federal investments in critical fields. The study finds that support for engineering research has been relatively stagnant for more than two decades. The result has been erosion in the infrastructure necessary for world-class engineering research and a worrisome decline in the number of engineering graduates, particularly native-born doctoral degree recipients. As other nations increase their investments in engineering research and education, the United States risks falling behind in critical research capabilities and ultimately the innovations that flow from research. To ensure continued U.S. competitiveness, the nation needs a renewed commitment to engineering research, most importantly by the federal government, but also by states, foundations, industry, and universities.

The committee recommends a number of actions to stimulate rapid changes in the current situation. The committee also recognizes the need for bold steps that will lead to long-term changes, not only in the level of resources available for basic engineering research, but also in the cultural environment that must attract the best and brightest individuals to pursue careers in engineering research. The committee proposes the creation of discovery-innovation institutes on the campuses of American research universities as a mechanism for achieving long-term change. By harnessing the intellectual power, diversity, and creativity on the nation's campuses and working in close collaboration with industry and government, discovery-innovation institutes can be engines of innovation.

On behalf of the National Academy of Engineering, I want to thank the study chairman, James J. Duderstadt, and other members of the study committee for their considerable efforts on this project. I also want to thank Proctor P. Reid, the study director, who managed the project and helped the committee members reach consensus. Thomas C. Mahoney, consultant to the committee, was extremely helpful throughout the project. Penelope Gibbs from the NAE Program Office provided critical administrative and logistical support. Carol Arenberg, NAE senior editor, was instrumental in preparing the report for publication.

I want to extend the committee's thanks to everyone from government, industry, and academia who contributed to the project. In particular, I want to express our appreciation to everyone who briefed the committee and everyone who submitted comments during the period of public review.

Finally, I would like to express my appreciation to the National Science Foundation for its generous support of this project.

Wm. A. Wulf

Wm. A. Wulf
President
National Academy of Engineering

ACKNOWLEDGMENTS

This report by the National Academy of Engineering (NAE) Committee to Assess the Capacity of the U.S. Engineering Research Enterprise was reviewed in three stages. The draft form was first reviewed by individuals with diverse perspectives and technical expertise chosen in accordance with procedures approved by NAE. The purpose of the stage-one peer review was to elicit candid, critical comments to assist the committee in making the preliminary report as sound as possible and to ensure that institutional standards for objectivity, evidence, and responsiveness to the study charge had been met. The reviewers were not asked to endorse the conclusions or recommendations and did not see the final draft of the preliminary report before its release for the stage-two public review. The stage-one review was overseen by Maxine Savitz, an NAE member appointed by NAE to ensure that an independent examination of the preliminary report was carried out in accordance with institutional procedures and that all review comments were carefully considered.

We wish to thank the following individuals for participating in the stage-one review: Craig R. Barrett, Intel Corporation; G. Wayne Clough, Georgia Institute of Technology; Siegfried S. Hecker, Los Alamos National Laboratory; C. Dan Mote Jr., University of Maryland; Karl S. Pister, University of California, Berkeley; William F. Powers, Ford Motor Company (ret.); and John A. White Jr., University of Arkansas.

In stage-two, the revised report was posted on the NAE website for 30 days for review by a larger cross section of the engineering community and the general public. During stage two of the review process, engineering leaders and other major stakeholders in the U.S. engineering enterprise had an opportunity to provide feedback on the preliminary report. All comments received during the stage-two public review were made anonymous and forwarded to the authoring committee. The committee considered all comments and revised the report accordingly.

The report was then submitted to a third and final peer review, which was also overseen by NAE member Maxine Savitz. Individuals for the stage-three review were chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by NAE. We thank the following individuals for participating in the stage-three review: Siegfried S. Hecker, Los Alamos National Laboratory; Robert M. Nerem, Georgia Institute of Technology; Laurence C. Seifert, AT&T Corporation (ret.); Morris Tanenbaum, AT&T Corporation (ret.); and Vince Vitto, Charles Stark Draper Laboratories.

Review comments received during all three reviews, as well as the original pre-review of the draft manuscript, remain confidential to protect the integrity of the deliberative process. Responsibility for the final content of the report rests entirely with the authoring committee and the institution.

CHARGE TO THE COMMITTEE

The National Academy of Engineering (NAE) Committee to Assess the Capacity of the U.S. Engineering Research Enterprise was charged by the Engineering Directorate of the National Science Foundation with conducting a "fast-track" evaluation of (1) the past and potential impact of the U.S. engineering research enterprise on the nation's economy, quality of life, security, and global leadership and (2) the adequacy of public and private investment to sustain U.S. preeminence in basic engineering research.

A two-decade-long decline in the share of federal investment in research and development devoted to engineering and the perceived erosion of basic, long-term engineering research capability in U.S. industry and federal laboratories have raised serious questions about the long-term health of engineering research in the United States. To address these concerns, this report documents and evaluates recent contributions of U.S.-based engineering research to the nation's interests, assesses potential contributions to meeting emerging national challenges and opportunities, and outlines a national strategy to ensure that the engineering research foundations of American global economic, military, scientific, and technological preeminence remain rock solid in the face of rapid, often disruptive, societal and global change. The report includes findings, recommendations, and a national action plan designed to engage all major constituents of the U.S. engineering enterprise.

PROCESS FOLLOWED BY THE COMMITTEE

The committee met three times during the summer of 2004. In addition to a substantive review of recent studies and policy analyses related to science and engineering activities and investments, the committee heard testimony from leaders in government, industry, and academia. This report is based on a consensus of the committee members and responses to a three-stage NAE peer-review and public-review process.

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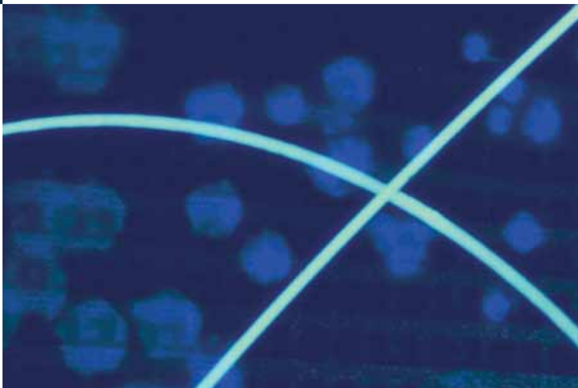
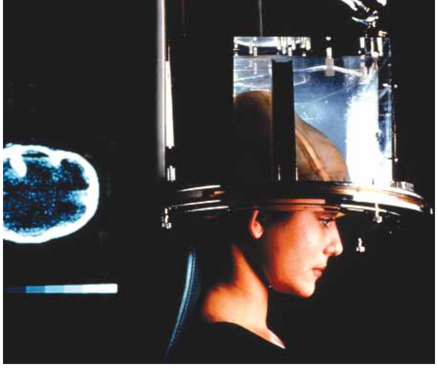


EXECUTIVE SUMMARY

Leadership in innovation is essential to U.S. prosperity and security. In a global, knowledge-driven economy, technological innovation—the transformation of knowledge into products, processes, and services—is critical to competitiveness, long-term productivity growth, and the generation of wealth. Preeminence in technological innovation requires leadership in all aspects of engineering: engineering research to bridge scientific discovery and practical applications; engineering education to give engineers and technologists the skills to create and exploit knowledge and technological innovation; and the engineering profession and practice to translate knowledge into innovative, competitive products and services.

Historically, engineering research has yielded knowledge essential to translating scientific advances into technologies that affect everyday life. The products, systems, and services developed by engineers are essential to national security, public health, and the economic competitiveness of U.S. business and industry. Engineering research has resulted in the creation of technologies that have increased life expectancy, driven economic growth, and improved America's standard of living. In the future, engineering research will generate technological innovations to address grand challenges in the areas of sustainable energy sources, affordable health care, sufficient water supplies, and homeland security.

Unfortunately, U.S. leadership in technological innovation seems certain to be seriously eroded unless current trends are reversed. The accelerating pace of discovery and application of new technologies, investments by other nations in research and development (R&D) and the education of a technical workforce, and an increasingly competitive global economy are challenging U.S. technological leadership and with it future U.S. prosperity and security. Although many current measures of technological leadership —percentage of gross domestic product invested in R&D, number of researchers, productivity level, volume of high-technology production and exports—still favor the United States, worrisome trends are already adversely affecting the U.S. capacity for innovation. These trends include: (1) a large and growing imbalance in federal research funding between the engineering and physical sciences on the one hand and biomedical and life sciences on the other; (2) increased emphasis on short-term applied R&D in industry and government-funded research at the expense of fundamental long-term research; (3) erosion of the engineering research infrastructure due to inadequate investment over many years;



(4) declining interest of American students in engineering, science, and other technical fields; and (5) growing uncertainty about the ability of the United States to attract and retain gifted engineering and science students from abroad at a time when foreign nationals constitute a large and productive component of the U.S. R&D workforce.

Today more than ever the nation's prosperity and security depend on its technical strengths. The United States will need robust capabilities in both fundamental and applied engineering research to address future economic, environmental, health, and security challenges. To capitalize on opportunities created by scientific discoveries, the nation must have engineers who can invent new products and services, create new industries and jobs, and generate new wealth. Applying technological advances to achieve global sustainability will require significant investment, creativity, and technical competence. Advances in nanotechnologies, biotechnologies, new materials, and information and communication technologies may lead to solutions to difficult environmental, health, and security challenges, but their development and application will require significant investments of money and effort in engineering research and the engineering workforce.

Current patterns in research funding do not bode well for future U.S. capabilities in these critical fields. Record levels of federal funds are being invested in R&D, but these levels reflect large increases in funding for biomedical and life sciences; investments in other fields of engineering and science have increased slowly and intermittently (if at all). Because of competitive pressures, U.S. industry has downsized its large, corporate R&D laboratories in physical sciences and engineering and reduced its already small share of funding for long-term, fundamental research. The committee believes that the decline in long-term industrial research is exacerbating the consequences of the current decline in federal R&D funding for long-term fundamental research in engineering and physical sciences.

These funding trends have had a predictably negative impact on academic research and student enrollments in engineering and physical sciences. In fact, foreign nationals now comprise 40 percent or more of graduate enrollments in physical sciences, mathematics and computer science, and engineering. In addition, nearly two-thirds of the graduate and undergraduate students in engineering who are U.S. citizens or permanent residents are white males. Increasing the overall number of American students pursuing degrees in physical sciences and engineering will be essential to meeting the future challenges facing the nation, but it will not be enough. We must also increase diversity by recruiting more women and underrepresented minorities in technical fields to ensure that we have the intellectual vitality to respond to profound and rapid change.

Current trends in research investment and workforce development are early warning signs that the United States could fall behind other nations, both in its capacity for technological innovation and in the size, quality, and capability of its technical workforce. Unless the United States maintains its resident capacity for technological innovation, as well as its ability to attract the best and brightest engineers and scientists from abroad, the economic benefits of technological advances may not accrue to Americans.

We must take action immediately to overcome existing imbalances in support for research to address emerging critical challenges. These actions must include both changes in direction by key stakeholders in the engineering research enterprise and bold new programs designed specifically to promote U.S. technological innovation. This conclusion echoes the findings of other recent assessments by the Council on Competitiveness (2001, 2004), President's Council of Advisors on Science and Technology (2002, 2004a,b), National Science Board (2003), National Academies (COSEPUP, 2002; NAE, 2003, 2004, 2005; NRC, 2001), and other distinguished bodies (DOE, 2003; National Commission on Mathematics and Science Teaching for the 21st Century, 2000).

Considering the magnitude and complexity of the challenges ahead in energy, security, health care, the environment, and economic competitiveness, we simply do not have the option of continuing to conduct business as usual. We must change how we prioritize, fund, and conduct research; how we attract, educate, and train engineers and scientists; how we consider and implement policies and legal structures that affect intellectual property rights and related issues; and how we maximize contributions from institutions engaged in technological innovation and workforce development (e.g., universities, corporate R&D laboratories, federal agencies, and national laboratories).

Of course, major undertakings in anticipation of opportunities are always difficult, but the United States has a history of rising to the occasion in times of need. At least twice before in times of great challenge and opportunity, the federal government responded in creative ways that not only served the needs of society, but also reshaped institutions. Consider, for example, the Land Grant Acts in the nineteenth century, which not only modernized American agriculture and spearheaded America's response to the industrial revolution, but also led to the creation of the great public universities that have transformed American society and sustained U.S. leadership in the production of new knowledge and the creation of human capital. Another example is the G.I. Bill and government-university research partnerships during the 1940s that were instrumental in establishing U.S. economic and military leadership.

With this history in mind, and with full recognition of the magnitude of the effort needed to prepare the United States for long-term technological leadership, the committee offers the following recommendations.

RECOMMENDATIONS

Federal Research and Development Budget

RECOMMENDATION 1. The committee strongly recommends that the federal R&D portfolio be rebalanced by increasing funding for research in engineering and physical science to levels sufficient to support the nation's most urgent priorities, such as national defense, homeland security, health care, energy security, and economic competitiveness. Allocations of federal funds should be determined by a strategic analysis to identify areas of research in engineering and science that support these priorities. The analysis should explicitly include interdependencies among engineering and scientific disciplines to ensure that important advances are supported by advances in complementary fields to accelerate technology transfer and innovation.

Long-Term Research and Industry

RECOMMENDATION 2. Long-term basic engineering research should be reestablished as a priority for American industry. The federal government should design and implement tax incentives and other policies to stimulate industry investment in long-term engineering research (e.g., tax credits to support private-sector investment in university-industry collaborative research).

