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Perspectives on U.S. Competitiveness in Science and Technology

Titus Galama • James Hosek

Editors

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Preface

Concern has grown that the United States is losing its competitive edge in science and technology (S&T). The factors driving this concern include globalization, the rise of science centers in developing countries such as China and India, the increasing number of foreign-born Ph.D. students in the United States, and claims of a shortage of S&T workers in the United States. A loss of prowess in S&T could hurt U.S. economic competitiveness, standard of living, and national security. The Under Secretary of Defense for Personnel and Readiness asked the RAND Corporation to convene a meeting in November 2006 to discuss these issues. The papers contained in this volume were prepared for the meeting.

This research was sponsored by the Office of the Under Secretary of Defense for Personnel and Readiness and conducted within the Forces and Resources Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Department of the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community.

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Introduction

Titus Galama¹ and James Hosek¹

By one estimate, from the 16th century to the present, scientific centers in the West have shifted, with an average period of scientific prosperity of about 80 years (Yuasa, 1962). Italy led in science from about 1540 to 1610, England from 1660 to 1730, France from 1770 to 1830, Germany from 1810 to 1920, and the United States from 1920 to the present—already a period of more than 80 years. Yet some argue that the United States is now in danger of losing its competitive edge in science and technology (S&T), and, if so, the consequences could be negative and profound. Discoveries in science and technology have been fundamental drivers of U.S. economic progress and improvement in the standard of living, and a weakening of the S&T capability would threaten both.

Motivated by this concern, the Under Secretary of Defense for Personnel and Readiness asked the National Defense Research Institute at RAND to convene a meeting to review the evidence and hear the views of experts with relevant knowledge. The meeting was held on November 8, 2006, in Washington, D.C.

This volume contains the short papers presented at the meeting and discussed by the analysts, policymakers, military officers, professors, and business leaders who attended (see p. 143 for the agenda, a list of attendees, and presenters' biographical information). The papers cover a broad range of topics, including science policy, the quantitative assessment of S&T capability, globalization, the rise of Asia (in particular, China and India), innovation, trade, technology diffusion, the increase in foreign-born Ph.D. recipients working in the United States, new directions in the management and compensation of federal S&T workers, and national security and the defense industry. Taken as a set, the papers provide at least a partial survey of the facts, challenges, and questions posed by the possible erosion of U.S. S&T capabilities. They are, in our view, germane, well grounded, thought provoking, and worthy of serious attention. In addition to this volume, a future report will draw on these papers and other research with the intent of creating an overview and presenting further discussion of the findings and policy implications. Because the follow-on report will involve the selection and interpretation of material by RAND researchers and will not necessarily represent the views of those attending the meeting, it will be issued separately, though it will also draw on the input of the attendees.

The importance of S&T to U.S. prosperity and security warrants that policymakers pay careful attention to the various high-level reports issued over the past five years that warn of pressures on the U.S. lead in S&T. The intellectual point of embarkation for the RAND meeting was the foremost recent such report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, by the National Academy of Sciences, the

¹ RAND Corporation.

National Academy of Engineering, and the Institute of Medicine.² The executive summary of the report appears as the first paper in this volume (pp. 9–27).³ The National Academies' report points to the increase in research and development (R&D) in major developing countries; the rapid transmission of new technologies throughout the global economy; the increase in the number of doctoral students in China and India; the seemingly small number of U.S. students entering science, technology, engineering, and mathematics (STEM); and the rising return home of foreign graduate students who have trained in the United States. Among its recommendations, the report calls for increased federal investments in STEM research facilities and funding, graduate stipends, and steps to increase the number of qualified STEM teachers down to the K–12 level. These recommendations were echoed in the President's State of the Union address in 2006.

The basic argument that the United States might be losing its competitive edge can, with some simplification, be summarized as follows (see, for further elaboration, Segal, pp. 29–35 of this volume; Segal 2004; and *Rising Above the Gathering Storm*):

1. Globalization and the rise of other geographic areas (e.g., India, China, and Europe) will lead to a relative decline in U.S. economic power and a relative decline of the U.S. innovation and R&D enterprise.
2. The United States has, for several decades, invested too little in sustaining its S&T leadership and flow of S&T workers; for example, there are too few teachers in science and mathematics in K–12 and they are not sufficiently well prepared, too few students study science and engineering at the K–12 and higher levels, federal funding in basic research has lagged, the United States is increasingly reliant on foreign S&T talent, and S&T careers have become increasingly unattractive.

The *Rising Above the Gathering Storm* report galvanized the policy community. Within a year of its release in November 2005, it had spawned over two dozen bills in Congress aimed at providing further funding for increasing the supply of teachers, improving teacher preparation, increasing financial aid to college students entering S&T fields, and increasing R&D funds, according to the presentation by Deborah Stine, National Academy of Sciences study director for the *Rising Above the Gathering Storm* report.

Jonathan Adams, a UK-based expert on measuring the scientific output of nations, presented information comparing the United States to the European Union, Japan, China, Korea, and other countries (see pp. 37–48). Jonathan Eaton and Samuel Kortum, economics professors, also presented such comparisons as part of their paper (see pp. 53–71). Their comparisons clearly indicate that the United States still dominates global science, technology, and innovation. (See also King 2004; May 1997; and Segal, 2004.) No other single nation is as strong in S&T, though, in many ways, the European Union, as a collection of nations, rivals the United States. The United States accounts for 40 percent of total R&D spending worldwide and about a third of patented new technology inventions, and employs 37 percent (1.3 million) of researchers (full-time equivalent) from Organisation for Economic Co-Operation and Devel-

² The report by the National Academies will be referred to in many places as the *Rising Above the Gathering Storm* report, though in some instances the shorter title, *Gathering Storm*, is used.

³ The executive summary is reprinted here with permission of the National Academies: the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine.

opment (OECD) countries, 70 percent of the world's Nobel Prize winners, and 66 percent of the most cited individuals; it produces 35, 49, and 63 percent, respectively, of the world's scientific publications, citations, and highly cited publications and is home to 75 percent of the world's top 20 and 58 percent of the world's top 100 universities. The United States leads the major global technology markets for aerospace, scientific instruments, computers and office machinery, and communication instruments. For the last two decades, U.S. firms have been the top providers of high-tech services, accounting for one-third of the world's total.

Jonathan Adams further points to the rise of China and a significantly improved Asia-Pacific knowledge base. China's R&D investment and science enterprise are growing rapidly but, at present, are quite small in comparison to those of the United States or the European Union. Adams also argues that better metrics are needed to measure the scientific performance of nations and stresses the importance of international collaboration. Publications resulting from international collaboration tend to be of better quality and there is much to be learned from research innovation elsewhere. The United States should encourage research partnerships and the mobility of U.S. researchers working in collaboration with foreign science centers, enhancing knowledge and understanding of innovation abroad.

Picking up on the theme of globalization and the rise of China, Adam Segal of the Council on Foreign Relations contends that the nature of innovation has changed and that today it is private, collaborative, and global. (See also Segal, 2004, and Hicks, 2001.) According to Segal, there are at least three ways in which the globalization of S&T complicates national security: (1) technological capability is more widely diffused to potential competitors; (2) U.S. access to the most advanced technology is no longer guaranteed, as the cutting edge of innovation in individual technology sectors may be located elsewhere; and (3) the historically long technological lead times over potential competitors are now measured in months and years, not decades. He concludes that the United States will need to track technology development abroad so as not to be surprised by swift technological breakthroughs. Monitoring these developments, and exploiting them, will require a different type of training and experience that the United States may currently lack.

David Warsh, journalist and author (pp. 49–52), describes the idea of “endogenous” (i.e., self-induced) technology change as an essential concept for understanding economic growth. (See also Warsh, 2006.) The importance of knowledge and technology to economic growth was recognized in Solow's 1957 contribution to the *Review of Economics and Statistics*, in which he presented a model of consumption, investment, and growth, with technological progress being a given. Solow found that technological progress accounted for 80 percent of the growth in U.S. output per worker since the turn of the last century (though subsequent estimates have been somewhat lower). Warsh recounts how Romer (1990) developed a model with endogenous technological change in which the pace of discovery was the result of individual actions taken in response to economic incentives. The Romer model significantly improved the understanding of the nature of economic growth through technological change.

Eaton and Kortum discuss the concept, characteristics, and importance of knowledge in creating economic growth, compared with those of more traditional and more tangible forms of economic resources, such as arable land, labor, capital, and natural resources such as oil. Eaton and Kortum show, for example, that U.S. labor, capital, and natural resources alone are nowhere near sufficient to explain the large size of its economy. Knowledge, they point out, is a substantial source of national wealth—and yet it has the essential characteristic that it tends to spread internationally like a genie that cannot be kept in the bottle.

But globalization, increased trade, and the international diffusion of technology will not necessarily immiserize the United States. In Eaton and Kortum's paper, and in a longer paper circulated as a background reading before the meeting (Eaton and Kortum, 2006), they argue that, even with an outflow of technology, a country that is more productive in creating new technology may increase the size of its technology sector, grow more rapidly, and improve its standard of living. This is not the only possible outcome, though; in the longer paper, they analyze a variety of other possibilities.

Eaton and Kortum argue that faster diffusion of technology to China, for instance, is not likely to pose much of a threat to U.S. living standards. When diffusion is complete, the innovating country (i.e., the United States) loses its wage advantage (which comes from initially exclusive use of the new technology, making U.S. labor more productive), giving up its gains from trade. Eaton and Kortum estimate U.S. gains from world trade in manufacturing to be under 1 percent of GDP—i.e., not large. Furthermore, to take a historical example, the rise of Europe and Japan in the three decades following WWII has not negatively impacted U.S. living standards or security.

Finally, Eaton and Kortum suggest that China's rapid growth is due to a substantial increase in China's ability to absorb a lot of foreign technology, rather than resulting from domestic innovation.

James D. Adams, an economist specializing in R&D studies (pp. 73–79), discusses future prospects and recent challenges facing U.S. science and engineering. He provides evidence of a decline of U.S. science in industry and in public universities since the early 1990s, as indicated by a decrease in scientific publications. The number of publications by the top 200 U.S. R&D firms (the largest R&D firms in 1998) peaked around 1990 and subsequently declined. While smaller firms' science output has grown, they have not made up for the difference. Adams suggests that a considerable part of the decline in scientific publications by the top 200 firms is due to the breakup of AT&T and the downsizing of Bell Laboratories. And, Adams concludes, it is difficult to replace the likes of them. In addition, weakened government support for basic research during the 1990s (federal funding for basic and applied research was flat from 1993 to 1998 but has grown substantially since 1999), perhaps related to the end of the Cold War, may have led to the decline and even disappearance of many central research facilities in large firms. Adams further shows that, while the number of publications from private universities has grown at a constant rate, the number by public universities grew more slowly in the 1990s.

Richard B. Freeman, a labor economist (pp. 81–89), argues that changes in the global job market for S&T workers are eroding U.S. dominance in S&T and diminishing its comparative advantage in high-tech production. (See also Freeman, 2005.) The U.S. share of the world's science and engineering graduates is declining rapidly, the job market has worsened for young workers in S&T fields relative to many other high-level occupations, and populous low-income countries such as China and India are able to compete with the United States in the high-tech sector by having many S&T workers (even though they are only a small fraction of the workforce) and by having a low-wage advantage. Loss of comparative advantage to a low-wage competitor, Freeman argues, can substantially harm an advanced country, as it must shift resources to less desirable sectors and monopoly rents from new products or innovations shift from the advanced to the poorer country. As a result, foreign countries that seek to compete in high-tech military areas have the potential resources to do so, and the diminished U.S. share of S&T talent will make it harder for some U.S. agencies to maintain high productivity if they rely solely on citizens for critical R&D work. Freeman recommends that the United States

develop new ways of monitoring and benefiting from scientific and technological advances in other countries.

Michael S. Teitelbaum of the Alfred P. Sloan Foundation (pp. 91–100) discusses the notorious difficulty of predicting shortages or surpluses of scientists and engineers (see also Freeman, pp. 81–89, and Oyer, pp. 113–119, in this volume, and Teitelbaum, 2003) and provides an account of repeated claims of shortages made since the 1960s that have not materialized. Teitelbaum argues that current studies have tended to find evidence to the contrary, of surpluses, not shortages of scientists and engineers (see Butz et al., 2004). This history raises doubt about concerns over the allegedly insufficient number of U.S. students graduating in science and engineering and the value of policy actions that would increase their supply. Teitelbaum notes the tendency to promote solutions to alleged current or “looming” shortages that focus primarily on the supply side, i.e., increasing the number of graduates, while paying scant attention to the demand for new graduates, i.e., stimulating the demand through R&D funding, fiscal incentives, and other methods. A balanced solution would entail both supply and demand.⁴ Teitelbaum points to the potential for increasing the number of S&T graduates by improving the retention rates in these fields of study; many students who intend to major in science and engineering in the end do not. Further, Teitelbaum summarizes the new professional science master’s (PSM) degrees, which have been designed for careers outside academe.

Paula E. Stephan, an economist specializing in training and science policy (pp. 101–106), provides suggestions for improvement to the recommendations of the *Rising Above the Gathering Storm* report. She praises the report for offering not only supply-side policy recommendations, as is often the case, but also demand-side policy recommendations, such as the recommendation to provide tax incentives for U.S.-based invention. Stephan agrees with the recommendation to recruit additional K–12 science and mathematics teachers but also emphasizes the need to improve teacher retention. Salary and, especially, working conditions need to be improved, as they are an important reason that teachers leave the profession. She points to the unintended consequences of some laudable recommendations, such as the negative signaling effect that may result if applicants’ success rate in applying for early-career research grants turns out to be disappointingly low, and the importance of ensuring a soft landing when the doubling of basic research funding ends. Stephan further brings up the issue of reliance on temporary workers in the form of graduate and postdoctoral students and argues that there are negative consequences of this U.S. practice.

Thomas L. Magnanti, a dean of engineering (pp. 107–111), remarks on the significance of universities in contributing to the nation’s economy through the development of new technologies, products, and services. (See also Adams, 2000.) He also emphasizes the role of openness: intellectual openness; openness in collaboration across disciplines, institutions, and organizations; and openness in terms of the flow of international students and scholars who contribute significantly to U.S. universities and economy. With 8 percent of bachelor’s, 46 percent of

⁴ The *Rising Above the Gathering Storm* recommendations would address both supply by increasing student financial aid in S&T, which would increase the number of students in the pipeline, and demand by increasing federal funds for basic research and early-career awards. The proposed increase in federal basic research funding represents a large long-term increase in federal basic research funds, but the increase is relatively small compared to total R&D funding (federal plus private). The proposal calls for an increase of basic research funds of 10 percent per year for the next seven years. The proposal, therefore, would increase the demand for S&T workers in basic research, but many would be graduate students and postdocs, and, in any case, would have relatively little impact on the overall demand for S&T workers in research and development.

master's, and 55 percent of doctoral degrees in engineering granted to foreigners, Magnanti argues that it is crucial for the United States to continue attracting and retaining this talent flow. He offers an example of openness with MIT OpenCourseWare, a project to make all course materials used at MIT to teach undergraduate and graduate subjects available on the Internet free of charge.

Paul Oyer (pp. 113–119) provides an organizational economics and business strategy perspective and asks whether the United States should “make” or “buy” a key input to technology, namely, scientists. National security is not, by definition, a function of domestic scientific talent alone, and the United States has historically also relied on foreign talent (a “buy” strategy). Oyer stresses the importance of general macroeconomic health to keep the United States an attractive place to work for scientists. He is concerned with the quality of education, arguing that if poor schools produce poorly skilled workers, the economy as a whole will be affected. Therefore, the nation should be concerned about the quality of education in general, not just education in science and engineering. There are two reasons why, despite increased spending on public schools, there is the perception of less value for the money: Salaries of college-educated employees have increased significantly and so has the price of real estate. As a result, it costs much more now to provide an education. But while costs have risen, there is less evidence that quality has risen, and the additional outlays on education may have gone mainly to cover the higher costs.

Brigitte W. Schay of the U.S. Office of Personnel Management (pp. 121–128; see also Shorter et al., 2002) examines the results of federal personnel management demonstration projects designed to improve effectiveness by creating a more flexible and responsive personnel system to recruit, develop, motivate and retain a high-quality workforce. The demonstration programs provided an opportunity to test broadband pay systems and pay-for-performance systems, enhance training and development of personnel, and change recruitment and staffing practice. The results of the demonstrations suggest growing worker acceptance and trust of pay-for-performance and broad banding, and, by most measures, the gains have been positive (or at least not negative) though small. Schay concludes with a discussion of the implications of these findings.

Beth J. Asch (pp. 129–141) summarizes lessons from the economics and management literature on improving incentives for performance in the context of the S&T workforce. (See also Asch, 2005.) Evidence suggests that explicit pay-for-performance compensation can provide significant incentives to attract the most productive workforce and increase worker productivity. But pay-for-performance schemes suffer from unintended consequences and have high measurement costs (e.g., there may be multiple objectives, multiple bosses, and not all objectives may be measured or measured accurately). There are, however, alternatives to explicit pay-for-performance systems that may have fewer disadvantages, such as promotion-based incentives, seniority-based compensation within a pay band, reputation-based compensation, and self-selection. The greater the problems caused by unintended consequences, the weaker the link between pay and explicit measurements of performance ought to be. Asch concludes that there are advantages and disadvantages to each of the pay-for-performance options that should be carefully considered before major changes are made.

In short, the debate around the question of whether the United States is losing its competitive edge is a lively one. We hope the reader will enjoy the perspectives offered in these proceedings and that they contribute to an improved understanding of the recent trends in U.S.

science and technology, the nature of the potential problem, its possible implications, and the effectiveness of proposed solutions.

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Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future—Executive Summary

*National Academy of Sciences,
National Academy of Engineering,
and Institute of Medicine of the National Academies^{1,2,3}*

The United States takes deserved pride in the vitality of its economy, which forms the foundation of our high quality of life, our national security, and our hope that our children and grandchildren will inherit ever-greater opportunities. That vitality is derived in large part from the productivity of well-trained people and the steady stream of scientific and technical innovations they produce. Without high-quality, knowledge-intensive jobs and the innovative enterprises that lead to discovery and new technology, our economy will suffer and our people will face a lower standard of living. Economic studies conducted even before the information-technology revolution have shown that as much as 85% of measured growth in US income per capita was due to technological change.⁴

Today, Americans are feeling the gradual and subtle effects of globalization that challenge the economic and strategic leadership that the United States has enjoyed since World War II. A substantial portion of our workforce finds itself in direct competition for jobs with lower-wage workers around the globe, and leading-edge scientific and engineering work is being accomplished in many parts of the world. Thanks to globalization, driven by modern communications and other advances, workers in virtually every sector must now face competitors who live just a mouse-click away in Ireland, Finland, China, India, or dozens of other nations whose economies are growing. This has been aptly referred to as “the Death of Distance.”

Charge to the Committee

The National Academies was asked by Senator Lamar Alexander and Senator Jeff Bingaman of the Committee on Energy and Natural Resources, with endorsement by Representative

¹ Committee on Prospering in the Global Economy of the 21st Century: An Agenda for American Science and Technology, Committee on Science, Engineering, and Public Policy, The National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine of the National Academies.

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³ Committee biographic information is provided at the end of the executive summary.

⁴ For example, work by Robert Solow and Moses Abramovitz published in the middle 1950s demonstrated that as much as 85% of measured growth in US income per capita during the 1890–1950 period could not be explained by increases in the capital stock or other measurable inputs. The unexplained portion, referred to alternatively as the “residual” or “the measure of ignorance,” has been widely attributed to the effects of technological change.

Sherwood Boehlert and Representative Bart Gordon of the House Committee on Science, to respond to the following questions:

What are the top 10 actions, in priority order, that federal policymakers could take to enhance the science and technology enterprise so that the United States can successfully compete, prosper, and be secure in the global community of the 21st century? What strategy, with several concrete steps, could be used to implement each of those actions?

The National Academies created the Committee on Prospering in the Global Economy of the 21st Century to respond to this request. The charge constitutes a challenge both daunting and exhilarating: to recommend to the nation specific steps that can best strengthen the quality of life in America—our prosperity, our health, and our security. The committee has been cautious in its analysis of information. The available information is only partly adequate for the committee's needs. In addition, the time allotted to develop the report (10 weeks from the time of the committee's first gathering to report release) limited the ability of the committee to conduct an exhaustive analysis. Even if unlimited time were available, definitive analyses on many issues are not possible given the uncertainties involved.⁵

This report reflects the consensus views and judgment of the committee members. Although the committee consists of leaders in academe, industry, and government—including several current and former industry chief executive officers, university presidents, researchers (including three Nobel prize winners), and former presidential appointees—the array of topics and policies covered is so broad that it was not possible to assemble a committee of 20 members with direct expertise in each relevant area. Because of those limitations, the committee has relied heavily on the judgment of many experts in the study's focus groups, additional consultations via e-mail and telephone with other experts, and an unusually large panel of reviewers. Although other solutions are undoubtedly possible, the committee believes that its recommendations, if implemented, will help the United States achieve prosperity in the 21st century.

Findings

Having reviewed trends in the United States and abroad, the committee is deeply concerned that the scientific and technological building blocks critical to our economic leadership are eroding at a time when many other nations are gathering strength. We strongly believe that a worldwide strengthening will benefit the world's economy—particularly in the creation of jobs in countries that are far less well-off than the United States. But we are worried about the future prosperity of the United States. Although many people assume that the United States will always be a world leader in science and technology, this may not continue to be the case inasmuch as great minds and ideas exist throughout the world. We fear the abruptness with which a lead in science and technology can be lost—and the difficulty of recovering a lead once lost, if indeed it can be regained at all.

⁵ Since the prepublication version of the report was released in October, certain changes have been made to correct editorial and factual errors, add relevant examples and indicators, and ensure consistency among sections of the report. Although modifications have been made to the text, the recommendations remain unchanged, except for a few corrections, which have been footnoted.

The committee found that multinational companies use such criteria⁶ as the following in determining where to locate their facilities and the jobs that result:

- Cost of labor (professional and general workforce).
- Availability and cost of capital.
- Availability and quality of research and innovation talent.
- Availability of qualified workforce.
- Taxation environment.
- Indirect costs (litigation, employee benefits such as healthcare, pensions, vacations).
- Quality of research universities.
- Convenience of transportation and communication (including language).
- Fraction of national research and development supported by government.
- Legal-judicial system (business integrity, property rights, contract sanctity, patent protection).
- Current and potential growth of domestic market.
- Attractiveness as place to live for employees.
- Effectiveness of national economic system.

Although the US economy is doing well today, current trends in each of those criteria indicate that the United States may not fare as well in the future without government intervention. This nation must prepare with great urgency to preserve its strategic and economic security. Because other nations have, and probably will continue to have, the competitive advantage of a low wage structure, the United States must compete by optimizing its knowledge-based resources, particularly in science and technology, and by sustaining the most fertile environment for new and revitalized industries and the well-paying jobs they bring. We have already seen that capital, factories, and laboratories readily move wherever they are thought to have the greatest promise of return to investors.

Recommendations

The committee reviewed hundreds of detailed suggestions—including various calls for novel and untested mechanisms—from other committees, from its focus groups, and from its own members. The challenge is immense, and the actions needed to respond are immense as well.

The committee identified two key challenges that are tightly coupled to scientific and engineering prowess: creating high-quality jobs for Americans, and responding to the nation's need for clean, affordable, and reliable energy. To address those challenges, the committee structured its ideas according to four basic recommendations that focus on the human, financial, and knowledge capital necessary for US prosperity.

⁶ D. H. Dalton, M. G. Serapio, Jr., P. G. Yoshida. 1999. Globalizing Industrial Research and Development. US Department of Commerce, Technology Administration, Office of Technology Policy. Grant Gross. 2003, October 9. "CEOs defend moving jobs offshore at tech summit." InfoWorld. Mehlman, Bruce. 2003. Offshore Outsourcing and the Future of American Competitiveness. "High tech in China: is it a threat to Silicon Valley?" 2002, October 28. Business Week online. B. Callan, S. Costigan, K. Keller. 1997. Exporting U.S. High Tech: Facts and Fiction about the Globalization of Industrial R&D, Council on Foreign Relations, New York, NY.

The four recommendations focus on actions in K–12 education (*10,000 Teachers, 10 Million Minds*), research (*Sowing the Seeds*), higher education (*Best and Brightest*), and economic policy (*Incentives for Innovation*) that are set forth in the following sections. Also provided are a total of 20 implementation steps for reaching the goals set forth in the recommendations.

Some actions involve changes in the law. Others require financial support that would come from reallocation of existing funds or, if necessary, from new funds. Overall, the committee believes that the investments are modest relative to the magnitude of the return the nation can expect in the creation of new high-quality jobs and in responding to its energy needs.

The committee notes that the nation is unlikely to receive some sudden “wakeup” call; rather, the problem is one that is likely to evidence itself gradually over a surprisingly short period.

10,000 Teachers, 10 Million Minds, and K–12 Science and Mathematics Education

Recommendation A: Increase America’s talent pool by vastly improving K–12 science and mathematics education.

Implementation Actions

The highest priority should be assigned to the following actions and programs. All should be subjected to continuing evaluation and refinement as they are implemented.

Action A-1: Annually recruit 10,000 science and mathematics teachers by awarding 4-year scholarships and thereby educating 10 million minds. Attract 10,000 of America’s brightest students to the teaching profession every year, each of whom can have an impact on 1,000 students over the course of their careers. The program would award competitive 4-year scholarships for students to obtain bachelor’s degrees in the physical or life sciences, engineering, or mathematics with concurrent certification as K–12 science and mathematics teachers. The merit-based scholarships would provide up to \$20,000 a year for 4 years for qualified educational expenses, including tuition and fees, and require a commitment to 5 years of service in public K–12 schools. A \$10,000 annual bonus would go to participating teachers in underserved schools in inner cities and rural areas. To provide the highest-quality education for undergraduates who want to become teachers, it would be important to award matching grants, on a one-to-one basis, of \$1 million a year for up to 5 years, to as many as 100 universities and colleges to encourage them to establish integrated 4-year undergraduate programs leading to bachelor’s degrees in the physical and life sciences, mathematics, computer sciences, or engineering *with teacher certification*. The models for this action are the UTeach and California Teach program.

Action A-2: Strengthen the skills of 250,000 teachers through training and education programs at summer institutes, in master’s programs, and in Advanced Placement (AP) and International Baccalaureate (IB) training programs. Use proven models to strengthen the skills (and compensation, which is based on education and skill level) of 250,000 *current* K–12 teachers.

- *Summer institutes:* Provide matching grants to state and regional 1- to 2-week summer institutes to upgrade the skills and state-of-the-art knowledge of as many as 50,000 practicing teachers each summer. The material covered would allow teachers to keep current with recent developments in science, mathematics, and technology and allow for the exchange of best teaching practices. The Merck Institute for Science Education is one model for this action.
- *Science and mathematics master's programs:* Provide grants to research universities to offer, over 5 years, 50,000 current middle school and high school science, mathematics, and technology teachers (with or without undergraduate science, mathematics, or engineering degrees) 2-year, part-time master's degree programs that focus on rigorous science and mathematics content and pedagogy. The model for this action is the University of Pennsylvania Science Teachers Institute.
- *AP, IB, and pre-AP or pre-IB training:* Train an additional 70,000 AP or IB and 80,000 pre-AP or pre-IB instructors to teach advanced courses in science and mathematics. Assuming satisfactory performance, teachers may receive incentive payments of \$1,800 per year, as well as \$100 for each student who passes an AP or IB exam in mathematics or science. There are two models for this program: the Advanced Placement Incentive Program and Laying the Foundation, a pre-AP program.
- *K–12 curriculum materials modeled on a world-class standard:* Foster high-quality teaching with world-class curricula, standards, and assessments of student learning. Convene a national panel to collect, evaluate, and develop rigorous K–12 materials that would be available free of charge as a voluntary national curriculum. The model for this action is the Project Lead the Way pre-engineering courseware.

Action A-3: Enlarge the pipeline of students who are prepared to enter college and graduate with a degree in science, engineering, or mathematics by increasing the number of students who pass AP and IB science and mathematics courses. Create opportunities and incentives for middle school and high school students to pursue advanced work in science and mathematics. By 2010, increase the number of students who take at least one AP or IB mathematics or science exam to 1.5 million, and set a goal of tripling the number who pass those tests to 700,000.⁷ Student incentives for success would include 50% examination fee rebates and \$100 mini-scholarships for each passing score on an AP or IB science or mathematics examination.

