

The Science and Engineering Workforce and National Security

by Michael L. Marshall, Timothy Coffey, Fred E. Saalfeld, and Rita R. Colwell

Overview

Trends in the American science and engineering (S&E) workforce and national research and development (R&D) funding patterns and priorities have troubling implications for the economic and national security of our nation. Especially worrisome are:

- A general lack of interest among American-born youth, especially women and minorities, in pursuing education in the physical sciences, mathematics, environmental sciences, and engineering at the undergraduate and graduate levels;
- A rapidly accelerating accumulation of intellectual capital, including an educated S&E workforce, in China, India, Japan, South Korea, and Taiwan;
- A long-term decline in the overall Federal investment in R&D as a percentage of gross domestic product, especially among the physical sciences and engineering; and
- Reduced Department of Defense funding for research throughout the 1990s, a trend that has exacerbated the general decline in the physical sciences and engineering, despite the importance of these fields to the development of new military capabilities.

There is no crisis today. Indeed, in several areas, such as computer science, the number of computer programmers exceeds

demand, a situation largely caused by the collapse of the dot.com bubble, softness in the overall economy in recent years, and a trend toward off-shore outsourcing of such work. The basic problem that we face lies in understanding the trends and their implications for the future. It is important to gain this understanding soon because of the long delays involved in building a workforce with the required skills to replace the scientists and engineers of the baby-boom generation, who are retiring just as the needs of national defense and homeland security are increasing.

In some important fields, the United States faces a potential S&E shortfall, while our foreign competitors are significantly increasing production of S&Es, and foreign graduate students are earning a significant percentage of the technical degrees granted by American universities.¹ (table 1.) Especially noteworthy is increasing home-grown technical capability in Asia, which is exemplified by the rapid growth in the number of students receiving S&E doctorates from Asian institutions. Moreover, the fact that other nations are acquiring high-end innovation capabilities by building up their sophisticated science and technology (S&T) infrastructures and capabilities signifies growing global competition for scientific and engineering talent. This trend raises a question whether the United States can over the long term rely on an international S&E labor force to satisfy its needs.²

Table 1. Foreign Graduate Student Enrollment in the United States by S&E field

	Total S&E	Natural Sciences, Including Physical Sciences	Mathematics and Computer Sciences	Social and Behavioral Sciences	Engineering
All Students	411,308	114,127	58,814	136,899	101,468
Foreign Students	109,904	27,442	23,077	17,968	41,417
Percent Foreign	26.7	24.0	39.2	13.1	40.8

Source: National Science Board, *Indicators 2002*, Appendix Table 2-38

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Table 2. Publication of Physics Articles (in thousands) 1988–2001

	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
U.S.	18.0	19.0	19.1	20.5	20.1	19.6	20.4	19.7	18.9	18.0	17.9	18.0	16.8	17.3
World	62.2	66.2	67.3	69.6	76.2	73.3	80.8	82.1	84.0	82.8	85.0	87.3	84.3	86.7
U.S. Share (%)	29.0	28.8	28.5	29.5	26.5	26.7	25.3	24.0	22.5	21.8	21.1	20.7	20.0	20.0

Source: Institute for Scientific Information

Table 3. Citation of Physics Articles 1982–2001

	1992	1996	2001
World citation of U.S. physics literature	137,922	138,417	120,493
World citation of physics literature	312,889	363,230	390,296
U.S. Share (%)	44	38	30
Average number of citations of U.S. physics articles (published 2 years earlier)	7	7	7

Source: Institute for Scientific Information

National research and development (R&D) funding patterns and priorities, particularly the declining DOD investment in the physical sciences and engineering, raise especially important national security issues. These reductions have exacerbated the general decline in the physical and mathematical sciences and engineering, even as defense remains heavily dependent on the application of these fields.

Cross-disciplinary sciences and enabling technologies are growing. Yet, they too are affected by declining funding for the physical sciences and engineering that underpin them. As just one indicator, the U.S. fraction of the world's physics publications is declining.³ More specifically, data compiled by the Institute for Scientific Information (ISI) suggest both a small absolute decline in U.S. physics articles and a noticeable decline in the U.S. world share of physics papers. (Table 2.) The citation impact of U.S. physics papers has remained relatively constant, despite the decline in world share. (Table 3.) There is some concern about how long the relatively high

impact of U.S. publications can continue given the buildup of the foreign science and engineering (S&E) communities overseas. Furthermore, it is known that the Federal research investment is strongly linked to the U.S. patent portfolio.⁴ As other nations catch up, these trends suggest that it will be more difficult for the United States to remain dominant in science and technology (S&T), which raises serious questions about our long-term economic and military dominance in S&T. Failure to address these issues will challenge America's leadership in S&T and undermine future economic strength, social stability, and national security.

Competitiveness and National Security

America has long enjoyed a level of prosperity rivaled by few other countries in the world. This prosperity is linked closely to American innovation—the ability to create new goods and services in response to changing needs and the emergence of new technologies. Indeed, over the last few years, Americans have enjoyed and benefited from a lifestyle made possible by a flood of new products largely enabled by technological innovation in the electronics, materials, information, and health fields.