Engineering Research Infrastructure

RECOMMENDATION 3. Federal and state governments and industry should invest in upgrading and expanding laboratories, equipment, and information technologies and meeting other infrastructural needs of research universities and schools of engineering to ensure that the national capacity to conduct world-class engineering research is sufficient to address the technical challenges that lie ahead.

Quality of the Technical Workforce

RECOMMENDATION 4. Considering the importance of technological innovation to the nation, a major effort should be made to increase the participation of American students in engineering. To this end, the committee endorses the findings and recommendations of a 2005 National Academy of Engineering report, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, which calls for system-wide efforts by professional societies, industry, federal agencies, and educators at the higher education and K–12 levels to align the engineering curriculum and engineering profession with the needs of a global,

knowledge-driven economy with the goal of increasing student interest in engineering careers. Engineering education requires innovations, not only in the content of engineering curricula, but also in teaching methods that emphasize the creative aspects of engineering to excite and motivate students.

RECOMMENDATION 5. All participants and stakeholders in the engineering community (industry, government, institutions of higher education, professional societies, et al.) should place a high priority on encouraging women and underrepresented minorities to pursue careers in engineering. Increasing diversity will not only increase the size and quality of the engineering workforce, but will also introduce diverse ideas and experiences that can stimulate creative approaches to solving difficult challenges. Although this is likely to require a very significant increase in investment from both public and private sources, increasing diversity is clearly essential to sustaining the capacity and quality of the U.S. scientific and engineering workforce.

RECOMMENDATION 6. A major federal fellowship-traineeship program in strategic areas (e.g., energ;, info-, nano-, and biotechnology; knowledge services; etc.), similar to the program created by the National Defense Education Act, should be established to ensure that the supply of next-generation scientists and engineers is adequate.

RECOMMENDATION 7. Immigration policies and practices should be streamlined (without compromising homeland security) to restore the flow of talented students, engineers, and scientists from around the world into American universities and industry.

Industry and Research Universities

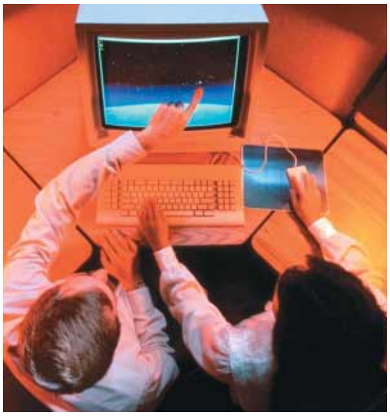
RECOMMENDATION 8. Links between industry and research universities should be expanded and strengthened. The committee recommends that the following actions, funded through a combination of tax incentives and federal grants, be taken:

- Support new initiatives that encourage multidisciplinary research to address major challenges facing the nation and the world.
- Streamline and standardize intellectual-property and technology-transfer policies in American universities to facilitate the transfer of new knowledge to industry.
- Support industry engineers and scientists as visiting "professors of practice" in engineering and science faculties.
- Provide incentives for corporate R&D laboratories to host advanced graduate and postdoctoral students (e.g., fellowships, internships, etc.).

Discovery-Innovation Institutes

RECOMMENDATION 9. Multidisciplinary discovery-innovation institutes should be established on the campuses of research universities to link fundamental scientific discoveries with technological innovations to create products, processes, and services to meet the

needs of society. Funding for the institutes should be provided by federal and state governments, industry, foundations, the venture capital and investing community, and universities.

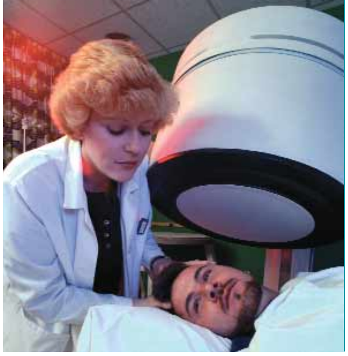


With the participation of many scientific disciplines and professions, as well as various economic sectors (industry, government, states, and institutions of higher education), discovery-innovation institutes would be similar in character and scale to academic medical centers and agricultural experiment stations that combine research, education, and professional practice and drive transformative change. As experience with academic medical centers and other large research initiatives has shown, discovery-innovation institutes would stimulate significant regional economic activity, such as the location nearby of clusters of start-up firms, private research organizations, suppliers, and other complementary groups and businesses.

On the federal level, the discovery-innovation institutes should be funded jointly by agencies with responsibilities for basic research and missions that address major national priorities (e.g., National Science Foundation [NSF], U.S. Department of Energy, National Aeronautics and Space Administration, U.S. Department of Defense, U.S. Department of Homeland Security, U.S. Department of Transportation, U.S. Department of Commerce, Environmental Protection Agency, and U.S. Department of Health and Human Services).

States would be required to contribute to the institutes (perhaps by providing capital facilities). Industry would provide challenging research problems, systems knowledge, and real-life market knowledge, as well as staff who would work with university faculty and students in the institutes. Industry would also fund student internships and provide direct financial support for facilities and equipment (or share its facilities and equipment). Universities would commit to providing a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure). Finally, the venture capital and investing community would contribute expertise in licensing, spin-off companies, and other avenues of commercialization.

Some of the existing NSF-sponsored engineering research centers (ERCs) may serve as a starting point for the development of discovery-innovation institutes. Yet the multidisciplinary scope and scale of the research, education, innovation, and technology-transfer activities of fully developed discovery-innovation institutes will certainly dwarf the important, but more limited, activities of ERCs.



To ensure that the discovery-innovation institutes lead to transformative change, they should be funded at a level commensurate with past federal initiatives and current investments in other areas of research, such as biomedicine and manned spaceflight. Federal funding would ultimately increase to several billion dollars per year distributed throughout the engineering research and education enterprise; states, industry, foundations, and universities would invest comparable amounts.

The committee recognizes that current federal and state budgets are severely constrained and are likely to remain so for the foreseeable future. Nevertheless, as the public comes to understand the importance of leadership in technological innovation to the nation's economic prosperity and security, the committee believes this initiative could be given a high priority in the federal budget process.

To transform the technological innovation capacity of the United States, the discovery-innovation institutes should be implemented on a national scale and backed by a strong commitment to excellence by all participants. Most of all, they would be engines of innovation that would transform institutions, policies, and cultures and enable our nation to solve critical problems and maintain its leadership in the global, knowledge-driven society of the twenty-first century.

CONCLUSION

Exciting opportunities in engineering lie ahead. Some involve rapidly emerging fields, such as information systems, bioengineering, and nanotechnology. Others involve critical national needs, such as sustainable energy sources and homeland security. Still others involve the restructuring of engineering education to ensure that engineering graduates have the skills, understanding, and imagination to design and manage complex systems. To take advantage of these opportunities, however, investment in engineering research and education must be a much higher priority.

The country is at a crossroads. We can either continue on our current course—living on incremental improvements to past technical developments and gradually conceding technological leadership to trading partners abroad—or we can take control of our destiny and conduct the necessary research, capture the intellectual property, commercialize and manufacture the products, and create the high-skill, high-value jobs that define a prosperous nation. The United States has the proven ability and resources to maintain the global lead in innovation. Engineers and scientists can meet the technological challenges of the twenty-first century, just as they met the challenges of World War II by creating the tools for military victory and just as they mounted an effective response to the challenge of Sputnik and Soviet advances in space.

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ENGINEERING RESEARCH: THE ENGINE OF INNOVATION

American success has been based on the creativity, ingenuity, and courage of innovators, and innovation will continue to be critical to U.S. success in the twenty-first century. As a superpower with the largest and richest market in the world, the United States has consistently set the standard for technological advances, both creating innovations and absorbing innovations created elsewhere. From Neil Armstrong's walk on the Moon to cellular camera phones, engineering and scientific advances have captured people's imaginations and demonstrated the wonders of science.

The astounding technological achievements of the twentieth century would not have been possible without engineering (see Box 1), specifically engineering research, which

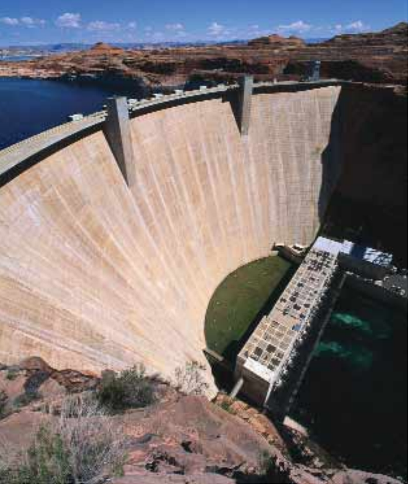
BOX 1 TWENTIETH-CENTURY INNOVATION

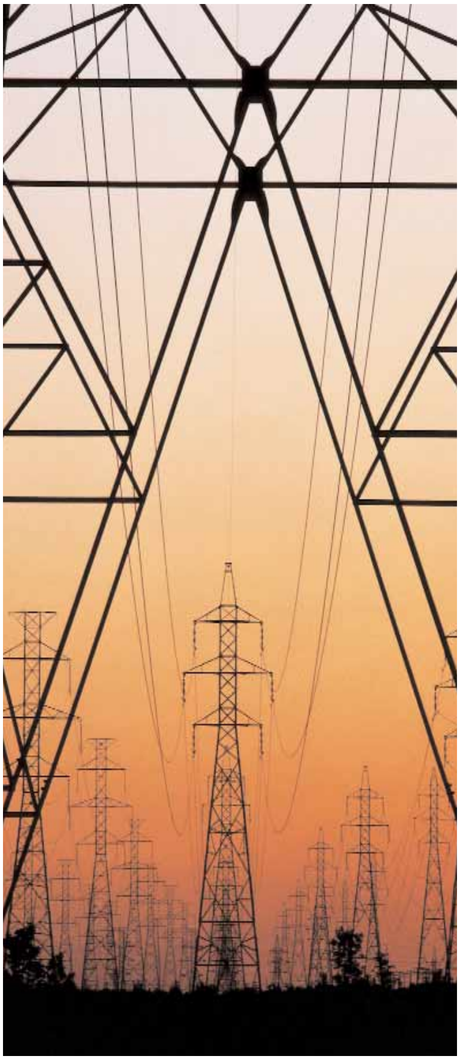
The greatest engineering achievements of the twentieth century led to innovations that transformed everyday life. Beginning with electricity, engineers have brought us a wide range of technologies, from the mundane to the spectacular. Refrigeration opened new markets for food and medicine. Air conditioning enabled population explosions in places like Florida and Arizona. The invention of the transistor, followed by integrated circuits, ushered in the age of ubiquitous computerization, impacting everything from education to entertainment. The control of electromagnetic radiation has given us not only radio and television, but also radar, x-rays, fiber optics, cell phones, and microwave ovens. The airplane and automobile have made the world smaller, and highways have transformed the landscape.

Even commonplace technologies, such as farm equipment, household appliances, water distribution, and medicine, required sophisticated engineering research and application. One of the essential, often overlooked, miracles of engineering in the twentieth century was the provision of clean drinking water, which was the primary contributor to doubling life expectancy in the United States.

So many complex engineering achievements have become part of everyday life that engineering and engineering research are often taken for granted. We give little thought, for example, to the vast worldwide system that brings oil from the ground to our fuel tanks. Without engineering research, the world would be less accessible, poorer, and far less interesting.

For more on the contributions of engineers, see Constable and Somerville, 2003.





leads to the conversion of scientific discoveries into functional, marketable, profitable products and services.

Engineers take new and existing knowledge and make it useful, typically generating new knowledge in the process. For example, an understanding of the physics of magnetic resonance on the atomic scale did not become useful in everyday life until engineers created magnetic resonance imaging machines and the computers to run them. And researchers could not have discovered these magnetic properties until engineers had created instrumentation that enabled them to pursue research on atomic and subatomic scales. Without engineering research, innovation, especially groundbreaking innovation that creates new industries and transforms old ones, simply does not happen.

In fact, groundbreaking innovation was the driving force behind American success in the last century. An endless number of innovations—from plastics to carbon fibers, electricity generation and distribution to wireless communications, clean water and transportation networks to pacemakers and dialysis machines—has transformed the economy, the military, and society, making Americans more prosperous, healthier, and safer in the process.

Consider, for example, the long, productive history of collaboration between engineering and medicine in the development of medical technologies (e.g., devices, equipment, and pharmaceuticals) and in support of medical research (e.g., instrumentation, computational tools, etc.) (NAE, 2003). Engineers created the tools of drug discovery and production, materials for joint replacements, lasers for eye surgery, heart-lung machines for open-heart surgery, and a host of imaging technologies, just to name a few remarkable achievements. Future engineering research will apply knowledge of microsystems and nanotechnology to diagnostics and therapeutics, providing effective treatment of a variety of chronic conditions (NAE, 2005a). Revolutions in bioengineering and genomics and the associated promise of huge advances in diagnostic tools and therapies testify to the continued vitality of the partnership between engineering and medicine.

Future breakthroughs dependent on engineering research will have equally powerful impacts. Sustainable energy technologies for power generation and transportation could

halt, and someday even reverse, the accumulation of atmospheric carbon dioxide and ozone. Low-cost, robust pumps, microfilters, and diagnostic tests could ensure that clean water is available to all and wipe out waterborne illnesses. Preventing terrorism could be greatly improved when vigilant sensors as small as grains of sand can activate autonomous robots to respond to security breaches (O'Harrow, 2004). Technological innovations already under development can make all of these things possible . . . with the help of engineers.