Although it is not included among the implementation actions, the committee also finds attractive the expansion of two approaches to improving K–12 science and mathematics education that are already in use:

- *Statewide specialty high schools:* Specialty secondary education can foster leaders in science, technology, and mathematics. Specialty schools immerse students in high-quality science, technology, and mathematics education; serve as a mechanism to test teaching materials; provide a training ground for K–12 teachers; and provide the resources and staff for summer programs that introduce students to science and mathematics.
- *Inquiry-based learning:* Summer internships and research opportunities provide especially valuable laboratory experience for both middle-school and high-school students.

⁷ This sentence was incorrectly phrased in the original October 12, 2005, edition of the executive summary and has now been corrected.

Sowing the Seeds Through Science and Engineering Research

Recommendation B: *Sustain and strengthen the nation's traditional commitment to long-term basic research that has the potential to be transformational to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life.*

Implementation Actions

Action B-1: Increase the federal investment in long-term basic research by 10% each year over the next 7 years through reallocation of existing funds⁸ or, if necessary, through the investment of new funds. Special attention should go to the physical sciences, engineering, mathematics, and information sciences and to Department of Defense (DoD) basic-research funding. This special attention does not mean that there should be a disinvestment in such important fields as the life sciences or the social sciences. A balanced research portfolio in all fields of science and engineering research is critical to US prosperity. Increasingly, the most significant new scientific and engineering advances are formed to cut across several disciplines. This investment should be evaluated regularly to realign the research portfolio to satisfy emerging needs and promises—unsuccessful projects and venues of research should be replaced with research projects and venues that have greater potential.

Action B-2: Provide new research grants of \$500,000 each annually, payable over 5 years, to 200 of the nation's most outstanding early-career researchers. The grants would be made through existing federal research agencies—the National Institutes of Health (NIH), the National Science Foundation (NSF), the Department of Energy (DOE), DOD, and the National Aeronautics and Space Administration (NASA)—to underwrite new research opportunities at universities and government laboratories.

Action B-3: Institute a National Coordination Office for Advanced Research Instrumentation and Facilities to manage a fund of \$500 million in incremental funds per year over the next 5 years—through reallocation of existing funds or, if necessary, through the investment of new funds—to ensure that universities and government laboratories create and maintain the facilities, instrumentation, and equipment needed for leading-edge scientific discovery and technological development. Universities and national laboratories would compete annually for these funds.

Action B-4: Allocate at least 8% of the budgets of federal research agencies to discretionary funding that would be managed by technical program managers in the agencies and be focused on catalyzing high-risk, high-payoff research of the type that often suffers in today's increasingly risk-averse environment.

⁸ The funds may come from anywhere in government, not just other research funds.

Action B-5: Create in the Department of Energy an organization like the Defense Advanced Research Projects Agency (DARPA) called the Advanced Research Projects Agency-Energy (ARPA-E).⁹ The director of ARPA-E would report to the under secretary for science and would be charged with sponsoring specific research and development programs to meet the nation's long-term energy challenges. The new agency would support creative “out-of-the-box” transformational generic energy research that industry by itself cannot or will not support and in which risk may be high but success would provide dramatic benefits for the nation. This would accelerate the process by which knowledge obtained through research is transformed to create jobs and address environmental, energy, and security issues. ARPA-E would be based on the historically successful DARPA model and would be designed as a lean and agile organization with a great deal of independence that can start and stop targeted programs on the basis of performance and do so in a timely manner. The agency would itself perform no research or transitional effort but would fund such work conducted by universities, startups, established firms, and others. Its staff would turn over approximately every 4 years. Although the agency would be focused on specific energy issues, it is expected that its work (like that of DARPA or NIH) will have important spinoff benefits, including aiding in the education of the next generation of researchers. Funding for ARPA-E would start at \$300 million the first year and increase to \$1 billion per year over 5–6 years, at which point the program's effectiveness would be evaluated and any appropriate actions taken.

Action B-6: Institute a Presidential Innovation Award to stimulate scientific and engineering advances in the national interest. Existing presidential awards recognize lifetime achievements or promising young scholars, but the proposed new awards would identify and recognize persons who develop unique scientific and engineering innovations in the national interest at the time they occur.

Best and Brightest in Science and Engineering Higher Education

Recommendation C: *Make the United States the most attractive setting in which to study and perform research so that we can develop, recruit, and retain the best and brightest students, scientists, and engineers from within the United States and throughout the world.*

Implementation Actions

Action C-1: Increase the number and proportion of US citizens who earn bachelor's degrees in the physical sciences, the life sciences, engineering, and mathematics by providing 25,000 new 4-year competitive undergraduate scholarships each year to US citizens attending US institutions. The Undergraduate Scholar Awards in Science, Technology, Engineering, and Mathematics (USA-STEM) would be distributed to states on the basis of the size of their congressional delegations and awarded on the basis of national examinations. An award would provide up to \$20,000 annually for tuition and fees.

⁹ One committee member, Lee Raymond, does not support this action item. He does not believe that ARPA-E is necessary, because energy research is already well funded by the federal government, along with formidable funding by the private sector. Also, ARPA-E would, in his view, put the federal government into the business of picking “winning energy technologies”—a role best left to the private sector.

Action C-2: Increase the number of US citizens pursuing graduate study in “areas of national need” by funding 5,000 new graduate fellowships each year. NSF should administer the program and draw on the advice of other federal research agencies to define national needs. The focus on national needs is important both to ensure an adequate supply of doctoral scientists and engineers and to ensure that there are appropriate employment opportunities for students once they receive their degrees. Portable fellowships would provide a stipend of \$30,000¹⁰ annually directly to students, who would choose where to pursue graduate studies instead of being required to follow faculty research grants, and up to \$20,000 annually for tuition and fees.

Action C-3: Provide a federal tax credit to encourage employers to make continuing education available (either internally or through colleges and universities) to practicing scientists and engineers. These incentives would promote career-long learning to keep the workforce productive in an environment of rapidly evolving scientific and engineering discoveries and technological advances and would allow for retraining to meet new demands of the job market.

Action C-4: Continue to improve visa processing for international students and scholars to provide less complex procedures and continue to make improvements on such issues as visa categories and duration, travel for scientific meetings, the technology alert list, reciprocity agreements, and changes in status.

Action C-5: Provide a 1-year automatic visa extension to international students who receive doctorates or the equivalent in science, technology, engineering, mathematics, or other fields of national need at qualified US institutions to remain in the United States to seek employment. If these students are offered jobs by US-based employers and pass a security screening test, they should be provided automatic work permits and expedited residence status. If students are unable to obtain employment within 1 year, their visas would expire.

Action C-6: Institute a new skills-based, preferential immigration option. Doctoral-level education and science and engineering skills would substantially raise an applicant’s chances and priority in obtaining US citizenship. In the interim, the number of H-1B visas should be increased by 10,000, and the additional visas should be available for industry to hire science and engineering applicants with doctorates from US universities.¹¹

Action C-7: Reform the current system of “deemed exports.” The new system should provide international students and researchers engaged in fundamental research in the United States with access to information and research equipment in US industrial, academic, and national

¹⁰ An incorrect number was provided for the graduate student stipend in the original October 12, 2005, edition of the executive summary.

¹¹ Since the report was released, the committee has learned that the Consolidated Appropriations Act of 2005, signed into law on December 8, 2004, exempts individuals that have received a master’s or higher education degree from a US university from the statutory cap (up to 20,000). The bill also raised the H-1b fee and allocated funds to train American workers. The committee believes that this provision is sufficient to respond to its recommendation—even though the 10,000 additional visas recommended is specifically for science and engineering doctoral candidates from US universities, which is a narrower subgroup.

laboratories comparable with the access provided to US citizens and permanent residents in a similar status. It would, of course, exclude information and facilities restricted under national-security regulations. In addition, the effect of deemed-exports¹² regulations on the education and fundamental research work of international students and scholars should be limited by removing from the deemed-exports technology list all technology items (information and equipment) that are available for purchase on the overseas open market from foreign or US companies or that have manuals that are available in the public domain, in libraries, over the Internet, or from manufacturers.

Incentives for Innovation

Recommendation D: *Ensure that the United States is the premier place in the world to innovate; invest in downstream activities such as manufacturing and marketing; and create high-paying jobs based on innovation by such actions as modernizing the patent system, realigning tax policies to encourage innovation, and ensuring affordable broadband access.*

Implementation Actions

Action D-1: Enhance intellectual-property protection for the 21st-century global economy to ensure that systems for protecting patents and other forms of intellectual property underlie the emerging knowledge economy but allow research to enhance innovation. The patent system requires reform of four specific kinds:

- Provide the US Patent and Trademark Office with sufficient resources to make intellectual-property protection more timely, predictable, and effective.
- Reconfigure the US patent system by switching to a “first-inventor-to-file” system and by instituting administrative review *after* a patent is granted. Those reforms would bring the US system into alignment with patent systems in Europe and Japan.
- Shield research uses of patented inventions from infringement liability. One recent court decision could jeopardize the long-assumed ability of academic researchers to use patented inventions for research.
- Change intellectual-property laws that act as barriers to innovation in specific industries, such as those related to data exclusivity (in pharmaceuticals) and those that increase the volume and unpredictability of litigation (especially in information-technology industries).

Action D-2: Enact a stronger research and development tax credit to encourage private investment in innovation. The current Research and Experimentation Tax Credit goes to companies that *increase* their research and development spending above a base amount calculated

¹² The controls governed by the Export Administration Act and its implementing regulations extend to the transfer of technology. Technology includes “specific information necessary for the ‘development,’ ‘production,’ or ‘use’ of a product.” Providing information that is subject to export controls—for example, about some kinds of computer hardware—to a foreign national within the United States may be “deemed” an export, and that transfer requires an export license. The primary responsibility for administering controls on deemed exports lies with the Department of Commerce, but other agencies have regulatory authority as well.

from their spending in prior years. Congress and the administration should make the credit permanent,¹³ and it should be increased from 20% to 40% of the qualifying increase so that the US tax credit is competitive with those of other countries. The credit should be extended to companies that have consistently spent large amounts on research and development so that they will not be subject to the current de facto penalties for having previously invested in research and development.

Action D-3: Provide tax incentives for US-based innovation. Many policies and programs affect innovation and the nation's ability to profit from it. It was not possible for the committee to conduct an exhaustive examination, but alternatives to current economic policies should be examined and, if deemed beneficial to the United States, pursued. These alternatives could include changes in overall corporate tax rates and special tax provisions providing incentives for the purchase of high-technology research and manufacturing equipment, treatment of capital gains, and incentives for long-term investments in innovation. The Council of Economic Advisers and the Congressional Budget Office should conduct a comprehensive analysis to examine how the United States compares with other nations as a location for innovation and related activities with a view to ensuring that the United States is one of the most attractive places in the world for long-term innovation-related investment and the jobs resulting from that investment. From a tax standpoint, that is not now the case.

Action D-4: Ensure ubiquitous broadband Internet access. Several nations are well ahead of the United States in providing broadband access for home, school, and business. That capability can be expected to do as much to drive innovation, the economy, and job creation in the 21st century as did access to the telephone, interstate highways, and air travel in the 20th century. Congress and the administration should take action—mainly in the regulatory arena and in spectrum management—to ensure widespread affordable broadband access in the very near future.

Conclusion

The committee believes that its recommendations and the actions proposed to implement them merit serious consideration if we are to ensure that our nation continues to enjoy the jobs, security, and high standard of living that this and previous generations worked so hard to create. Although the committee was asked only to recommend actions that can be taken by the federal government, it is clear that related actions at the state and local levels are equally important for US prosperity, as are actions taken by each American family. The United States faces an enormous challenge because of the disparity it faces in labor costs. Science and technology provide the opportunity to overcome that disparity by creating scientists and engineers with the ability to create entire new industries—much as has been done in the past.

It is easy to be complacent about US competitiveness and preeminence in science and technology. We have led the world for decades, and we continue to do so in many research fields today. But the world is changing rapidly, and our advantages are no longer unique. Some will argue that this is a problem for market forces to resolve—but that is exactly the concern.

¹³ The current R&D tax credit expires in December 2005.

Market forces are *already at work* moving jobs to countries with less costly, often better educated, highly motivated workforces and friendlier tax policies.

Without a renewed effort to bolster the foundations of our competitiveness, we can expect to lose our privileged position. For the first time in generations, the nation's children could face poorer prospects than their parents and grandparents did. We owe our current prosperity, security, and good health to the investments of past generations, and we are obliged to renew those commitments in education, research, and innovation policies to ensure that the American people continue to benefit from the remarkable opportunities provided by the rapid development of the global economy and its not inconsiderable underpinning in science and technology.

Some Competitiveness Indicators

US Economy

- The United States is today a net importer of *high-technology* products. Its trade balance in high-technology manufactured goods shifted from *plus* \$54 billion in 1990 to *negative* \$50 billion in 2001.¹
- In one recent period, low-wage employers, such as Wal-Mart (now the nation's largest employer) and McDonald's, created 44% of the new jobs while high-wage employers created only 29% of the new jobs.²
- The United States is one of the few countries in which industry plays a major role in providing health care for its employees and their families. Starbucks spends more on health-care than on coffee. General Motors spends more on health care than on steel.³
- US scheduled airlines currently outsource portions of their aircraft maintenance to China and El Salvador.⁴
- IBM recently sold its personal computer business to an entity in China.⁵
- Ford and General Motors both have junk bond ratings.⁶
- It has been estimated that within a decade nearly 80% of the world's middle-income consumers would live in nations outside the currently industrialized world. China alone could have 595 million middle-income consumers and 82 million upper-middle-income consumers. The total population of the United States is currently 300 million and it is projected to be 315 million in a decade.⁷
- Some economists estimate that about half of US economic growth since World War II has been the result of technological innovation.⁸
- In 2005, American investors put more new money in foreign stock funds than in domestic stock portfolios.⁹

Comparative Economics

- Chemical companies closed 70 facilities in the United States in 2004 and tagged 40 more for shutdown. Of 120 chemical plants being built around the world with price tags of \$1 billion or more, one is in the United States and 50 are in China. No new refineries have been built in the United States since 1976.¹⁰
- The United States is said to have 7 million illegal immigrants,¹¹ but under the law the number of visas set aside for "highly qualified foreign workers," many of whom contrib-

ute significantly to the nation's innovations, dropped to 65,000 a year from its 195,000 peak.¹²

- When asked in spring 2005 what is the most attractive place in the world in which to “lead a good life”, respondents in only one (India) of the 16 countries polled indicated the United States.¹³
- A company can hire nine factory workers in Mexico for the cost of one in America. A company can hire eight young professional engineers in India for the cost of one in America.¹⁴
- The share of leading-edge semiconductor manufacturing capacity owned or partly owned by US companies today is half what it was as recently as 2001.¹⁵
- During 2004, China overtook the United States to become the leading exporter of information-technology products, according to the OECD.¹⁶
- The United States ranks only 12th among OECD countries in the number of broadband connections per 100 inhabitants.¹⁷

K–12 Education

- Fewer than one-third of US 4th grade and 8th grade students performed at or above a level called “proficient” in mathematics; “proficiency” was considered the ability to exhibit competence with challenging subject matter. Alarming, about one-third of the 4th graders and one-fifth of the 8th graders lacked the competence to perform even basic mathematical computations.¹⁸
- In 1999, 68% of US 8th grade students received instruction from a mathematics teacher who did not hold a degree or certification in mathematics.¹⁹
- In 2000, 93% of students in grades 5–9 were taught physical science by a teacher lacking a major or certification in the physical sciences (chemistry, geology, general science, or physics).²⁰
- In 1995 (the most recent data available), US 12th graders performed below the international average for 21 countries on a test of general knowledge in mathematics and science.²¹
- US 15-year-olds ranked 24th out of 40 countries that participated in a 2003 administration of the Program for International Student Assessment (PISA) examination, which assessed students’ ability to apply mathematical concepts to real-world problems.²²
- According to a recent survey, 86% of US voters believe that the United States must increase the number of workers with a background in science and mathematics or America’s ability to compete in the global economy will be diminished.²³
- American youth spend more time watching television²⁴ than in school.²⁵
- Because the United States does not have a set of national curricula, changing K–12 education is challenging, given that there are almost 15,000 school systems in the United States and the average district has only about 6 schools.²⁶

Higher Education

- In South Korea, 38% of all undergraduates receive their degrees in natural science or engineering. In France, the figure is 47%, in China, 50%, and in Singapore 67%. In the United States, the corresponding figure is 15%.²⁷

- Some 34% of doctoral degrees in natural sciences (including the physical, biological, earth, ocean, and atmospheric sciences) and 56% of engineering PhDs in the United States are awarded to foreign-born students.²⁸
- In the U.S. science and technology workforce in 2000, 38% of PhDs were foreign-born.²⁹
- Estimates of the number of engineers, computer scientists, and information technology students who obtain 2-, 3-, or 4-year degrees vary. One estimate is that in 2004, China graduated about 350,000 engineers, computer scientists, and information technologists with 4-year degrees, while the United States graduated about 140,000. China also graduated about 290,000 with 3-year degrees in these same fields, while the US graduated about 85,000 with 2- or 3-year degrees.³⁰ Over the past 3 years alone, both China³¹ and India³² have doubled their production of 3- and 4-year degrees in these fields, while the United States³³ production of engineers is stagnant and the rate of production of computer scientists and information technologists doubled.
- About one-third of US students intending to major in engineering switch majors before graduating.³⁴
- There were almost twice as many US physics bachelor's degrees awarded in 1956, the last graduating class before Sputnik than in 2004.³⁵
- More S&P 500 CEOs obtained their undergraduate degrees in engineering than in any other field.³⁶

Research

- In 2001 (the most recent year for which data are available), US industry spent more on tort litigation than on research and development.³⁷
- In 2005, only four American companies ranked among the top 10 corporate recipients of patents granted by the *United States* Patent and Trademark Office.³⁸
- Beginning in 2007, the most capable high-energy particle accelerator on Earth will, for the first time, reside outside the United States.³⁹
- Federal funding of research in the physical sciences, as a percentage of GDP, was 45% less in FY 2004 than in FY 1976.⁴⁰ The amount invested annually by the US federal government in research in the physical sciences, mathematics, and engineering combined equals the annual increase in US health care costs incurred every 20 days.⁴¹

Perspectives

- “If you can solve the education problem, you don’t have to do anything else. If you don’t solve it, nothing else is going to matter all that much.” —Alan Greenspan, outgoing Federal Reserve Board chairman⁴²
- “We go where the smart people are. Now our business operations are two-thirds in the U.S. and one-third overseas. But that ratio will flip over the next ten years.” —Intel spokesman Howard High⁴³
- “If we don’t step up to the challenge of finding and supporting the best teachers, we’ll undermine everything else we are trying to do to improve our schools.” —Louis V. Gerstner, Jr., Former Chairman, IBM⁴⁴

- “If you want good manufacturing jobs, one thing you could do is graduate more engineers. We had more sports exercise majors graduate than electrical engineering grads last year.” —Jeffrey R. Immelt, Chairman and Chief Executive Office, General Electric⁴⁵
- “If I take the revenue in January and look again in December of that year 90% of my December revenue comes from products which were not there in January.” —Craig Barrett, Chairman of the Intel Corporation⁴⁶
- “When I compare our high schools to what I see when I’m traveling abroad, I am terrified for our workforce of tomorrow.” —Bill Gates, Chairman and Chief Software Architect of Microsoft Corporation⁴⁷
- “Where once nations measured their strength by the size of their armies and arsenals, in the world of the future knowledge will matter most.” —President Bill Clinton⁴⁸
- “Science and technology have never been more essential to the defense of the nation and the health of our economy.” —President George W. Bush⁴⁹

Notes for Some Competitiveness Indicators and Perspectives

¹ For 2001, the dollar value of high-technology imports was \$561 billion; the value of high-technology exports was \$511 billion. See National Science Board. 2004. *Science and Engineering Indicators 2004* (NSB 04-01). Arlington, Virginia. National Science Foundation. Appendix Table 6-01. Page A6-5 provides the export numbers for 1990 and 2001 and page A6-6 has the import numbers.

² Steve Roach. “More Jobs, Worse Work.” *New York Times*. July 22, 2004.

³ Chris Noon. 2005. “Starbuck’s Schultz Bemoans Health Care Costs.” *Forbes.com*, September 19. Available at: http://www.forbes.com/facesinthenews/2005/09/15/starbuckshealthcarebenefitscx_cn_0915autofacescan01.html?partner=yahooti; Ron Scherer. 2005. “Rising Benefits Burden.” *Christian Science Monitor*, June 9. Available at: <http://www.csmonitor.com/2005/0609/p01s01-usec.html>

⁴ Sara Kehaulani Goo. “Airlines Outsource Upkeep.” *Washington Post*. August 21, 2005. Available at: <http://www.washingtonpost.com/wp-dyn/content/article/2005/08/20/AR2005082000979.html>
Sara Kehaulani Goo. “Two-Way Traffic in Airplane Repair.” *Washington Post*. June 1 2004. Available at: <http://www.washingtonpost.com/wp-dyn/articles/A5138-2004May31.html>

⁵ Michael Kanellos. 2004. “IBM Sells PC Group to Lenovo.” *News.com*. December 8. Available at: http://news.com.com/IBM+sells+PC+group+to+Lenovo/2100-1042_3-5482284.html

⁶ <http://www.nytimes.com/2005/05/05/business/05cnd-auto.html?ex=1137128400&en=ac63687768634c6d&ei=5070>

⁷ In China, Paul A. Laudicina, *World Out of Balance: Navigating Global Risks to Seize Competitive Advantage*. New York: McGraw-Hill, 2005, p. 76. For the United States, see U.S. Census Bureau. U.S. Population Clock. Available at: www.census.gov. For current population and for the projected population, see Population Projections Program, Population Division, U.S. Census Bureau. Population Projections of the United States by Age, Sex, Race, Hispanic Origin, and Nativity: 1999 TO 2100. Washington, DC January 13, 2000. Available at: <http://www.census.gov/population/www/projections/natsum-T3.html>.

⁸ Michael J. Boskin and Lawrence J. Lau. 1992. Capital, Technology, and Economic Growth. in Nathan Rosenberg, Ralph Landau, and David C. Mowery, eds. *Technology and the Wealth of Nations*. Stanford, CA: Stanford University Press.

⁹ Paul J. Lim. Looking Ahead Means Looking Abroad. *New York Times*. January 8, 2006.

¹⁰ Michael Arndt. 2005. “No Longer the Lab of the World: U.S. Chemical Plants are Closing in Drove as Production Heads Abroad.” *BusinessWeek*, May 2. Available at: http://www.businessweek.com/magazine/content/05_18/b3931106.htm and <http://www.usnews.com/usnews/biztech/articles/051010/10energy.htm>

¹¹ As of 2000, the unauthorized resident population in the United States was 7 million. See US Citizenship and Immigration Services. 2003. "Executive Summary: Estimates of the Unauthorized Immigrant Population Residing in the United States: 1990 to 2000." January 31. Available at: <http://uscis.gov/graphics/shared/statistics/publications/2000ExecSumm.pdf>.

¹² Section 214(g) of the Immigration and Nationality Act (Act) sets an annual limit on the number of aliens that can receive H-1B status in a fiscal year. For FY2000 the limit was set at 115,000. The American Competitiveness in the Twenty-First Century Act increased the annual limit to 195,000 for 2001, 2002, and 2003. After that date the cap reverts back to 65,000. H-1B visas allow employers to have access to highly educated foreign professionals who have experience in specialized fields and who have at least a bachelor's degree or the equivalent. The cap does not apply to educational institutions. In November 2004, Congress created an exemption for 20,000 foreign nationals earning advanced degrees from US universities. See Immigration and Nationality Act Section 101(a)(15)(h)(1)(b). See US Citizenship and Immigration Services. 2005. Public Notice: "USCIS Announces Update Regarding New H-1B Exemptions" July 12. Available at: http://uscis.gov/graphics/publicaffairs/newsrels/H1B_06Cap_011806PR.pdf and US Citizenship and Immigration Services. 2000. "Questions and Answers: Changes to the H-1B Program" November 21. Available at: <http://uscis.gov/graphics/publicaffairs/questsans/H1BChang.htm>.

¹³ Pew Research Center. 2005. "U.S. Image Up Slightly, But Still Negative, American Character Gets Mixed Reviews" Pew Global Attitudes Project. Washington, DC. Available at: <http://pewglobal.org/reports/display.php?ReportID=247>

The interview asked nearly 17,000 people the question: "Supposed a young person who wanted to leave this country asked you to recommend where to go to lead a good life—what country would you recommend?" Except for respondents in India, Poland, and Canada, no more than one-tenth of the people in the other nations said they would recommend the United States. Canada and Australia won the popularity contest.

¹⁴ United States Bureau of Labor Statistics. 2005. International Comparisons of Hourly Compensation Costs for Production Workers in Manufacturing, 2004. November 18. Available at: <ftp://ftp.bls.gov/pub/news.release/History/ichcc.11182005.news>

¹⁵ Semiconductor Industry Association. 2005. "Choosing to Compete." December 12. Available at: <http://www.sia-online.org/downloads/FAD%20'05%20-%20Scalise%20Presentation.pdf>

¹⁶ OECD. 2005. "China Overtakes U.S. As World's Leading Exporter of Information Technology Goods." December 12. Available at: http://www.oecd.org/document/60/0,2340,en_2649_201185_35834236_1_1_1_1,00.html. The main categories included in OECD's definition of ICT (information and communications technology) goods are electronic components, computers and related equipment, audio and video equipment, and telecommunication equipment.

¹⁷ OECD. 2005. "OECD Broadband Statistics, June 2005." October 20. Available at: http://www.oecd.org/document/16/0,2340,en_2649_201185_35526608_1_1_1_1,00.html#data2004

¹⁸ National Center for Education Statistics. 2006. "The Nation's Report Card: Mathematics 2005." See <http://nces.ed.gov/nationsreportcard/pdf/main2005/2006453.pdf>

¹⁹ National Science Board. 2004. Science and Engineering Indicators 2004 (NSB 04-01). Arlington, VA: National Science Foundation. Chapter 1.

²⁰ National Center for Education Statistics. 2004. Schools and Staffing Survey, 2004. "Qualifications of the Public School Teacher Workforce: Prevalence of Out-of-Field Teaching 1987–88 to 1999–2000 (Revised)," p. 10. Available at: <http://nces.ed.gov/pubs2002/2002603.pdf>

²¹ National Center for Education Statistics. 1999. *Highlights from TIMSS*. <http://nces.ed.gov/pubs99/1999081.pdf>

²² National Center for Education Statistics. 2005. "International Outcomes of Learning in Mathematics Literacy and Problem Solving: PISA 2003 Results from the U.S. Perspective," pp. 15 & 29 (<http://nces.ed.gov/pubs2005/2005003.pdf>).