Sustaining this innovation requires an understanding of the factors that contribute to it. The Council on Competitiveness, a consortium of industry, university, and labor leaders, has developed quantitative measures of national competitiveness that use the following factors: the number of R&D personnel in the available workforce; total R&D investment; the percentage of R&D funded by private industry; the percentage of R&D performed by the university sector; spending on higher education; the strength of intellectual property protection, openness to international competition; and per capita gross domestic product.⁵ The World Bank Group has developed a similar set of indicators of competitiveness,⁶ and the National Science Foundation (NSF) has compiled voluminous data on the subject.⁷ The important point underscored by these indicators is

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that, for America to remain a prosperous and secure country, it absolutely must maintain its technological leadership in the world.

The issue of whether we have enough or the right kinds of S&Es to maintain our current technological leadership is not without controversy. Some, using classic supply and demand models, suggest current market conditions do not support the view that there is a shortage.⁸ Others argue the data “paint a much more nuanced picture of the emerging U.S. scientific workforce,” and that “some of the numbers and trends about enrollments and degrees are at odds with the conventional wisdom, whereas others show a cyclical pattern with both slumps and spurts.”⁹ It is clear that the conclusions reached depend upon the question asked. DOD is dependent on the physical sciences and engineering, where the data show declines in both funding and production of S&Es. These particular trends are masked when one focuses on the aggregate funding of science but, nevertheless, should be of serious concern to DOD. Indeed, the U.S. Commission on National Security for the 21st century—better known as the Hart-Rudman Commission, after its co-chairs, former Senators Gary Hart and Warren Rudman—drew the link between U.S. national security and the need for a strong national effort in S&T, underpinned by a well-educated S&E workforce and stated in stark terms:

The harsh fact is that the U.S. need for the highest quality human capital in science, mathematics, and engineering is not being met . . . This [situation] is not merely of national pride or international image. It is an issue of the utmost importance to national security. In a knowledge-based future, only an America that remains at the cutting edge of S&T will sustain its current world leadership . . . Complacency with our current achievement of national wealth and international power will put all of this at risk.¹⁰

The events of September 11, 2001, and the continuing aftermath dramatically underline the need for a powerful national S&T effort, an imperative reflected by the recent establishment of a Department of Homeland Security with a directorate for S&T.¹¹ Without doubt, America’s economic progress depends on a continuing supply of S&Es engaged in and funded across the spectrum, from long-term basic research to product development and product improvement. Without an adequate domestic S&E workforce, U.S. industry will move R&D and production facilities to countries willing and eager to provide it, with an inevitable loss of jobs in the United States and a declining ability to compete in the world marketplace. Economic forces will be ruthless in this regard. There will be no generosity of spirit in this fierce competition.

DOD has staked continuing American military dominance on technological superiority rather than on maintaining large numbers of people in the uniformed services capable of overwhelming future adversaries, a strategy that is working well for now. What is missing,

however, is a clearly stated recognition that our current military dominance derives from S&T investments made in the 1950s through the 1970s by DOD and other Federal agencies, such as NSF, the Department of Energy (DOE), and the National Aeronautics and Space Administration (NASA). For example, work on atomic clocks enabled the development of the Global Positioning System, while research in the chemistry of explosives allowed development of the thermobaric bomb used recently in Afghanistan. Moreover, defense capability that is just now entering service is based upon the S&T investments of the 1980s and 1990s. There is some concern, however,

that “the focus of the current DOD S&T program is primarily on incremental improvements in current capabilities . . . and does not place sufficient emphasis on innovative technology initiatives leading to entirely new military capabilities.”¹² Robert Frosch, a former Assistant Secretary of the Navy for R&D and NASA administrator, has described the current situation as akin to a farmer who wishes only to harvest and not to sow.¹³ In the long-term, this situation is

simply untenable. As other countries build their indigenous S&E workforces and accompanying S&T infrastructure, if we do not build our own, the balance inevitably will shift, thereby eroding or ending our military advantage.

The Dwindling Pool of American S&Es

As the Council on Competitiveness has noted: “a well-educated and technically-trained workforce is essential to a nation’s competitiveness in two ways. First, it enables a country to shift more of its economic activity into higher technology and more productive activities that support higher wages. Second, an educated workforce is necessary to retain domestic investment and attract multinational investment.”¹⁴ Unfortunately, as the Hart-Rudman Commission reported, the need for “the highest quality human capital in science, mathematics, and engineering is not being met.”¹⁵

Even as this need goes unmet, current workforce trends portend even greater difficulties ahead. For one thing, given current degree production levels, retirement behavior, and immigration, growth of the S&E workforce will slow, and this trend could be exacerbated by lower levels of domestic degree production, immigration, or declining stay rates of foreign-born students. This comes at a time when the current workforce is graying; more than half of all S&E-degreed workers are age 40 or older. With the exception of those working in relatively newer fields, such as computer sciences (in which 56 percent of degree-holders are younger than age 40), most S&Es in the workforce are between their late 30s and early 50s, with the largest cohort being 40–44 years of age.¹⁶ Unless there is an increase in degree production, the average age of S&Es will continue to rise, even as retirements among this group increase dramatically over the next 20 years as the baby-boom generation ages.