The innovations that flow from engineering research are not simply nice to have, like high-definition television; many are essential to the solutions of previously intractable challenges. Engineering research in materials, electronics, optics, software, mechanics, and many other fields will provide technologies to slow, or even reverse, global warming, to maintain water supplies for growing populations, to ameliorate traffic congestion and other urban maladies, and to generate high-value products and services to maintain the U.S. standard of living in a world of intense competition. To meet these and other grand challenges, the United States must be an innovation-driven nation that can capitalize on advances in life sciences, physical sciences, and engineering.

Based on current trends in research funding, graduate enrollments, and student achievement, however, serious doubts are emerging about the long-term health of the U.S. engineering research enterprise. Unless something is done quickly to reverse these trends, the United States risks becoming a consumer of innovations developed elsewhere rather than a leader. Leadership in the life sciences alone, although very important to the national welfare, will not be enough. To enjoy the full benefits of innovation, generate the jobs and wealth that flow from commercialization, and improve the lives of as many Americans as possible, the United States must invest in fundamental engineering research and the education and training of world-class researchers.

CHALLENGES TO SUSTAINED LEADERSHIP

The United States is part of a global economy, and research and development (R&D) are performed worldwide. Multinational corporations manage their R&D activities to take advantage of the most capable, most creative, and most cost-efficient engineering and scientific talent, wherever they find it. Smaller U.S. firms without global resources are facing stiff competition from foreign companies with access to talented scientists and engineers—many of them trained in the United States—who are the equals of any in this country. Relentless competition is driving a faster pace of innovation, shorter product life cycles, lower prices, and higher quality than ever before.

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

Even though current measures of technological leadership—percentage of gross domestic product invested in R&D, absolute numbers of researchers, labor productivity, and high-technology production and exports—still favor the United States, a closer look at the engineering research and education enterprise and the age and makeup of the technical workforce reveals several interrelated trends indicating that the United States may have difficulty maintaining its global leadership in technological innovation over the long term. These well documented trends include: (1) a large and growing imbalance in federal research funding between the engineering and physical sciences on the one hand and biomedical and life sciences on the other; (2) increased emphasis on applied R&D in industry and government-funded research at the expense of fundamental long-term research; (3) erosion of the engineering research infrastructure due to inadequate investment over many years; (4) declining interest of American students in science, engineering, and other technical fields; and (5) growing uncertainty about the ability of the United States to attract and retain gifted science and engineering students from abroad at a time when foreign nationals account for a large, and productive, component of the U.S. R&D workforce (COSEPUP, 2000; Council on Competitiveness, 2001, 2004; PCAST, 2002, 2004a,b; NAE, 2003, 2004, 2005; NCMST, 2000; NRC, 2001).

IMBALANCE IN THE RESEARCH PORTFOLIO

Despite record levels of federal funding for research, most of the increases in the past quarter century have been focused on the life sciences, which currently account for about two-thirds of federal funds for academic R&D. In fiscal year (FY) 2002, 45 percent of these funds went directly to medical schools. By contrast, as data from the National Science Foundation (NSF) show, federal funding for research in other scientific and engineering fields has been relatively stagnant for the past two decades (Figure 1) (NSB, 2004). A new institute, the National Institute for Biomedical Imaging and Bioengineering, was created at the National Institutes of Health in late 2000, and support for applied engineering research did increase briefly between 2000 and 2003, mainly as a result of funding increases at the U.S. Departments of Defense (DOD) and Homeland Security (DHS), but subsequent federal budgets suggest a return to minimal increases (AAAS, 2005; NSB, 2004). Thus, the funding trend is on a collision course with the changing nature of technological innovation, which is becoming increasingly dependent on interdisciplinary, systems-oriented research.

> "Medical advances may seem like wizardry. But pull back the curtain and sitting at the lever is a high-energy physicist, a combinatorial chemist, or an engineer.... In other words, the various sciences together constitute the vanguard of medical research." Harold Varmus, Nobel Prize winner and former director of the National Institutes of Health (2000).

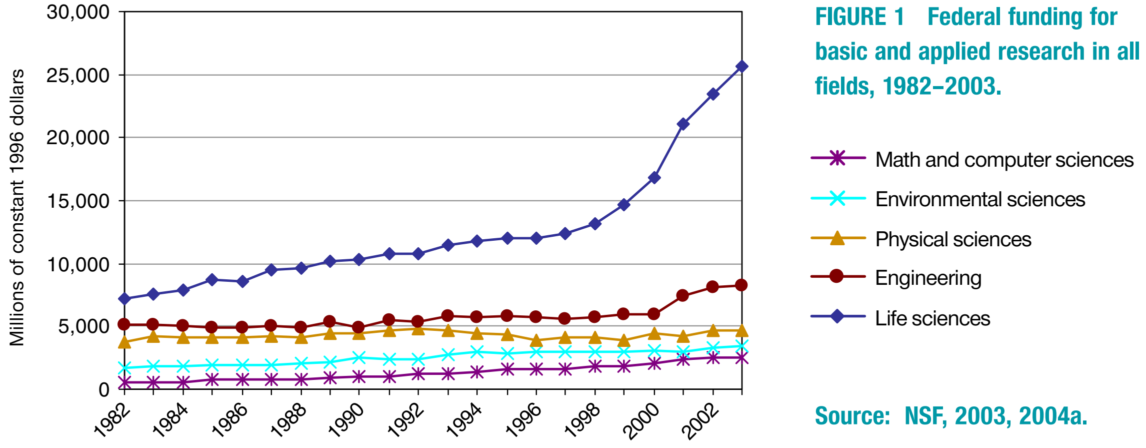
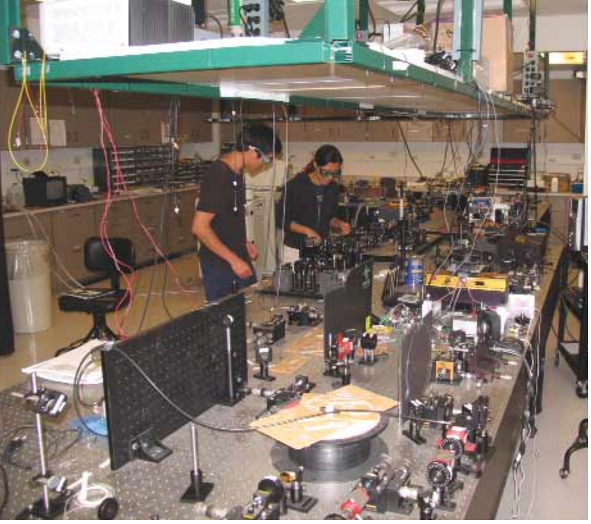


FIGURE 1 Federal funding for basic and applied research in all fields, 1982–2003.

Source: NSF, 2003, 2004a.

The National Academies have long urged the federal government to adopt a more strategic approach to prioritizing federal funding for R&D. In a report published in 1995, recommendations were proposed urging that federal investment be sufficient to (1) achieve absolute leadership in research areas of key strategic interest to the nation (e.g., areas that clearly determine public health and national security) and (2) keep the nation among the leaders in all other scientific and technological areas to ensure that rapid progress can be made in those areas in the event of technology surprises (NAS, 1995). The current federally funded R&D portfolio clearly falls short of both of these goals. Current investments



in engineering and physical science research are not sufficient to support the broad range of key national priorities, such as national defense, homeland security, and the economic competitiveness of American industry.

Indeed, the nation's ability to capitalize on new knowledge resulting from large investments in life sciences research will depend on contributions from other sciences, especially engineering. Engineering research is founded on a disciplined approach to problem solving and the application of sophisticated modeling, design, and testing tools to solve problems. For instance, fundamental engineering research led to the creation of finite-element methods of stress analysis, which have provided sophisticated computational tools used by mechanical and structural engineers in a vast array of applications. Engineering researchers have also made significant progress in using molecular dynamics to measure time more precisely, a critical enabling technology for faster computers, global positioning systems, wireless communications, and many other products in common use.

Many other technologies are based on the results of fundamental engineering research, mostly conducted at universities. Thus, the investment gap between basic research in the life sciences and fundamental, long-term research in complementary disciplines in engineering and other fields not only undermines the nation's capacity to capitalize on life sciences research, but also compromises its ability to address large, complex challenges and take advantage of technological opportunities related to energy sustainability, affordable health care, and homeland security.

Broadly speaking, the most daunting challenges facing the nation in health care delivery, energy production and distribution, environmental remediation and sustainability, national and homeland security, communications, and transportation pose complex systems challenges that require parallel advances in knowledge in multiple disciplines of engineering and science and collaboration and cross-fertilization among disciplines. In fact, both basic and applied engineering research will be critical to the design and control of processes and systems on which every major sector of the U.S. economy depends and will be essential to meeting the challenges and taking advantage of the opportunities that lie ahead. Yet federal investment in engineering and physical science research, particularly long-term fundamental research, associated infrastructure, and education, does not reflect their critical importance.

RECOMMENDATION 1. The committee strongly recommends that the federal R&D portfolio be rebalanced by increasing funding for research in engineering and physical science to levels sufficient to support the nation's most urgent priorities, such as national defense, homeland security, health care, energy security, and economic competitiveness. Allocations of federal funds should be determined by a strategic analysis to identify areas of research in engineering and science that support these priorities. The analysis should explicitly include interdependencies among engineering and scientific disciplines to ensure that important advances are supported by advances in complementary fields to accelerate technology transfer and innovation.

DECLINE IN LONG-TERM RESEARCH

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

Consequently, federal investment in long-term research in universities and national laboratories has become increasingly important to sustaining the nation's technological strength. But just as industry has greatly reduced its investment in long-term engineering research, engineering-intensive mission agencies have also shifted their focus to short-term research. For example, DOD funding for both basic and applied research has fallen substantially from peak levels in the 1990s, and cuts of more than 20 percent in 6.1, 6.2, and 6.3 budget categories are projected for FY 2006 (AAAS, 2005). Given the importance of DOD funding to engineering research in key disciplines—DOD funds about 40 percent of engineering research at universities and more than 50 percent of research in electrical and mechanical engineering—these reductions have had a significant impact on the level of fundamental research conducted in a number of engineering fields (NRC, 2005).

Currently, most support for engineering research comes from federal mission agencies and NSF. Major federal initiatives by mission agencies in areas such as manned space flight, energy, and defense have played a critical role in stimulating the nation's capacity to engage in large-scale complex systems engineering and engineering research. Within NSF, the Engineering Directorate has historically focused on basic engineering research and the integration of research and education through engineering research centers (ERCs) and other mechanisms. Thus, NSF is uniquely situated to catalyze change in engineering research, education, and practice and to head a buildup of long-term fundamental engineering research at the nation's universities. NSF is especially important for linking basic engineering research and education to fundamental scientific discoveries in physical, natural, and social sciences.

The committee believes that restoring long-term engineering research in industry to a substantial level would enhance the nation's long-term economic health. Although publicly traded corporations continue to be subject to intense financial pressures to limit R&D to near-term product development, a strong case can be made for federal incentives to encourage individual companies or consortia to reestablish basic research programs. In addition, more investment by NSF and mission agencies will be necessary, not only to keep pace with the accelerating rate of technological change, but also to meet the economic, social, environmental, and security challenges of an increasingly competitive, knowledge-driven, global economy.

RECOMMENDATION 2. Long-term basic engineering research should be reestablished as a priority for American industry. The federal government should design and implement tax incentives and other policies to stimulate industry investment in long-term engineering research (e.g., tax credits to support private sector investment in university-industry collaborative research).

EROSION OF THE ENGINEERING RESEARCH INFRASTRUCTURE

One result of the stagnation of federal investment in engineering research has been the deterioration of the engineering research infrastructure at many schools of engineering. Only a few research universities have facilities adequate for advanced engineering research that can support increasingly systems-oriented, interdisciplinary technological innovation. Many engineering schools operate in old facilities, with laboratory equipment dating from before the invention of the transistor, let alone the personal computer. These institutions do not have the clean rooms, information systems, or instrumentation necessary to contribute to technological leadership.

Research in many fields of engineering requires sophisticated, expensive equipment and instruments that rapidly depreciate. Effective research in many areas of microelectronics, bioengineering, and materials science requires Class 10 and Class 100 clean rooms and precision instruments; costs for these can exceed $100 million. Research and education in emerging fields, such as quantum computing, as well as established fields, such as nuclear engineering, are suffering for want of resources for the development and/or maintenance of facilities. In fact, it will take billions of dollars to update facilities at hundreds of engineering schools nationwide. This investment, however, would create geographically dispersed, world-class research facilities that would make engineering attractive to more students (at home and from abroad), stimulate cooperation, and maybe competition, among research groups working on related problems, and provide a locus for networks of researchers and clusters of industry across the nation.

RECOMMENDATION 3. Federal and state governments and industry should invest in upgrading and expanding laboratories, equipment, and information technologies and meeting other infrastructural needs of research universities and schools of engineering to ensure that the national capacity to conduct world-class engineering research is sufficient to address the technical challenges that lie ahead.