²³ The Business Roundtable. 2006. "Innovation and U.S. Competitiveness: Addressing the Talent Gap. Public Opinion Research." January 12. Available at: <http://www.businessroundtable.org/pdf/20060112Two-pager.pdf>

- ²⁴ American Academy of Pediatrics. "Television—How it Affects Children." Available at: http://www.aap.org/pubed/ZZZGF8VOQ7C.htm?&sub_cat=1. The American Academy of Pediatrics reports that "Children in the United States watch about four hours of TV every day"; this works out to be 1460 hours per year.
- ²⁵ National Center for Education Statistics. 2005. The Condition of Education. Table 26-2 Average Number of Instructional Hours Per Year Spent in Public School, By Age or Grade of Student and Country: 2000 and 2001. Available at: <http://nces.ed.gov/programs/coe/2005/section4/table.asp?tableID=284>. NCES reports that in 2000 US 15 year-olds spent 990 hours in school; during the same year 4th graders spent 1040 hours.
- ²⁶ National Center for Education Statistics. 2006. "Public Elementary and Secondary Students, Staff, Schools, and School Districts: School Year 2003–04." Available at: <http://nces.ed.gov/pubs2006/2006307.pdf>
- ²⁷ Analysis conducted by the Association of American Universities. 2006. *National Defense Education and Innovation Initiative*. Based on data in National Science Board. 2004. *Science and Engineering Indicators 2004* (NSB 04-01). Arlington, VA: National Science Foundation. Appendix Table 2-33. For countries with both short and long degrees, the ratios are calculated with both short and long degrees as the numerator.
- ²⁸ National Science Board. 2004. *Science and Engineering Indicators 2004* (NSB 04-01). Arlington, VA: National Science Foundation. Chapter 2 Figure 2-23.
- ²⁹ National Science Board. 2004. *Science and Engineering Indicators 2004* (NSB 04-01). Arlington, VA: National Science Foundation.
- ³⁰ G. Gereffi and V. Wadhwa. 2005. Framing the Engineering Outsourcing Debate: Placing the United States on a Level Playing Field with China and India. http://memp.pratt.duke.edu/downloads/duke_outsourcing_2005.pdf.
- ³¹ Ministry of Science and Technology (MOST). 2004. *Chinese Statistical Yearbook 2004*. People's Republic of China, Chapter 21, Table 21-11. Available at: <http://www.stats.gov.cn/english/statisticaldata/yearlydata/yb2004-e/indexeh.htm>. The extent to which engineering degrees from China are comparable to those from the United States is uncertain.
- ³² NASSCOM. 2005. *Strategic Review 2005*. National Association of Software and Service Companies, India. Chapter 6. Sustaining the India Advantage. Available at: <http://www.nasscom.org/strategic2005.asp>
- ³³ National Center for Education Statistics. 2004. *Digest of Education Statistics 2004*. Institute of Education Sciences, Department of Education, Washington DC, Table 250. Available at: http://nces.ed.gov/programs/digest/d04/tables/dt04_250.asp.
- ³⁴ Myles Boylan. 2004. Assessing Changes in Student Interest in Engineering Careers Over the Last Decade. CASEE, National Academy of Engineering. Available at: [http://www.nae.edu/NAE/caseecomnew.nsf/weblinks/NFOY-6GHJ7B/\\$file/Engineering%20Interest%20-%20HS%20through%20College_V21.pdf](http://www.nae.edu/NAE/caseecomnew.nsf/weblinks/NFOY-6GHJ7B/$file/Engineering%20Interest%20-%20HS%20through%20College_V21.pdf); Clifford Adelman. 1998. Women and Men on the Engineering Path: A Model for Analysis of Undergraduate Careers. Washington, DC: US Department of Education. [http://www.nae.edu/nae/diversitycom.nsf/98b72da8aad70f1785256da20053deaf/85256cfb00484b5c85256da000002f83/\\$FILE/Adelman_Women_and_Men_of_the_Engineering_Path.pdf](http://www.nae.edu/nae/diversitycom.nsf/98b72da8aad70f1785256da20053deaf/85256cfb00484b5c85256da000002f83/$FILE/Adelman_Women_and_Men_of_the_Engineering_Path.pdf). According to this Department of Education analysis, the majority of students who switch from engineering majors complete a major in business or other non-science and engineering fields.
- ³⁵ National Center for Education Statistics. *Digest of Education Statistics*. The American Institute of Physics Statistical Research Center.
- ³⁶ Spencer Stuart. 2005. "2004 CEO Study: A Statistical Snapshot of Leading CEOs." Available at: http://content.spencerstuart.com/sswebsite/pdf/lib/Statistical_Snapshot_of_Leading_CEOs_relB3.pdf#search=ceo%20educational%20background
- ³⁷ US research and development spending in 2001 was \$273.6 billion, of which industry performed \$194 billion and funded about \$184 billion. National Science Board. 2004. *Science and Engineering Indicators 2004* (NSB 04-01). Arlington, VA: National Science Foundation. One estimate of tort litigation costs in the United States was \$205 billion in 2001. Jeremy A. Leonard. 2003. "How Structural Costs Imposed on U.S. Manufacturers Harm Workers and Threaten Competitiveness." Prepared for the Manufacturing Institute of the National Association of Manufacturers. Available at: http://www.nam.org/s_nam/bin.asp?CID=216&DID=227525&DOC=FILE.PDF.

³⁸ US Patent and Trademark Office 2006. USPTO Annual List of Top 10 Organizations Receiving Most U.S. Patents. January 10, 2006. <http://www.uspto.gov/web/offices/com/speeches/06-03.htm>

³⁹ CERN. Internet Homepage. <http://public.web.cern.ch/Public/Welcome.html>.

⁴⁰ AAAS. 2004. "Trends in Federal Research by Discipline, FY 1976–2004." October. Available at: <http://www.aaas.org/spp/rd/disc04tb.pdf> and <http://www.aaas.org/spp/rd/discip04c.pdf>

⁴¹ Centers for Medicare and Medicaid Services. 2005. *National Health Expenditures*. Available at: <http://www.cms.hhs.gov/NationalHealthExpendData/downloads/tables.pdf>

⁴² U.S. Department of Education, Office of the Secretary, *Meeting the Challenge of a Changing World: Strengthening Education for the 21st Century*, Washington, D.C., 2006.

⁴³ In: Wallace, Kathryn. 2005. "America's Brain Drain Crisis Why Our Best Scientists are Disappearing, and What's Really at Stake." *Readers Digest*. December.

⁴⁴ Louis V. Gerstner, Jr. Former Chairman, IBM in The Teaching Commission. 2004. *Teaching at Risk: A Call to Action*. New York: City University of New York. www.theteachingcommission.org.

⁴⁵ Remarks by Jeffrey R. Immelt to Economic Club of Washington as reported in Irwin, Neil. 2006. "US Needs More Engineers, GE Chief Says." *Washington Post*. January 23, 2006.

⁴⁶ Craig Barrett. 2006. Comments at public briefing on the release of The Gathering Storm report. October 12, 2005. See <http://www.nationalacademies.org/morenews/20051012.html>

⁴⁷ Bill Gates. 2005. Speech to the National Education Summit on High Schools. February 26. Available at: <http://www.gatesfoundation.org/MediaCenter/Speeches/BillSpeeches/BGSpeechNGA-050226.htm>

⁴⁸ William Jefferson Clinton. "Commencement Address at Morgan State University in Baltimore, Maryland." May 18, 1997. Government Printing Office. *1997 Public Papers of the Presidents of the United States, Books I and II*. Available at: <http://www.gpoaccess.gov/pubpapers/wjclinton.html>

⁴⁹ Remarks by President George W. Bush in Meeting with High-Tech Leaders. March 28, 2001. Available at: <http://www.whitehouse.gov/news/releases/2001/03/20010328-2.html>

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More information, including the full body of the report, is available at COSEPUP's Web site, www.nationalacademies.org/cosepup.

The Global Diffusion of S&T and the Rise of China

*Adam Segal*¹

While the sky is not yet falling—the United States still accounts for more than 30 percent of total global research and development and the American economy remains the world’s most innovative—the increasingly global nature of science and technology development raises significant economic, political and security challenges for the United States. For the past 50 years, America’s edge has depended on its ability to invent and exploit new technologies faster than anyone else. That edge is no longer a given. Globalization is changing how and where innovation occurs; and new, serious competitors are emerging in Asia.

Innovation today is private, collaborative, and global. Private businesses have replaced national governments as the primary source of funds for R&D. Cheaper communication technologies, especially the Internet, have allowed American companies to operate more globally, divide production into discrete functions, contract out to producers in different countries, and transfer technological know-how to foreign partners. As soon as scientists begin work on a new chip for Intel at its Oregon headquarters, Indian programmers simultaneously begin working on the software, while manufacturing engineers in Taiwan fine-tune Intel’s production process to speed new chips to market. This internationalization is not new. What is new is that more R&D is going to developing countries; according to the UN, more than half the world’s top R&D spenders are already conducting research and development in China, India, or Singapore.

Greater China (China, Hong Kong, and Taiwan) and India are trying to exploit the opportunities created by globalization. These countries want to do more than provide the lab space for American firms to innovate; they want to develop the next wave of advanced technologies that generate new industries, new jobs, and higher standards of living. They have made innovation a national priority, and they are amassing the investment, talent, and infrastructure required to compete globally. In China, expenditures on R&D rose from 0.6 percent of GDP in 1995 to 1.44 percent in 2005; the goal for 2020 is 2.5 percent of GDP. In support of the drive toward a “knowledge-based economy,” Chinese universities have awarded a growing number of advanced degrees. In order to encourage individual risk taking and reward technological entrepreneurship, countries throughout the region are experimenting with stock options and venture capital funds; cities such as Shanghai and Beijing now offer financial incentives to students and managers to return from Silicon Valley to set up their own companies.

Political influence and military power all flow from the United States’ technological predominance. After World War II, the United States built a political order in Asia based on close security alliances and economic access to the U.S. domestic markets. As allies in the battle against communism Japan, Korea, and Taiwan were allowed to sell increasingly sophisticated

¹ Maurice R. Greenberg Senior Fellow in China Studies, Council on Foreign Relations.

goods to American consumers, even as they protected their own markets from competition. Today, the emergence of China and India as technology innovators not only raises the possibility of bitter conflicts over trade, but also that new consumer markets within Asia may displace the American economy as the most important final market for technology products. During his April 2005 trip to India, Chinese premier Wen Jiabao spoke of the potential combination of Chinese hardware and Indian software, claiming, “We will be able to lead the world in the sector and a day will come when we can herald the beginning of the Asian century of information technology.”

Technological capacity also generates less traditional forms of influence. Having the most innovative economy not only gives the United States the ability to set the rules for technology standards and implementation, it also means that it takes the leading role in defining business practices that brush against political and cultural values like the right to privacy, the uses of information security, and the granting of intellectual property rights. There is also a diffusion of American culture and values as scientists and engineers return home from Silicon Valley with new ideas about competition, opportunity, and personal relations. During the Cold War, Soviet scientists and students returned home to become key forces in liberalizing the Communist Party. The political scientist James Kurth has written that the real source of American soft power is

. . . the foreign students who come to American universities and learn American principles and practices. . . . When (or if) they return to their home countries, they will know both the culture and customs of their own society and the principles and practices of American society. . . .

National security is also clearly tied to technological capabilities, and the rest of this paper focuses on how the globalization of S&T complicates the security environment in at least three ways, especially in regard to China. First, technological capability is now more widely diffused to potential competitors.² As a 1999 Defense Science Board Task Force on Globalization and Security argued, “Over time, all states—not just the United States and its allies—will share access to much of the technology underpinning the modern military” (Hicks, 1999). India and China are building new, technologically advanced militaries. They are trying to replicate the U.S. model of close relations between the defense sector and private high-technology companies, and they are busy buying and using off-the-shelf software, computers, and telecommunication equipment in order to modernize their armies.

Second, the United States’ access to the most advanced technologies is no longer guaranteed. The leading edge of innovation in individual technological sectors may be located outside of the United States. Moreover, the leading edge may be difficult to situate as it jumps around from country to country. In addition, the dispersal of the components of the American innovation system to other countries—manufacturing to China or R&D to India—may disrupt the ecosystem of innovation at home. Third, even as the United States remains the predominant science and technology power, the long lead times it historically has had over potential competitors are likely to disappear. The United States will have to begin to think about how to respond when its technological lead is measured in months or years, not decades.

² There is also the reality that individuals or small groups with access to new technologies can now do greater damage to U.S. national interests. I will, however, focus on state actors.

During the Cold War, the American and Soviet economies were essentially two separate entities with little or no contact between them. For security (and analytical) purposes, the ownership, operation, and control of technology were all fairly limited and unified. Those neat distinctions no longer exist; the Chinese and American economies, for example, are highly interdependent, and production chains stretch across the Pacific, involving Chinese, American, and Taiwanese enterprises, managers, and technicians. In the final section, I raise some of the analytical questions brought about by the globalization of science and technology.

Diffusion

The globalization of technology has both raised the indigenous capabilities of defense and defense-related industries in Asia and increased the opportunities for militaries to purchase dual-use, commercial-off-the-shelf technologies in the global marketplace.

China is perhaps the biggest beneficiary from the globalization of science and technology. Global production networks link Chinese firms to foreign customers, investors, technology suppliers, and strategic partners through foreign direct investment (FDI) and contract-based alliances. The networks now embrace more than manufacturing as R&D centers are being located in China and India. In China, the number of foreign R&D units rose from zero to over 700 in a decade. Of 885 greenfield R&D projects announced between 2002 and 2004 in Asia, 723 (more than 80 percent) were in China and India. In addition, China benefits from the growth of informal knowledge networks, students and scientists who return to newly established labs in Beijing, and technological entrepreneurs and venture capitalists moving from Silicon Valley to Shanghai.³ The end result is that China can leverage the international system of innovation, and that of the United States in particular, to offset weaknesses in its own national innovation system.

Indigenous innovative capabilities are seen as an important strategic priority. Chinese policymakers are working to ensure that the civilian economy makes a more direct contribution to defense modernization. Policies like the 863 and 973 plans straddle civilian and defense S&T agencies and foster the development of critical dual-use technologies such as information technology, aerospace, and lasers.

The January 2006 mid- to long-term science and technology plan makes explicit the need to develop dual-use technologies:

We must set up new mechanisms that are suited to the characteristics of defense-related science research and dual-use military and civilian science research activities. We must make overall plans and coordinate basic military-civilian research, enhance the integration of high-tech R&D forces for military and civilian applications, establish coordinating mechanisms to promote effective interaction between the military and civilian sectors, achieve the coordinated development and production of military products and civilian products, and promote the integration of various links of S&T for military and civilian purposes. (Xinhua, 2006)

³ There are also espionage networks. The national counterintelligence strategy declares that the “key modality is no longer the spy, but the businessman, student, or academic.”

The plan continues to list 16 critical technologies, among them core electronic components, high-end universal chips, and basic software; very-large-scale integrated circuit manufacturing technologies and turnkey techniques; new-generation broadband wireless mobile communications; high-grade numerically controlled machine tools and basic manufacturing technologies.

So far the most progress has been made in the IT sector. The People's Liberation Army (PLA) can now turn to Chinese firms for subcomponents and modified commercial goods—computers and communication systems especially—but not advanced weapon systems. Still, these have had a real impact, and research by James Mulvenon (2002) ably shows how Huawei and other commercially competitive firms enabled the PLA to move to digital communications via fiber-optic cable, satellite, microwave, and encrypted high-frequency radio and thus greatly improved Chinese command, control, communication, computer, intelligence, surveillance, and reconnaissance (C4ISR) capabilities. At the same time, Chinese policymakers have begun the process of dismantling many of the barriers between civilian and defense R&D as well as creating new institutions to promote cooperation between the defense S&T establishment and its civil counterparts. Currently, the military is looking to repeat the success of the IT sector and develop and utilize commercial capabilities in microelectronics, space, new materials, sensors and tracking, and computer-aided manufacturing processes.

The globalization of technology has also meant that there are few technologies unique to any one company or country. The 2005 annual report to Congress on Chinese military power claims that foreign import is central to Beijing's technology acquisition strategy, and priorities include IT, microelectronics, nanotechnology, space, new materials, propulsion, CAD, and CAM.⁴ For most of these technologies, China can look to suppliers in Europe, Japan, Korea, Taiwan, Russia, Israel, or elsewhere as there is little political support for export controls on dual-use technologies outside of the United States.

Access

Another security challenge raised by the globalization of science and technology is the continued access of the United States to critical technologies. This is the result not only of locating R&D abroad and of the rising capabilities of potential competitors. It is also a question of whether weapons and other defense systems have become so complex (and dependent on so many suppliers, foreign and domestic) that it may no longer be possible to build something that is just for the U.S. military.

The Defense Science Board report, *High Performance Microchip Supply* (2005), addresses both of these concerns with regard to the migration of IC manufacturing abroad. The report argues that "trustworthiness and supply assurance for components used in critical military and infrastructure applications are casualties of this migration." In response to this challenge, the report recommends combating foreign government efforts to lure IC manufactures offshore, increased university research funding for microelectronic in order to ensure that the United States remains the most attractive locale for students and professors, greater cooperation between the Department of Defense and commercial producers through initiatives such

⁴ See Office of the Secretary of Defense (2005). CAD is computer-aided design. CAM is computer-aided manufacturing.

as the trusted foundry initiative, and bilateral negotiations with allies, and with Taiwan, to harmonize export control regulations practices and standards.

The United States will also have to dedicate more resources to tracking technology developments abroad so as not to be surprised by swift technological breakthroughs. China, India, Korea, and Japan are all trying to take the lead in three areas that are likely to generate the next wave of innovation: information technology, biotech, and nanotechnology. Progress is not likely to be linear and may occur in rapid bursts. Monitoring these developments, and exploiting them, will require a different type of training than most graduate students (and defense analysts) now receive. It will require more international experience, preferably in a foreign lab; a greater understanding of how new technologies are developed, applied, and commercialized; and coursework that emphasizes interdisciplinary flexibility over specialization in one field.

There is also the larger issue of what impact the changing structure of innovation has on economic security. The increasingly widespread perception that most engineering jobs are subject to offshoring makes a career path that most undergraduates already find unattractive—especially when compared to the financial rewards of pursuing law or an MBA—even less desirable. More restrictive visa regulations and the increasing opportunities back in Bangalore and Beijing may deprive the United States of graduate students and a source of entrepreneurship.

Finally, while innovation is global, it is still embedded in certain types of industrial structures, social organizations, and regulatory frameworks. The movement of R&D, design, or key manufacturing processes to Asia may destabilize the complex interactions between firms and universities that drive technological discovery at home. Removing any one component from technology clusters in Austin or Research Triangle could diminish its ability to generate new technologies.

Analytical Issues

Responding to the problems of diffusion and access requires a clear understanding of the process of innovation within China, an increasingly difficult task even with greater access to Chinese sources and a (relative) degree of transparency about S&T developments. Part of the problem is understanding innovation as a nonlinear process and securing reliable data about China. But there is also a mismatch between most traditional S&T analysis, which is based in the national innovation school, and what is an increasingly international process. So while writings about S&T policy may focus on the reform of the Chinese Academy of Science or the shift of R&D funding to state-owned enterprises, the more critical developments may be occurring at the nexus between multinational R&D centers and local firms, or U.S. venture capital funds and local chip design companies. Compounding this problem is the fact that the outcomes of these processes remain unclear. As Chinese analysts are fond of saying, “Globalization is a double-edged sword.” The United States fears that shifting patterns of manufacturing could play havoc with the delicate ecosystem of innovation at home, but the Chinese also worry that foreign multinational corporations attract the best and the brightest talent with higher salaries and greater international opportunities, effectively removing them from the Chinese system.

A related problem is it is increasingly difficult for outside observers to measure the rate of progress in the Chinese system because progress in the system is dependent on development in what can be called the *software of innovation*: rule of law, transparency, governance, and management structures; analytical, operations, and language skills; academic honesty; risk toler-

ance; and creativity. These developments are not easily observable nor do they have established metrics.

Finally, despite being about globalization, this paper is still focused on geography: Shanghai as opposed to Silicon Valley, or Shanghai connected to Silicon Valley. It is the link that is important, and these networks are built by individuals who interact at the nexus of the Chinese and American systems of innovation. Having a better understanding of the strategies and objectives of these individuals might make it easier to develop adequate policy prescriptions.

The policy responses to the changing structure of innovation have fallen into three broad frameworks: run faster, reinforce the walls, and learn to live with it. The “run faster” proposals have grown out of *Rising Above the Gathering Storm* and focus on supporting and bolstering the innovation ecosystem in the United States. President Bush’s American competitiveness initiative promises to double federal spending on basic research over a decade and to train 70,000 high school teachers to lead advanced-placement courses in math and science. On the “reinforce the walls” side, the Department of Commerce has been looking for ways to balance the economic benefits of U.S.-China technological trade with the security risks. Commerce tried to tighten the deemed export controls,⁵ but withdrew the provisions after protests from the academic and business community. It is now discussing new controls on approximately 47 items, mainly from the anti-terrorism list, and affects the chemical, computer, telecommunication, electronics, and encryption software industries. Finally, there are those proposing a more collaborative approach, one that assumes that the United States cannot maintain a technological lead in all sectors and must pick and choose areas where it should compete and where it can collaborate with foreign producers. So far, these responses have not been mutually exclusive, and a combination of the strategies seems the most appropriate given the uncertainties about globalization.

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⁵ According to the Bureau of Industry and Security, U.S. Department of Commerce, the “deemed” export rule is an export of technology or source code (except encryption source code) “deemed” to take place when it is released to a foreign national within the United States. See §734.2(b)(2)(ii) of the Export Administration Regulations (EAR). For brevity, these questions and answers refer only to “technology” but apply equally to source code.

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Scientific Wealth and the Scientific Investments of Nations

Jonathan Adams¹

The background for the meeting identifies an agenda shared by the United States, the UK, and other countries that have been able to enjoy a prime position at the edge of science and technology's endless frontier. The geography along the frontier is getting complex and the territory is more densely populated. Resources are limited. We have to get better at exploiting as well as creating scientific wealth.

Wealth, in scientific terms, is the intellectual property that potentially contributes to innovative products and processes and thereby creates real economic value. In the late 20th century, economists could attribute half the gains in gross national product and 85 percent of the gains in per capita income to the application and exploitation of science and technology research. The scientific investments of nations have made that growth possible.

But wealth is threatened, financially and in other ways, by competition from elsewhere. I was asked to reflect on what the work carried out by my company, Evidence, for research agencies in the UK and elsewhere in Europe has to say about the issues, particularly for U.S. national security, raised by the *Rising Above the Gathering Storm* report. Do the trends in U.S. science and technology pose a problem and what is its nature? Where and when will the impact be felt most? What steps should be taken at the policy level, and how might the United States judge which steps will be most effective and cost-effective?

We cannot sufficiently anticipate what will happen “next” and the sad history of “fore-sight” exercises shows us that consensus judgments all too often aim for a low horizon. Pointing to simple answers only addresses simple questions of what is happening “now.” We cannot stop others discovering things, so we must take an overview of the broad research environment and ask how we can best position ourselves to make use of the widest range of discovery, in a broad sense. Then we must make the most effective use of that knowledge by bringing decades of research and technology experience to bear.

What factors seem to be most influential? **First, there is a new geography of science.** The United States remains the outstanding global leader in research; I will discuss analyses around this. However, because greater scientific investment is being made by other nations, their research base activity is now closer to that of the United States than was formerly the case. The United States is not necessarily poorer scientifically, but it is not as uniquely “rich.” On the other hand, it also has a more diverse external basket of wealth on which to draw because there was a deficit of investment (and achievement) elsewhere in the past. I believe that the United States can look to use this, not suffer from it.

¹ Evidence, Ltd., UK.

Second, we need new pictures for interpreting research performance. Almost all widely discussed analyses rely on single-point metrics: averages of income or outputs. That makes good headline stuff and is readily interpretable but it does not capture the complexity of the research process. I prefer to look at research in the round, across several indicators or across several disciplines through, e.g., radar diagrams, which we call Research Footprints®. The U.S. Footprint remains big!

We should consider the spread of activity rather than its average. The UK has average citation performance² above world benchmark, but about one-quarter of its papers never get cited and more than half have lower-than-world-average citation counts (which is a shock to policymakers). I believe we should look at performance profiles rather than averages if we want to understand the underlying structure, because only then can we identify points for change.

We should spend less time looking at performance in single disciplines. We know that most universities that have great chemistry programs also have great physics programs, but we are less certain about synergies and coincidence. We should pay attention to analyses that allow us to look across the breadth of a nation's activity, which means analyzing its research diversity and the variance in its performance as well as peaks. The United States has an outstanding position in this regard, and I will show that the UK also does well. I suggest that research-diverse nations are able to switch into new areas more rapidly as they evaluate opportunities and respond to threats than are those that invest only in current peaks.

Third, there are significant rewards to be gained in international collaboration. We have looked at the pattern of collaboration between the UK, United States, and Germany, and we have started to look at the growing interface with China. There is no doubt that internationally collaborative work tends to be of a higher average impact (as measured by, e.g., citation data) than solely national work. The value added is seen for leading U.S. universities as well as for their UK partners.

Collaboration has costs—sharing agendas and reaching compromises on priorities as well as time, travel, and equipment—so people only work together when there are major gains to be made. But when they collaborate they also share ideas, information, and access to networks, which adds hugely to the accessible intellectual property for the project and drives more significant and pervasive outcomes.

I suggest that there would be advantage to the United States in considering how collaboration with preferred partners can be enabled without so many hurdles. Much international collaboration fails to fly because of the “double jeopardy” when researchers in two different research bases each have to win funds for their joint operation, the success of which depends on the delivery of both funding elements.

Fourth, researcher mobility confers great benefit. The United States has been the target country for generations of young researchers from all over the world. They have benefited from U.S. investment in the equipment and facilities of its research base, from an open intellectual atmosphere, and from the quality of life on offer during their stay. Many have then gone back

² Citations are subsequent references to earlier publications, indicating the influence of the earlier work on the new. Analysts generally agree that more frequently cited outputs are (with certain caveats) those that have had greater influence in their field. By extension, highly cited outputs (defined by Thomson Scientific as the world's top 1 percent most cited papers) or high average citation rates are taken as an indicator of excellence in basic research. Note that underlying citation rates are culturally influenced and vary between fields, so comparator data need to be normalized to account for such differences.

to their country of origin and contributed significantly to the development and growth of their original research base.

Many of the UK's most highly cited researchers have spent time abroad; many had spent time in the United States, sometimes at several stages of their progression. By contrast, fewer than 10 percent of highly cited U.S. researchers had spent work-time in other countries. (We acknowledged that the opportunities for extensive mobility within the United States were, of course, a confounding factor.)

High mobility is also a characteristic of small but research-effective nations such as the Netherlands and the Scandinavian countries. The greatest degree of international mobility is found among the Swiss. Switzerland has an extraordinarily powerful research economy and it also has a very high degree of internationally collaborative authorship in its publications. We believe that the Swiss gain a great degree of gearing from sending their researchers out, recruiting from a diverse diaspora, and encouraging their research establishment to maintain collaborative links so as to enable their institutions to benefit from partner-country as well as domestic investment.

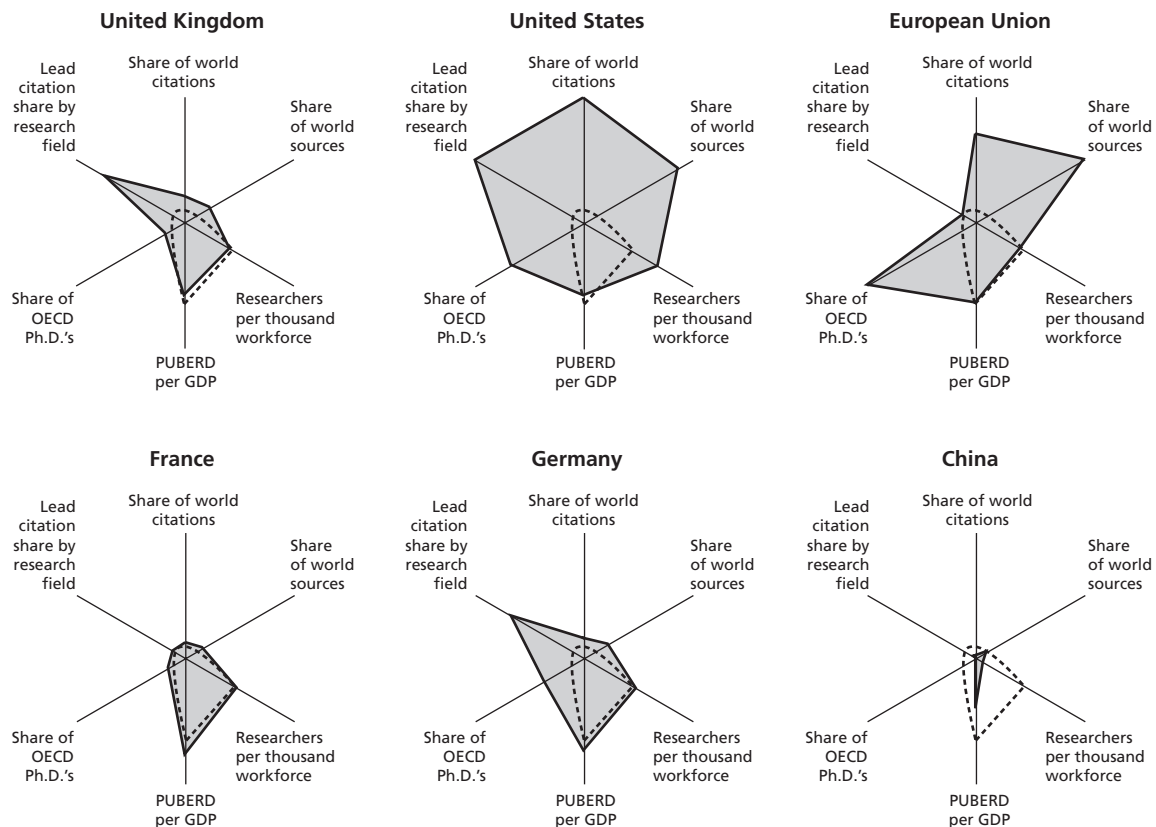
Our conclusion is that to maintain the scientific wealth of the United States—the diversity and richness of innovative ideas drawn from a growing world pool of knowledge—its researchers should get out more. U.S.-trained researchers in their early careers will be attractive recruits for many leading research institutions across the world. They will be able to establish selective links with international collaborative networks, increase their understanding of current research in these other domains (not only current knowledge but philosophy, structure, approach, and method), and they can readily maintain preferred links on their return. Other nations have used research visits to get to know the United States; now is the time for the United States to increase its intelligence about the emerging leaders in the new research geography and draw on their scientific wealth as well as its own.