Given current trends, there may not be enough new graduates to sustain the growth rate of the S&E workforce, because relatively few young Americans are pursuing S&E degrees today. In fact, the

percentage of 24-year-old Americans with degrees in the natural sciences and engineering generally has remained between 4 and 6 percent for several decades, even though more high school graduates are going to college. Many of America's high-technology competitors in the world are doing better, including the United Kingdom, South Korea, Germany, Singapore, and Japan, which range from 7 to over 9 percent.¹⁷ Furthermore, undergraduate engineering enrollment in the United States declined by 7 percent between 1983 (the peak year) and 2001.¹⁸ A just-released ACT policy report, "Maintaining a Strong Engineering Workforce," found a drop in the percentage of high school seniors planning to study engineering from 9 percent in 1992 to 6 percent in 2002; a decrease in the percentage of students interested in engineering who had taken college preparatory courses in high school; a drop in the number of female ACT test takers considering engineering careers; and a gap between aspirations of racial/ethnic minority test takers, as indicated by expressed interest in engineering, and their relevant preparation with more than basic coursework.¹⁹

The graduate school picture is bleaker. NSF data show that, from 1994 to 2001, the number of U.S. citizens and permanent visa holders enrolling in graduate programs in the natural sciences and engineering decreased, with the largest declines in mathematics/statistics (25 percent), engineering (21 percent), physical sciences (17 percent), and earth, atmospheric, and ocean sciences (6 percent).²⁰ The numbers were somewhat more encouraging in the life sciences and computer science, which showed increases of 14 and 18 percent, respectively.²¹

The reasons why young Americans are rejecting careers in S&E vary, but, according to a recent study, many of the nation's best and brightest are pursuing quicker and often more lucrative payoffs in the private sector.²² Reasons cited include the prospect of low-paid apprenticeships in S&E, training that requires a decade or more, and constricted academic job opportunities after the arduous preparation for an S&E career. According to the study, training and apprenticeship times in science can exceed 10 years, and compensation for graduate students and postdoctoral appointees is modest for professionals, who often are in their mid-thirties.²³ Probably most important, however, is that "prospects for autonomous research positions in academe and related research intensive employment opportunities that most would-be scientists aspire to at the end of their long road are uncertain and increasingly slim."²⁴ The study also found science

majors increasingly leaving science after graduation, turning instead to business and health professions; during this same period, master's degrees in business administration increased by nearly one-third, with evidence that top S&E majors played a part in this growth.²⁵ Recognizing the deterrent of unattractive stipend levels, the NSF has doubled stipends for its graduate fellowships.

As serious as the overall situation is with regard to attracting young American citizens to the study of S&E, it is even more so with respect to women and minorities. The NSF data show that, in 1999, although women made up 46 percent of the overall American workforce, they constituted only 24 percent of the scientific and engineering workforce.²⁶ Furthermore, in

2000, the percentages of historically underrepresented groups in scientific and engineering occupations were lower than the percentages of those groups in the total college-educated workforce: women were 48.6 percent of the college-degreed workforce, but only 24.7 percent of the S&E workforce; blacks were 7.4 percent of the

college-degreed workforce, but only 6.9 percent of the S&E workforce; and Hispanics were 4.3 percent of the college-degreed workforce, but only 3.2 percent of the S&E workforce.²⁷ The good news is that these percentages are more than double the shares of S&E occupations since 1980.

In 1999, women made up more than half of social scientists but only 23 percent of physical scientists and 10 percent of engineers.²⁸ Within engineering, women are 15 percent of chemical and industrial engineers but only 6 percent of aerospace, electrical, and mechanical engineers.²⁹ In many occupational fields, women scientists have a lower level of educational attainment than men: in the science workforce as a whole, 16 percent of women and 20 percent of men hold PhD degrees.³⁰ These numbers vary considerably by discipline. In biology, 26 percent of women and 40 percent of men hold doctoral degrees. In chemistry, 14 percent of women and 27 percent of men hold doctoral degrees.³¹ The difference is much less in engineering, where about 5 percent of women and 6 percent of men have PhDs.³²

Data also show that the age distributions of women compared with men, and of minorities compared with the majority, are also quite different. For example, women S&Es in the workforce are younger, on average, than men; 50 percent of women and 36 percent of men employed as S&Es in 1999 had received their degrees within the previous 10 years.³³ Because women and minorities have entered S&E fields only recently, women and minority men generally are younger and have fewer years of experience. This is important

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Table 4. Foreign Doctorate Earners as Percent of Total Degrees Granted 2001

	Math/Computer	Physical Sciences	Engineering	Total
Temporary	43	36	50	30
Temporary + Permanent	49	41	56	35

Source: NSF/Division of Science Resources Statistics

Figure 1. Asian Doctoral S&E Degrees



Source: National Science Board, *Indicators 2002*, Appendix Table 2-41

because age and stage in career influence such employment-related factors as salary, rank, tenure, and work activity.

Foreign Graduate Students and National Security

While American students are rejecting graduate study in mathematics, engineering, and the physical sciences, the numbers of international graduate students in these areas has increased in recent years. As a result, more doctorates are awarded in engineering to international students than to domestic students.

According to NSF data, the number of new U.S. doctorates earned by students on temporary visas rose from about 4,300 in 1986 to about 8,000 in 1991, a figure around which it has fluctuated for a decade. Significantly, foreign students, both temporary and permanent visa holders, earn a larger proportion of degrees awarded at the doctoral level than at any other degree level. (Table 4.)