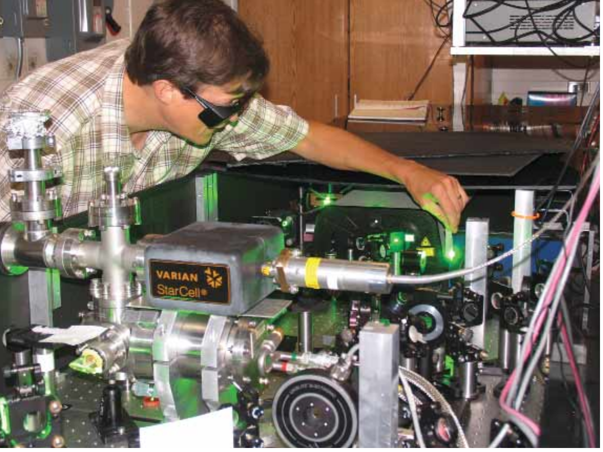
ENDANGERED TECHNICAL WORKFORCE

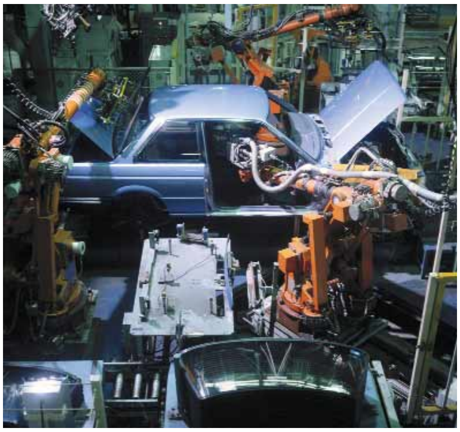
A technically skilled workforce is essential to maintaining leadership in innovation. Although future demand for specific science and engineering skills is notoriously difficult to predict, it is reasonable to assume that an increasingly technical world will require a technically proficient workforce. We can also predict that meeting national and homeland security needs will require many more U.S. citizens who are educated in engineering. But simply increasing the number of engineers will not be enough. The United States needs engineers with the skills, imagination, and drive to compete and take the lead in the world. Moreover, the United States must ensure that it can still attract talented scientists and engineers from abroad.

The stagnating federal investment in engineering research and research infrastructure has weakened the human-capital foundation of the engineering research enterprise. The innovation-driven nation we envision will require a large cadre of engineering researchers with the depth of knowledge and creativity to create breakthrough technologies and systems. In addition to solid grounding in fundamental engineering concepts, these engineers must have the ability to address complex systems in multidisciplinary research environments.

However, like the engineering research infrastructure, the engineering professoriate is aging rapidly. The faculty hiring boom of the 1960s, which was followed by a sharp downturn in hiring in the 1970s and a moderate pace since then, has resulted in increasing numbers of engineering faculty at or near retirement age (NSB, 2003). Along with many other factors, the aging research infrastructure and aging faculty, combined with inadequate support for and commitment to long-term, interdisciplinary research and associated curricular innovation, have made it extremely difficult to interest qualified American students in pursuing undergraduate and graduate programs in engineering and science.

Comparisons with other countries reveal alarming differences. In China and Japan, more than two-thirds of bachelor's degrees are awarded in science and engineering. In the 25 member countries of the European Union, 36 percent of bachelor's degrees are in science and engineering, compared to only 24 percent in the United States, even though a comparable number of degrees are awarded. The gap is even larger for science and engineering Ph.D.s, (OECD, 2003).





In addition, American secondary schools are not graduating enough students with sufficient skills in mathematics and science to ensure that an adequate supply of technically competent workers will be available to meet future needs. International comparisons of math and science proficiency at various grade levels indicate that, although American primary school students perform well, U.S. high school students perform relatively poorly (Martin et al., 2004; Mullis et al., 1998; National Commission on Mathematics and Science Teaching for the 21st Century, 2000; OECD, 2004). In a 1995 international assessment of mathematics and science achievement in the final years of secondary school, American high school students ranked close to last among students in the 21 nations tested (Mullis et al., 1998). Eight years later, despite significant investment and attention to the problem in K–12 education, a similar assessment of mathematics achievement of first- and second-year high school students showed little improvement. In 2004, American students ranked between 25th and 28th among students in the 41 nations tested (OECD, 2004).

RECOMMENDATION 4. Considering the importance of technological innovation to the nation, a major effort should be made to increase the participation of American students in engineering. To this end, the committee endorses the findings and recommendations of the 2005 National Academy of Engineering report, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, which calls for system-wide efforts by professional societies, industry, federal agencies, and educators at the higher education and K–12 levels to align the engineering curriculum and engineering profession with the needs of a global, knowledge-driven economy with the goal of increasing student interest in engineering careers. Engineering education requires innovations, not only in the content of engineering curricula, but also in teaching methods that emphasize the creative aspects of engineering to excite and motivate students.

One key approach to increasing the number of U.S. citizens with advanced degrees in science and engineering is to attract more women and minorities to these fields. Currently, males receive more than 75 percent of the doctoral degrees granted in physical sciences, mathematics and computer science, and engineering, and more than two-thirds of graduate students in these fields are white (Figure 2). Increasing diversity in the engineering student population and, ultimately, the engineering workforce will be essential to generating the intellectual vitality and tapping into the reservoirs of talent essential to long-term U.S. economic and technological success.

In April 2004, White House Science Advisor Dr. John Marburger stated:

> The future strength of the U.S. science and engineering workforce is imperiled by two long-term trends. First, the global competition for science and engineering talent is intensifying, such that the U.S. may not be able to rely on the international

science and engineering labor market for its unmet skill needs. Second, the number of native-born science and engineering graduates entering the workforce is likely to decline unless the nation intervenes to improve the education of science and engineering students from all demographic groups, especially those that have been underrepresented in science and engineering careers.

Clearly, an important part of a strategy for reinvigorating U.S. engineering research capacity will be attracting more women and underrepresented minorities into science and engineering careers. This will require both a major commitment and more effective strategies for diversifying the science and engineering workforce.

RECOMMENDATION 5. All participants and stakeholders in the engineering community (industry, government, institutions of higher education, professional societies, et al.) should place a high priority on encouraging women and underrepresented minorities to pursue careers in engineering. Increasing diversity will not only increase the size and quality of the engineering workforce, but will also introduce diverse ideas and experiences that can stimulate creative approaches to solving difficult challenges. Although this is likely to require a very significant increase in investment from both public and private

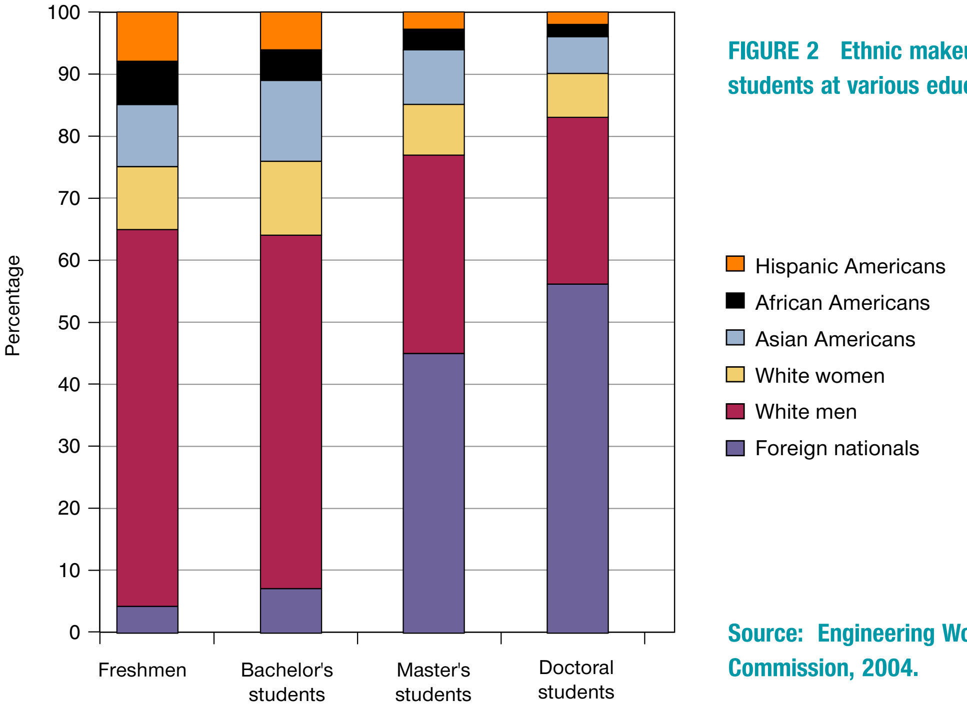
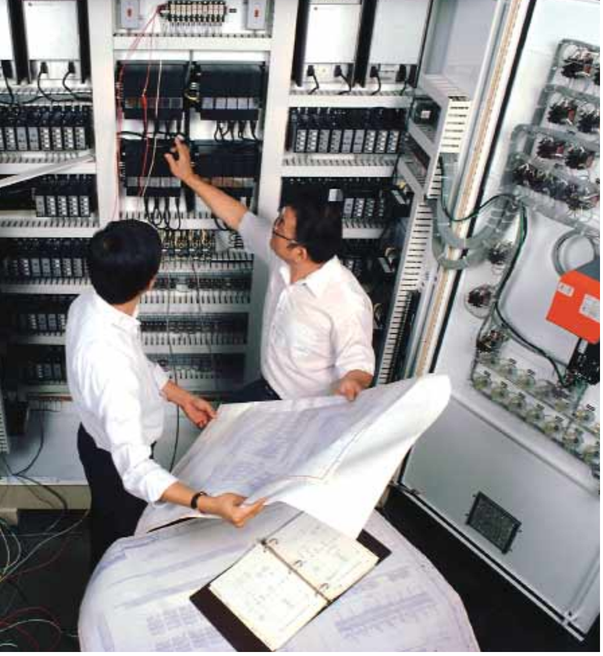


FIGURE 2 Ethnic makeup of engineering students at various educational levels.

Source: Engineering Workforce Commission, 2004.



sources, increasing diversity is clearly essential to sustaining the capacity and quality of the U.S. scientific and engineering workforce.

Up to now, foreign nationals have made up for the shortfall in domestic technical talent. More than 50 percent of U.S. workers with doctorates in engineering and nearly 30 percent with master's degrees in engineering in 2000 were foreign nationals (NSB, 2003). In U.S. graduate schools, almost one-third of all science and engineering graduate students are foreign-born; in computer science and engineering, the proportion is almost half (NSF, 2004a). The U.S. R&D workforce in industry and academia is, and will continue to be, heavily dependent on foreign nationals, who have made significant contributions to U.S. innovation in the past and will certainly continue to do so in the future (NAE, 1996; National Academies, 2003).

However, as technical capabilities and economic opportunities abroad improve and as global competition for workers skilled in science and engineering increases, questions are being raised about the ability of the United States to continue to attract and retain as many foreign-born engineers and scientists in the future (NSB, 2003). Moreover, post-9/11 changes to U.S. immigration procedures may make attracting and retaining foreign scientists and engineers even more difficult (National Academies, 2003; NSB, 2003).

At the same time, the national security research establishment, which will be looking for a large technical workforce for the foreseeable future and is currently populated by a rapidly aging engineering workforce, has introduced strict security requirements that often preclude the hiring of foreign-born engineers and scientists (DOE, 1995; Sega, 2004). Thus, the technical requirements for national defense and homeland security are contributing to the growing demand for engineers who are U.S. citizens.

RECOMMENDATION 6. A major federal fellowship-traineeship program in strategic areas (e.g., energy; info-, nano-, and biotechnology; knowledge services; etc.), similar to the program created by the National Defense Education Act, should be established to ensure that the supply of next-generation scientists and engineers is adequate.

RECOMMENDATION 7. Immigration policies and practices should be streamlined (without compromising homeland security) to restore the flow of talented students, engineers, and scientists from around the world into American universities and industry.

ROLE OF COLLEGES AND UNIVERSITIES

Colleges and universities have a long history of contributing to U.S. preeminence in technological innovation. Since 1862 when the Morrill Act created land-grant universities, Congress has passed legislation to support institutions of higher education as providers of new knowledge and educators of the technical workforce. The Hatch Act of 1887 created agricultural and engineering experiment stations to encourage technological advances in agriculture and the emerging industrial economy (see Box 2). The second Morrill Act of 1890, which created 17 originally black land-grant colleges, provided opportunities for minority students to participate in knowledge-based occupations. The G.I. Bill in the 1940s, which provided educational opportunities to returning servicemen and servicewomen, laid the foundations for America's preeminence in science and engineering. Large-scale government investment in research at academic medical centers laid the foundations for U.S. preeminence in biomedicine (see Box 3).

BOX 2 AGRICULTURAL EXPERIMENT STATIONS

Created by the Hatch Act of 1887, agricultural experiment stations are the agricultural research arm of land-grant universities. Their mission is to conduct research, investigations, and experiments bearing on and contributing to the establishment and maintenance of a permanent and effective agricultural industry in the United States. When the Hatch Act was passed, farmers made up most of the population and controlled most of the assets and inputs associated with agricultural industry.

Research at agricultural experiment stations both contributed to and benefited from the industrialization of U.S. agriculture. Over the years, research has led to the development of standardized equipment, seeds, fertilizers, pesticides, feed formulations, farm management, marketing, food processing, distribution, and transportation. In addition, farmers and agricultural scientists have been educated and trained (Holt and Bullock, 1999).

Core funding for agricultural experiment stations is provided by a combination of state and federal monies. Federal funding is allocated to each state based on a formula that takes into account the state's rural population and research cooperation. Average federal funding per state is $2.8 million annually. Federal funds must be matched dollar for dollar with nonfederal funding.

Source: DOA, 2004.

By combining research with education, universities not only tap into the creativity of young people, but also train them in critical thinking, research methodologies, and solid engineering skills. Because of the high quality of the people and tools provided by American universities, industries have chosen to locate their facilities in the United States, and emerging industries have tended to cluster around major engineering research universities (e.g., Silicon Valley, Route 128, Research Triangle, etc.) where they have access to a continuous supply of technical talent.