The United States and the Geography of Science

I will start by summarizing some key information from our annual report to the UK government, including some of the statistics comparing the input, activity, and output performance of the G8 and select members of the rest of the world. We regularly cover a basket of about 30 countries, chosen to cover all regions and to cover both established and emergent research players. We prefer to look at the research process as a whole, for which we use seven themes from inputs to productivity to outcomes, and we structure our analyses around specific disciplines to which the various data sources will map sensibly.

Our work suggests that the current situation of the United States continues to compare well to that of other countries. This is most readily seen in the grand summary we produce in our Research Footprints, which cover a select group of key indicators (public R&D [PUBERD] as a share of GDP, share of OECD Ph.D.'s, share of world publications, share of world citations, lead citation share by research field, researchers per thousand workforce).

Figure 1
Research Footprints



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The status of the United States is quite clear. It will continue to be a strong performer across the board and it contributes the maximum volume performance on most indicators because of its sheer size. But ratios change the picture: U.S. nominal efficiency is less impressive and its effectiveness is being challenged. One example of an exception is in terms of public expenditure on R&D as a proportion of GDP. On that indicator there are smaller nations, such as Sweden, Denmark, and the Netherlands, that all spend relatively more. Other indicators show that they all have relatively highly skilled populations and rising performance in niche research areas.

Research is not about quantity, so efficiency measures need careful consideration. If we talk about a “bang per buck” index such as citations per GERD (gross domestic expenditure on R&D), then the United States has not only slipped back in ranking, now behind major EU countries, but has actually seen a decrease in value while others are on a rising gradient. But this is *nominal* because it does not take into account the value of the work being done, only the cost per unit. The relationship between the value of a research outcome and the cost of acquisition is not simple, but we can agree that each successive step in a challenging research program probably costs more. Denmark produces more research papers per unit expenditure than the UK, and Sussex University does better than Cambridge on the same measure, but where would you put a \$10 million investment?

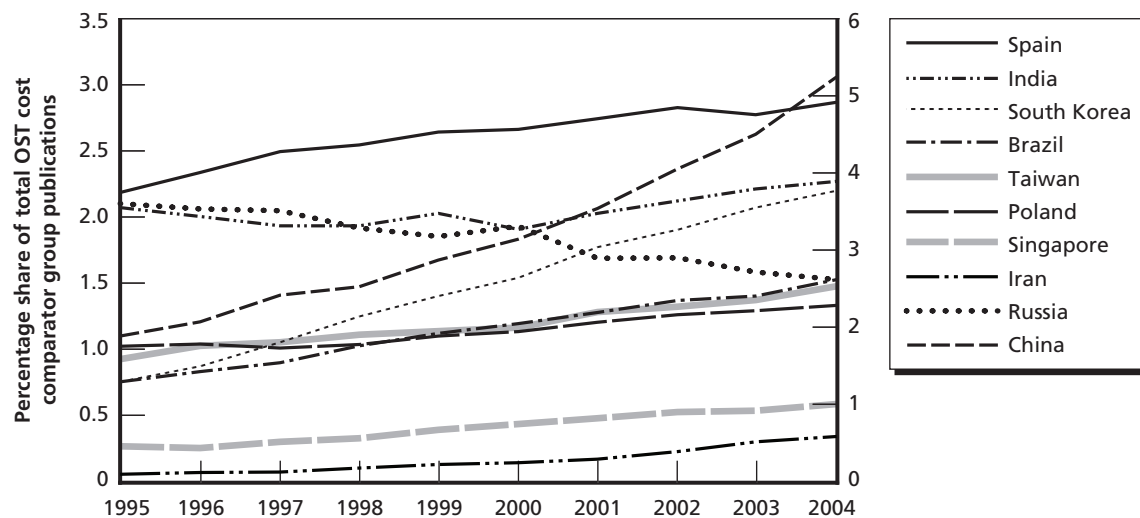
The primary factor affecting the relative U.S. position is that others—particularly but not only new research nations—have invested and improved their position. It is difficult to find, and probably erroneous to seek, evidence that the United States has declined in absolute terms.

- Input GERD for the United States is about 36 percent of the comparison group of nations that we monitor (which includes the G8 and most of the lead EU15). OECD data show this is about 2.6 percent of GDP, which is similar to group average and ahead of the EU15.
- Total business R&D (BERD) is about 1.9 percent of U.S. GDP, compared to an OECD average around 1.5 percent. Business R&D investment fell as a percentage of total R&D spend in the U.S. public sector, however, from around 4 percent in the late 1990s to around 3 percent now. There is a similar and worrying drop in the UK. Figures for business R&D in countries such as China are unreliable at present.
- The U.S. workforce has about 9.5 researchers per thousand, which is higher than the group average (around seven). Researchers also make up an above-average percentage of the national population. The UK has below-average workforce research capacity. China's workforce percentage of researchers remains low (around one per thousand) but in absolute terms this is already about half as many researchers as the United States.
- Output is a smaller share of group activity than input. The United States produces about 30 percent of group Ph.D.'s (down from 34 percent over the five years that data cover) and about 30 percent of journal articles in serials covered by Thomson Scientific (down from 36 percent over ten years, 1996–2005). There are no Ph.D. data for China but its publication output has more than tripled since 1996, is now similar in volume to France, and is accelerating. Iran's publication output has increased tenfold.
- The United States produces about 0.95 research articles per workforce “researcher” (down from 1.2 over the decade) and has consistently ranked 16th of 20 nations (the UK is third at 2.1 articles per head).
- Outcomes are excellent. The United States has 37 percent of group citations (above input share although down from 44 percent) but has an amazing 61 percent of the world's most highly cited papers. China, by contrast, has yet to make a major impact with the quality of its growing output.

So, there is a possible argument that U.S. productivity is below average, but against that must be seen the continuing level of excellence. Good science just does not come cheap.

The pattern of business investment is a concern for the United States and Europe. It is clearly influenced by costs, but it is a particular problem when science quality is so high. Surely investment should be in centers of excellence? The answer is that multinational companies can expatriate parts of their research investments with major savings while retaining access at modest cost to all the scientific wealth generated and held in their domestic domain.

Figure 2
Publication Share Among Fast-Growing Nations



NOTE: Russia and China on axis on the right-hand side.

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This is part of the changing world research map. We have all been aware of the improved Asia-Pacific technology base. The pattern of learning, investment, and improvement had fed into other parts of the R&D cycle and is reflected in the rapid growth of the research base in Singapore, South Korea, and Taiwan. The unit cost of research is much lower in those economies and rapid growth in employing an expanding, highly trained workforce has been feasible. Now their profile is dwarfed by the even steeper trajectory of China. Observers forecast much for the research potential of India, although that has yet to deliver. In other regions there is also rapid R&D development—from a very low historical base—in previously nontechnological countries like Iran.

The status of research leaders in this changing map needs to be analyzed with care. Much of the growth is in quantity of basic research investment rather than achievement, but some of the countries have niche expertise. That expertise varies from field to field so the position of the established players is threatened on many fronts, but most challengers are still individually far behind the lead positions.

The key destabilizing factor is the emergence of China, far more rapidly and on a far greater scale than the others in the new geography. This changes the map even more because it brings with it profound economic influences as well as intellectual challenges. What China has yet to show is whether it has a research management structure that can deliver the quality of output that the United States continues to achieve, and whether it can then apply this across the diversity of fields in which the United States excels.

We also compare research performance between countries at the level of nine broad fields. Based on citations received by each research paper published, the United States has been the leader among the G8 and other major research economies in all of these fields. However, its citation performance has tended to be “flat” where others have shown an upturn in recent years. This is partly a problem born of success: when you’re at the top there is only one direction you can move. In our most recent citation data from Thomson Scientific:

- The United States remains ahead in clinical, physical, and social sciences and in business.
- The position in mathematics and primary health is fuzzier, but the U.S. position is probably sound.
- It has been caught by the UK in the biological sciences and by Germany in engineering.
- It has been passed by Germany in environmental sciences.
- The Netherlands and Switzerland have also moved ahead in some areas but on a smaller, niche platform. Switzerland often produces a great profile for its small size.

The United States has exceptional performance across many disciplines. It is being challenged in some areas, but by different countries that specialize in particular competencies. Few can seek to emulate the depth and breadth of U.S. performance. The next section looks at ways of visualizing this side of scientific wealth.

The Distribution of Research Performance

Research performance indicators are interesting reporting tools, and when many point in the same direction then they are probably telling a sound story. The problem is that such metrics as averages explain nothing about the reasons behind the net performance.

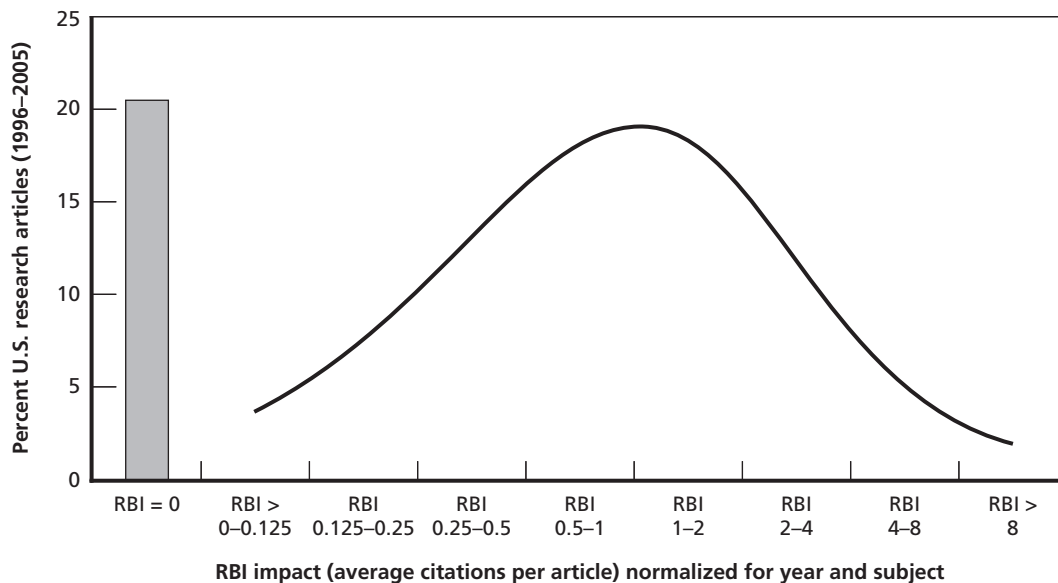
We spend a lot of time looking for new ways of presenting our analyses of research data so that we can either see the data in a new light or see how different indicators “fit” with one another. A Research Footprint is one way of doing that, because it allows us to look at several factors simultaneously and see whether an institution has a balanced performance, how its shape compares with competitors’, and whether it is consistent over time.

We have also taken steps to look at the spread of data behind an indicator. Research performance indicators frequently draw on large data samples and produce an average. This may be income per unit activity, Ph.D.’s per staff, or citations per paper. The underlying data are always highly skewed, with many low-performing points and a long scatter of high-performing points. The average thus differs markedly from such metrics as median and mean.

If we can see the components of research performance then we may be able to better identify possible courses for action. We need pictures that tell us more about the real distribution: how much is underachieving, and how much is truly excellent. We have therefore developed a simple but powerful approach to indexing and categorizing data—citation data for the present purpose, but the methodology is generic.

The following chart (analyzing cites for 2.9 million articles over ten years) reveals the underlying Impact Profile™ of U.S. research performance. RBI is citation impact normalized for field and year, where the world average equals 1.0. The bell-shaped curve changes its precise parameters but is consistent across disciplines, time periods, and sub-sectors of the research base. Such an analysis reveals the spread of achievement across performance categories and the proportion of U.S. research that is of exceptional excellence and that which is not.

Figure 3
Percent U.S. Research Articles (1996–2005) Versus RBI



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Research Diversity

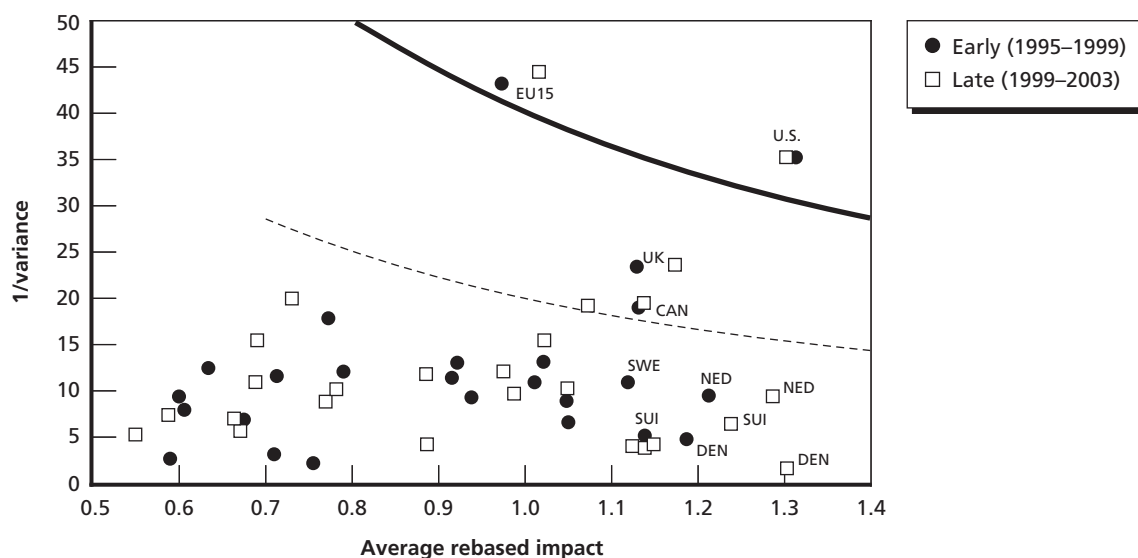
Another aspect of disaggregated research performance that has received little previous attention is the spread of achievement across disciplines. There are two variables to take into account: diversity and variance.

Diversity is desirable: Competence in a range of disciplines confers strength on the research base. Variance is to be avoided: Consistency in performance is an advantage whereas weaknesses reduce the potential to build on positions of strength. The problem is balance. If resources are spread thinly then no research area performs significantly, but if resources are unduly concentrated then the research base loses all agility and cannot exploit new opportunities.

We looked at the spread of performance across countries in these terms. We used citation data to see what average performance was across 100 research categories and we looked at how much the performance varied between disciplines. We plotted the data and computed the tracks that would be followed for “balanced mixes” of average impact (as an indicator of diversity) and variance. We then looked to see which nations had the better balance.

The United States stands out ahead of any other nation in its combination of strength in breadth. The UK has lower average strength than some of its smaller European competitors such as the Netherlands and Switzerland. However, its performance is more consistent: There is less variance and it has significant achievement in many fields in which the smaller countries have just a few niche specializations.

Figure 4
1/Variance Versus RBI



What is interesting is that the EU15 is on a par with the United States. There is complementarity between the European nations that brings the combined performance up to a level that is competitive. This is what one might expect from other data and suggests that the model has relevance to the real-world situation.

Seeking for a balanced portfolio has a value that goes beyond outstanding achievement in just a few areas. In the context of national security, you cannot predict all the knowledge and competencies that you will require to answer new threats. Maintaining the diversity of U.S. science and technology, both to enable underpinning science and interdisciplinary innovation and to support the widest possible range of technology development, makes eminent good sense.

International Collaboration

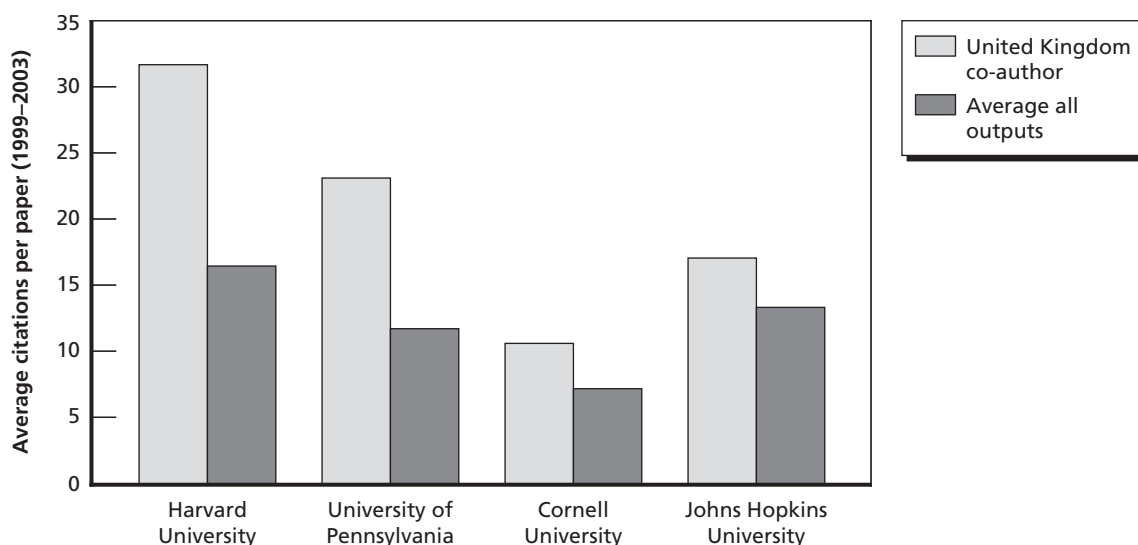
One way of improving your apparent strength is to team up with others. Researchers collaborate to draw on the competency of colleagues and thereby win access to more resources.

There has been a general increase in international collaboration over a long period. The U.S.-UK link is the strongest pairing. The United States is the most common partner for the UK (30 percent of 4831 international papers, 1997-2001) as it is for other G8 countries. The UK is also the most common U.S. partner (it shares 6.2 percent of U.S. output, cf. Germany, 5 percent; Canada, 4.4 percent) and U.S.-UK collaboration is growing faster than for others (+2 percent annually for the UK, cf. +1.5 percent, Germany; 1 percent, average).

About 70 percent of the UK's collaboration with the United States is via higher education institutions (HEIs), and the proportion of HEI papers with a U.S. co-author is growing. Not surprisingly, collaboration is mostly with research-intensive institutions.

The UK's co-U.S. papers are more highly cited on average than are other UK papers. This effect of collaboration on average citation counts is seen across all subject categories and at a

Figure 5
Average Citations per Paper (1999–2003), UK Collaboration with Selected U.S. Universities



RAND CF235-4.5

sub-sector level (in three sub-groupings of UK data—UK HEIs overall, a group of 20 research-led universities with the big four in London and Oxford and Cambridge).

The effect is reciprocal. The U.S. universities that co-author with the UK benefit from their collaboration through papers of exceptional quality.

Across partner nations, the United States has evidently been selective and collaborates in a rational fashion, not happenstance. The United States collaborates more with the UK in bio-medical-related areas and with Germany in areas related to physical sciences. This difference can be attributed to the relative research power of the two partner countries in these fields.

What might we conclude from this?

The United States has as much to gain from collaboration as any other country. It is already making rational strategic decisions, albeit unknowingly, when individual researchers choose strong partners in select areas. As the rest of the world invests more in R&D, the United States should access this growing basket of innovation by promoting its collaborative programs, making the links easier to establish. Historically, it has been a preferred partner for many countries. By investing and building up programs now it can use that preference to engage with emerging research leaders and ensure that while working with them it also accesses their competencies and shares the benefits of their work. Indeed, as a supportive partner, it will add value and can accelerate the innovation process to mutual advantage.

Mobility

People transfer makes a good route to knowledge transfer. By staying home and letting the world beat a path to its research door, the United States has gained status while allowing a less obvious, one-way canal of know-how to grow. U.S. researchers really should get out more.

Only just over 5 percent of U.S. researchers whose career track we have analyzed have experience elsewhere. Only two of 153 leading U.S. researchers we checked indicated that

their Ph.D. was awarded in the UK, compared to 139 awarded within the United States. However, the UK gained 15 researchers with Ph.D.'s from North America. Only one of 146 U.S. researchers went to the UK at postdoctoral level while 41 of 142 UK researchers had visited the United States.

About 45 percent of highly cited researchers based in the UK have spent some period of time in a country other than the UK during their research careers. This is a lower mobility rate than many European countries, or Canada or Australia, though greater than the United States and France. It is higher, however, than is typical for UK researchers and academics. A typical "mobile" UK research career starts with a Ph.D./D.Phil. in a leading research group, followed by postdoctoral experience in the United States, then returning either directly to the UK or after a post overseas. The United States is also the most frequent destination for mobile researchers from other countries.

There is no net "brain drain" from the UK to the United States among highly cited researchers but rather the reverse. In our data, there are four U.S.-born and 15 U.S. Ph.D.-awarded researchers in the UK (sample = 203) against only one UK-born and two UK Ph.D.-awarded researchers in the United States (sample = 166). In other words, people go to the United States for research training and then return home. U.S. citizens who do leave for research training tend more often then to stay away.

There are some indications of cultural and language factors in mobility patterns, with a high level of movement between Anglophone countries, but distance does not seem to be critical. In Europe, the Swiss and Dutch are most mobile and this may be a factor behind the relatively high international research performance of those countries. Almost 90 percent of highly cited researchers based in Switzerland have had some experience in another country.

Table 1
Highly Cited Researchers with Non-Home Research Experience

Current Country	Number of Highly Cited Researchers with Relevant Data	Number of Researchers with Non-Home Research Experience	Non-Home as % Total Researchers
UK	192	87	45
USA	160	23	14
Australia	22	18	82
Canada	21	15	71
France	18	4	22
Germany	15	8	53
Italy	18	11	61
Japan	16	6	38
Netherlands	16	8	50
Switzerland	16	14	88
Total	494	194	

The opportunities for mobility between research-excellent institutions within the United States is so great that it may seem strange to argue that overseas experience can add further value. But the research culture within the United States is more uniform than that available internationally and it is supported by common priorities and policy structure. Indeed, networking within the United States may be so easy that there is in fact greater uniformity than within a similar-sized network elsewhere.

The United States would enhance its knowledge and its understanding of the diversity of research innovation elsewhere by stimulating greater international mobility.

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The World Is What?

David Warsh¹

Popular books in recent years have offered some striking vocabulary for talking about the changes wrought by technological advance: *The Death of Distance*, *The Weightless World*, *The Invisible Continent*, and, most famously, Thomas Friedman's best-seller, *The World Is Flat*. ("[I]t is now possible," wrote Friedman, "for more people than ever to collaborate and compete in real time with more other people on more different kinds of work in more different corners of the planet and on a more equal footing than at any previous time in the history of the world. . . .")

But what do these figures of speech actually mean? None captures with much depth or precision the essence of the change that is taking place. For that we have to turn from journalism to technical economics. There we find an important new idea—a *discovery*, actually, in a science that most people consider to be pretty much the same as it ever was.

In the last ten years, economists have learned to distinguish between *rival* and *nonrival* goods, and the degree to which their use by others may be excluded by those who create them. This is definitely *not* the familiar old distinction between public goods and private goods. It is a new and important way of dividing up the world in order to think more clearly about the wellsprings of economic value.

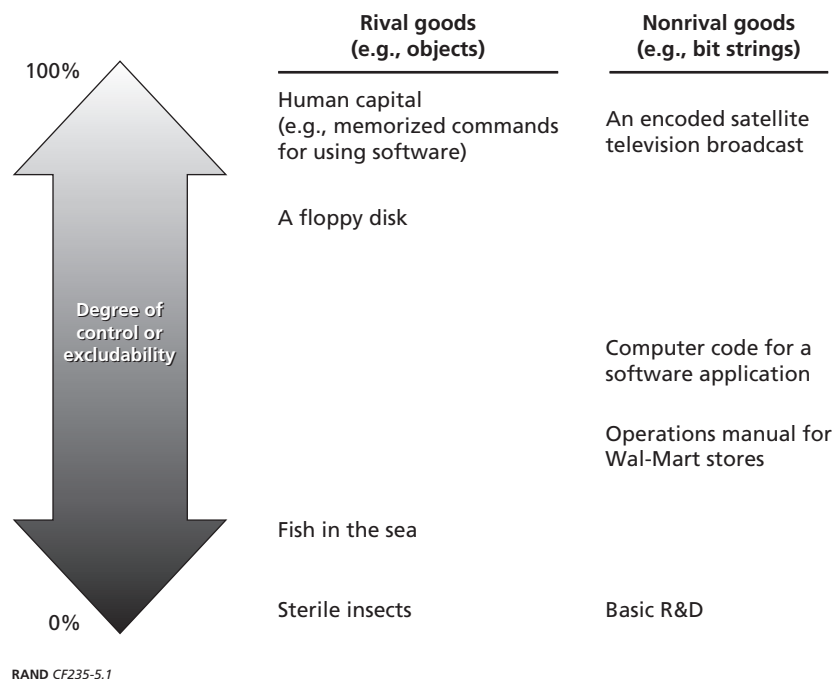
A nonrival good is characterized by the fact that its use or consumption by one person or in one process doesn't reduce the amount of it that can be consumed by another. Once it has been created, a nonrival good can be used over and over again with almost no additional cost.

What's an example? A nonrival good is as simple as the time of day—if I tell you what time it is, I don't lose track of it myself—or as complicated as the design of my wristwatch. The specifications of a new airplane. The formula for a wonder drug. The manuscript of Tom Friedman's book. Or the text of "Endogenous Technological Change," the 32-page article in the *Journal of Political Economy* that introduced the rival/nonrival distinction to a wide audience in economics in 1990. (Friedman describes Romer as "my economics tutor.")

The essence of these distinctions can be seen in the simple tables depicting the economic attributes of different goods that have begun appearing in introductory texts. This one is from the 1992 paper with which Romer introduced the article:

¹ economicprincipals.com.

Figure 1
Rival and Nonrival Goods



Note that the provision of any good or service inevitably possesses both rival and non-rival aspects. A Beatles recording may be stored and communicated as an LP with an ounce of vinyl, a couple grams of polycarbonate plastic as a CD, or a stream of bits that can be sent as a file over the Internet and stored on a chip in a hard drive or in an Apple® iPod®, but, even there it still takes up space. The important thing, however, is the original recording, of which the record, the CD, the MP3 file are just another nonrival copy—four lads named John, Paul, George, and Ringo singing a certain song together on a certain day in London in 1965.

Some slang can further illuminate the difference here: Economists and others speak sometimes of atoms and bits. Atoms comprise the rival part of a particular good, that which may be possessed corporeally by just one person at a time—an apple, say, or a Cuisinart®, or a paperback edition of *A Tale of Two Cities*. Bits comprise the nonrival portion, that which can be written down and encoded in a computer, and therefore used simultaneously by any number of persons—the genome of the apple, the design of the food processor, the text of Dickens’ novel.

Our customary shorthand for nonrival goods is *technology*. But then a World Cup football match is a nonrival good; so is a concert, a performance, a novel, a painting, or the design of a dress. Individual nonrival goods are best described as *ideas*. The incalculably many ideas of humankind sum up to what we call *knowledge*. More knowledge, incidentally, usually means less mass: the iPod, for example. The declining ratio of atoms to bits is a favorite hobbyhorse of former Federal Reserve chairman Alan Greenspan.