During the period 1986–99, foreign students earned 120,000 doctoral degrees in S&E fields, with China being the top country of origin of these foreign students. Almost 24,000 Chinese students earned S&E doctoral degrees at universities in the United States during this period.³⁴

Regarding Asian students generally, it can be seen from figure 1 that the number receiving doctorates in S&E from Asian institutions is increasing, far surpassing the total number earned by Asian students at U.S. universities. According to NSF data, universities in five Asian countries now produce more engineering doctorates than American universities, with China and Japan leading the way. The Chinese emphasis on higher-education in S&E is consistent with an S&E workforce push by the Peoples Liberation Army, according to a recently-released Chinese white paper.³⁵ As reported by a defense newsletter, “China’s military is intent on maintaining fewer troops with greater capabilities and is pursuing increased ‘mechanization

and [information technology] application’ to bring about ‘leapfrog’ technology development . . . and is building up its arsenal of science and technology experts—mirroring efforts in the United States.”³⁶ These trends will have profound, long-term, economic and military implications for the United States. Data show that many foreign students who graduate from American universities remain in the United States. Michael Finn of the Oak Ridge Institute for Science and Education has studied the stay rates of these foreign-born students. His research shows that the stay rate for all foreign-born Ph.D. recipients, observed two years after graduation, increased from 49 percent in 1989 to 69 percent in 1999, with the highest stay rates in the fields of computer/electrical engineering, computer science, and the physical sciences, and the lowest in the social sciences.³⁷ Finn’s work shows that 51 percent of 1994–95 U.S. S&E doctorate recipients with temporary visas were still in the United States in 1999. About 3,500 foreign students remained from each annual cohort of new S&E doctorates in all fields.³⁸ The question, however, is whether foreign students will continue to remain in the United States, given that countries “that once supplied much of the U.S. foreign S&E workforce, such as South Korea, now have the ability to provide their own students and graduates with first-world opportunities.”³⁹

Aside from the question of whether foreign students remain in the United States, contributing to our S&T resources, there are issues associated with admitting large numbers of foreign students to American universities and allowing many of them to stay on after graduation. National security implications related to America’s growing reliance on foreign graduate students and workers in the S&E fields is the most serious of these. For one thing, it may mean a dwindling pool of scientific and engineering talent for DOD and other security-related departments and agencies of the Federal government, most of which require U.S. citizenship as a prerequisite to employment. Another issue stems from the large number of foreign S&E graduate students on American campuses and relates to the increasing post-9/11 scrutiny of research being conducted in American universities and of students engaged in such research. Issues surrounding this controversy burst into the open in the spring of 2002, when DOD proposed a new policy aimed at the handling of unclassified research in both DOD and private-sector laboratories.⁴⁰ According to *Science*, under the proposed policy “the first step would have Pentagon program managers decide if DOD-funded studies at universities, companies, or military laboratories involve critical research technologies, or critical program information. If so, the institutions and researchers conducting the work would have to prepare detailed security plans, label documents as protected, obtain prior review of publication and travel plans, and decide whether to place restrictions on any foreign scientists involved in the project.”⁴¹ Many of the areas that would be affected by such a policy are precisely the areas in which additional talent is needed.

Issues surrounding national security and foreign students are discussed in a Congressional Research Service report that examines impacts of counter terrorism efforts on foreign students in S&T. The report notes that most educators agree on the need for increased controls on foreign students and the tracking of them and their courses of

study in order to help deter terrorism. However, some say it is possible that intensified monitoring of foreign students will result in fewer students, especially graduate students, coming to study scientific and technical subjects in American colleges and universities and ultimately will reduce the supply of scientific and technical personnel available for employment in the United States.⁴² Such concerns have been voiced by numerous academics worried by potential restrictions on foreign students. M.R.C. Greenwood, chancellor of the University of California, Santa Cruz, comments that the decision to restrict foreign students “will make sense only if we can also develop a policy that secures our supply of scientists and engineers in the future . . . if we block access to foreign students, who is going to do the research of the future, and who will be our faculty of the future?”⁴³ Chancellor Greenwood concludes that this is a serious question that will impact directly on our long-term national economic security.

National R&D Investment

The vitality of America’s R&D enterprise clearly is complicated by the workforce-related issues mentioned above. However, other significant issues involving U.S. R&D funding patterns and priorities also challenge America’s ability to sustain the vitality of its R&D enterprise and, therefore, its security and prosperity. These issues relate to funding sources and levels, and how funding is distributed among scientific disciplines. These issues have been widely discussed by the NSF, the National Academies of Science and Engineering, the National Science and Technology Council (NSTC), the President’s Council of Advisors on Science and Technology (PCAST), and many others.

PCAST was established to enable the President to receive advice from the business and academic communities on technology, scientific research priorities, mathematics, and science education. Its members are drawn from industry, education, research institutions, and other non-governmental organizations. The PCAST recently formed a panel on “Federal Investment in Science and Technology and Its National Benefits” to examine trends in Federal funding for R&D to determine their consistency with the nation’s present and future needs. As part of its effort, the panel commissioned a study by the RAND Corporation to examine Federal support for R&D over the past 25 years and compare U.S. Federal and private sector R&D investments to those of our global competitors.⁴⁴ The RAND study and other information gathered by the panel were used to develop final report.⁴⁵ Its findings and recommendations include the following: Federal R&D funding relative to GDP continues to decline; private sector R&D investments are generally of a different nature than Federal support; and Federal funding for physical sciences and engineering benefits all scientific disciplines.⁴⁶

With regard to our national investment in R&D, the panel notes that 20 years ago, Federal funding for R&D exceeded that of private industry, but today the reverse is true. The panel notes that this is significant because activities emanating from R&D investments that produced new growth have never been higher, including increasing numbers of patents and discovery disclosures. Indeed, there is strong linkage between federally-funded science and innovation. For example, a 1998 CHI Research study of the linkage of patent citations to the scientific literature found that, of patents granted to U.S. industry, approximately 73 percent of the science articles cited in the

patent resulted from publicly-funded science.⁴⁷ The PCAST panel was not comforted by signs of increased private sector funding of R&D, noting: “While strong support of R&D by private industry is to be commended, this source of funding cycles with business patterns and focuses on short term results by emphasizing development of existing technology rather than establishing new frontiers. Growing private investments in research do not replace the need for Federal support in certain critical areas and for long-term basic research, where the benefits cannot be measured in short cycles.”⁴⁸