BOX 3 ACADEMIC MEDICAL CENTERS

Academic medical centers (AMCs) typify an innovative model in which research, teaching, education, and practice are integrated to achieve a constant upward spiral of the development and implementation of medical technology and the training and education of skilled professionals prepared to make full use of medical innovations. A typical AMC comprises a medical school, a teaching hospital, a network of affiliated hospitals, and a nursing school. Some AMCs also have schools of dentistry, schools for allied health professionals, and schools of public health. These complex, multifunctional organizations have a three-part mission:

1. Training clinicians and biomedical researchers, thereby ensuring the distribution of medical skills and specialties.
2. Providing advanced specialty and tertiary care and, therefore, adopting the latest technologies.
3. Conducting biomedical research, ranging from laboratory-based fundamental research to population-based clinical studies.

Between 1960 and 1992, the average medical school budget in the United States increased nearly tenfold. Basic science faculty increased from 4,023 to 15,579, and clinical faculty increased even more rapidly, from 7,201 to 65,913. As of the late 1990s, about 30 percent of all health-related R&D in the nation was being done at AMCs.

AMC research is funded from a variety of sources. The federal government funds the majority of AMC research (nearly 70 percent), especially basic biomedical research. Foundations, philanthropic organizations, and individual donors are also important sources of research funding. In addition, a substantial portion of research is funded internally. Revenues from faculty practice plans, for example, underwrite about 9 percent of research (mostly clinical). Universities also provide institutional funding to support the direct costs of research.

Source: NAE, 2003.

An academic campus is one of the few places where precompetitive, use-inspired, long-term basic research can be conducted without the constraints of quarterly earnings. In partnership with industry and national laboratories, universities can bring together experts from many disciplines to investigate problems related to agency missions or meet specific product/service goals. At the same time, university students can learn systems thinking and gain an understanding of market forces through internships and participation in research projects. No other institutions have the same capabilities.

The federal government must take the lead in initiating and sustaining investment to maximize the potential of universities to generate human capital, fundamental knowledge, and systems understanding. With sufficient resources, many schools of engineering could modernize their facilities, thereby making engineering much more attractive to incoming freshmen and helping to sustain their interest in pursuing advanced degrees. Engineering laboratories with state-of-the-art technology would greatly improve the quality of engineering education and create opportunities for thousands of creative young people to contribute to the innovation process. Increased funding for engineering research would also create opportunities for doctoral students and attract gifted U.S. citizens, as well as talented students from around the world, to doctoral programs. The influx of dollars and creativity would make research more exciting and diverse.

Today, most federal investment in engineering research and education is provided by a handful of mission agencies—DOD, DHS, U.S. Department of Energy (DOE), U.S. Department of Transportation (DOT), National Aeronautics and Space Administration

(NASA)—as well as NSF (NSB, 2003). Although NSF is a relatively small contributor, the agency plays an important role in linking basic engineering research and education to fundamental scientific discoveries in physical, natural, and social sciences.

In the past two decades, NSF has sponsored a significant number of interdisciplinary research centers involving engineering. Most prominent among these are the 22 university-based ERCs, each focusing on a single topical area. To ensure that the research is directed toward meeting real-world needs, the research priorities for ERCs are agreed upon by industry and the university. Other university-based research centers involving engineering include NSF science and technology centers and materials research science and engineering centers; DOE materials research centers; DOT transportation research centers; and the nanotechnology research centers sponsored by NSF, NASA, and DOE (DOE, 2004; DOT, 2004; NNI, 2004; NSF, 2004b,c). The activities of these multidisciplinary centers have not only contributed to the solutions of engineering-systems problems, but have also expanded the educational scope of students, faculty, and industry researchers (NSF, 2004c; Parker, 1997).

In spite of severe fiscal constraints, several large states have recognized that research and technology-development capacity are key elements in restoring their economic prosperity in an intensely competitive, global, technology-driven marketplace. California, Texas, Ohio, Wisconsin, and other states have either made or are planning to make major investments in their research universities in specific technological areas, including nanotechnology, biotechnology, and information systems and communications (CAL-ISI, 2004; Ohio 3rd Frontier Project, 2004; Seely, 2004; State of Texas, 2004). The governor of Texas, for example, recently announced plans to invest $150 million in regional centers of innovation and commercialization to house collaborative projects between universities and private industry (State of Texas, 2004). In California, centers have been created throughout the University of California system to focus resources on advanced technology development (CAL-ISI, 2004). Many other state governments have acknowledged the importance of technology-based economic development and the critical role of universities, particularly schools of engineering, in their economic development strategies.

RECOMMENDATION 8. Links between industry and research universities should be expanded and strengthened. The committee recommends that the following actions, funded through a combination of tax incentives and federal grants, be taken:

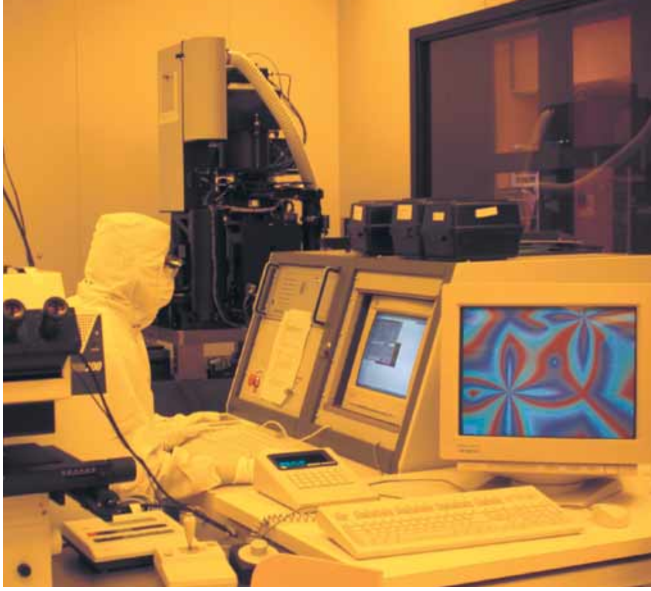
- Support new initiatives that foster multidisciplinary research to address major challenges facing the nation and the world.
- Streamline and standardize intellectual property and technology-transfer policies in American universities to facilitate the transfer of new knowledge to industry.
- Support industry engineers and scientists as visiting "professors of practice" in engineering and science faculties.
- Provide incentives for corporate R&D laboratories to host advanced graduate and postdoctoral students (e.g., fellowships, internships, etc.).

DISCOVERY-INNOVATION INSTITUTES: A PATH AHEAD

U.S. leadership in innovation will require commitments and investments of funds and energy by the private sector, federal and state governments, and colleges and universities. The committee believes that a bold, transformative initiative, similar in character and scope to initiatives undertaken in response to other difficult challenges (e.g., the Land Grant Acts, the G.I. Bill, and the government-university research partnerships) will be necessary for the United States to maintain its leadership in technological innovation. The United States will have to reshape its engineering research, education, and practices to respond to challenges in global markets, national security, energy sustainability, and public health. The changes we envision are not only technological, but also cultural; they will affect the structure of organizations and relationships between institutional sectors of the country. This task cannot be accomplished by any one sector of society. The federal government, states, industry, foundations, and academia must all be involved.

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

RECOMMENDATION 9. Multidisciplinary discovery-innovation institutes should be established on the campuses of research universities to link fundamental scientific discoveries with technological innovations to create products, processes, and services to meet the needs of society. Funding should be provided by federal and state governments, industry, foundations, the venture capital and investing community, and universities.



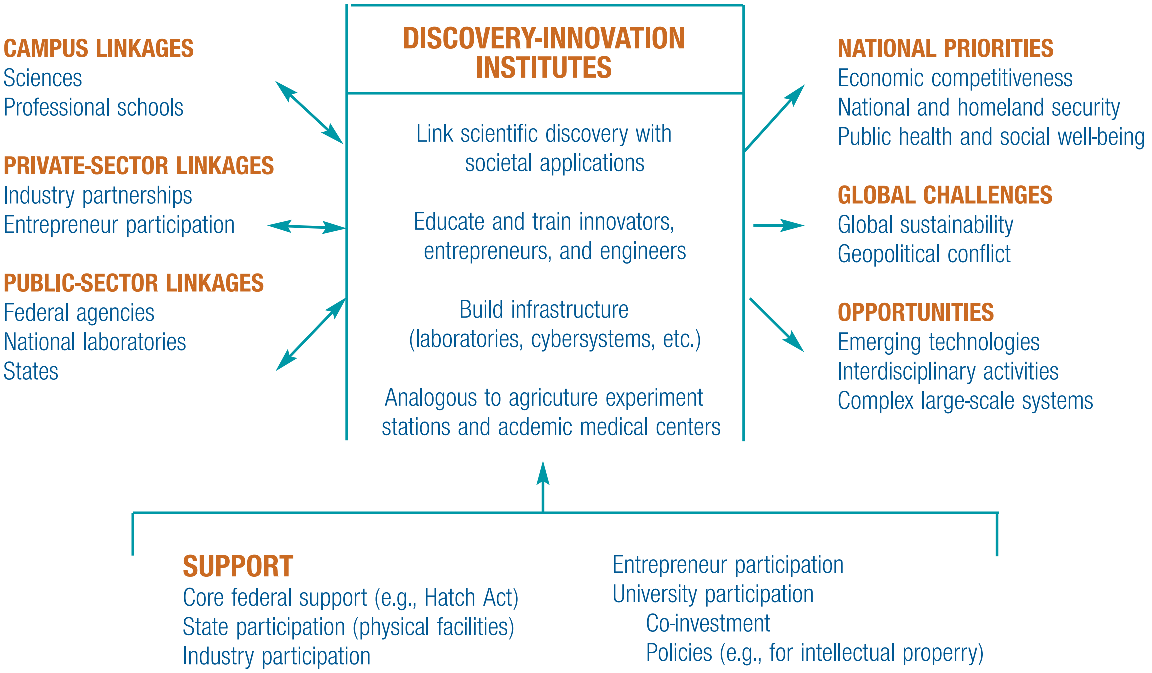
Discovery-innovation institutes would be foci for long-term fundamental and applied engineering research on major societal challenges and opportunities, would create new models of sectoral and disciplinary interaction on university campuses, and, indeed, would change the culture of research in this country. The committee envisions a large number of diverse institutes, some based at single universities, some involving consortia of institutions, and some focused on strengthening the research and educational capacity of a wide variety of institutions. With the participation of many scientific disciplines and professions, as well as various economic sectors (e.g., industry, federal and state governments, foundations, entrepreneurs, and venture capitalists), the institutes would be similar in character and scale to academic medical centers and agricultural experiment stations. In scope and transformational power, discovery-innovation institutes would be analogous to the agricultural experiment stations created by the Hatch Act of 1887 and the complementary creation of cooperative extension programs authorized by the Smith-Lever Act of 1914.

Operationally, discovery-innovation institutes would be comparable to academic medical centers, which combine research, education, and practice in state-of-the-art facilities and address significant national priorities rather than applications-driven research and technology centers, such as engineering experiment stations and federally funded R&D centers (e.g., MIT's Lincoln Laboratory and Carnegie Mellon's Software Engineering Institute). Like academic medical centers and other large research initiatives, discovery-innovation institutes would stimulate significant commercial activity, as clusters of start-up firms, private research organizations, suppliers, and other complementary groups and businesses locate nearby; in this way, the institutes would stimulate regional economic development. Some of the existing NSF-sponsored ERCs could serve as starting points for the development of discovery-innovation institutes. An effective way to initiate a discovery-innovation institute program on a pilot basis might be to expand the charter of one or two ERCs to include the multidisciplinary scope and scale of the research, education, innovation, and technology transfer activity of fully developed discovery-innovation institutes.

Discovery-innovation institutes would require the active involvement of industry and national laboratories to fulfill their missions of conducting long-term research to convert basic scientific discoveries into innovative products, processes, services, and systems. They would stimulate the creation of new infrastructure, encourage (in fact, require) interdisciplinary linkages, and lead to the development of educational programs that could produce new knowledge for innovation and educate the engineers, scientists, innovators, and

entrepreneurs of the future (Figure 3). Discovery-innovation institutes would be characterized by partnership, interdisciplinary research, education, and outreach.

FIGURE 3 Discovery-innovation institutes.



Partnership

The federal government would provide core support for the discovery-innovation institutes on a long-term basis (perhaps a decade or more, with possible renewal). States would be required to contribute to the institutes (perhaps by providing capital facilities). Industry would provide challenging research problems, systems knowledge, and real-life market knowledge, as well as staff who would work with university faculty and students in the institutes. Industry would also fund student internships and provide direct financial support for facilities and equipment (or share its facilities and equipment). Universities would commit to providing a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure). Finally, the venture capital and investing community would contribute expertise in licensing, spin-off companies, and other avenues of commercialization.

Interdisciplinary Research

Although most discovery-innovation institutes would involve engineering schools (just as the agricultural experiment stations involve schools of agriculture), they would require strong links with other academic programs that generate fundamental new knowledge through basic research (e.g., physical sciences, life sciences, and social sciences), as well as other disciplines critical to the innovation process (e.g., business, medicine, and other professional disciplines). These campus-based institutes would also attract the participation (and possibly financial support) of established innovators and entrepreneurs.

Education

Engineering schools and other programs related to the discovery-innovation institutes would be stimulated to restructure their organizations, research activities, and educational programs. Changes would reflect the interdisciplinary team approaches for research that can convert new knowledge into innovative products, processes, services, and systems and, at the same time, provide graduates with the skills necessary for innovation. These changes would also generate strategies for retaining undergraduates in engineering programs and attracting and retaining students from diverse backgrounds. Discovery-innovation institutes would provide a mechanism for developing and implementing innovative curricula and teaching methods.