Not surprisingly, excludability is usually the key to whether or not a nonrival good gets produced. (In the past, economists spoke of an invention’s “appropriability,” which amounts to the same thing.) Patents, trademarks, and copyrights exist to exclude nonpaying customers from the use of nonrival goods—but so do secrets, locks and keys, tickets, applications,

programming interfaces, encryption devices, and rapid serial innovation. Manufacturing *anything* requires a vast array of inputs that are essentially nonrival: recipes, formulas, techniques, arrangements, designs, blueprints, procedures, texts, and so on. So naturally, a great many workers are employed in the excludability industry, from engineers and lawyers to railway conductors and game wardens.

The rival/nonrival distinction augments the much more familiar dichotomy between public and private. Private goods, we say, are those provided by markets; public goods either occur naturally (well water, fresh air) or are supplied by governments when there is some kind of “market failure.” National defense is a public good, we say, so are streetlights. Each is nonrival and nonexcludable. Yet all kinds of nonrivalrous items in the modern world are not at all what we think of as being public goods. The cholesterol-lowering medicine Lipitor®, for example, is mostly a nonrival good (a chemical formula) whose manufacture as a chemical tablet is carefully protected by a patent. The Windows® computer operating system is protected against copying or modification both by copyright and by the secrets of its source code.

You’d think this conceptual apparatus would have always been around. And in fact as early as 1832, Charles Babbage, in *The Economy of Machinery and Manufactures*, identified the basic idea of nonrivalry, in a chapter on copying. But mainstream economics has had a hard time with knowledge. Lacking the kind of mathematical intuition of diminishing returns that has made the “invisible hand” such a powerful idea, economists have either cloaked the economic role of the growth of knowledge (and the increasing returns that flow from it) in the tricky language of uncompensated external effects (good externalities are called *spillovers*; bad externalities *congestion*, *pollution*, and so on); or deliberately left it out of their account altogether, letting an essentially unexplained residual measure the importance of apparently autonomous technological change.

So instead, the law of intellectual property has evolved over the centuries to protect the ownership of these goods, a complicated doctrine that often verges on the metaphysical. The underlying rationale is no different today than when Nathaniel Ward wrote it up in 1641 for the civil code of the Massachusetts Bay Colony known as the Body of Liberties: “No monopolies shall be granted or allowed amongst us, but of such new Inventions that are profitable to the Countrie, and that for a short time.” Why protect inventions at all? To spur their creation, naturally. But which inventions warrant protection? And for how long? A good question, when a cholesterol-busting compound similar to Lipitor could be produced for a tiny fraction of the price and even introduced into the communal water supply, like fluoride, as a truly public good.

Not until the early 1990s did the new distinctions emerge clearly, mostly from the work of Paul M. Romer, then a professor of economics at the University of Chicago, today at the Graduate School of Business at Stanford University. Romer achieved his breakthrough, not through literary investigation, but via the exploration of the properties of mathematical models. The rival/nonrival distinction he found in the attic of public finance, created by Richard Musgrave in 1966 yet all but unemployed. He combined it with potential excludability, and, thanks to new models of monopolistic competition, applied it to the theory of economic growth, thereby giving intellectual property its first real standing in aggregate economics. The result, at its most fundamental level, has been a gradual reorganization of the mental filing system that we call the *factors of production*—from land, labor, and capital to people, ideas, and things.

It is the nonrivalry of knowledge that is behind globalization, not some mysterious flattening of the earth. What has fundamentally changed is the willingness of previously non-

participating nations of the world to join in the chase, by educating their citizens and permitting them to acquire and create and deploy new knowledge in global markets. The economy of the fledgling United States soared after Boston merchant Francis Cabot Lowell traveled to Manchester in 1811 to surreptitiously memorize the design of the Cartwright power looms, machinery whose export had been strictly forbidden. It did not matter. By broadening the market, American entry into textile manufacturing stimulated the industry in Great Britain, too—the nonrivalry of technology meant that the price of clothing fell dramatically. Eighty years later, Japan did the same thing.

Today it is China and India (and Russia, Brazil, and all the rest) that have entered global markets, computers and software having replaced power looms. Central banks in Germany and France have sold much of their gold reserves in order to symbolically plow the proceeds into research universities. (Note to governments: the reform of higher education is harder than it looks.) In the United States, a blue-ribbon panel of the National Academies of Sciences and Engineering and the Institute of Medicine, in *Rising Above the Gathering Storm*, last year prescribed a range of far-reaching reforms, from investing more heavily in K–12 education to funding more high-risk research and modernizing the patent system. “The rapid pace of technological change and the increasing mobility of capital and talent mean that our current lead in science and technology could evaporate quickly if we fail to support it,” the authors wrote. “The consequences would be enormous, and once lost, our lead would be difficult to regain.”

Romer’s contribution to this debate is a scheme for subsidizing the supply of scientists and engineers, rather than government demand for their services—a slightly souped-up version of the 1958 National Defense Education Act (NDEA). The NDEA was the principle American response to the Soviet Union’s success in hoisting the first satellite into earth orbit: It produced the generation of scientists, engineers, and entrepreneurs that vaulted the United States into technological preeminence. It is important, however, to master the analysis on which Romer’s proposal is based. The new distinctions are still working their way into the textbooks, under the banner of “endogenous” growth. You can’t think clearly about globalization without them.

Distance is not dead. The world is not flat. All kinds of frictions remain. But knowledge definitely is nonrival and, at best, only temporarily excludable. The result is that there is much more competition for new know-how than ever before, with many more people anxious to absorb existing knowledge in order to compete. And *that* is what globalization is all about.

National Security in a Knowledge-Based Global Economy

Jonathan Eaton¹ and Samuel Kortum²

What challenges does a knowledge-based global economy pose for U.S. public policy? We approach this question from three angles: (1) We relate economists' concept of knowledge to more traditional, tangible economic resources, discussing what issues each raises for national security and well-being. (2) We review some basic measures of economic output and indicators of innovation and technology diffusion to get a sense of the roles of key countries in the knowledge-based global economy, and to see how these roles have evolved over the last two decades. At points we use the analysis to interpret recent developments in China. (3) We outline a basic economic model of innovation and diffusion that allows us to interpret these indicators to provide some answers to basic questions about policy.

The Economics of National Security and Wealth

Economists relate a country's standard of living and security to the resources available to it. Resources constitute a broad range of goods and services that are used for production. Traditionally the main categories of resources were tangible (labor, land, and capital), while more recently knowledge has been recognized as a key intangible factor. Our discussion here focuses on nonhuman resources. We offer some comments on human resources at the end.

Resources, like all goods, can be positioned along three standard dimensions. Their location along each of these dimensions has important implications for the role of government policy in securing these resources for the nation.³

1. *Rivalry*. Does use by one agent preclude use by another? At the global level, resources that are rival can be exploited by only one country.
2. *Excludability*. Can an agent assigned ownership of the good easily prevent use by others? In the global context, is it easy for a country to keep others from using the resource? In a global context excludability is highly endogenous as the national security apparatus is itself key to enforcing excludability.
3. *Producibility*. Is the supply of the resource given or can it be augmented through economic endeavor? Nonreproducible resources are in given supply to the world as a whole.

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³ These dimensions correspond to concepts with a long history in the economics literature. The first two were recently articulated very cogently in a paper by Paul Romer (1990), one of the seminal contributions to the New Growth Theory. See Warsh (2006) for a very readable account of the history of economic thought leading up to the writing of Romer's paper.

Hence one country exploits more of the resource at the expense of another. If the resource is reproducible, however, each country can add to the world's supply.

The first two dimensions, rivalry and excludability, are the standard ones for determining the extent to which the market can be expected to provide and allocate the good efficiently. According to these characteristics, goods fall into four categories:

1. Most amenable to market provision are private goods, ones that are both rival and excludable.
2. At the other extreme, pure public goods are both nonrival and nonexcludable.
3. Goods that are nonrival but excludable are sometimes called "club goods" or "natural monopolies."
4. Goods that are rival but nonexcludable are sometimes called "common pool goods."

The following table provides a rough categorization of three types of nonhuman resources along the three dimensions listed above:

Table 1

Type	Rival	Nonrival	Excludable	Nonexcludable	Producible
Natural resources	Oil Land	Oxygen Sea lanes	Oil Land	Atmospheric resources	None
Capital	Most	Underused supercomputer	Most	Internet	All
Knowledge	—	All	Depends, inter alia, on strength of intellectual property (IP) protection		Much

We now elaborate.

Natural Resources

By definition natural resources are nonreproducible. Nevertheless, changes in technology have vastly changed the extent to which we rely on different natural resources. Arable land has fallen significantly in its relative importance as a resource over the last two centuries, while other natural resources, such as oil, have become much more important.

While some natural resources, such as oxygen, are nonrival, the rival ones are of greatest concern for national policy. In recent times nations have been relatively successful in enforcing excludability of land-based natural resources, although the 1991 Iraqi invasion of Kuwait and the allied response serves as a reminder that enforcement is not costless.

Excludability is more problematic for sea-based resources outside of territorial waters, such as fisheries and underwater oil supplies. For atmospheric resources such as the ozone layer and reduced greenhouse gasses, excludability is nearly impossible through any unilateral enforcement mechanism.

We are skirting over another distinction: resources that can be used up (like oil) versus resources that can be reused (like air and water). Pollution of air and water resources reduces the supply, although, in principle, policies can be aimed at reversing this process.

While natural resources are no longer at the center of geopolitical competition in the global economy, they nevertheless remain an important factor, especially in the case of resources that

are distributed very asymmetrically across countries, such as oil. We turn to some statistics on oil below.

Capital

The industrial revolution entailed a redirection of economic activity away from agriculture toward manufacturing, which is much less intensive in its use of land. Instead, manufacturing combines labor with equipment and structures, what economists refer to as the capital stock. For the most part, capital goods are pure private goods in their rival and excludable nature. The key difference from natural resources is that they are produced through economic activity. World supply is not given, and ownership of the resource is not tied to sovereignty over a particular piece of land. A country can accumulate capital by putting resources aside from consumption.

Data from the Bureau of Economic Analysis imply a ratio of private nonresidential capital to GDP for the United States of very close to 1. Capital stock data are known for unreliability, especially in making cross-country comparisons. But data from other countries yield figures of roughly this magnitude.

Throughout the 19th and first half of the 20th centuries, economists focused on capital accumulation as the key ingredient to economic growth. David Ricardo formulated a basic model of saving and growth that formed the basis of subsequent neoclassical and Marxian analysis. Soviet central planning, imposed elsewhere and mimicked in many third-world countries, imposed high savings rates.

In terms of national security, warring nations, particularly during World War II, sought advantage through the destruction of their enemy's capital stock. Indeed, Japan and Germany, two previously advanced countries whose capital stocks were decimated by the war, emerged from it impoverished.

But by the late 1950s thinking began to change for two reasons. For one, West Germany and Japan quickly reestablished themselves as industrial leaders, suggesting that their large capital stocks were a reflection of their manufacturing prowess rather than its source. More systematic evidence came from Robert Solow's (1957) analysis of U.S. data through the prism of his basic neoclassical growth model: Capital accumulation could explain only about half of U.S. growth. The rest he attributed to the residual of "technical progress."

Knowledge

Solow's finding that the economy grew through the accumulation of new ideas posed a serious challenge to the profession, in terms both of theory and of measurement.

Giving ideas rather than capital the star role in economic progress, Solow pushed the profession into uncharted territory. Economists had the analysis of private goods, like capital, under control. Private goods were consistent with general equilibrium analysis as it existed at the time. Of course the insight that ideas are essential to growth was not new. It was central, for example, in the early 20th-century writings of Schumpeter (1959). The impasse occurred because economists did not have the tools to formalize and quantify Schumpeter's insights. To the extent that people may arrive at ideas by accident, through no willful effort on their own, there was no problem. Assuming that ideas are not forgotten, an economy can grow simply through the serendipitous arrival of ideas. In fact, until the industrial revolution, economic progress seems to have taken this form. As Diamond (1999) documents, in regions of the globe, such as Eurasia, where large numbers of people interacted, more ideas accumulated and

technology became more complex. In regions such as Australia, where populations were sparse and isolated, technology was less advanced. With the industrial revolution came systematic, concerted efforts to develop ideas to advance technologies. Individuals, governments, universities, and corporations devote substantial resources to coming up with ideas. But what drives them to do so?

A second challenge was to measurement. While putting a figure on a nation's capital stock is challenging, economists understood in principle how an army of assessors could be dispatched to do the job. Moreover, investment data in the national income accounts provide direct measures of additions to the capital stock. But how could one come up with a measure of the stock ideas available to an economy, or even the arrival of new ideas?

As for the challenge to theory, a few isolated papers sought answers to these questions as the interest of the profession in growth waned. But the late 1980s, as Warsh (2006) reviews, saw a return to them, with many of these challenges addressed. The literature developed general equilibrium models in which the process of innovation responded to market mechanisms.

As for the challenge to measurement, economists turned to various indirect indicators, some of which we review in the next section. These measures include data on research expenditures, research personnel, patenting, and royalties.⁴

Recognizing, then, that knowledge is a critical resource for national wealth and security, what issues for public policy arise? The characteristics of knowledge make for complex answers. Intellectual property protection that provides sufficient excludability to make research profitable does so at the cost of monopoly distortion: The nonrival aspect of knowledge is underexploited as users are required to pay for something that incurs no additional cost. Moreover, private incentives may fail to direct research in its most socially useful directions.

In a global context the issues are more complex still. Since ideas are nonrival, to what extent are countries making use of their own ideas or those of others? What is the connection between knowledge creation, security, and welfare? As for public policy, if a country can obtain ideas from abroad, while its own ideas may be used abroad, how much support should it provide to innovation? Should countries free ride off others' research? Can and should governments try to restrict the dissemination of ideas abroad? We'll present a framework to try to answer some of these questions below. We first turn to some basic indicators of resources, production, and technology.

Measures of Output, Innovation, and Diffusion

We consider eight countries or regions, emphasizing those that have recently emerged to exert substantial influence on the global economy. From west to east they are: the United States, Europe, the Russian Federation, India, China, South Korea, and Japan. The residual region is the rest of the world (ROW). Europe includes the 15 members of the European Union as of early 2004 plus Iceland, Norway, and Switzerland.⁵ We include Hong Kong with China.⁶ We

⁴ Zvi Griliches and his students and collaborators were pioneers in this endeavor. Griliches (1994) contains a number of important contributions.

⁵ Prior to the addition of 10 new members in May 2004, the EU15 consisted of Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the UK. Where data for Europe as a whole are difficult to obtain, we sometimes substitute series for Germany and/or the United Kingdom.

⁶ Going back in time, we replace the USSR with the Russian Federation.

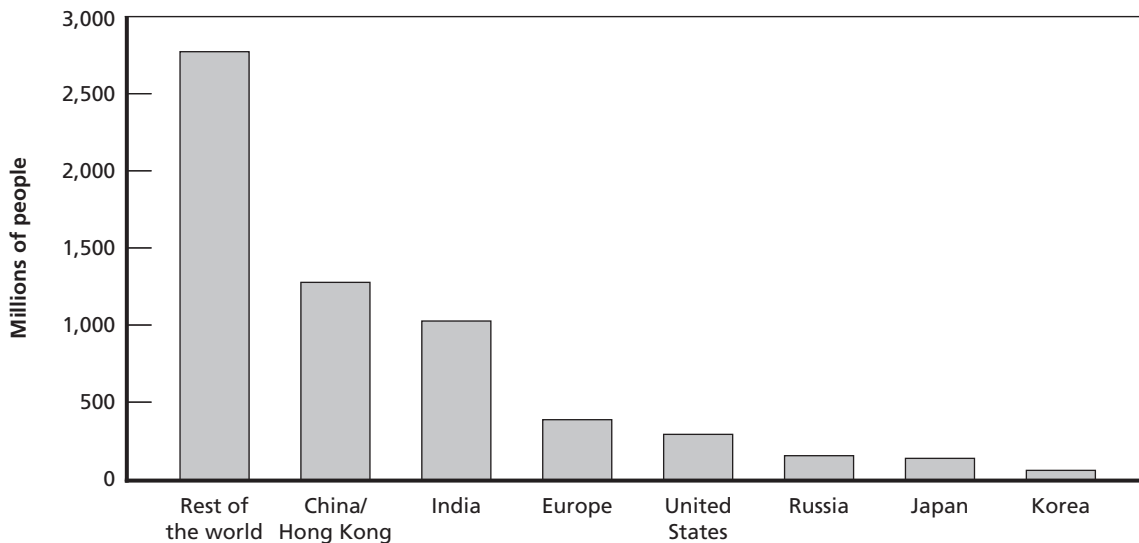
focus on the last two decades. For cross-country comparisons, we use 2000 as the benchmark year.⁷

Land, Labor, and Production

A basic measure of the importance of a region is simply the number of people who live there. Figure 1 shows the population of our eight regions in 2000. The United States, with about 300 million people, is dwarfed by all but three of the regions in a world of over six billion. The United States and Europe combined are still smaller than either India or China on its own. If other regions catch up to the United States in per capita production, the world economy would be vastly larger. Since human brainpower is the underlying source of new ideas, the vast populations of these regions suggest an enormous world capacity for technological discovery which remains unexploited.

Land was traditionally the key resource for economic prosperity, but not in today's world. Figure 2 plots the quantity of agricultural land in each of the eight regions. The ROW dominates all other regions combined. An important country like Japan is merely a speck. As we will see, economic activity across regions looks nothing like this allocation of land.

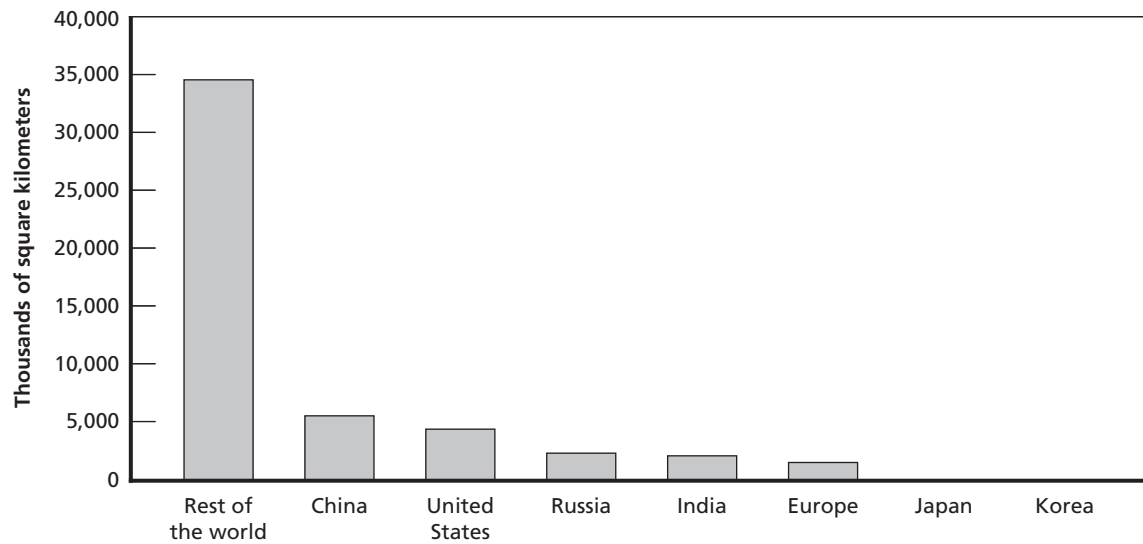
Figure 1
World Population, 2000



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⁷ Data on population, land, and GDP are from the World Bank's World Development Indicators (WDI). Data on research and on triadic patents are from the OECD's Science and Technology Indicators (augmented for a few countries from WDI). Data on patents granted in the United States are from the U.S. Patent and Trademark Office (USPTO). Data on patents granted in South Korea and China are from the World Intellectual Property Organization. Data on royalties are from the Bureau of Economic Analysis, trade in services.

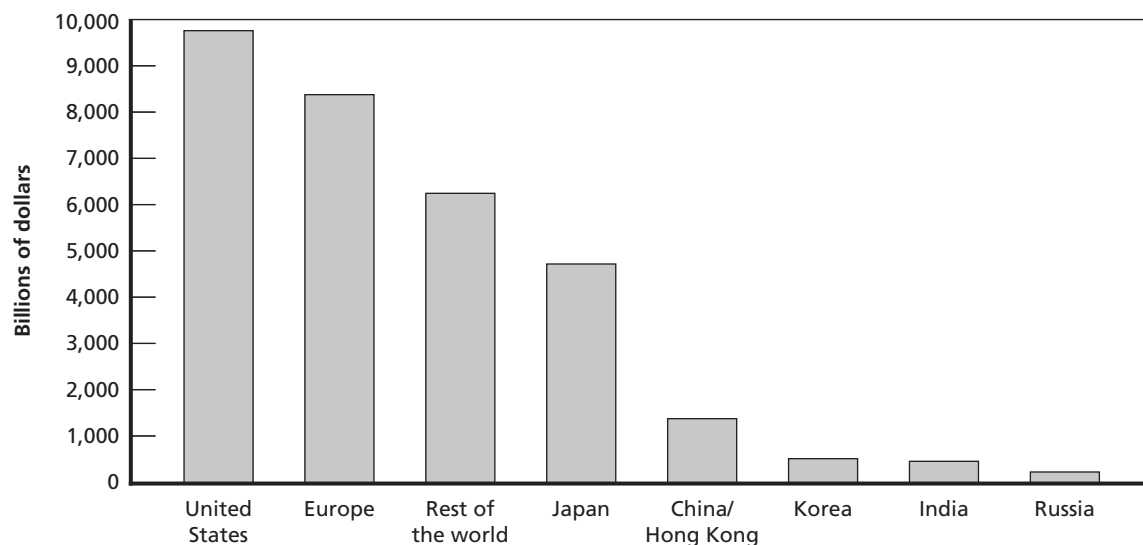
Figure 2
Agricultural Land



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A basic measure of the current economic power of a region is its gross domestic product (GDP), the value of all goods and services produced there. We can translate each region's GDP from the local currency into U.S. dollars using the exchange rate. The result, as of 2000, is displayed in Figure 3. By this measure the United States and Europe are dominant. China and India appear miniscule in comparison. What China can purchase of European luxury goods with 7 percent of its GDP the United States can purchase with less than 1 percent of its national income.

Figure 3
GDP at Current Exchange Rates, 2000



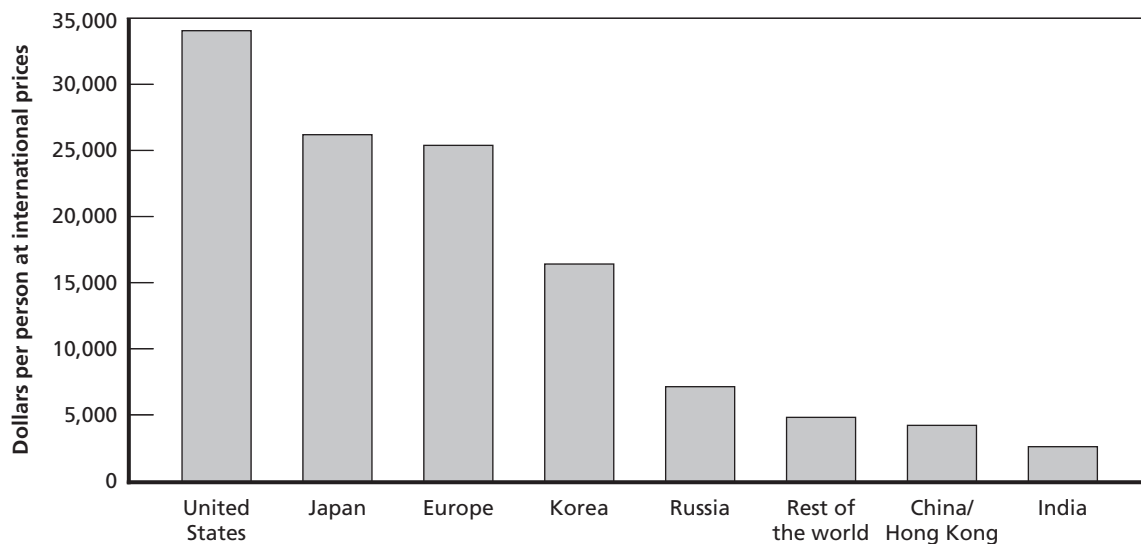
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While comparing GDPs via the exchange rate is fine for assessing what countries can afford to purchase abroad, it is misleading for assessing their productive power. The reason is that most of GDP consists of goods and services that are subject to high trade costs or are not traded at all, such as housing. If these goods are produced equally efficiently across countries, they will be cheaper in countries with lower wages. As a result, there can be huge differences in how much a dollar, converted at the current exchange rate, will buy in different countries. It will typically buy a lot more in China or India than in Europe, Japan, or the United States. To correct for this discrepancy, economists typically compare the output of nations using GDP at international prices. Switching to international prices causes India's GDP to rise by a factor of five and China's by nearly a factor of four relative to what we saw in Figure 3.

To focus on the role of a country's nonhuman resources, we express GDP (at international prices) in per capita terms. Figure 4 shows that with the resources at his or her disposal, the average person in the United States produces \$35,000 of GDP, about seven times what is produced by the average person in China. Korea is right in between. This figure points to the enormous disparities in productivity that remain in the world. Yet, in a world in which knowledge is the most important productive resource, another lesson is the potential for countries like China and India to grow faster than the United States over the foreseeable future.

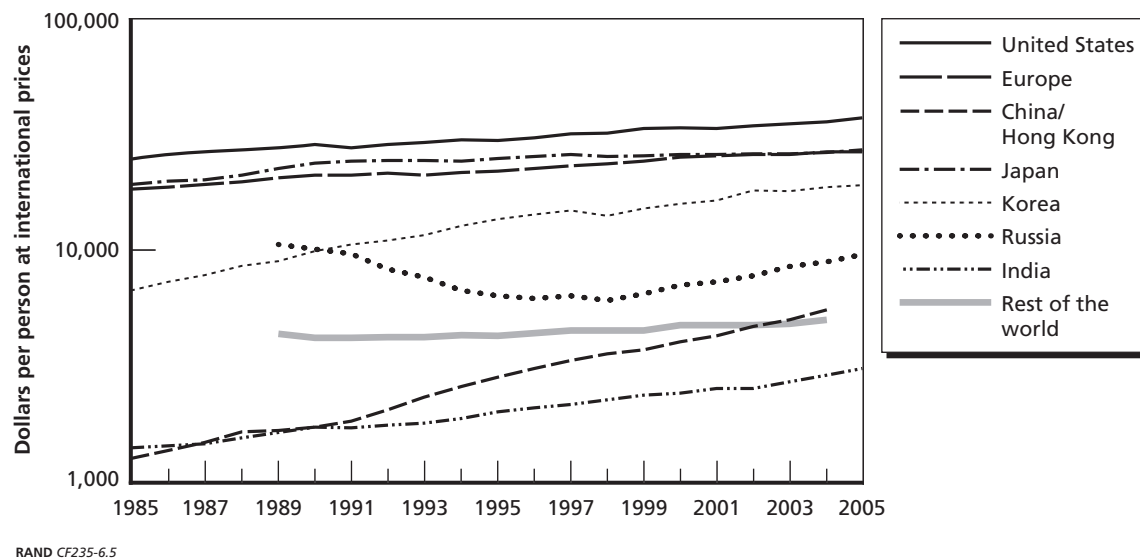
Figure 5 looks at how GDP per capita has evolved in the past two decades. It is displayed on a logarithmic scale so that proportional growth rates are indicated by the slopes of the lines. The big picture is one of parallel growth, with the United States, Europe, Japan, and ROW growing at about the same pace. But, notice that within that overall pattern, China, Korea, and even India have made substantial progress in closing the gap with richer countries in the last 20 years. Most notably, China has moved up by a factor of three relative to the United States. And this catching up was during a time of strong growth in the U.S. economy.

Figure 4
Per Capita GDP, 2000



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Figure 5
Per Capita GDP



Technology Indicators

We now turn to measures of knowledge creation and diffusion. Some basic issues of measurement are: (1) Who produces knowledge? (2) Who uses it? (3) Are the users paying the producers? There are no direct measures, but various indirect ones, sometimes termed *indicators*.