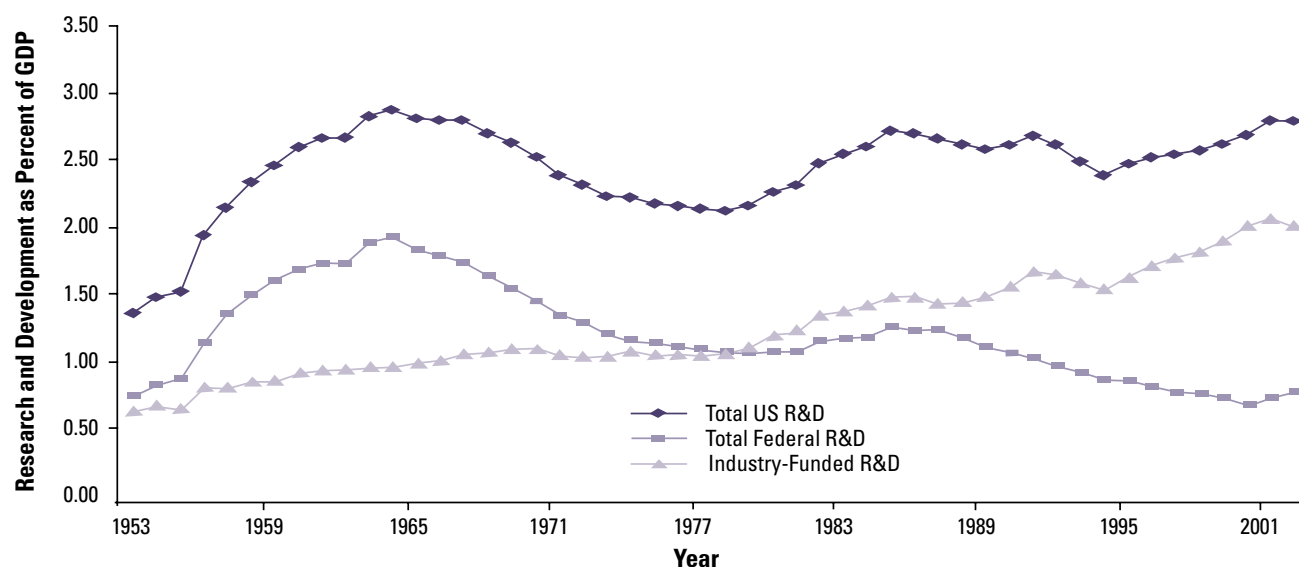
Lack of long-term, often high-risk, investment in research is especially problematic for DOD. A recent study by the Naval Research Advisory Committee, sponsored by the Director of Defense and Engineering for all three services, considered this issue and found that while “industry will pursue high-profit major weapons systems—[Military] labs are crucial to address high-risk, low-volume S&T like that that enabled the thermobaric bomb, Predator, robotic countermeasure systems, and countless others.”⁴⁹ Despite such findings, a persistent perception that military labs are no longer a major force in S&T exacerbates the problem of these labs in attracting S&Es into careers in DOD. Consider, for example, a statement in a recent Defense Science Board study that the military labs “are not competitive with leading industrial and university laboratories in terms of innovation.”⁵⁰

While total U.S. R&D expenditures as a percentage of GDP have grown since 1994, this growth is largely due to increased non-Federal investment for development rather than basic research. At the same time, the Federal investment in R&D as a percent of GDP has fallen from a high of 1.92 percent in 1964 to an estimated 0.78 percent in 2002, a decline of almost 60 percent, Figure 2.⁵¹ The Council on Competitiveness has also drawn attention to the fall-off of Federal support for R&D and notes that “the single largest influence on the changing of U.S. R&D investment has been the disinvestments by the Federal government from all forms of research and development.”⁵²

Shifting Research Funding Patterns

In its report, “Federal Investment in R&D,” RAND points out that “unlike many other nations, in which government R&D is funded predominantly by a single science agency under the goal of advancing science, the U.S. Federal R&D funding system is mission oriented, with the exception of NSF, which funds basic research. R&D programs are funded according to their contributions to national goals and broad national missions, each of which is the responsibility of a different government agency or agencies.”⁵³ This is a very healthy approach to meeting the nation’s needs for S&T. A single science agency would represent a setback for U.S. S&E research and workforce production. It is the complementary funding of NSF, NIH, DOD, DOE, NASA, and the National Institute of Standards and Technology that has made America a world leader, economically, socially, and militarily. The funding by NSF, in partnership with its sister S&T agencies, of the basic sciences, especially the physical, mathematical, environmental, and engineering sciences, has proven critical to the United States. Some effort has been made by several administrations to increase the NSF budget. This is badly needed, and progress must

Figure 2. Research and Development (R&D) Expenditure as Percentage of GDP 1953–2002



Source: NSF/Division of Science Resources Statistics

be significant in the immediate future. But it also is critical that the mission agencies be appropriate to national need.