Outreach

Just as the success of the agricultural experiment stations depended on their ability to disseminate new technologies and methodologies to the farming community through the cooperative extension service, a key factor in the success of discovery-innovation institutes would be their ability to facilitate implementation of their discoveries in the user community. Extensive outreach efforts based on existing industry and manufacturing extension programs at engineering schools would be an essential complement to the research and educational activities of the institutes. Outreach should also include programs for K–12 students and teachers that would build enthusiasm for the innovation process and generate interest in math and science.

Research Priorities

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

BOX 4 LARGE COMPLEX SYSTEMS

The development of methodologies for creating very large, complex systems would be an ideal focus for a discovery-innovation institute. Experience shows that the development of such systems always costs more and takes longer than anticipated, and usually results in less capability than desired. The solutions require the integration of knowledge from many disciplines and the modification of plans based on experience gained from the implementation of subsystems.

To create systems on a "learn as you go" basis requires a strategy for collecting and analyzing information from the early use of subsystems and dynamic management of budgets and schedules, without compromising accountability. However, there are no accepted methodologies for this type of sequential management of systems based on incremental implementation. Even selecting the sequence of subsystem implementation based on where the most valuable experience is likely to be gained as early as possible is not standard practice.

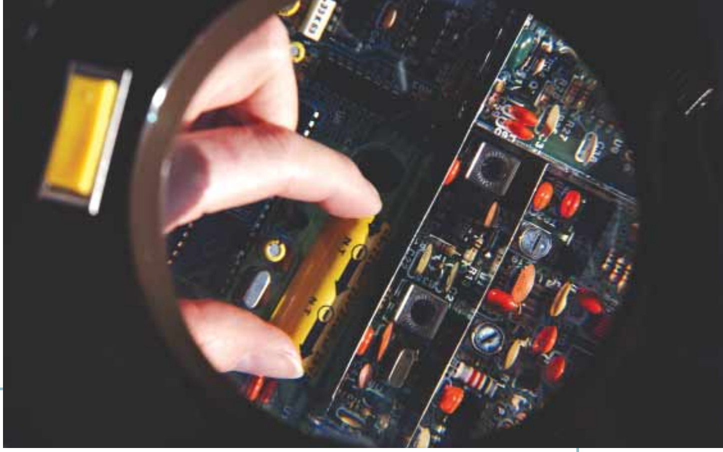
Although computer-based tools are emerging to improve collaboration among large teams working on common problems, analogous tools for the development of large, complex systems are not available. Systems-engineering researchers at the nation's universities could integrate research from many disciplines to develop new methodologies and tools for the creation and management of large, complex systems. Faculty members who work on these projects would gain direct experience with the pressures and problems of system development.

System development could lead to new approaches to embedding automated information-collection capabilities into systems, using collaborative computing to gain early insight into system performance, broadening the education of engineers to include exposure to management complexities, and developing new materials for research and education.

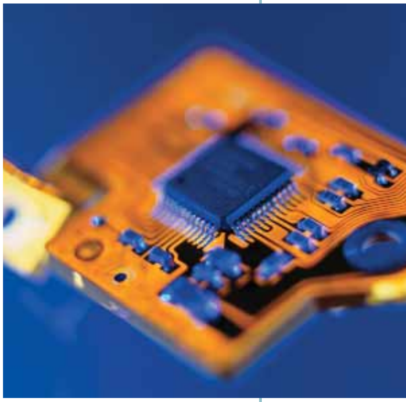
These systems reside and operate in a complex environment that raises financial, political, social, and ethical issues. Mobilizing multidisciplinary teams to address these issues would be an important step toward maximizing their social and economic benefits.

would ensure that the institutes remain productive and continue to progress on both short- and long-term deliverables. The examples below suggest some areas of focus for institutes (see also Boxes 4 and 5):

- Institutes linking engineering with the physical sciences, social sciences, environmental sciences, and business programs to address the urgent national challenge of developing sustainable energy sources, including, for instance, the production, storage, distribution, and uses of hydrogen-based fuels for transportation.
- Institutes linking engineering with the creative arts (visual and performing arts, architecture, and design) and the cognitive sciences (psychology, neuroscience) to conduct research on the innovation process per se.
- Institutes linking engineering systems research with business schools, medical schools, schools of education, and the social and behavioral sciences to address issues associated with the knowledge-services sector of the economy.



BOX 5 BEYOND CMOS



Semiconductors represent a critical foundational technology for innovation in most industries and have helped the United States achieve unprecedented economic prosperity and defense superiority. Most semiconductor products are based on CMOS technology, which is likely to reach its fundamental limits–primarily for power dissipation and reliability–in about 15 years. Because there is typically a 15-year lag from research to production, the time to initiate the successor to CMOS is now. The successor technology will be in the broad area of nanoelectronics, but currently it is neither defined nor understood.

The Semiconductor Industry Association has proposed the concept of a nanoelectronics research initiative (NRI) to meet this urgent need. The objective of the NRI is: "By 2020 to discover and reduce to practice via technology transfer to industry novel non-CMOS devices, technology, and new manufacturing paradigms which will extend the historical cost/function reduction, along with increased performance and density for another several orders of magnitude beyond the limits of CMOS."

Like the discovery-innovation institutes initiative, the NRI is envisioned as a partnership of industry, government, and academia. The NRI would be primarily university-based, with federal funds leveraged by state and industry contributions. Industry assignees will effectively and swiftly move results from universities to companies.

Source: Apte and Matisoo, 2004.

- Institutes linking engineering with social sciences and professional schools to conduct research on communication networks to determine capacity, identify bottlenecks, estimate extendibility, and define performance characteristics of complex systems that comprise terrestrial, wired, wireless, and satellite subnets, as well as the legal, ethical, political, and social issues raised by the universal accessibility of information.
- Institutes linking engineering, business, and public policy programs with biomedical sciences programs to develop drugs, medical procedures, protocols, and policies to address the health care needs and complex societal choices for an aging population.

Funding

The committee recognizes that federal and state budgets are severely constrained and are likely to remain so for the foreseeable future. Nevertheless, with revised national R&D investment priorities and public understanding of the critical need for public investment in research to sustain national security and prosperity, the required sums could be made available. The level of investment and commitment would be analogous to the investments in the late nineteenth century that created and sustained the agricultural experiment stations, which endure to this day and have had incalculable benefits for agriculture and the nation as a whole. We expect similar results from discovery-innovation institutes.

On the federal level, the discovery-innovation institutes should be funded jointly by agencies with responsibilities for basic research and missions that address major national priorities (e.g., NSF, DOE, NASA, DOD, DHS, DOT, U.S. Department of Commerce, Envirnmental Protection Agency, and U.S. Department of Health and Human Services).

States would be required to contribute to the institutes (perhaps by providing capital facilities). Industry would provide challenging research problems, systems knowledge, and real-life market knowledge, as well as staff who would work with university faculty and students in the institutes. Industry would also fund student internships and provide direct financial support for facilities and equipment (or share its facilities and equipment). Universities would commit to providing a policy framework (e.g., transparent and efficient intellectual property policies, flexible faculty appointments, responsible financial management, etc.), educational opportunities (e.g., integrated curricula, multifaceted student interaction), knowledge and technology transfer (e.g., publications, industrial outreach), and additional investments (e.g., in physical facilities and cyberinfrastructure). Finally, the venture capital and investing community would contribute expertise in licensing, spin-off companies, and other avenues of commercialization.

CONCLUSION

Exciting opportunities in engineering lie ahead. Some involve rapidly emerging fields, such as information systems, bioengineering, and nanotechnology. Others involve critical national needs, such as sustainable energy sources and homeland security. Still others involve the restructuring of engineering education to ensure that engineering graduates have the skills, understanding, and imagination to design and manage complex systems. To take advantage of these opportunities, however, investment in engineering education and research must be a much higher priority.

"We are not graduating the volume [of scientists and engineers], we do not have a lock on the infrastructure, we do not have a lock on the new ideas, and we are either flat-lining, or in real dollars cutting back, our investments in physical science. The only crisis the U.S. thinks it is in today is the war on terrorism. It's not!" Craig Barrett, CEO of Intel and current chairman of the National Academy of Engineering (Friedman, 2004).

The United States has the proven ability and resources to take the global lead in innovation. Scientists and engineers can meet the technological challenges of the twenty-first century, just as they responded to the challenges of World War II by creating the tools for military victory and just as they mounted an effective response to the challenge of Sputnik and Soviet advances in space. With adequate federal investment and the participation of other stakeholders in engineering research, education, and professional practice, we can realize this vision.

The country is at a crossroads. We can either continue on our current course—living on incremental improvements to past technical developments and gradually conceding technological leadership to trading partners abroad—or we can take control of our destiny and conduct the necessary research, capture the intellectual property, commercialize and manufacture the products, and create the high-skill, high-value jobs that define a prosperous nation.

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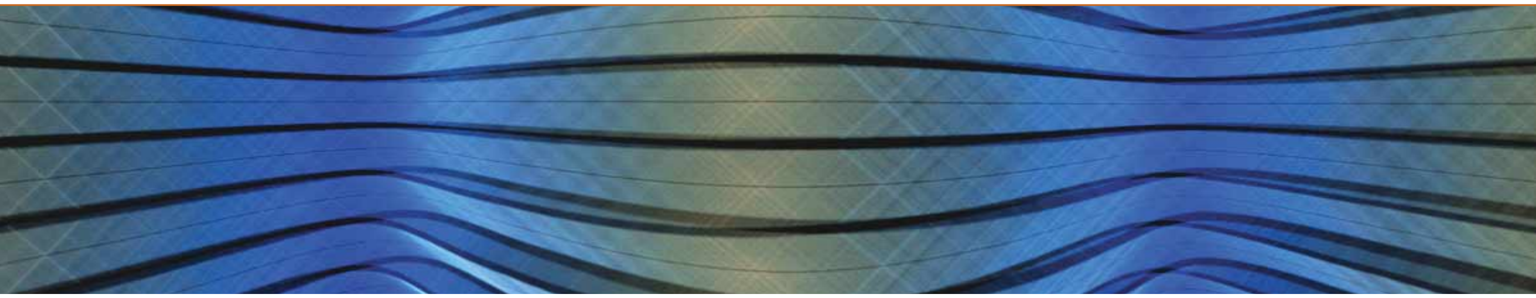


Vital Assets: Federal Investment in Research and Development at the Nation's Universities and Colleges. RAND. 2004.

Between fiscal year (FY) 1996 and FY 2002, total federal research and development (R&D) funds going to universities and colleges increased from $12.8 billion to $21.4 billion, an overall increase of 45.7 percent in constant 1996 dollars. The increase was more than twice the overall increase in total federal R&D funds of 20.9 percent. In FY 2002, 45 percent of all federal R&D funds provided to universities and colleges by the U.S. Department of Health and Human Services and all other federal agencies went directly to medical schools. The Medical School at Johns Hopkins University alone received more in R&D funding than all but nine universities and colleges in the nation.

The profile of federally funded R&D at universities and colleges that emerges from this analysis raises questions about the proportionality of funding. In the current funding profile, approximately two-thirds of the federal funds going to universities and colleges for R&D is focused on one field of science—life science—and is concentrated at a few research universities. These findings raise questions about whether other critical national needs that have substantial R&D components (e.g., the environment, energy, homeland security, and education) are receiving the investment they require and whether the concentration of dollars at a few institutions is shortchanging science students at institutions that receive little or no federal R&D funding.

Critical Choices: Science, Energy, and Security. Final Report of the Secretary of Energy Advisory Board Task Force on the Future of Science Programs at the Department of Energy. October 2003.

In the last 30 years, the federal investment in research in the physical sciences and engineering has been nearly stagnant, having increased less than 25 percent in constant dollars. The corresponding investment in life science research has increased more than 300 percent. In 1970, research in physical sciences, engineering, and life sciences was funded at a total annual level of approximately $5 billion in 2002 dollars. Today, physical science and engineering research are funded at approximately $5 billion and $7.5 billion, respectively. The current funding for life sciences is about $22 billion.

During this same period, the U.S. Department of Energy (DOE) national laboratories have suffered from decay and deferred maintenance, and U.S. industry has largely phased out its basic physical sciences, mathematics, and engineering research programs and organizations. As a result, the United States is no longer the clear leader in some important areas of science.

The report recommends that DOE embark on three major, highly visible research initiatives to fulfill its mission of leadership in energy, security, and science. The first initiative should directly address a basic issue in energy production, storage, distribution, or conservation. The second should establish world leadership in the application of advanced computation and simulation to basic scientific problems. And the third should provide a pioneering research facility for the pursuit of basic science.

Assessing the U.S. R&D Investment. Prepared by the Panel on Federal Investment in Science and Technology and Its National Benefits, President's Council of Advisors on Science and Technology. October 2002.

FUNDING FOR RESEARCH AND DEVELOPMENT. There have been considerable shifts in the sources of funding for U.S. R&D. In FY 2000, private sector R&D accounted for 67 percent of the total, and federal funding accounted for a mere 30 percent. In 1976, the split was about 50/50, and prior to 1975, the share of federal funding was larger than the industry share. With the predominance of industry R&D, basic and applied research as a percentage of total R&D will most likely drop. If there is not enough investment in basic and applied research, no significant advances in new products, services, defense, or health will be made, and we can expect that 25 years from now the United States will be an importer, rather than an exporter, of most goods and services.