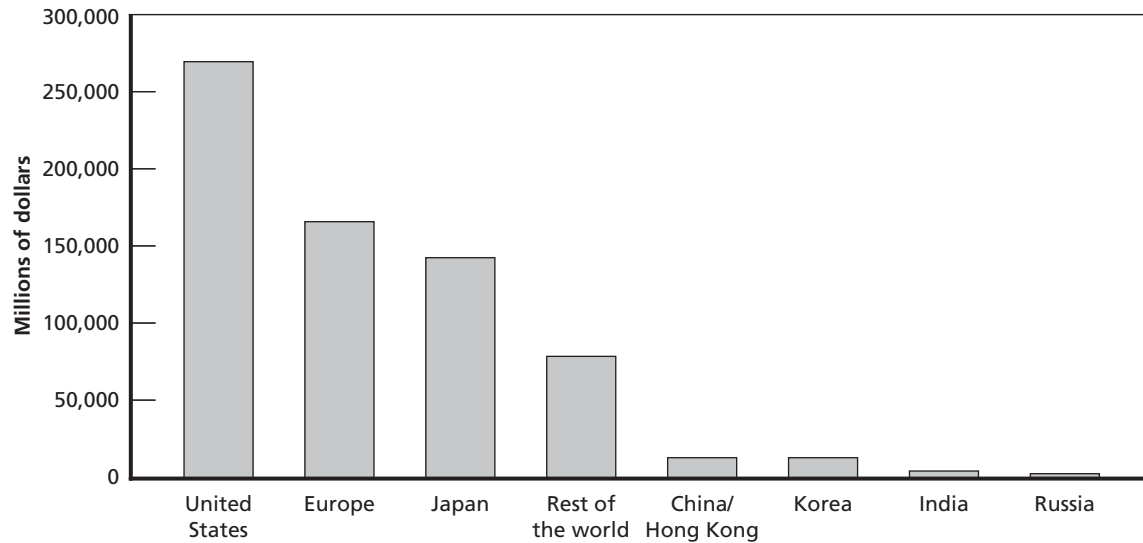
We start with expenditure on research. Because technology is nonrival, we should not lose sight of the fact that scale matters. A big country that devotes the same fraction of its income to research as does a smaller one is likely to generate a lot more new technology. With this thought in mind, we begin by comparing overall research effort across countries. Figure 6 measures research effort in terms of spending while Figure 7 is in terms of human resources devoted to research (missing data reduced our sample to just five regions). While the United States is a leader on both counts, its lead is substantially greater when measured by R&D spending rather than by numbers of research scientists and engineers. This contrast in the two measures reflects the same issues that arose in comparing GDPs. A poorer country with lower wages will spend much less employing the same number of researchers. The question is, of course, how productive are the researchers? If researchers everywhere are equally productive the body measure is appropriate. If differences in researcher compensation reflect differences in research productivity, the expenditure measure tells us more about how much research is being produced. The truth is likely somewhere in between.

Before turning to indicators of research output, we first examine changes over time in research effort. Figure 8 tracks R&D expenditure as a percentage of GDP, often called *research intensity*.⁸ Research intensity exhibits a slight upward trend over time, with a more pronounced rise in China and Korea. Research intensity in Korea now exceeds that in the United States. Figure 9 shows largely similar results for research scientists and engineers per million population.

⁸ Missing data make it difficult to construct consistent numbers for aggregates, so we drop ROW and add Germany and the UK in place of Europe. These problems are magnified when we turn to data on research scientists and engineers.

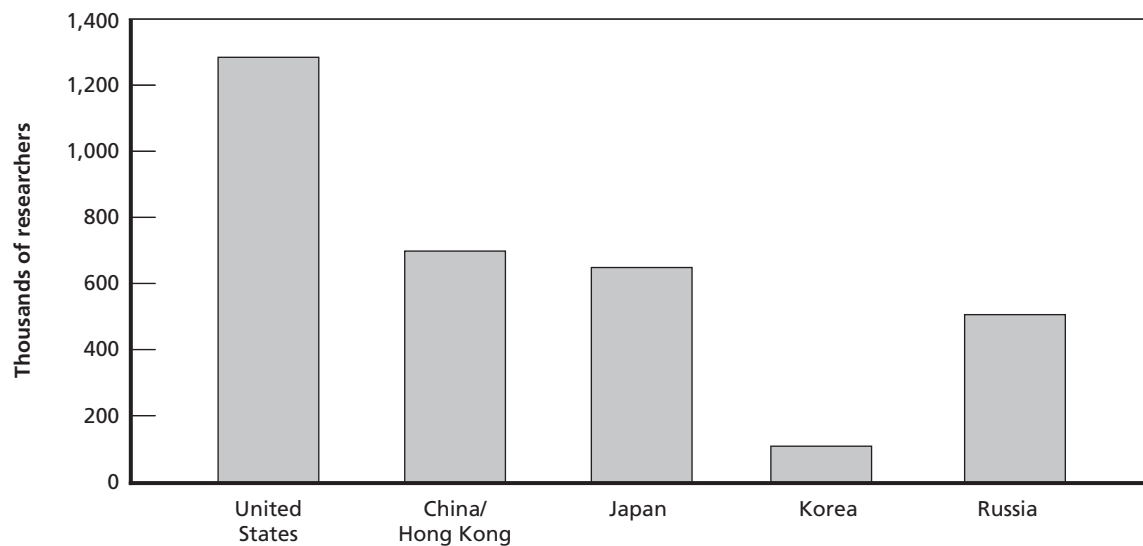
One indicator of the output of these research inputs is the number of patented inventions. Patent counts are a notoriously misleading indicator of invention due to, among other things, the peculiarities in the granting practices of patent offices. If we look at patents granted by a single country's office, however, comparing inventors from our eight regions seeking protection

Figure 6
R&D Expenditure, 2000



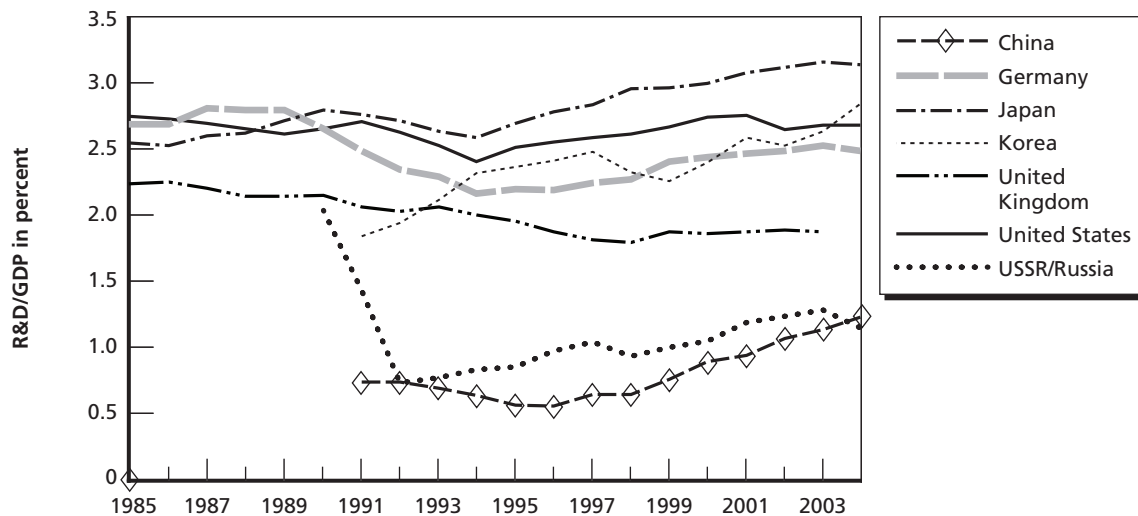
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Figure 7
Research Scientists and Engineers



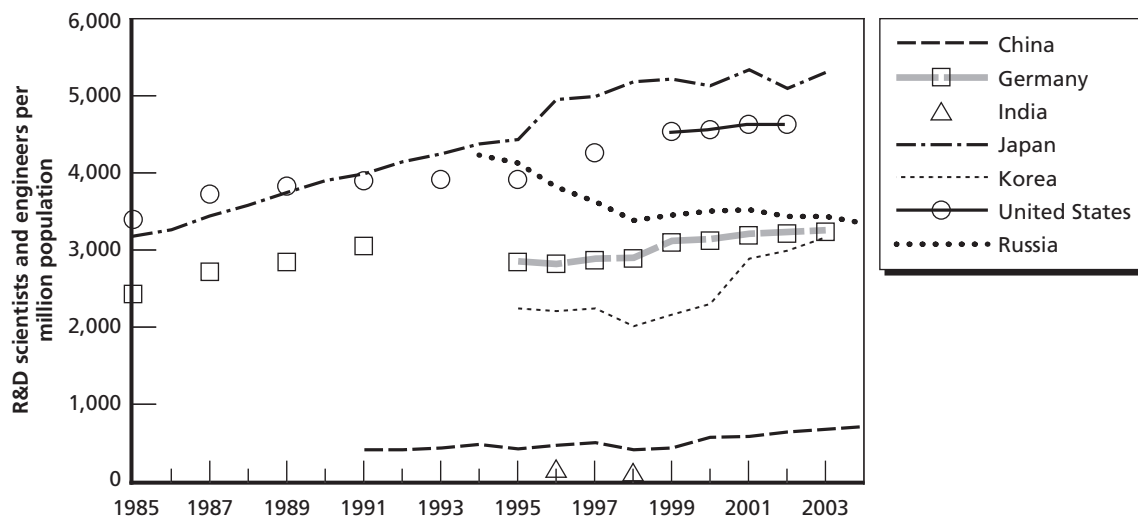
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Figure 8
R&D Intensity



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Figure 9
Researcher Intensity

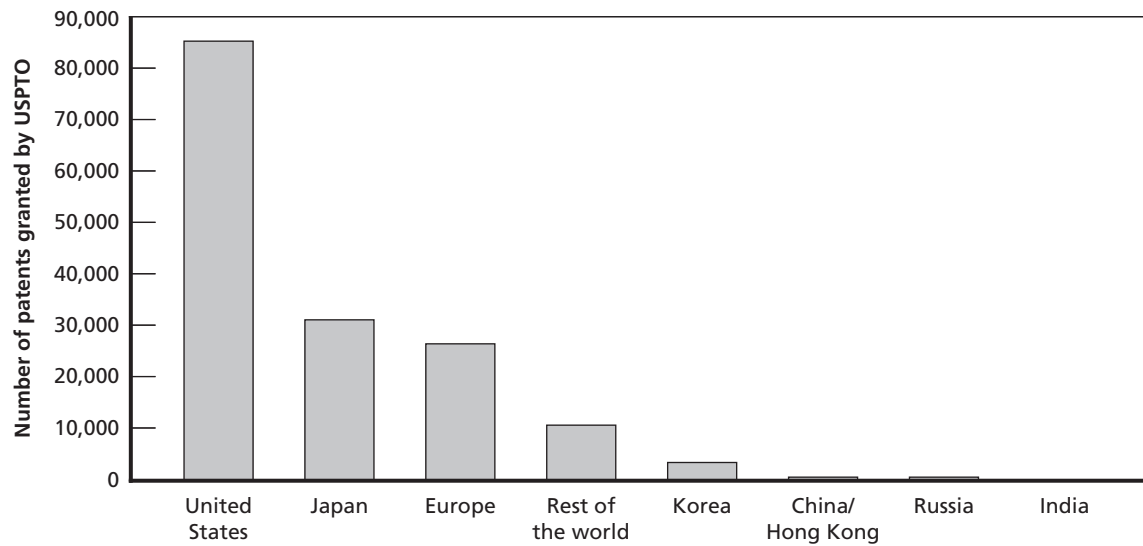


NOTE: Lines indicate consecutive years of data availability.

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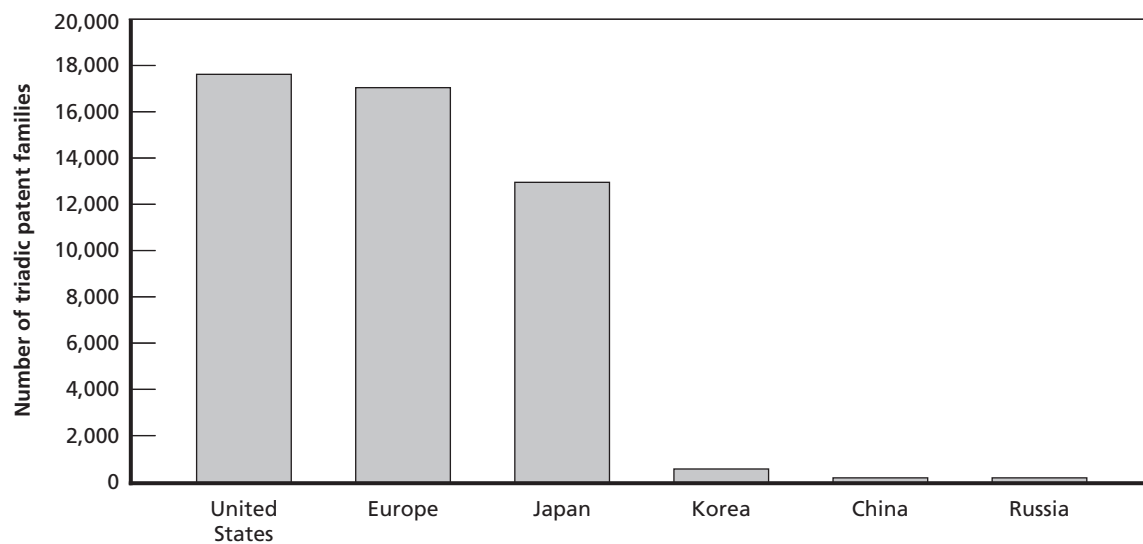
there, we effectively correct for many of the problems. Figure 10 shows that Korea, China, Russia, and India generate very few inventions good enough to be granted U.S. patents. Even Japan and Europe look rather pedestrian relative to the United States itself, but concluding that the United States is much more inventive is unwarranted given the tendency for many inventors to seek patents only in the domestic market. To get around this bias, we look at inventions that are patented broadly in the United States, Europe, and Japan, what the OECD terms *tri-adic families*. As shown in Figure 11, by this metric the United States, Europe, and Japan are roughly equal. While Korea, and even China, have made great gains in inventive output in

Figure 10
U.S. Patents by Residence of Inventor



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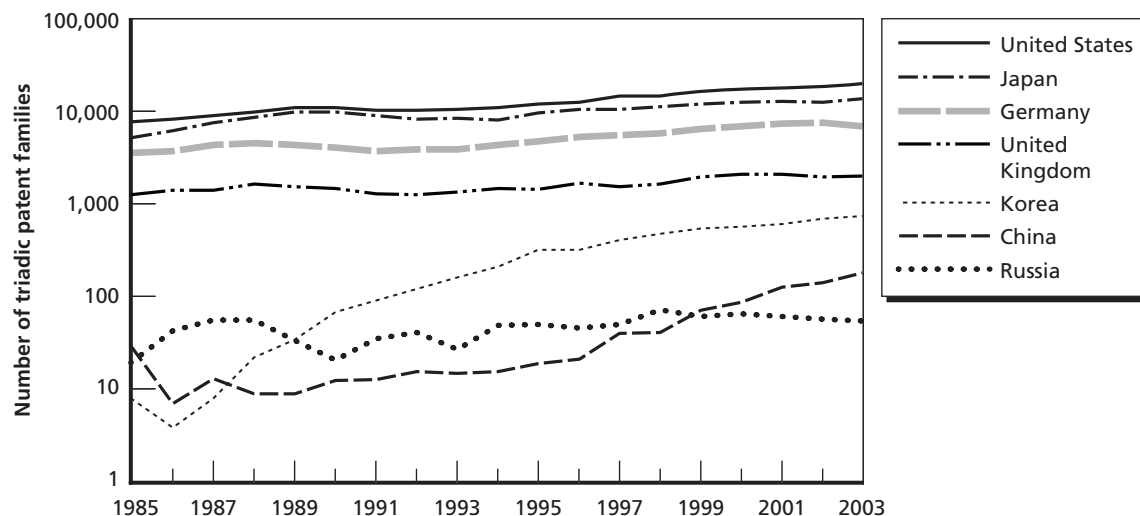
Figure 11
World-Class Inventions by Source, 2000



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the last two decades (see Figure 12) they still lag far behind. These figures point out that currently only the United States, Europe, and Japan contribute substantially to the world pool of patented new technology, and their relative positions have been very stable. One hypothesis is that research effort in the other regions is aimed at more incremental innovation or imitation. Another hypothesis is that research effort there is truly inventive but that lower-wage countries see little threat from competitors in Europe, Japan, or the United States, so don't bother to seek patent protection there.

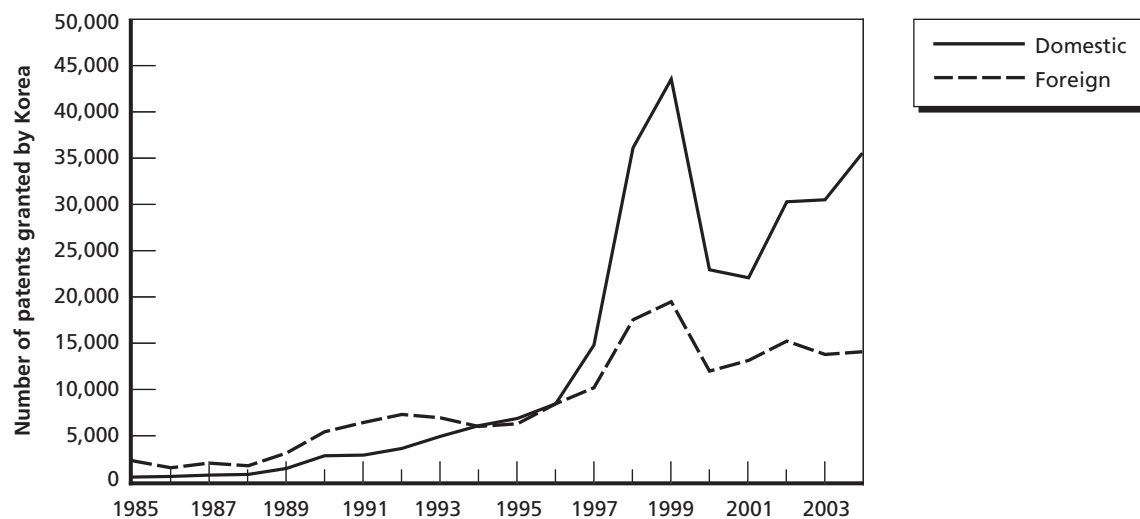
Figure 12
World-Class Inventions, by Source



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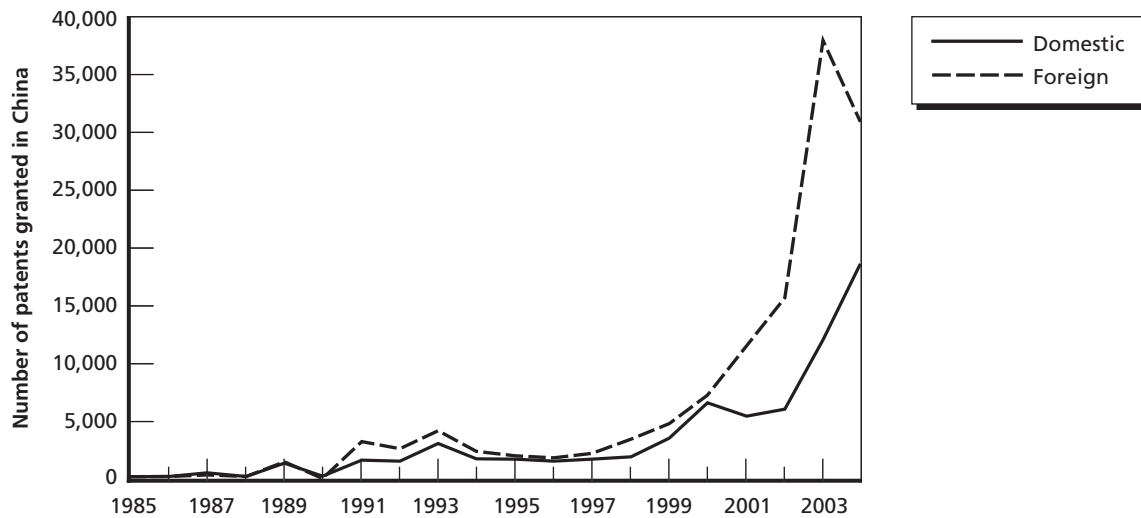
With these hypotheses in mind we turn to data on patents granted elsewhere. Figure 13 shows that since the late 1990s, Korean inventors have begun to patent a lot of their inventions in Korea itself, far more than foreigners. As we saw earlier, however, only a tiny fraction of these inventions become triadic families. In China, we see a very recent surge in patenting (Figure 14), with foreign inventors leading the way. This finding fits in with the view that foreign

Figure 13
Korean Patents Granted



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Figure 14
Chinese Patents Granted

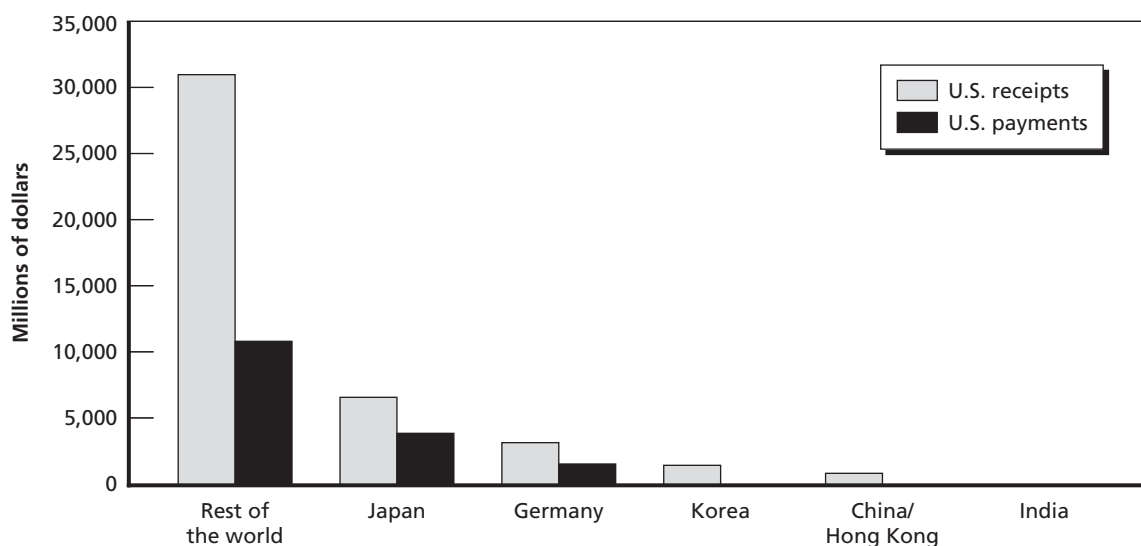


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technology is moving to China and the owners of that technology are hoping to exclude Chinese producers from using it for free.

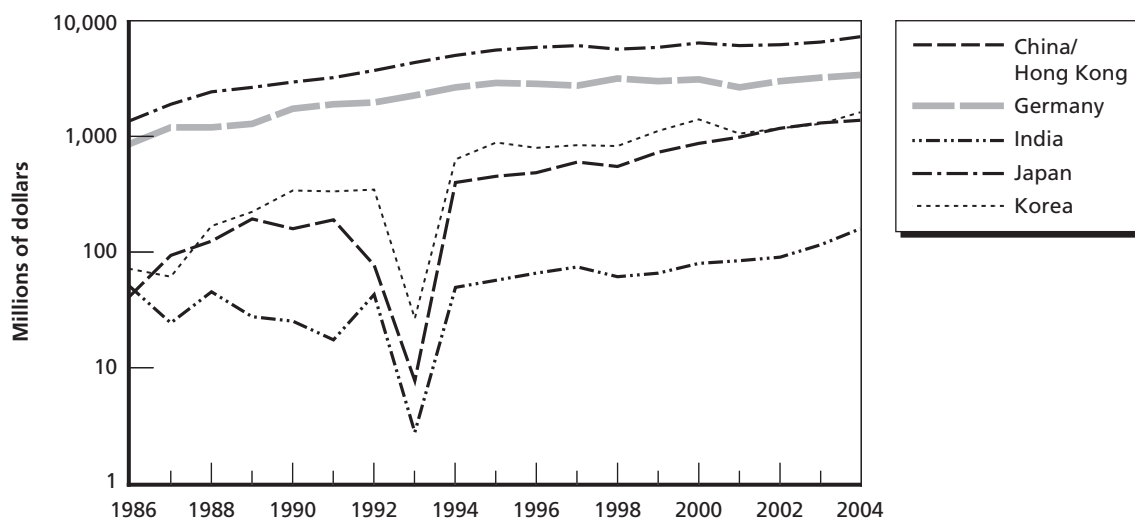
If, in fact, a large piece of U.S. technology has made its way into the production process in China, do we see corresponding technology payments to the United States, or should we think of it more as a free lunch for China? Figure 15 plots U.S. receipts and payments of royalties and license fees in 2000. The first thing to notice is that receipts do far outweigh payments. But the magnitudes are rather paltry, less than \$100 billion, and only a tiny fraction of the receipts come from China. Figure 16 shows that, while receipts from China have grown, it would take

Figure 15
Royalties and License Fees, 2000



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Figure 16
U.S. Receipts of Royalty and License Fees



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many decades at this rate for them to add up to a substantial sum. It appears that the free-lunch hypothesis has merit, or else that the payments are being reinvested in China and so do not yet appear in services trade.

A Comparison with Oil

We find it useful for comparison purposes to present some data on a traditional tangible resource, oil. Oil and knowledge, while very different in most respects, share two striking similarities: (1) The creation of knowledge, like the production of oil, is highly concentrated in a small number of countries. (2) The United States spends roughly comparable amounts on each. A difference, of course is that while the United States is a major net exporter of knowledge, it is a major net importer of oil.

The table below reports the shares of world oil reserves held by various countries or regions, as calculated from U.S. Energy Information Agency (EIA) reserve estimates:⁹

Table 2

Region or Country	Share (%)
Middle East	57.5
Saudi Arabia	20.6
Iran	10.2
Canada	13.8
Venezuela	6.2
United States	1.7

⁹ These figures reflect the EIA's inclusion of Albertan shale oil in the total.

How important is oil for the U.S. and world economies? In 2005, U.S. expenditures on oil constituted around 4 percent of U.S. GDP, with around half imported. This share is somewhat greater than U.S. R&D intensity (see Figure 8). Pricing the EIA's estimate of total world oil supplies at the current price of \$60 per barrel implies a world "oil wealth," gross of extraction costs, of around 70 percent of world GDP. Obviously this share was substantially less at the 1999 price of around \$15 per barrel.

A Basic Framework for Analysis

Our framework involves several building blocks. We begin by modeling the creation and diffusion of ideas, given the resources that countries put into innovation. We then model how the distribution of ideas affects international trade. We complete the framework by examining how diffusion and trade in turn influence the resources that countries put into research.

Innovation and Diffusion

A country's technological frontier is the set of its best practice techniques for producing goods. At any moment t we can express country i 's best idea for making good j in terms of the efficiency $z_i(j)$ of that technique in transforming physical inputs into output of good j . Physical inputs include the other resources we listed in the section "The Economics of National Security and Wealth." We can thus write the production function for good j in country i at time t as

$$q_i(j) = z_i(j)F(x_i(j)),$$

where $x_i(j)$ is a vector of resources that country i devotes to good j and F is a generic constant-returns-to-scale function transforming resources into output. For simplicity we treat F as the same for all countries and goods.

Innovation is the creation of ideas for producing goods. It is common to express a country's output of ideas in terms of an innovation production function:

$$I_i(t) = \alpha_i(t)G(x_i^R(t)),$$

where $x_i^R(t)$ is a vector of the physical resources country i devotes to innovation and G is a function that aggregates these physical inputs. The term $\alpha_i(t)$ reflects the ability of country i to turn innovative effort into new ideas. Hence differences across countries in innovative output can be decomposed into (1) differences in research effort, the vectors $x_i^R(t)$, and (2) differences in research productivity, the parameters $\alpha_i(t)$.