A case in point is defense R&D. Historically, the largest share of Federal R&D funding has come from DOD, which, until recently, exceeded all other Federal R&D spending combined. Two major trends have affected this since the mid-1980s: the dramatic increase in spending during the Reagan-era defense build-up and the significant decline in spending following the end of the Cold War. According to NSF data, from FY 1980 to its peak in FY 1987, defense R&D nearly doubled in real terms.⁵⁴ Funding began to fall before the end of the Cold War, and the slide accelerated in the early 1990s. After bottoming in FY 1996, defense R&D has seen increases in the past several years.⁵⁵

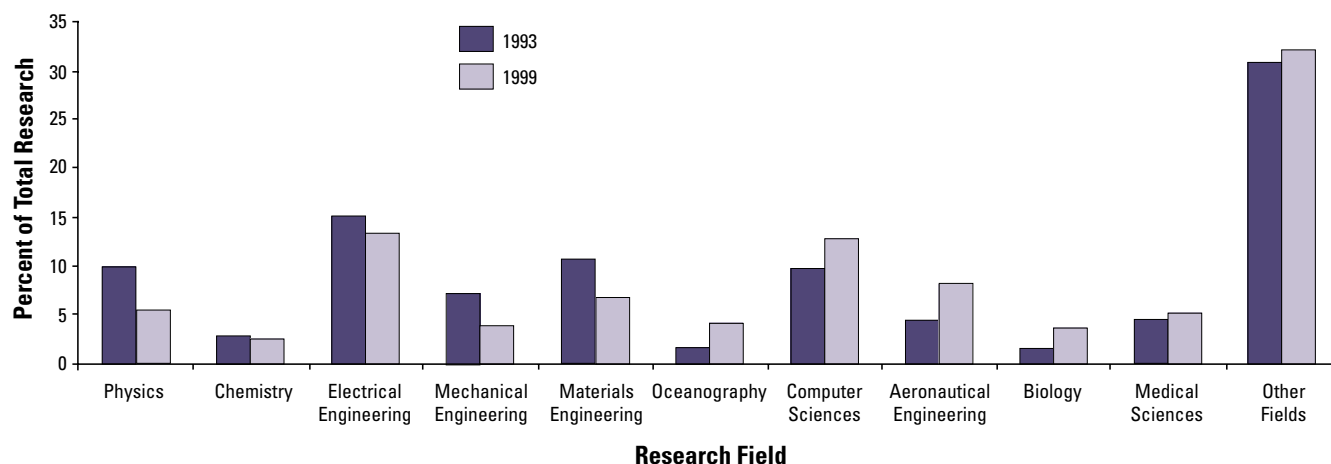
It should be understood, however, that most defense R&D is directed toward the development, testing, and evaluation of specific weapon or warfare systems (budget categories 6.4 through 6.7). Only a small fraction of the total is directed toward S&T (budget categories 6.1 through 6.3), and this is primarily focused on meeting future defense requirements and training the next generation of American S&Es in such fields as mathematics, computer sciences, and engineering. In fact, according to NSF data, the DOD S&T budget supports 12.8 percent of all Federal basic (6.1) and applied research (6.2), and is a key source of funding for several S&E disciplines.⁵⁶ Importantly, DOD provides funds for 35 percent of all Federal research in the computer sciences, nearly 40 percent of all engineering research, and significant shares of research in oceanography and mathematics.⁵⁷ The National Research Council has studied trends in

Federal spending on scientific and engineering research and found a decline in DOD funding of key S&E fields (See figure 3).⁵⁸

Changing funding priorities of Federal agencies have led to significant shifts in the balance of funding among the various fields of S&E. A 1999 study of research trends commissioned by the National Academies' Board on Science, Technology, and Economic Policy (STEP) found that several agencies spent less on research in 1997 than they had in 1993. (DOD was down 28 percent).⁵⁹ Importantly, these agency reductions disproportionately affected most fields in the physical sciences (physics, chemistry, and geology), engineering (chemical, civil, electrical, and mechanical), environmental (geology, geophysics, oceanography, atmospheric sciences, ecological sciences), and mathematics, because these fields received most of their support from the agencies with reduced funding. The study found that Federal funding decreased by 20 percent or more between 1993 and 1997 in four fields: mechanical engineering, electrical engineering, physics, and geological sciences.⁶⁰ The study found growth in such areas as computer sciences, medical sciences, metallurgy, and materials engineering. In particular, it noted that most recent increases came in research fields supported by the National Institutes of Health (NIH), largely because Congress doubled that agency's budget from FY 1999 to FY 2003.

In 2001, the STEP Board published a follow-up to its 1999 study of Federal research funding trends. It found that funding for the life sciences had increased to 46 percent of Federal funding for research in 1999, compared to 40 percent in 1993, while funding for the physical sciences and engineering decreased from 37 percent of the research portfolio in 1993 to 31 percent in 1999.⁶¹ More specifically, it found Federal funding in 1999 was still below 1993 levels for seven fields of research.⁶² Five of these fields—physics, geological sciences, and chemical, electrical, and mechanical engineering—were down

Figure 3. DOD Research Funding by Fields, FY 1993 vs. FY 1999



Source: National Research Council, *Trends in Federal Support of Research and Graduate Education*.

20 percent or more from 1993. The STEP Board concluded that a substantial shift had occurred in Federal funding, with significant declines in the physical sciences and certain fields of engineering, and substantial increases in the medically-related life sciences.