Another major change has taken place in the disciplinary areas funded over the last 25 years. In FY 1970, support for the three major areas of research (physical and environmental sciences, life sciences, and engineering) was about equal. Today, the life sciences receive 48 percent of federal R&D funding compared to 11 percent for the physical sciences and 15 percent for engineering. The lack of funding in the latter two disciplines raises a number of concerns:

- The number of full-time graduate students and Ph.D. students in most physical sciences, mathematics, and engineering disciplines is decreasing; the number in the life sciences is increasing.
- Facilities and infrastructure in general for the physical sciences are less than adequate for the needs of today's researchers.
- Interdependencies among disciplines require that research in all disciplines advance together.

HUMAN RESOURCES. The number of full-time graduate students in most fields of science and engineering has either declined or remained stagnant (based on 1998 data). Nearly half of the students earning doctorates in science and engineering fields and nearly 35 percent of those earning master's degrees in the United States are foreign born.

Compared to other countries, the United States is at the low end in terms of the number of 24-year-olds attracted to the natural sciences and engineering; in 1975, the United States was at the high end. These statistics are for four-year degrees and higher degrees, but similar problems exist at the technical/community college level.

KEY RECOMMENDATIONS. 1. Beginning with FY 2004, the R&D budget should be adjusted upward for the physical sciences and engineering to bring them collectively to parity with the life sciences over the next four budget cycles. **2.** A major program of fellowships should be established to attract U.S. citizens to science and engineering fields that support critical national needs.

Sustaining the Nation's Innovation Ecosystems, Information Technology Manufacturing and Competitiveness. Prepared by the Subcommittee on Information Technology Manufacturing and Competitiveness, President's Council of Advisors on Science and Technology. January 2004.

The world is on the brink of a new industrial world order. Those who simply make commodities faster and cheaper than the competition will not be the big winners in the increasingly fierce global scramble for supremacy. The winners will be those who develop talent, techniques, and tools so advanced that they have no competition. This will mean securing unquestioned superiority in nanotechnology, biotechnology, and information science and engineering. And it will require upgrading and protecting investments that have given us our present national stature and unsurpassed standard of living.

U.S. leadership in technology and innovation depends on dynamic innovation ecosystems, built on strong investment in basic R&D, skilled scientists and engineers, a flexible, skilled workforce, reliable infrastructure, and a supportive regulatory and legal environment. The United States will need increased federal funding for basic research in nanotechnology, information technology, and manufacturing R&D and improvements in science and technology education and related workforce skills to maximize its advantages.

High-Technology Manufacturing and U.S. Competitiveness. RAND. March 2004.

From 1977 to 2001, U.S. manufacturing output nearly doubled when measured in constant 1996 dollars. In the same period, real output per manufacturing worker more than doubled to more than $86,000. This large increase in productivity is the reason for decreases in manufacturing employment. U.S. manufacturing activities that have remained in the United States tend to be the most advanced, complex kinds of manufacturing, typically requiring close coordination with engineering or design staff. But routine manufacturing, in which every efficiency must be pursued, tends to locate overseas.

Research universities, national laboratories, and technology industries depend on R&D funding for the development of emerging technologies and cutting-edge innovation. In 1970, federal R&D funding was slightly more than 1 percent of gross domestic product (GDP). By 2000, federal funding had fallen to about 0.25 percent of GDP.

Pasteur's Quadrant. Donald. E. Stokes. Brookings Institution. 1997.

Stokes argues persuasively that the post-WWII linear paradigm of research, from basic to applied research, has scientific, political, and social shortcomings. He documents how adherence to this paradigm influenced patterns of federal sponsorship for research after the war, including the emergence of the National Science Foundation (NSF) and the distribution of federal research funds to mission agencies, NSF, and the National Institutes of Health. For instance, the U.S. Department of Defense definitions of research (e.g., 6.1, 6.2, etc.) are based directly on the linear model.

As an alternative to the linear model, Stokes proposes a planar model with four quadrants:

		CONSIDERATION OF USE?	
		YES	NO
QUEST FOR FUNDAMENTAL UNDERSTANDING?	YES	Pure basic research (Bohr)	Use-inspired basic research (Pasteur)
	NO	Wissenschaft	Pure applied research (Edison)

Stokes argues that a national debate should be opened to discuss the limitations of the linear model and develop agendas for the future based on use-inspired basic science that bears on the nation's needs. This research should be funded by agencies throughout the government.

Revolutionizing Science and Engineering Through Cyberinfrastructure. NSF Blue Ribbon Advisory Panel on Cyberinfrastructure. January 2003.

A new age has dawned in scientific and engineering research, pushed forward by continuing progress in computing, information, and communication technology and pulled ahead by the increasing complexity, scope, and scale of today's challenges. The panel recommends that the National Science Foundation establish and lead a large-scale, interagency, and internationally coordinated advanced cyberinfrastructure program to create, deploy, and apply cyberinfrastructure in ways that radically empower all scientific and engineering research and related fields of education. Sustained funding of $1 billion per year will be necessary to achieve critical mass and leverage co-investments from other federal agencies, universities, industry, and international sources.

Invention: Enhancing Inventiveness for Quality of Life, Competitiveness, and Sustainability. Committee for the Study of Invention, Lemelson-MIT Program and the National Science Foundation. April 2004.

To meet the challenges and take advantage of our recent opportunities, it is important that we leverage human ingenuity. The United States has an enviable record of scientific discovery and engineering invention but has not been as good at anticipating the long-term effects and larger implications of new technologies. Economic forces, including government support for research and development, play a decisive role in the direction of inventiveness. Federal support for large systems projects has stimulated inventiveness; support for individual investigators doing basic research has expanded discovery-type knowledge but has been less effective in stimulating invention.

Engineering schools should examine their tenure and promotion policies to determine how they can put greater emphasis on invention and the teaching of inventiveness. They should also support research projects and external collaborations, and maintain policies, that promote creativity among students and faculty.

The Future of University Nuclear Engineering Programs and University Research and Training Reactors. Department of Energy Office of Nuclear Energy, Science and Technology. May 2000.

The U.S. nuclear science and engineering educational structure has not only stagnated, but has actually declined significantly. The number of independent nuclear engineering programs and the number of operating university nuclear reactors have both fallen by about half since the mid-1980s. The survival of nuclear engineering as a discipline is becoming problematic, as falling enrollments result in fewer programs, which in turn result in further declines in enrollment. Nevertheless, the demand for nuclear-trained personnel is on the rise.

Preparing for the 21st Century: Science and Engineering Research in a Changing World. National Research Council. 1997.

This report aggregates the findings and recommendations of National Research Council reports from the early and mid-1990s. A primary recommendation is that the federal government establish a new budget category, federal science and technology to enable individual agencies to consider their science and technology budgets properly.

New Perspectives on Economic Growth and Technological Innovation. F.M. Scherer. Brookings Institution. 1999.

Economic studies have shown that increases in productivity are significantly correlated with the level of spending on R&D. Technological progress in industry requires concerted, profit-oriented activity that yields (1) products that can be patented and produced and (2) knowledge, which tends to spill over into the general pool of knowledge. As knowledge increases, R&D becomes more productive, creating more knowledge, more new products, and more economic growth. The cycle is dependent on sufficient human capital, which is the most important component in advancing science and technology.

After World War II, the United States allocated more of its human capital to R&D than any other country in the world. But growth slowed in the 1980s, and a decline began in the early 1990s, when Japan led the world with 41 scientists and engineers per 10,000 people. The United States was second with 38, followed by Norway with 32, West Germany with 28, and Singapore with 23. In 1993, China had 3, and India had 1. Reasons for the decline in U.S. science and engineering graduates include a lack of academic openings, low earnings relative to other professions, and the poor quality of math and science education, which limits interest and ability in science and engineering studies.

COMMITTEE BIOGRAPHIES

JAMES J. DUDERSTADT (NAE), chair, is President Emeritus and University Professor of Science and Engineering at the University of Michigan. He received his baccalaureate degree in electrical engineering with highest honors from Yale University and his doctorate in engineering science and physics from the California Institute of Technology. His teaching and research interests include nuclear fission reactors, thermonuclear fusion, high-powered lasers, computer simulation, science policy, information technology, and higher education. Dr. Duderstadt has been awarded the E.O. Lawrence Award for excellence in nuclear research, the Arthur Holly Compton Prize for outstanding teaching, and the National Medal of Technology for exemplary service to the nation. Dr. Duderstadt has served on and/or chaired numerous public and private boards, including the National Science Board; the Executive Council of the National Academy of Engineering; the Commission on Science, Engineering and Public Policy of the National Academy of Sciences; the Big Ten Athletic Conference; the University of Michigan Hospitals; Unisys; and CMS Energy. He has also been elected to numerous honorific societies, including the National Academy of Engineering, the American Academy of Arts and Sciences, Phi Beta Kappa, and Tau Beta Pi.

ERICH BLOCH (NAE), currently a consultant and Distinguished Fellow with the Council on Competitiveness, was director of the National Science Foundation from 1984 to 1990. He received his B.S. in electrical engineering from the University of Buffalo in 1952 and has been awarded honorary degrees from the University of Massachusetts, George Washington University, Colorado School of Mines, SUNY Buffalo, University of Rochester, Oberlin College, University of Notre Dame, Ohio State University, Rensselaer Polytechnic Institute, Washington College, and City University of New York. Mr. Bloch's extensive work history with IBM Corporation culminated in his appointment as vice president of technical personnel development (1980–1984). From 1980 to 1984, he was also a member of the National Research Council Committee on Commercial Computers in Automated Manufacturing. He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and recipient of the IEEE Founder's Award (1990), a member of the American Association for the Advancement of Science, and an honorary member of the American Society of Manufacturing Engineers. He was elected to the National Academy of Engineering in 1980.

RAY M. BOWEN is President Emeritus and professor in the Department of Mechanical Engineering, Texas A&M University. Dr. Bowen earned his B.S. in mechanical engineering from Texas A&M University, his M.S. from the California Institute of Technology, and his Ph.D. in mechanical engineering from Texas A&M University. His research interests are focused on nonlinear continuum mechanics, especially the theory of mixtures. From 1994 to 2002, Dr. Bowen was president of Texas A&M. During Dr. Bowen's tenure, the university was admitted to the Association of American Universities, numerous academic programs were expanded and enhanced, and a major capital campaign was completed successfully. Before assuming the presidency of Texas A&M, Dr. Bowen held appointments at Oklahoma State University, University of Kentucky, Rice University, and Louisiana State University. He has held two managerial positions at the National Science Foundation, is a member of several professional societies, and has authored or coauthored numerous professional articles and books. Dr. Bowen was appointed to the National Science Board in 2002.

BARRY HOROWITZ (NAE) is professor of systems engineering at the University of Virginia. Prior to joining the faculty there, he was chairman and founder of Concept Five Technologies, an e-business solutions provider specializing in applying enterprise application integration and security technologies to business-to-business systems. He was also president and CEO of MITRE Corporation and president and CEO of Mitretek Systems. Dr. Horowitz was awarded the highest civilian award of the U.S. Air Force for his contributions to the Gulf War related to locating, tracking, and destroying SCUD missiles. He holds a B.S.E.E. from City College of New York and an M.S.E.E. and Ph.D. in electrical engineering from New York University.

LEE L. HUNTSMAN is President Emeritus of the University of Washington (UW). Prior to his term as president, he was UW provost and vice president for academic affairs and associate dean for scientific affairs in the School of Medicine. Dr. Huntsman joined the UW faculty in 1968 as a professor of bioengineering. His research, which has received continuous funding from the National Institutes of Health (NIH), is on the application of engineering principles to biology and medicine, particularly in the measurement and regulation of the cardiovascular system. Dr. Huntsman received a B.S. in electrical engineering from Stanford University in 1963 and a Ph.D. in biomedical engineering from the University of Pennsylvania in 1968. He is a fellow of the American Association for the Advancement of Science and the American Institute of Medical and Biological Engineering and has served on the Board of Directors of the Biomedical Engineering Society and the Whitaker Foundation Governing Committee. In 1998, Dr. Huntsman chaired the NIH Working Group on Review of Bioengineering and Technology and the Instrumentation Development Research Group for the Center for Scientific Review.

JAMES H. JOHNSON JR. is a professor of civil engineering and dean of the College of Engineering, Architecture and Computer Sciences at Howard University. Dr. Johnson received his B.S. from Howard University, M.S. from the University of Illinois, and Ph.D. from the University of Delaware. His research interests include the treatment and disposal of hazardous substances, the evaluation of environmental policy issues in relation to minorities, and the development of environmental curricula and strategies to increase the number of underrepresented groups in science, technology, engineering, and math disciplines.

Dr. Johnson is chair of the Board of Scientific Counselors Executive Committee of the U.S. Environmental Protection Agency (EPA), a member of EPA's Science Advisory Board, and co-principal investigator of the U.S. Department of Energy (DOE)-sponsored HBCU/MI Environmental Technology Consortium. He is also a member of the Environmental, Health and Safety Panel, which monitors activities at the three DOE national laboratories operated by the University of California. Dr. Johnson is a member of the National Research Council (NRC) Board on Environmental Studies and Toxicology and the Engineering Deans Council of the American Society for Engineering Education and a member of several university and private-sector advisory committees. He has published more than 50 scholarly articles, contributed to three books, and co-edited two books. A fellow of the American Society of Civil Engineers and a member of the American Association of Environmental Engineering and Science Professors, American Water Works Association, American Society for Engineering Education, and Tau Beta Pi, Dr. Johnson is also a registered professional engineer in the District of Columbia and a diplomate of the American Academy of Environmental Engineers. In 2005, he was awarded the National Society of Black Engineers Lifetime Achievement Award in Academia.