The diffusion lag is the delay between the creation of an idea (in some country i) to its availability as a technique for production in country n . We denote the stock of techniques available for production in country n at time t as $T_n(t)$. If the diffusion lag between country i and country n is exponentially distributed with parameter ε_{ni} (so that the expected delay is $1/\varepsilon_{ni}$ years), then the rate of change of ideas in destination n is

$$\dot{T}_n(t) = \sum_{i=1}^N \varepsilon_{ni} \int_{-\infty}^t e^{-\varepsilon_{ni}(t-s)} I_i(s) ds.$$

As we show in Eaton and Kortum (1999), if the parameters α_i and ε_{ni} along with the resources x_i^R that countries devote to research are stable, then the system will settle down to a common world growth rate. Countries that absorb ideas into their technology stocks more quickly are on average more efficient, and thus richer. It is plausible to suppose that an idea translates into an idea at home much faster than it does abroad, meaning that $\varepsilon_{ii} \gg \varepsilon_{ni}$ for $n \neq i$. In that case, more innovative countries will also be richer ones. At the same time some countries (e.g., Denmark) may be rich even while there is little evidence that they do much innovation. The reason is that they are quick to exploit ideas from elsewhere. In fact, the research indicators presented here point to stability in terms of who is doing research.

An outcome of this framework is a world where some techniques may be available only in a small number of countries while others are shared widely. If innovations get translated into techniques faster at home, highly innovative countries will have a larger share of ideas that are exclusively theirs.

In terms of this framework, a natural explanation for the rapid increase in China's manufacturing prowess is a large increase in the parameters $\varepsilon_{\text{China},i}$, allowing it to suddenly absorb a lot of foreign technology. A natural explanation is institutional change, e.g., policies more welcoming to foreign direct investment, that facilitated technology transfer. An implication of this change, of course, is not a permanently higher growth rate for China, but its transition into a club of much wealthier countries eventually growing at similar rates.

In the absence of trade, the nonrival nature of ideas means that more rapid diffusion of a country's technology abroad has no impact on the country's productivity. It can go on producing as efficiently as ever. Absolute, not relative, technological advancement is what matters for economic performance.

From a national security perspective, relative advancement does matter for the balance of power. Offsetting issues of military balance is the observation that advanced countries pose much less threat to world order. In simple economic terms, access to advanced technology enhances a country's ability to supply a military threat, but reduces its demand for one.

International Trade

If a bundle of physical inputs in country i cost w_i , it can produce good j at cost $w_i / z_i(j)$. Say that selling the good to destination n raises that cost in proportion $d_{ni} \geq 1$. Then its cost of delivering the good to market n is $w_i d_{ni} / q_i(j)$. Country n will buy the good from the lowest-cost source, looking across all sources, i . Country i 's market share in destination n is thus the fraction of goods for which it is low cost there.

To the extent that a country has techniques that are in its exclusive domain, it need not have the lowest input cost to be the low-cost supplier to a market. It can rely on its technological superiority. But when techniques are widely available, who is low cost depends on input costs. Some industries, such as textiles and shoes, rely on old ideas that have diffused widely, so that competitiveness in world markets depends very much on factor costs. Industries such as wide-bodied aircraft rely on newer ideas that are much less commonly available, so that technological superiority is key.

The surge in China's market share in many countries can thus be attributed to its rapid acquisition of better techniques, ones that were previously available only in higher-wage coun-

tries. In principle, the equilibrating mechanism is an increase in the cost of inputs in China. China's vast labor pool may have delayed this adjustment.¹⁰

As in Krugman (1979), faster diffusion reduces relative wages in innovating countries, given their innovative output. The consequence for their standard of living is ambiguous. What they always bought from developing countries gets more expensive, but they can import a wider range of goods at lower cost. At the extreme, if diffusion is complete, the innovating country loses its wage advantage, giving up its gains from trade. The gains from trade thus put an upper bound on the potential loss in living standard an innovating country can experience from faster diffusion of its technologies abroad. In Eaton and Kortum (2002), we estimate the U.S. gains from world trade in manufacturing at under 1 percent of GDP. Hence, given their innovative output, there is little reason to think that faster diffusion of U.S. ideas to China, a single trading partner, poses much threat to U.S. living standards. Moreover, taking into account the incentive to innovate makes a positive effect more likely.¹¹

Incentives to Innovate

For inventors to be rewarded they need to appropriate some share of the returns from innovation. Say that a technique in country n on average would generate a flow of profit π_n there, which we can posit varies in proportion to market size. In a world of complete intellectual property protection, this profit would accrue to the inventor regardless of nationality. Even so, an inventor has to wait until his idea has diffused to a region before earning this profit. Very slow diffusion into a country thus means that the country is largely irrelevant in terms of its effect on the incentive to do research: It takes too long for an idea to generate rents there.

In Eaton and Kortum (2001), we show that, in the absence of any cross-country diffusion, the amount of research that a country does is independent of its research productivity. Countries that are more research productive are richer because the resources they devote to research produce more innovative output.

In equilibrium, technology diffusion (think of it as trade in ideas) concentrates research in countries that are better at doing it. The logic is similar to international trade in goods, which allows for greater specialization in production. With perfect worldwide IP protection it's even possible for more diffusion to result in innovating countries having more ideas that are exclusively theirs.

In the case of China, faster diffusion there can create incentives for more U.S. research only if U.S. inventors can earn profits there. So far, however, China does not seem to have generated much in the way of royalties for the United States, and there have been complaints about the quality of its patent system. Nevertheless we have seen a precipitous increase in foreign patenting in China.

Another issue is a potential increase in Chinese innovative efficiency. As we see, however, revealed comparative advantage in research is extremely stable over time. While policy changes that affect a country's ability to absorb ideas can come into effect quite rapidly, building the institutions necessary for a high rate of innovation can take a long time. While a more innova-

¹⁰ In fact, recent reports from China suggest that input costs are rising there. "Wages in China are definitely going up at a fast pace," said Behlen Chairman Tony Raimondo. "The movement of land value and wages has surprised many of us" (*Yahoo! Finance*, October 16, 2006). The argument for a yuan revaluation is that it would provide a faster means of raising effective Chinese input costs.

¹¹ Many of these ideas were expressed very simply a decade ago by Krugman (1994).

tive China would mean that U.S. inventors faced more competition from abroad, it would not be all bad for the United States. For one thing, it might reduce prices for U.S. consumers. For another, it might put pressure on China to provide better IP protection overall, allowing U.S. inventors to earn higher rewards there.

Human Resources

Our analysis follows standard trade modeling in treating labor markets as national in scope. Our framework thus cannot address a key topic of the conference, the international market for research scientists and engineers. We now speculate on how our framework could be expanded to allow for a world market in research talent.

Individuals differ widely in their abilities to do perform various tasks. There is reason to think that variability in ability is particularly pronounced when it comes to doing research. An efficient labor market will thus allocate those most talented at research (relative to their other talents) into that endeavor.

For reasons discussed here, countries that are very efficient at doing research are likely to have high wages, both inside the research sector and out. To the extent that talented researchers are mobile, they are likely to gravitate toward countries where they are most productive. Thus talent mobility, like the diffusion of ideas, leads to even greater concentration of research in countries that are most efficient at it.

A standard model of research production would predict that their entry would not be fully additive to research effort overall. Foreigners with greater research ability would drive the least research-productive indigenous workers to other sectors.

Conclusion

We summarize with the following points:

- Economists now recognize that knowledge is a substantial source of national wealth. Unlike tangible resources, knowledge naturally spreads internationally. The direction and speed may be hard to predict, however. A country may find it more difficult to keep knowledge within its jurisdiction, relative to tangible resources. But, given its nonrival nature, there is much less point in doing so.
- Research indicators show that a few countries, such as South Korea, have significantly increased their presence as world innovators in the last two decades. Nonetheless, the United States' position as the largest source of innovation, followed closely by Europe and Japan, has remained fairly stable.
- While China employs a large number of research scientists and engineers, they don't register in standard indicators of the international impact of research, such as patents and royalty receipts. An implication is that the source of Chinese growth is much more rapid adoption of advanced technologies from abroad rather than domestic innovation.
- The consequence of faster diffusion to China on living standards in innovating countries is likely to be modest, whether positive or negative. The downside is limited to the loss of cheap Chinese imports. While the implications for global security are less certain, there is substantial upside potential if greater wealth leads China to assume a more responsible role in world affairs.

- Just as countries such as South Korea and China have grown rapidly relative to the United States in the last two decades, Western Europe and Japan grew rapidly relative to the United States in the three decades following WWII. At the time, their emergence generated concern about the potential erosion of U.S. living standards and security. This growth turned out to reflect a catching up that, while reducing the U.S. share of world GDP, has not undermined the U.S. standard of living or threatened U.S. national security.

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Recent Trends in U.S. Science and Engineering: Prospects, Challenges, and Implications

James D. Adams¹

Summary

Building on a policy of intellectual property protection, as well as early efforts to promote practical forms of higher education, the United States has from the start encouraged the use of knowledge in industry, including the use of formal science and engineering. This paper discusses recent challenges and future prospects facing U.S. science and engineering at the start of the 21st century. Of special interest is the recent decline of science in industry and its slowdown in public universities since the early 1990s. The paper offers explanations for these breaks in trend, focusing on domestic policy changes rather than the international environment for science or on depletion of growth opportunities.

Prospects: The Past as Prologue

From the beginning the United States has promoted the use of knowledge in industry. Building on English precedent the Constitution and the Patent Law of 1790 awarded patents for invention. Soon afterward, noting a rising demand for useful higher education early in the nineteenth century, a few universities imitated German practice by founding schools of science. Then, in 1862, Congress passed the Morrill Act, which furthered practical education by establishing the Land Grant colleges. Huffman and Evenson (1993, Chapter 1) recount these events.

Over the next century co-evolution of R&D firms and universities supported robust growth of the scientific workforce. The United States drew on this workforce to fight World War II. Major advances in computation, airplane manufacture, weaponry, and pharmaceuticals were the direct result (Mowery and Rosenberg, 1998). These successes contributed to postwar expansion of the federal laboratories, the creation of the National Science Foundation and the National Institutes of Health, and subsequently, wide-ranging support for university research. This system prevailed intact until the 1980s.

All else equal, public subsidies for science combined with patent protection provide incentives to learn as well as to create. They produce an economy rife with knowledge flows. Incentives for firms to learn about outside knowledge build absorptive capacity in firms (Cohen and Levinthal, 1989). This applies as well to industrial research aimed at learning about science in universities and other firms, which alters direction according to perceived valuation of outside knowledge (Adams, 2006). Learning from universities to solve standard problems is localized

¹ Rensselaer Polytechnic Institute and National Bureau of Economic Research.

(Mansfield and Lee, 1996). Learning from universities is more localized than learning from firms and is probably conditioned by the land grant system, since learning from top universities is not localized (Adams, 2002).

Recent evidence (Adams and Clemmons, 2006b) suggests that much of firms' own scientific discoveries can be attributed to learning from outside science. These results survive rigorous tests. They imply that knowledge spillovers are perhaps the main source of discovery. At this juncture it is worth remembering that government still foots many of the bills that universities and firms accumulate in conducting scientific research, and thus plays a vital role in the generation of the spillovers.

The above may oversimplify by assuming that outside knowledge is free for the asking. Especially in collaborative work, incentives are required for researchers in different organizations to work together. One example is the early-stage idea, which requires help from its creators to be understood (Jensen and Thursby, 2001).

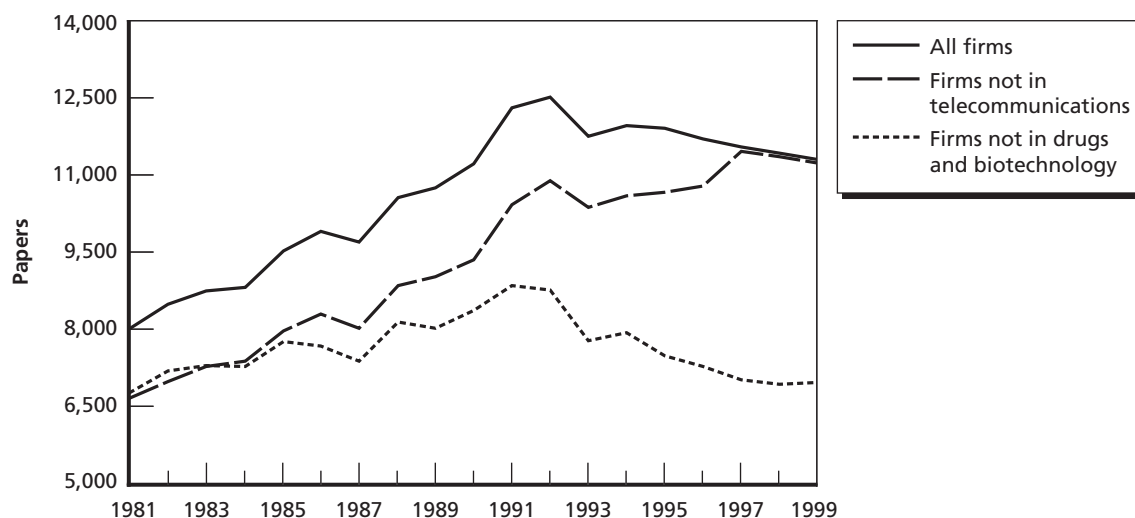
Cooperative Research and Development Agreements (CRADAs) date from the Stevenson-Wydler Act of 1980. Implicit in these arrangements is the importance of incentives to successful collaboration. Gains from CRADAs are based on an assumption of complementarity between firm and federal laboratory R&D. CRADAs can be viewed skeptically, as a means of protecting federal laboratories (Cohen and Noll, 1996). And yet Adams, Chiang, and Jensen (2003) find that CRADAs increase private R&D and patents while procurement and contracts do not. Incentives in collaborative research seem to play a role in knowledge transfer in many different contexts. These ideas have grown more relevant over time, since collaboration has risen sharply from 1980 to the present (Adams, Black, Clemmons, and Stephan, 2005). The same period coincides with a series of challenges to U.S. science. These trials form the topic of the next section.

Challenges: The Recent Slowdown of U.S. Science

Figures 1 through 4 illustrate challenges that have confronted U.S. science in recent years. Figure 1 graphs scientific papers of the top 200 U.S. R&D firms from 1981 to 1999. These are the 200 U.S.-based firms with the largest R&D in 1998. The source of these data is ISI, the Institute for Scientific Information, in Philadelphia, Pennsylvania.

The key feature of Figure 1 is the peaking of industrial scientific papers at 12,500 in 1992 and their decline to 11,300 in 1999. This is a fall of 10 percent, and it is surprising for so strong a period of economic growth. The figure points to a reason for the decline. In the peak year of 1992, over 1,600 papers originated in firms whose primary industry was telecommunications, notably AT&T. By 1999 the number of scientific papers in telecommunications firms declined to 100. This corresponds to a downsizing of the Bell Laboratory system before and after the divestiture of Lucent Technologies. In a space of seven years, basic research in telecommunications falls to one-sixteenth of its baseline value! Without telecommunications, papers increase from 6,600 in 1981 to 11,200 in 1999. But nearly all of this growth is due to drug and biotechnology firms. Papers of all firms increase from 8,000 to 11,300. Without drugs and biotechnology firms, papers start at 6,750, peak at 8,700, and fall back to 6,900 by

Figure 1
Scientific Papers of Top 200 U.S. R&D Firms, 1981–1999



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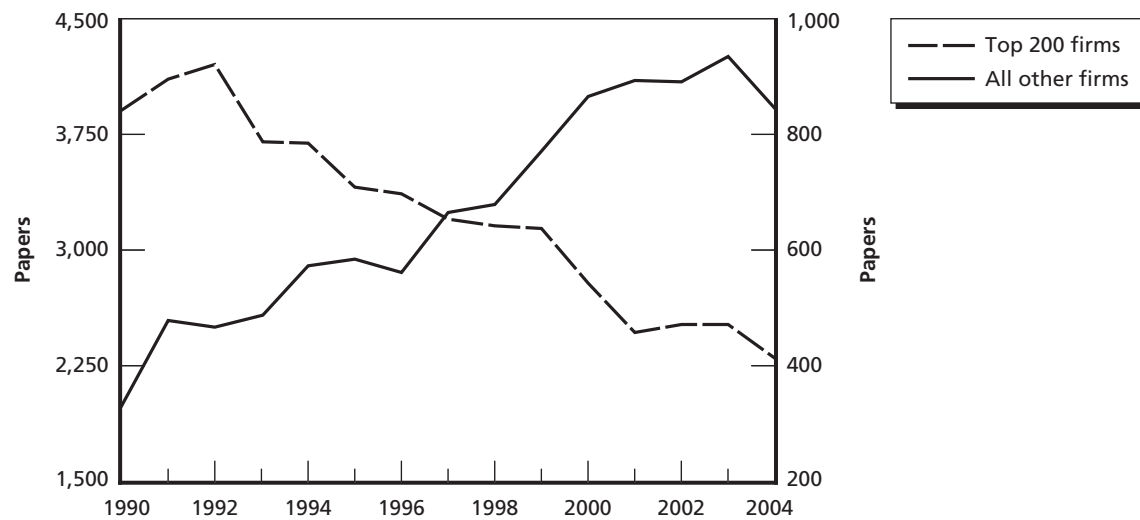
1999. In view of the substantial growth of academic chemistry, computer science, engineering, and physics, the absence of this growth in the 200 largest firms indicates the size of the shocks to industrial science.

Figures 2 and 3 draw from a different sample. This is described in Adams, Wang, and Yang (2006). The sample consists of 823 firms, of which 284 are public and the other 539 are private. Of the 284 public firms, 70 are top 200 firms in the sense described above. The data cover the period 1990 to 2004. Besides the inclusion of small as well as large firms, and the difference in time periods, the sample also differs in that observations consist of firm-regions defined around two-digit zip codes of each firm location, rather than the totality of firm locations, including overseas divisions.

Because the scale of scientific activity differs greatly between top 200 and other firms, Figure 2 graphs top 200 papers on the left scale and papers of all other firms on the right scale. Again, the top 200 data peak in 1992 at 4,200 papers and decrease to 2,300 papers by 2004, a decline of almost one-half. The decline in Figure 1 continues through 2004 for this sample of 70 of the top 200. The situation is reversed for all other firms, whose publications increase from 300 to around 900. But this increase has not made up for the decrease within the top 200.

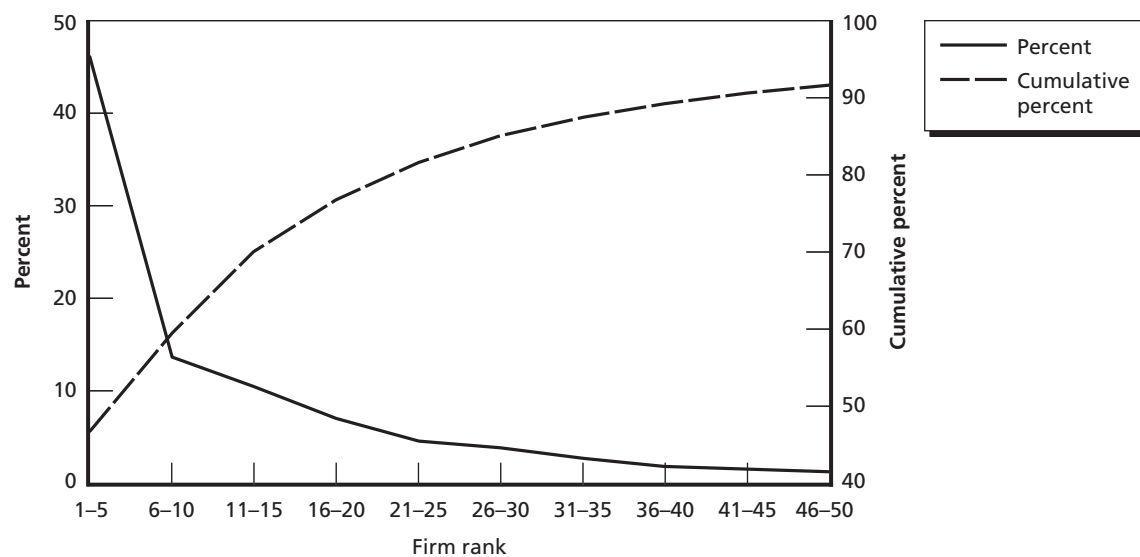
Figure 3 brings to light an important feature of science in industry. Nearly all of it is carried on in large, diversified concerns whose sales in each line of business and whose range of business lines justify investment in science (Adams and Clemmons, 2006b). In Figure 3, one observes, by groups of five firms at a time, the empirical probability function and the cumulative distribution function for the top 50 of the 823 firms shown in Figure 2. When the 50th firm is reached, 92 percent of all papers have been accounted for by 6 percent of all firms. It is no easy task to replace an AT&T, IBM, or Merck with a group of lesser entities.

Figure 2
Scientific Papers of a Sample of Public and Private Firms, 1990–2004



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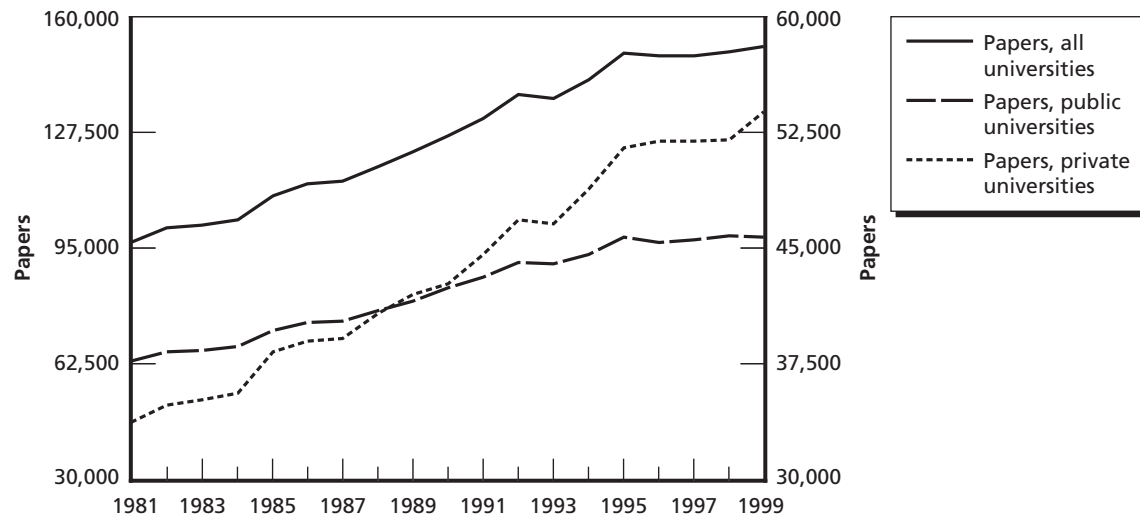
Figure 3
Sample of Public and Private Firms, 1990–2004: Concentration of Scientific Papers



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Figure 4 graphs scientific papers of the top 110 U.S. universities during 1981–1999. The left scale reports papers of all universities and public universities. The right scale reports papers of private universities. Notice that the total U.S. university curve flattens during the 1990s, as does the curve for public universities. And yet the data on private universities (right scale) do not flatten in the same way. This shows up in the gap between total and public university papers, which widens during the 1990s. Production of science in public universities has risen more slowly than in private ones, an issue that is explored in Adams and Clemmons (2006a) and here.

Figure 4
Scientific Papers of the Top 110 U.S. Universities, 1981–1999



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This section has described the recent decline in U.S. industrial science and slowdown in U.S. academic science, where it has shown that the slowdown is concentrated in the public universities. The next step is to explore what these phenomena might imply for the future of the U.S. economy and its defense readiness, and to suggest what might be done about them. This forms the subject of the final section.

Implications for the Economy and Defense Readiness

The main justification for government support is that science contributes to invention outside the institution where it is practiced. In the language of the Poisson distribution, science increases the arrival rate of ideas, and it does so beyond the limits of the institutions where it is practiced. If this is true, then science is not appropriable. Globalization and the Internet contribute something extra to this argument. Under globalization, ideas spread rapidly beyond the nation giving rise to them. One view of this (Krugman, 1979; Grossman and Helpman, 1991) examines a moving equilibrium where the inflow of new ideas in innovating countries is balanced by its outflow to imitators. Implicit in this view is the idea that finite diffusion from a nation allows for some return to innovation by placing a temporary value on new technology. By increasing the diffusion speed, the Internet reduces but does not eliminate this advantage.

Globalization is not new to the United States. In the past it has offered cheaper goods, international knowledge spillovers, and larger markets for products where the United States has an advantage. Past globalization has not clearly reduced incentives to invest in science and technology, nor may it in the future. Moreover, the erosion of U.S. dominance in science and technology is already in the cards (Freeman, 2006). The United States will learn to benefit from changing and often expanding markets, and from increasing international spillovers that will be brokered by improving telecommunications.

Let us return to the decline and slowdown in U.S. science that we observed in Section II. It seems obvious that this has little to do with globalization, but much to do with the United

States To see this, notice that the decline is peculiar to U.S. industrial science. Using its own funds, in 1980 industry spent 1.1 percent of GDP on R&D. In 1990 this figure was 1.4 percent; in 2000 it was 2.0 percent; and in 2004 it was 1.6 percent (National Science Board, 2006; Appendix Tables 4.1 and 4.4). Private incentives to invest in R&D have favored a rising and not a falling R&D intensity over time. The decline of industrial science in Figures 1 and 2 is the result of deregulation, downsizing of the federal laboratories (especially in defense), and cutbacks in government support of industrial science. In support of this we turn again to *Science Indicators 2006*. In 1980 the ratio of federal R&D in industry to GDP was 0.5 percent; in 1990 it was 0.4 percent, in 2000 0.2 percent, and in 2004 it was again 0.2 percent. The decline is clear. The other piece of this puzzle is the slowdown in U.S. university research shown in Figure 4, specifically that of public universities. During the 1990s, state governments came under intense pressure from mandated health expenditures. That and a declining propensity of students to remain in their states have reduced the willingness of states to pay for higher education.

Barring a decline in the social rates of return to science and engineering, which seems distinctly unlikely over such a short period of time, a case can thus be made for an increase in competitively based federal R&D spending, and perhaps an increase in international cost sharing, coupled with privatization of the finance of teaching in public universities (Adams and Clemmons, 2006a). A more tantalizing issue, of some concern, falls under the heading of human capital policy, which favors early childhood development (Heckman and Krueger, 2003). Trends in the way that U.S. youth spends its time appear to be adverse, with more distractions than ever before from the work of learning hard things while still young. So far a solution has not been found, even though investment in knowledge capital at young ages is inexpensive because the opportunity cost of time is exceedingly low at these ages. Earlier times have repeatedly demonstrated this truth by turning out small bands of scholars and inventors who have permanently changed the way that people think.

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Globalization of the Scientific/Engineering Workforce and National Security

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Abstract

This paper shows that changes in the global job market for science and engineering (S&E) workers are eroding U.S. dominance in S&E and diminishing comparative advantages in high-tech production.² This will make it more difficult for the United States to maintain its technological dominance in production, including areas of national security. The evidence shows that

1. The U.S. share of the world's science and engineering graduates is declining rapidly as European and Asian universities, particularly those in China, have increased S&E degrees while U.S. degree production has stagnated.
2. The job market has worsened for young workers in S&E fields relative to many other high-level occupations, which discourages U.S. students from going on in S&E, but which still has sufficient rewards to attract large immigrant flows, particularly from developing countries.
3. Populous low-income countries such as China and India can compete with the United States in high tech by having many S&E specialists although those workers are a small proportion of their workforces. This will weaken U.S. dominance in high tech, potentially including sectors involved in national security.

These trends have three implications for U.S. national security:

4. The increased supply of S&E specialists overseas and accompanying economic and technological competence will give foreign countries that seek to compete in high-tech military areas the potential resources to do so.
5. The diminished U.S. share of S&E talent will make it harder for some U.S. agencies to maintain high productivity if they rely solely on citizens for critical research and development work.
6. The diminished U.S. share of scientific papers suggests that the United States develop new ways of monitoring and benefiting from scientific and technological advances in other countries.

¹ National Bureau of Economic Research.

² Detailed references and notes to the statistics are given in Freeman (2006). I have eliminated footnotes and most references for the sake of brevity.