Graduate Education and Research Outputs

How have shifting priorities in national research funding affected graduate education and research outputs in S&E? For one thing, the total number of graduate students enrolled in S&E declined from its 1993 high of 435,703 to 429,492 in 2001, largely as a result of a fall-off in part-time enrollment.⁶³ Full-time enrollment fell from about 294,000 in 1993 to about 279,000 in 1998, then rebounded to about 304,000 by 2001. During the period 1993–2001, the number of U.S. citizens and permanent residents enrolled in S&E fell from 330,037 to 296,194. Over this same period, students with temporary visas increased from 105,666 to 133,298. Overall, there were fewer graduate students in the physical sciences in 2001 than in 1993—14 percent fewer in physics and 8 percent fewer in chemistry, while the mathematical sciences had 15 percent fewer graduate students and the earth, atmospheric and ocean sciences (atmospheric sciences, geosciences, and oceanography) had 13 percent fewer graduate students. Not surprisingly, the number of graduate students in health fields increased dramatically—by 40 percent—between 1993 and 2000, spurred by the burgeoning NIH research investment.⁶⁴ Overall, the number of S&E graduate students receiving Federal support declined by 2 percent between these same years, while the number of graduate students in health fields receiving Federal support increased by 15 percent.⁶⁵

The PCAST also examined the issue of how funding patterns have affected U.S. research outputs of S&Es and found that, “the number of scientific and technical articles published by U.S. authors peaked in 1992 and then decreased steadily throughout the 1990s, and was down 10 percent by 1999.”⁶⁶ However, it should be said that there seems to be no simple correlation between funds and publications output by field; observed trends may reflect changes in publishing dynamics and the international S&T scene.

Regardless, this downward trend in U.S.-authored scientific and technical articles is evident in most fields of S&E, with the greatest decrease occurring in engineering and technology articles (down 26 percent between 1992 and 1999).⁶⁷ Other declines over this same period included mathematics, physics, chemistry, and oceanography.⁶⁸ A closer look at the U.S. portfolio of technical publications is, however, instructive; it is dominated by publications in medically related life sciences (55 percent). Only about a quarter (24 percent) are dedicated to the physical sciences, and only eight percent to engineering, technology, and mathematics.⁶⁹

The decline in the number of U.S.-authored scientific and technical articles in the physical sciences and engineering appears to have been partially offset by their impact measured by the number of times a paper is cited by other S&Es in their research. Citations provide an indication of the perceived influence of a nation’s scientific outputs to other countries’ scientific and technical work. In this regard, data show that U.S. literature is the most widely cited in the world, although its share fell in the last decade from 52 percent in 1990 to 45 percent in 1999, a decline similar in magnitude to that of the fall in the U.S. share of scientific literature.⁷⁰ Over the past two decades, the U.S. share of cited scientific research on average has been 35 percent greater than the U.S. share of scientific literature.⁷¹

Clearly, America is still highly productive in terms of total scientific output as measured by numbers of journal articles. But, what

about other forms of output, such as patents? This subject, too, was studied for PCAST by RAND, which found that the number of U.S. patents increased by about 70 percent between 1990 and 1999, increasing rapidly in the late 1990s to a record high of 153,487 in 1999.⁷² About 55 percent of the U.S. patents granted in 1999 were issued to U.S. inventors.⁷³ Interestingly, the number of patents issued to academic institutions increased from 462 in 1982 to 3,151 in 1998.⁷⁴ The rapid rise in the number of scientific articles cited in patents is largely due to huge increases in the number of citations to articles in fields of biomedical research and clinical medicine; in 2000, citations to these two fields accounted for approximately 75 percent of all citations.⁷⁵

Over the last 25 years, there have been major changes in disciplinary areas supported by R&D, including large shifts in funding patterns among such S&E disciplines as the physical and life sciences. PCAST summarizes this as follows: "As a base point: in FY 1970, support for the three major areas of research, namely physical and environmental sciences, medically related life sciences and engineering was equally balanced. Today, the medically related life sciences receive 48 percent of Federal R&D funding compared to the physical sciences' 11 percent and engineering's 15 percent. Even if physical sciences, environmental sciences, math and computer sciences are combined, their total share is 18 percent."⁷⁶

According to the PCAST, the lack of funding in these disciplines, other than those that are medically related, is a cause of concern for a number of reasons. First, this has given rise to a situation in which both full-time masters and doctoral students in most areas of the physical sciences, mathematics, environmental, non-medically-related sciences, and engineering are decreasing. Over this same period, the numbers in the medically-related life sciences increased. Second, facilities and infrastructure in general for S&E are becoming less than adequate for meeting the challenges of today's research problems. Third, it is widely understood and acknowledged that the interdependencies of the various disciplines require that all advance together.⁷⁷ In other words, progress in such areas as the medically-related life sciences depends on continued progress in more fundamental areas, such as physics, chemistry, mathematics, and engineering. As an illustration of this latter point, PCAST points out that, at IBM, over 95 percent of the Ph.D.s who compose its nanotechnology research staff have degrees in the physical sciences and electrical engineering, areas in which graduate training is largely dependent upon support by the Federal government.⁷⁸ The increasing vitality and exciting discovery-initiating areas of interdisciplinary and multidisciplinary research and education cannot be sustained without investment in the non-medically-related basic sciences. Nanotechnology is only one example. The interdisciplinary research involving biological, information, nano- and cognitive (neuro-) sciences is moving rapidly. To sustain the extraordinary advances being made in these interdisciplinary areas, new collaborations in the fundamental, non-medically-related S&E disciplines must be nurtured now, not in some distant future.