KRISTINA M. JOHNSON is dean of engineering and professor of electrical and computer engineering at Duke University. Before joining the faculty at Duke, Dr. Johnson was a professor of electrical and computer engineering at the University of Colorado and cofounder and director of the National Science Foundation Engineering Research Center for Optoelectronic Computing Systems. Dr. Johnson received her B.S. (with distinction), M.S., and Ph.D. in electrical engineering from Stanford University. Her areas of expertise include liquid crystal electro-optics and liquid crystal-on-silicon microdisplays. She has 44 patents or patents pending.

Dr. Johnson has been recognized as a National Science Foundation Presidential Young Investigator (1985), IBM Faculty Fellow (1985), Fulbright Fellow (1991), Optical Society of America Fellow (1995), and IEEE Fellow (2002). She is a recipient of the Dennis Gabor Prize for Creativity and Innovation in Modern Optics (1993), the Photonics Spectra Circle of Excellence Award (1994), and the State of Colorado Technology Transfer Award (1987). In 2003, she became a member of the Women in Technology International Hall of Fame (2003). Dr. Johnson is a founder of four companies and a member of the boards of directors of Mineral Technologies Inc., Dycom Industries; the advisory boards of Smith College Pickering, Carnegie Mellon University School of Engineering, Colorado School of Mines, and the National Science Foundation Advisory Committee to the Engineering Directorate. She is also a member of the Fulbright Association, Sigma Xi, Lasers and Electro-optic Society, Society of Photo-Instrumentation Engineers, Society for Information Display, Tau Beta Pi, IEEE, and American Society of Engineering Education.

LINDA P.B. KATEHI is John A. Edwardson Dean of Engineering and professor of electrical and computer engineering at Purdue University. Before joining Purdue, she was associate dean for academic affairs in the College of Engineering and professor of electrical engineering and computer science at the University of Michigan. Dr. Katehi has a master's degree and doctorate in electrical engineering from the University of California at Los Angeles and a bachelor's degree in electrical engineering from the National Technical University of Athens. Her areas of expertise include the development and characterization of microwave, millimeter-printed circuits; the computer-aided design of VLSI interconnects; the development and characterization of micromachined circuits for microwave, millimeter-wave, and submillimeter-wave applications, including microelectromechanical (MEMS) switches, high-Q evanescent mode filters, and MEMS devices for circuit reconfigurability; and the development of low-loss lines for submillimeter-wave and terahertz-frequency applications. She has five patents.

Dr. Katehi has received many honors, including the Distinguished Educator Award of the IEEE Microwave Theory and Techniques Society (2002), IEEE Marconi Prize (2001), the Third Millennium Medal of the IEEE Microwave Theory and Techniques Society (2000), the Microwave Prize of the IEEE Microwave Theory and Techniques Society (1997), Fellow, IEEE (1995), Humboldt Research Award (1994), the Presidential Young Investigator Award of the National Science Foundation (1987), the Schelkunoff Award of the IEEE Antennas and Propagation Society (1985), and the W.R. King Award of the IEEE Antennas and Propagation Society (1984).

DAVID MOWERY is William A. and Betty H. Hasler Professor of New Enterprise Development at the Walter A. Haas School of Business at the University of California, Berkeley, and a research associate of the National Bureau of Economic Research. During the 2003–2004 academic year, he was Marvin Bower Fellow at the Harvard Business School. He received his undergraduate degree and Ph.D. in economics from Stanford University and was a postdoctoral fellow at the Harvard Business School. Dr. Mowery taught at Carnegie Mellon University, was study director for the Panel on Technology and Employment of the National Academy of Sciences, served in the Office of the United States Trade Representative, and has been a member of several National Research Council panels. His research interests include the economics of technological innovation and the effects of public policies on innovation. He has testified before Congress and served as an adviser to the Organization for Economic Cooperation and Development, various federal agencies, and industrial firms.

Dr. Mowery has published numerous academic papers and has written or edited many books. His academic awards include the Raymond Vernon Prize from the Association for Public Policy Analysis and Management, the Economic History Association Fritz Redlich Prize, the Business History Review Newcomen Prize, and the Cheit Outstanding Teaching Award.

CHERRY MURRAY (NAE, NAS) is deputy director for science and technology at Lawrence Livermore National Laboratory. Prior to this appointment, she was physical sciences research senior vice president, Bell Laboratories, Lucent Technologies. Dr. Murray has been recognized for her work in surface physics, light scattering, and complex fluids; she is best known for her work on imaging in phase transitions of colloidal systems. After receiving a B.S. and Ph.D. in physics from the Massachusetts Institute of Technology, she joined Bell Laboratories as a member of the technical staff in 1978. She has numerous publications and two patents to her credit. She is currently chair of the New Jersey Nanotechnology Consortium, a wholly owned subsidiary of Lucent managed by Bell Laboratories to promote research in nanotechnology as part of the economic development of New Jersey.

Dr. Murray is a member of the National Academy of Engineering, National Academy of Sciences, and American Academy of Art and Sciences. She is a fellow of the American Physical Society (APS) and the American Association for the Advancement of Science and a member of numerous advisory committees and boards. Currently, she is a general councilor of APS and a member of the Executive Board of the National Academy of Sciences, Governing Board of the National Research Council, and University of Chicago Board of Governors for Argonne National Laboratory.

MALCOLM R. O'NEILL is vice president and chief technical officer of Lockheed Martin Corporation. He joined the company in 1996 as vice president, Mission Success, Operation, and Best Practices in Space Systems, after retiring from the U.S. Army. During his military career, he held numerous prominent positions, including director, Ballistic Missile Defense Organization; deputy director, Strategic Defense Initiative Organization; director, Army Acquisition Corps; commander, Army Laboratory Command; and deputy for program assessment and international cooperation, Office of the Assistant Secretary of the Army (Research, Development and Acquisition). He also directed numerous research, development, engineering, and manufacturing operations. Dr. O'Neill earned a B.S. in physics from De Paul University and an M.A. and Ph.D. in physics from Rice University.

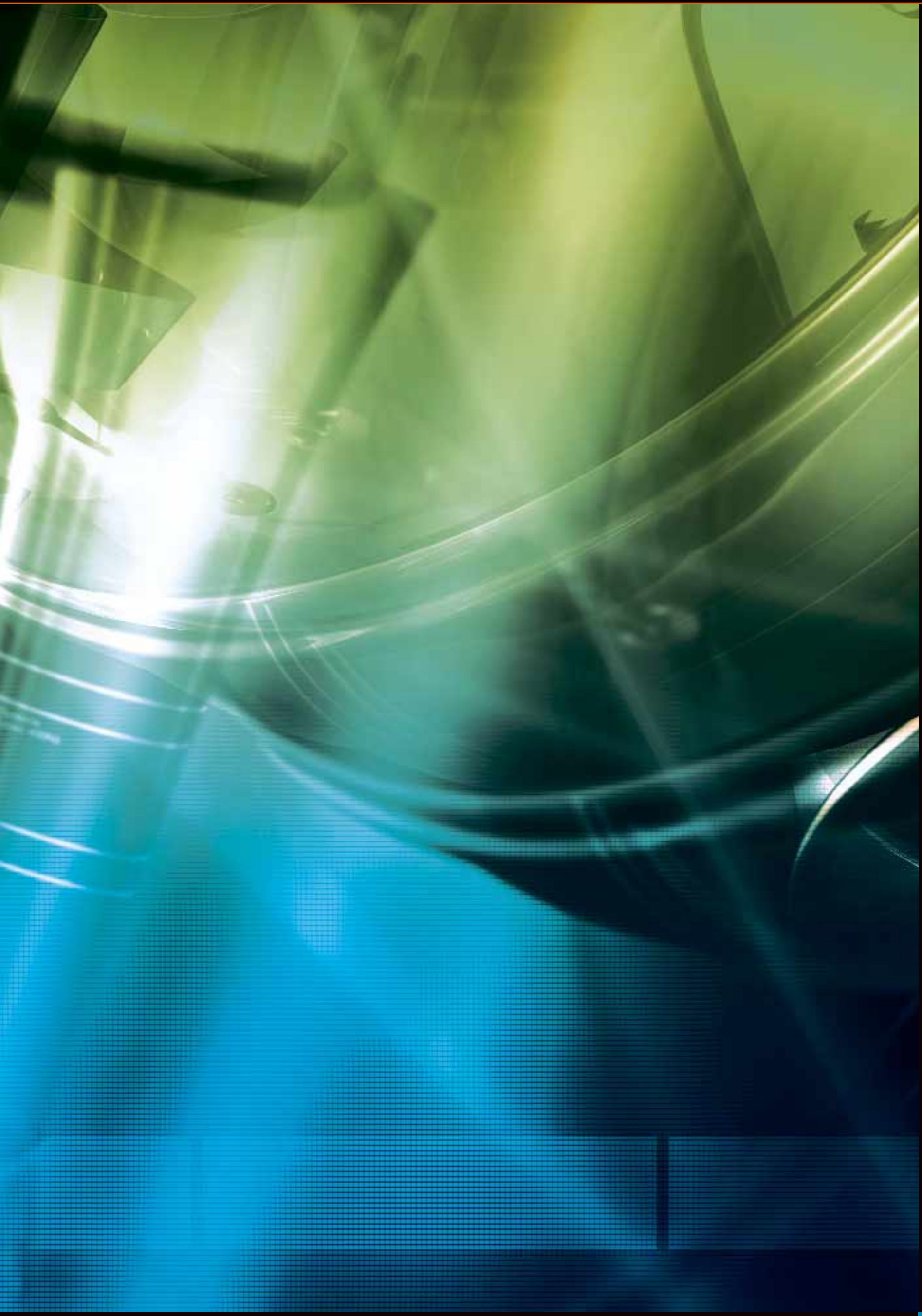
GEORGE SCALISE is president of the Semiconductor Industry Association (SIA), the trade association that represents the microchip industry. During a 30-year career in the industry before joining SIA in 1997, Mr. Scalise was executive vice president of operations and chief administrative officer at Apple Computer and held numerous executive positions at National Semiconductor Corporation, Maxtor Corporation, Advanced Micro Devices, Fairchild Semiconductor, and Motorola Semiconductor. He was chairman of SIA's Public Policy Committee, a founder, member, and chairman of the board of the Semiconductor Research Corporation, and a member of the Board of Directors of SEMATECH. Mr. Scalise is active on many boards and advisory committees, including the Board of Directors of the Federal Reserve Bank of San Francisco, Twelfth Federal Reserve District; Cadence Design Systems; Network Equipment Technologies; and the Foreign Policy Association. In addition, he has served on a number of university and government boards. He earned a B.S. in mechanical engineering from Purdue University.

ERNEST T. SMERDON (NAE) is Dean Emeritus of the University of Arizona. Prior to this, he was vice provost and dean of the College of Engineering, Janet S. Cockrell Centennial Chair in the Civil Engineering Department, Bess Harris Jones Centennial Professor in Natural Resource Policy Studies in the LBJ School of Public Affairs at the University of Texas at Austin, and vice chancellor for academic affairs for the University of Texas System. Dr. Smerdon was elected to the National Academy of Engineering (NAE) in 1986 and has served on seven NAE committees, including the Committee on Career-Long Education for Engineers, Academic Advisory Board, and Committee on the Technology Policy Options in a Global Economy.

Dr. Smerdon has served on 11 National Research Council committees and chaired two. He was a board member of ABET and represented the board on the Engineering Accreditation Commission. Dr. Smerdon received awards from the American Society of Civil Engineers, American Society of Agricultural Engineers, American Water Resources Association, and American Society for Engineering Education. In 1982, he received the Honor Award for Distinguished Service in Engineering and, in 2003, the degree, Doctor of Science, honoris causa, from the University of Missouri-Columbia, his alma mater. Dr. Smerdon has written widely on engineering education and spoken on the subject in 12 countries outside the United States.

ROBERT F. SPROULL (NAE), vice president and fellow at Sun Microsystems Laboratories, founded and led the Massachusetts branch of Sun Microsystems Laboratories for more than 10 years, and he is still involved in research there. Since his undergraduate days, he has been building hardware and software for computer graphics: clipping hardware, an early device-independent graphics package, page description languages, laser printing hardware and software, and window systems. He has also been involved in VLSI design, especially of asynchronous circuits and systems. Before joining Sun, he was a principal with Sutherland, Sproull & Associates, an associate professor at Carnegie Mellon University, and a member of the Xerox Palo Alto Research Center. He is coauthor with William Newman of *Principles of Interactive Computer Graphics* and an author of the recently published *Logical Effort*, which deals with designing fast CMOS circuits. Dr. Sproull is a member of the National Academy of Engineering, a fellow of the American Academy of Arts and Sciences, and has served on the U.S. Air Force Scientific Advisory Board. He is currently a special partner of Advanced Technology Ventures.

DAVID N. WORMLEY is dean of the College of Engineering at Pennsylvania State University. His previous positions include associate dean of engineering and head of the Department of Mechanical Engineering at Massachusetts Institute of Technology (MIT). Dr. Wormley's research is focused on the dynamic analysis, optimization, and design of advanced control systems, transportation systems, and fossil-fuel energy systems. He is a fellow of the American Society of Mechanical Engineers (ASME) and American Society for Engineering Education. Dr. Wormley is a former member of the Executive Committee of the National Research Council Transportation Research Board, which he chaired in 1997. He has received the ASME Lewis Moody Award and the NASA Certificate of Recognition. Dr. Wormley earned his B.S., M.S., and Ph.D. in mechanical engineering from MIT.



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