The imbalance between disciplines grew during the 1990s, as funding in physics, chemistry, math, and some engineering fields declined in real terms, while investment in the life sciences grew

substantially. The increasing complexity of advanced technology, which integrates multiple disciplines and technologies, depends on concurrent advances across many fields. The imbalance in America's scientific portfolio runs a serious risk of adversely affecting the capacity for innovation in a range of key sectors and impeding the ability to fulfill other critical national missions.⁷⁹

In its discussion, the Council on Competitiveness suggests three national challenges that face the country: improved health care; energy and environmental quality; and national defense.⁸⁰ In each of these areas of national challenge, the Council claims there are both a number of "contributing sciences," as well as a number of "enabling technologies," providing another perspective on the inter-disciplinarity of S&T as it is being done in today's world. Therefore, if we are to make headway in meeting national challenges in defense, the economy, and social stability, we must also do so in the contributing sciences and enabling technologies that underpin them, most of which are included among the fields that are, today, funded at considerably lower levels than in the past. So, again, we see that the physical, environmental, and non-medically-related sciences, engineering, and mathematics are pillars on which progress toward meeting national challenges stand.

The national challenge of defense (including homeland defense) is a major concern. The Council cites a number of contributing sciences and enabling technologies on which national defense depends. Contributing sciences include computer sciences, electromagnetic theory, materials sciences, physics, quantum mechanics, robotics, and transport physics. Enabling technologies include electronics, computing, the social sciences, human-interface technology, manufacturing technology, materials technology, nuclear technology, optical technology, and plasma technology.⁸¹ Because of shifting national funding patterns, many of these areas are being reduced in absolute funding levels, with a potential negative impact on our ability to meet future national security needs.

Besides investment and workforce issues, many other trends challenge American technical leadership, including an increase in the number of other nations that are acquiring high-end innovation capabilities by focusing their investments in R&D and technical talent. In addition, America's "first-mover" advantage in information technology (IT), which played a major role in the U.S. economic expansion of the 1990s, is being eroded as other countries invest in IT infrastructure and increase their use of computers, the Internet, and other forms of telecommunications.⁸² However, it is not just a matter of other countries building up their R&D capabilities; it is the development of very broad technical infrastructures that matters most. The roles that trade and industry play in the genesis of trade-partner/trade-competition relationships around the world, and the inevitable transfer of technology and skills, also are important factors.

In this regard, the offshore accumulation of intellectual capital and industrial capability, particularly in the area of microelectronics, may have an adverse impact on the ability of DOD to maintain its technological lead over adversaries.⁸³ There also are worrying trends with regard to American elementary and secondary achievement in mathematics and science. The NSF has compiled data showing that, internationally, the relative performance of U.S. students becomes increasingly weaker at higher grade levels.⁸⁴

What Must Be Done?

An adequate supply of S&E graduates at all levels cannot be assured by focusing only on students in college and high school—by that time the battle is lost. Appropriate education must begin in the formative years. The excitement and intellectual satisfaction gained from pursuing careers in S&E must be maintained, emphasized, and conveyed to youngsters beginning at preschool ages and reinforced throughout their elementary and secondary education.

The large pool of S&Es expected to retire over the next decade or so represents a valuable resource of scientific and technical knowledge. Many will remain technically active and involved, and many have a strong interest in contributing to the education of young people in S&E. The use of modern IT should contribute significantly to their ability to continue contributing in their fields and to help educate a new generation of S&Es.

Special efforts must be made to reach women and minorities, because the demographics clearly point to their importance in the future work force. The country also must retain more foreign S&Es preferably encouraging them to become citizens. Without this human capital, the country surely will become less competitive. This must, of course, be accomplished in a way that is consistent with security concerns. The reality is, however, that the United States cannot afford to discourage the temporary residency or immigration of foreign S&Es.

It is clear and irrefutable that federally-funded research from many sources has been a significant factor in U.S. patent productivity and economic strength. The Federal government must step up to its responsibility to fund a balanced portfolio of long-term research across agencies. Particular attention should be paid to restoring the balance in federally funded research in the physical sciences and engineering relative to the health sciences.

Seminal discoveries and breakthroughs in S&T do not occur at 18-month intervals. Developments that occur at such intervals are rarely, if ever, transformational discoveries, but rather exploitation of past investments in S&T. The Federal government must manage its S&T accordingly, because it has a special responsibility for ensuring that long-term, fundamental R&D is undertaken, not only for sustaining and obtaining new capability, but also to convince young people that one can make a viable career in the pursuit of S&E. The Federal government should enunciate a clear policy of sustaining long-term research as an inducement to young people to enter careers in S&E. Equally important, the Federal government must clearly acknowledge its role in funding high-risk S&T not likely to be undertaken by industry; a purely market-driven approach will not generate the knowledge needed to sustain the American economy and U.S. military superiority in the long term.

There are no easy solutions to the problems that threaten America's global leadership position in S&T, but one point is clear: solutions must be found. As the Hart-Rudman report stated, it is not merely national pride or international image at stake, but our future security and stability as a nation. While these problems pose a challenge to our economic security and social stability, and national security, the challenge to national security is imminent. While industry and academia can continue to rely on foreign workers and students for some time, it is different for the national security agencies and fundamental

research funding agencies upon which the national security agencies depend. Solutions to the problems outlined here must be aggressively sought. To do otherwise will risk our country's economic future and security.

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Notes

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