For the past half century the United States has been the world scientific and technological leader and the preeminent market economy. With just 5 percent of the world's population, the United States employs nearly one-third of the world's scientific and engineering researchers, accounts for 40 percent of research and development (R&D) spending, publishes 35 percent of S&E articles, obtains 44 percent of S&E citations, and wins numerous Nobel prizes. Leadership in science and technology gives the United States its comparative advantage in the global economy. U.S. exports are disproportionately from sectors that rely extensively on scientific and engineering workers and that embody the newest technologies. Aggregate measures of scientific and technological prowess place the United States at the top of global rankings. Analysts attribute the country's rapid productivity growth in the 1990s/2000s to the adoption of new information and communication technologies to production. Scientific and technological preeminence is also critical to the nation's defense, as evidenced by the employment of R&D scientists and engineers in defense-related activities and in the technological dominance of the U.S. military on battlefields.

Changes in the global job market for S&E workers is eroding U.S. dominance in science and engineering, diminishing the country's comparative advantage in high-tech goods and services, and reducing the country's global economic leadership, as the following propositions demonstrate.

Proposition 1: The United States' share of the world's S&E workforce is declining rapidly.

The number of young persons going to college has increased more rapidly in other OECD countries and in many less developed countries, particularly China, than in the United States. Enrollment in college or university per person aged 20–24 in several OECD countries exceeded that in the United States. In 2001–2002, the United States enrolled just 14 percent of tertiary-level students—less than half the U.S. share 30 years earlier. In most countries, moreover, a larger proportion of college students studied science and engineering than in the United States, so the U.S. share of students in those fields was considerably lower than the U.S. share overall. The U.S. share of world bachelor's engineering degrees granted dropped from approximately 12 percent in 1991 to 6 percent in 2000.

Table 1 records the ratios of Ph.D.'s earned in science and engineering in major Ph.D.-producing countries relative to the numbers granted in the United States from 1975 to 2001 and extrapolates the numbers to 2010. Ph.D.'s in science and engineering outside the United States rise sharply whereas the number granted in the United States stabilizes at about 18,000 per year. The greatest growth is in China. In 1975 China produced almost no S&E doctorates. In 2003, the country graduated 13,000 Ph.D.'s, approximately 70 percent in science and engineering. China will produce more S&E doctorates than the United States by 2010! The quality of doctorate education surely suffers from such expansion, so the numbers should be discounted to some extent. But overall, the U.S. share of world S&E Ph.D.'s will fall to about 15 percent by 2010. Within the United States, moreover, international students earn an increasing proportion of S&E Ph.D.'s. In 2000, 35 percent of Ph.D.'s in the physical sciences, and 59 percent in engineering went to the foreign-born.

Table 1
Ratio of S&E Ph.D.'s from Foreign Universities to Those from U.S. Universities

Region	1975	1989	2001	2003 ^a	2010 ^a
Asia, major nations	0.22	0.48	0.96		
China	NA	0.05	0.32	0.49	1.26
Japan	0.11	0.16	0.29		
EU major (France, Germany, UK)	0.64	0.84	1.07		
All EU	0.93	1.22	1.54	1.62 ^c	1.92 ^c
Chinese "diaspora" vs. U.S. "stayers" (estimate)			0.72 ^b		

SOURCE: National Science Board (2004) and primary sources referenced therein; Weiguo and Zhaohui, National Research Center for S&T Development (China), private communication.

^a For 2003 and 2010, ratios calculated using U.S. doctorates at 2001 production level.

^b "Diaspora" includes estimates of Chinese doctoral graduates from UK, Japan, and the United States (with temporary visas). U.S. "stayers" include U.S. citizens and permanent residents.

^c EU data extrapolated from earlier years.

While proportionately fewer U.S. men have chosen science and engineering careers, more women and underrepresented minorities have chosen to major in science and engineering as undergraduates and to go on to master's and doctorate degrees. As a result the proportion of bachelor's, masters, and doctorates degrees awarded to women and minorities in science and engineering fields has trended upward from the 1970s through the early 2000s. In 2004, women won 55 percent of National Science Foundation Graduate Research Fellowships.

Turning to employment, census data show that in 2000 the foreign-born made up 17 percent of bachelor's S&E workers, 29 percent of master's S&E workers, and 38 percent of the Ph.D. S&E workforce—huge increases over the comparable proportions in 1990. The foreign-born made up over half of doctorate scientists and engineers under the age of 45 in 2000 and approximately 60 percent of postdoctorate workers. Nearly 60 percent of the *growth* in the number of Ph.D. scientists and engineers in the country in the 1990s came from the foreign-born.

With increased supplies of S&E workers in other countries, U.S. dominance of the scientific and technological literatures has dropped in many areas. In spring 2004, the front page of the *New York Times* reported a fall in the U.S. share of papers in physics journals while *Nature* reported a rise in the share of papers in China. The NSF records a drop in the U.S. share of scientific papers from 38 percent in 1988 to 31 percent in 2001 and a drop in the U.S. share of citations from 52 percent in 1992 to 44 percent.

Proposition 2: Despite concerns over shortages of scientific and engineering specialists, such as those expressed in *Rising Above the Gathering Storm*, the job market in most S&E specialties is too weak to attract increasing numbers of U.S. students.

Economists have struggled to interpret claims that the United States had a shortage of scientific and engineering workers since the 1950s, when such claims first surfaced. In any market-clearing transaction where wages equilibrate demand and supply, there can be no "shortage" or "surplus." There is disappointment about the price, either by suppliers (when a "surplus"

reduces prices) or by demanders (when a “shortage” raises prices), that can generate longer-run responses in the form of investment to increase the supply or substitution of alternative inputs for the high-priced input.

There is no indication in levels or changes in salaries of shortages in the job market for scientists and engineers. Scientists and engineers earn less than law and medical school graduates. Rates of increase in earnings for science and engineering in the 1990s fell short of the rates of increase for doctors and lawyers and for persons with bachelor’s degrees. Combining the pay differences between doctorate scientists and engineers and highly educated workers in other fields together with the difference in years of education and postdoctorate training produces huge differences in lifetime earnings. Translating census of population earnings by age group into lifetime incomes, discounted at 5 percent, biological scientists had lifetime earning on the order of \$3 million dollars less over their lifetime than doctors and 1.8 million dollars less than lawyers.

Looking beyond salaries, the demographics of the academic job market made it increasingly difficult for doctorate graduates to obtain faculty jobs even as older scientists retired. In 1973, roughly 73 percent of new Ph.D.’s obtained faculty jobs within three years of earning their degrees. By 1999, just 37 percent of new Ph.D.’s obtained faculty jobs within three years of earning their degrees.

Finally, because NIH grants are awarded to faculty members rather than to postdoctorate scientists, the probability that young scientists obtain grants to work as independent investigators has fallen to negligible numbers. The proportion of NIH awards given to scientists less than 35 years old fell from 20 percent in 1980 to 4 percent in 2002 whereas the proportion of grants going to scientists aged 45 years and older rose from 22 percent to 60 percent (see Table 2).

If labor market measures show that the job market for scientists and engineers has been relatively weak, what explains the large influx of international students and scientists and engineers from overseas into the country? The reason is that the foreign-born have lower opportunity costs from other specialties than do Americans. The higher average incomes in the United States compared to developing countries, and the greater dispersion of earnings in the

Table 2
Younger Scientists Don’t Get NIH Grants

Share of NIH Grants	1980	2001
<35	23%	4%
>45	22%	60%
Relative Odds of Getting NIH, by age (ratio of shares of NIH grants to shares of Ph.D.’s)		
<35	1.21	0.30
>45	0.52	1.07
Younger/older	2.33	0.28

SOURCE: Goldman and Marshall (2002); National Science Foundation (2001).

United States compared to other high-income countries means that U.S. students, particularly the most able, have more lucrative non-S&E options than do foreign-born students.

Even the 1995–2004 doubling of the R&D budget for NIH did not improve the well-being of new investigators enough to attract as many U.S. students as foreign students into postdoctorate positions in the bio/medical sciences. The foreign-born share of postdoctoral appointments in biological science and medical/other life sciences rose from 48.0 percent (1995) to 54.7 percent (2002).

Since labor market measures show no evidence of shortages of S&E workers, is there any way to make sense of claims that the United States has a shortage of scientists and engineers and of calls for more young Americans to enter these fields rather than others? How can there be a shortage which does not show up in the job market—a shortage that is not a shortage?

There are three ways to interpret the concerns in the *Rising Above the Gathering Storm*. First is the riskiness of relying extensively on international students and immigrants for the science and engineering workforce. The United States has an adequate supply of scientists and engineers only because of the sizeable influx of foreign-born students and employees. Any interruption or change in the flow of immigrant scientists and engineers would certainly harm U.S. research and development. From this perspective, the call for more U.S. students to go into science and engineering reflects a belief that the balance between the supply of U.S.-born and foreign-born scientists and engineers may have tilted too much toward the latter.

Second is the belief that federal research and development spending, particularly basic R&D in the physical sciences and engineering, has not kept pace with the economic and security needs of the country. If the nation were to demand the number of scientists and engineers that would meet the challenges of the next several decades—in maintaining U.S. comparative advantage in high tech, in meeting national security challenges, in dealing with global warming and energy problems—it would need more scientists and engineers than it currently is producing and importing from overseas.

Third is the policy adopted by some agencies and national laboratory projects—for instance the National Security Agency—that projects critical to national security are undertaken solely by U.S. citizens. If the supply of U.S. Ph.D. mathematicians declines, the NSA has a major problem.

Proposition 3: Human resource leapfrogging and global competition in high technology.

A large part of global trade occurs because countries gain advantages from being the first-mover on new technologies, which require R&D resources, and/or from increasing returns gained through learning as output increases or through positive spillovers from one firm in a sector to another. The north-south version of the trade model postulates that the advanced area (the north) has the skilled workforce and R&D capability to innovate new goods and services, while the less advanced area (the south) cannot compete in these areas (Krugman, 1979). As a result, the north innovates new goods and trades them with the south, which produces older goods as it gains the technology do so. Once the two regions have access to the same technology, the lower-wage south produces the good or service. Workers are paid higher in the north than in the south, both because they are more skilled and because the north has a monopoly on the new products. More rapid technological advance increases wages in the north relative to wages in the south while more rapid diffusion of technology has the opposite effect. In terms of national security, the north's monopoly on high-tech production guarantees its dominance in military technology.

The increased supply of scientific and engineering workers, including doctorate researchers and others able to advance scientific and technological knowledge in large developing countries, is outmoding this vision of the division of technology and production between advanced and developing countries. It creates the possibility of *human resource leapfrogging*, in which large, populous, developing countries employ enough scientists and engineers to compete with the advanced countries in the high-tech vanguard sectors that innovate new products and processes.

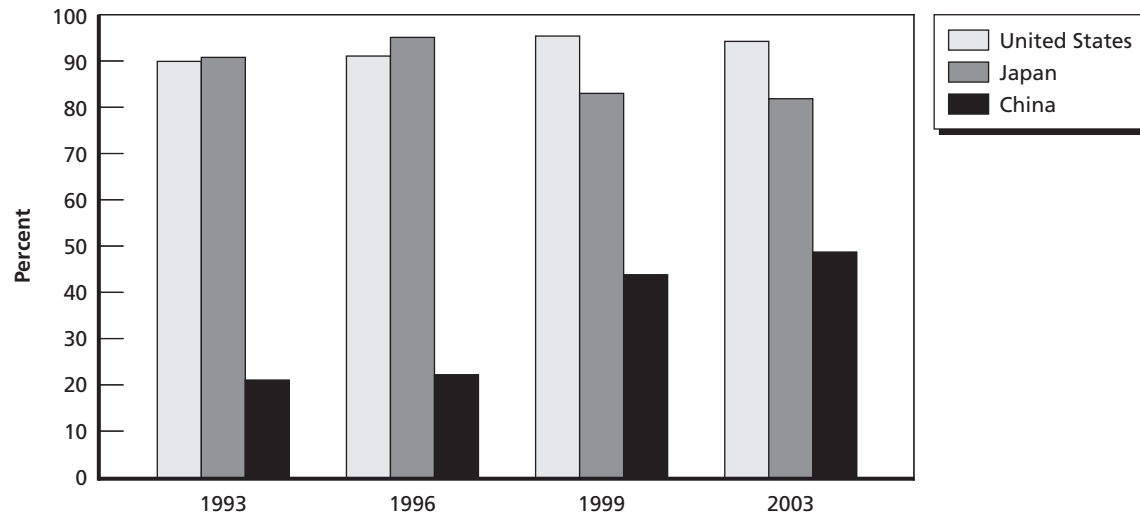
Loss of comparative advantage in the high-tech sector to a low-wage competitor can substantially harm an advanced country. The advanced country would have to shift resources to less desirable sectors, where productivity growth through learning is likely to be smaller. Wages and living standards would remain high in the advanced country because of its skilled workforce and infrastructure. But the monopoly rents from new products or innovations would shift from the advanced country to the poorer country. The magnitude of the loss would depend in part on the number of persons working in the advanced sector, and their next best alternatives. If the low-wage country were to use its scientists and engineers to take a global lead in space exploration, there would be little impact on the economy of the advanced country. But, if the low-wage country deployed its scientists and engineers to take a global lead in sectors with sizable employment and significant throughput to the rest of the economy, in this case, the economic losses to the advanced country could be substantial. During the Cold War the former Soviet Union devoted its scientific and technological expertise to the military area rather than to economic activity. A low-wage competitor could do the same today, though the Soviet experience suggests that this could be a self-defeating exercise.

Real Concerns or Paranoia?

Several indicators suggest that human resource leapfrogging is rapidly reducing U.S. technological and economic leadership:

- Major high-tech firms, from IBM to Cisco to Microsoft, are locating new R&D facilities in China and India, in part because they want to create products for those markets but also because of the supply of science and engineering talent at wages far below those in the United States.
- Off-shoring of some forms of skilled work.
- Indices of technological prowess show a huge improvement in the technological capability of China, in particular (see Figure 1). In 1993 China received a 20.7 measure in the Georgia Tech measure of technology, whereas in 2003 it was at 49.3. Consistent with this, the Georgia Tech group found that China was fourth in the world, after the United States, Japan, and Germany, in publications in four emerging technologies in 1999; the Nanotechnology Research Institute of Japan reported in 2004 that China was third and close behind Japan in publications and patents in this area.
- Production and exports of high-tech products show that the improved capability of China in high technology is showing in the economy, though many experts believe that the data exaggerate Chinese high-tech production because firms import the highest tech parts or services.

Figure 1
Technological Standing Index, United States, Japan, China, 1993–2003



SOURCE: Graph by Alan Porter in Georgia Tech Technology Policy and Assessment Center (2003). Used with permission.

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In sum, research and technological activity and production are moving where the people are, even when they are located in the low-wage “south.” Such research, activity, and production are moving to China because China is graduating huge numbers of scientists and engineers and to India, as well, though more slowly.

Implications for National Security

Loss of dominance in the supply of scientific and engineering talent and in high-tech production has three implications for U.S. national security:

Proposition 4: Foreign countries and groups will have potentially ample supplies of S&E workers for developing high-tech sectors that may be critical for national security.

As the number of scientists and engineers working in foreign countries continues to increase, the United States’ comparative advantage in generating scientific and engineering knowledge and in the high-tech sectors and products associated with that knowledge will decline. Increased numbers of scientists and engineers will stimulate the rate of technological advance, expanding the global production possibility frontier, and benefiting people worldwide. But the United States will also face economic difficulties as its technological superiority erodes. The group facing the biggest danger from the loss of America’s technological edge is workers whose living standards depend critically on America’s technological superiority. The big winners from the spread of technology will be workers in developing countries and the firms that employ them, including many U.S. multinational corporations. In the long term, the spread of knowledge and technology around the world will almost certainly outweigh the loss of U.S. hegemony in science and technology, but the transition period is likely to be lengthy and difficult—more formidable than that associated with the recovery of Europe and Japan after World War II.

In national security, however, the risks to the United States—in the form of more countries with potentially competitive technologies in the military area or more groups with access to possibly dangerous technologies—may outweigh any gains from a more multipolar world in which other leading countries could take on greater responsibilities. The increased supply of S&E specialists overseas and accompanying economic and technological competence will give foreign countries that seek to compete in high-tech military areas the potential resources to do so.

Proposition 5: U.S. agencies that hire citizen S&E talent only will have increasing difficulty maintaining top-flight workforces.

With a smaller U.S. share in the global supply of science and engineering talent, any policy that restricts agencies involved in R&D and national security issues to U.S. citizens risks lowering the productivity of those agencies relative to what it would be if, like the major multinationals, they globally searched for the best candidates for jobs. There is a quick fix to this: fast track citizenship for non-citizens to work on key projects or in critical agencies. There is another solution as well: provide more fellowships and higher pay to attract the best U.S. graduates.

Proposition 6: The United States must develop new ways of monitoring and benefiting from scientific and technological advances in other countries.

To deal with the globalization of science and engineering, the United States will have to consider new policies in the market for R&D and technology to build on existing strengths that maintain scientific and technical leadership in some sectors and to remain close to the frontier in other areas. The country will also have to find ways to take scientific and technological advances from other countries and turn them into commercial products rapidly. If more advances come from overseas, the United States will benefit from investing in paying close attention to those advances and seeking ways to use them in the economy and in national security.

Proposed Efforts to Augment Our Supply

Continued growth in the supplies of highly talented young people in the United States can maintain the United States as a center of scientific and technological excellence, albeit a less dominant center. The country could continue to encourage large numbers of foreign students and S&E immigrants to study and work in the country. But an increase in the supply of immigrant S&E workers will, all else the same, reduce earnings and employment opportunities below what they otherwise would have been, thus lowering the incentives for persons from that and from other sources to enter the S&E job market.

To counteract this and increase domestic supplies without discouraging foreign students and immigrants, it is necessary to provide more lucrative graduate research fellowships (which go to U.S. students or residents only) and improve opportunities to do independent research early in a career, both of which are likely to increase U.S. supplies more than those from foreign countries. From 1999 to 2005 NSF increased the value of its Graduate Research Fellowship Award from \$15,000 to \$30,000. The number of applicants nearly doubled as well, indicating a high elasticity of supply to the awards. But the number of awards has not changed much since the early days of the programs, so that in the 2000s approximately one-third as

many NSF fellowships were granted per S&E baccalaureate than in the 1950s and 1970s. An increase in the number of awards at the new value of stipends could substantially increase the supply of citizens choosing S&E studies.

But any such policies must also seek to improve the work life of new S&E persons—for instance, by increasing their chances of doing independent work. And without increased demand, any programs to increase the supply of scientists and engineers will have little long-term impact.

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The Gathering Storm and Its Implications for National Security

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The National Academies report *Rising Above the Gathering Storm* has been a visible and influential addition to the literature on U.S. policy regarding scientists and engineers. It was produced in near-record time—about 20 weeks—in response to a request by two members of the U.S. Senate. It is primarily based upon the views of members of a blue-ribbon committee of current and former CEOs, university presidents, and scientists/educators.² Many of the report's recommendations were quickly incorporated into legislation introduced by its senatorial sponsors; this legislation was not passed by Congress in 2006, but is likely to return to the agenda in 2007.

It is always judicious to observe and track gathering storms, and to prepare in advance for the havoc they may cause. Some gathering storms are distinct and visible, with clearly threatening implications should they follow relatively predictable courses. Others take forms that are far more hazy and indistinct, and with future trajectories that are refractory to accurate forecasting.

The Haze Surrounding Past “Shortages” and “Looming Shortfalls”

Claims of shortages of scientists and engineers—sometimes current, more often “looming”—have been among the most hardy of perennials in the American political garden over the past half-century. Vigorous varieties have emerged every one to two decades since at least the late 1950s and 1960s.

The 1960s concerns followed the shock of Sputnik, and led to large expansions of federal support for research and education in science, mathematics, and engineering. In the 1980s the claims of “looming shortfalls” came primarily from a small policy office reporting to the then-Director of the National Science Foundation; its reports were amplified by the press and by a few leaders of research universities. In the late 1990s the primary proponents of shortage claims were multinational companies in then-hot high-tech sectors such as software, IT, and telecommunications, working in close coalition with the immigration bar.³ The most recent concerns about shortages have been led again by corporate lobbyists, especially in the IT and

¹ The author is vice president of the Alfred P. Sloan Foundation, New York. The views expressed are the author's, and not necessarily those of the Alfred P. Sloan Foundation.

² In the interest of full disclosure, the author served at the request of the National Academies as an external peer reviewer of the draft report.

³ Their shared legislative goal was a tripling of the annual number of temporary visas known as H-1Bs. This goal was successfully achieved as part of legislation passed in 2000, the year before the collapse of the high-tech boom.

software sectors (though not telecommunications), by immigration lawyers, by some in higher education, and by some focused on security concerns both foreign and domestic.

The shortage or shortfall assertions of the 1960s, 1980s, and 1990s proved to be significant in policy terms, especially convincing to politicians, journalists, and pundits. It remains to be seen how influential current shortage/shortfall claims will prove to be.

Quantitative Evidence

Proponents of past shortage/shortfall claims usually provided some supportive quantitative evidence. In retrospect these can now be seen to have been quite weak. The focus of the 1960s concerns was the perceived strategic advantage accruing to the USSR from the large numbers of scientists and engineers being produced by Soviet universities and technical institutes. Proponents paid rather little attention to the quality and productivity of these Soviet professionals.

In the 1980s the focus was the economic challenge from Japan, with its rapidly growing export-led economy. This Japanese economic advance was propelled by highly productive manufacturers that competed very effectively with U.S. producers in industries such as autos, consumer electronics, and semiconductors. Quantitative projections undertaken for the U.S. labor force by the NSF policy office—now known to have been based on methodologically weak use of demographic and economic models⁴—showed large “looming shortfalls” of scientists and engineers, i.e., projected future demand substantially in excess of projected future supply. The U.S. Congress responded expeditiously, providing substantial budget increases for NSF’s science and mathematics education programs. Only a few years later, when it became evident that instead of the projected growing “shortfall” there was evidence of an excessive supply of newly minted scientists and engineers, an investigation by the Investigations and Oversight Subcommittee of the Science, Space and Technology Committee of the House of Representatives produced harshly critical assessments of the episode (U.S. House of Representatives, 1993).

In the late 1990s, quantitative evidence also was provided by proponents of shortage claims, but in this case such evidence was perhaps even weaker than that of the late 1980s. Much was based upon unverifiable reports from software and IT employers about difficulties they were experiencing in hiring skilled personnel. These were supported by a few non-representative surveys that reported large and growing numbers of job “openings” in IT; these surveys were undertaken by one of the industry’s own trade associations, the Information Technology Association of America (ITAA).

The most recent expressions of concern have tended to highlight data suggesting that the United States is again falling behind its economic competitors (in this case China, India, and Europe rather than the USSR or Japan) in the numbers of bachelor and doctoral graduates in science and engineering fields. Although the very large numbers often cited for China and India evidently are weakly founded (see for example Gereffi et al., 2005), graduation numbers

⁴ It is worth reporting that the methodologies used in these projections were sharply criticized by experts on the science and engineering workforce from within the NSF’s own professional staff, who noted that the separate demand and supply projections that were used were both overly simplistic and did not allow for mechanisms by which supply might be expected to adjust to demand and vice versa. The projections were not released as “official” NSF reports, but their conclusions of “looming shortfalls” were frequently cited by the then-NSF director, by those outside NSF who supported his arguments, by the lay and specialized press, and by many members of Congress.

in these countries do appear to be increasing rapidly. Of course it is too early to be sure if the significance of these comparisons is as doubtful as the earlier ones proved to be.

There have not been many careful and objective studies of U.S. science and engineering labor markets to assess the validity of claims about current or prospective shortages of scientists and engineers. Several studies by the RAND Corporation concluded that their efforts to find credible data supportive of such shortage claims did not yield any convincing evidence. Indeed, one 2002 RAND study reported that labor market data from even the late 1990s—the period of simultaneous booms in IT, telecommunications, and biotech, when the press was full of stories of companies competing fiercely for scarce talent—surprisingly showed that “neither earnings patterns nor unemployment patterns indicate shortage in the data we were able to find.” If anything, the report noted evidence of rising unemployment among scientists and engineers during this same period, evidence that “while the overall economy is doing well, is a strong indicator of developing surpluses of workers, not shortages” (Butz et al., 2003).

Studies emanating from the National Bureau of Economic Research’s Science and Engineering Workforce Project (SEWP)⁵ also have sought to identify credible quantitative evidence of science/engineering shortages. Instead these studies have tended to find contrary labor market indicators. These include relatively unattractive and even deteriorating remuneration and career prospects for entry-level and mid-career scientists and engineers as compared with those experienced by other highly educated professionals (see, for example, Freeman, 2003).

The Hazy Future

As to the credibility of “looming” shortages or shortfalls, i.e., projected future insufficiencies in the number of scientists and engineers, there is much that should be written that cannot fit into a brief paper. The embarrassing 1980s episode described earlier offers but one example of the need for caution. Suffice it to say that it has proved to be exceedingly difficult to produce projections that can be used as credible forecasts of future demand and supply in science and engineering. Indeed, a National Research Council expert panel that evaluated the success of past forecasts for the science and engineering workforce reported in 2000 that labor market projections for scientists and engineers that go more than a few years into the future are notoriously difficult, and that “accurate forecasts have not been produced” (National Research Council, 2000).

Much of the difficulty in such projections is due to the unpredictability of future domestic demand for such personnel. In general, projecting future demand in labor markets is always fraught with difficulties. In this case the challenge is far greater, given that funding both for basic research and for procurement in R&D-intensive fields such as aerospace is heavily dependent upon appropriations available to federal agencies (e.g., DoD, DoE, NIH, NSF). These, in turn, depend upon political decisions by Congress and the executive branch that are exceptionally difficult to forecast. To this must be added the evident reality that some industries that are highly visible employers of scientists and engineers (e.g., computers, software, IT, telecommunications, civilian aircraft) are prone to rather rapid but unpredicted (and unpredictable) cycles of booms and busts. More recently, some of these same industries have been leading the growth of offshore outsourcing of high-skilled services to low-wage countries such

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as India and China—the longer-term trends of which are exceedingly difficult to anticipate. In short, the development of credible forecasts for U.S. science and engineering labor markets beyond the near term would require credible forecasts of the future trajectories of federal appropriations, of future business cycles of high-tech economic sectors, and of offshore outsourcing in science and engineering fields.

Misdirected Solutions

Whatever might be the validity of claimed shortages or looming shortfalls, it is quite surprising that the focus of recent discussions of these issues has been directed primarily to the supply side of science and engineering labor markets. A 2005 report by a group of 15 business organizations highlighted its central and ambitious recommendation prominently on the report's front cover: *Goal: Double the Number of Science, Technology, Engineering and Mathematics Graduates by 2015*. (U.S. Chamber of Commerce, 2005). Its recommendations emphasize measures to “[m]otivate U.S. students and adults to study and enter science, technology, engineering and mathematics careers.” Little attention is paid to the demand situation that might await such doubled numbers of labor force entrants.

The *Rising Above the Gathering Storm* report also places emphasis upon recommendations to increase supply, along with some attention to demand. One set of its recommendations calls for numerous actions by the U.S. government to increase the number of U.S. students who pursue education and careers in science, math and engineering (for K–12 levels: recommended actions A-1, A-2, A-3; for postsecondary levels, actions C-1, C-2, C-3). A second set of recommendations is devoted to U.S. government actions to increase the number of foreign students and professionals in science and engineering fields (actions C-4, C-5, C-6, C-7).

When the demand side is considered along with the supply side (usually the best way to think about labor markets), it is apparent that if both sets of recommendations were implemented they might be expected to work perversely against one another. For in the absence of sharply rising demand, the second set of recommendations (designed to increase the supply of foreign students and professionals in the U.S. workforce) might be expected to lead to further deterioration of the relative attractiveness of science and engineering career paths for would-be domestic entrants—thereby discouraging rather than encouraging the increases recommended in the number of U.S. students pursuing these paths. Such deterrent effects would likely be less powerful for foreign students and professionals from low-wage countries such as China and India, for whom the relative attractiveness equations would be completely different.

To be fair, the *Rising Above the Gathering Storm* report does also recommend some actions that might well increase demand in science and engineering fields, e.g.,

- Double federal research funding in physical sciences, engineering, math, and information sciences (B-1).
- Fund new \$2.5 million, 5-year research grants to 200 outstanding early-career researchers (B-2).
- Double and make permanent the corporate R&D tax credit, and assess other tax incentives (D-2).

Substantial increases in federal basic research funding in the physical sciences, engineering, math, and information sciences would be desirable in many ways. But it is also only fair to note that such a rapid increase in basic research funding, if implemented without structural changes in the way federal research funds are deployed, would be more likely to increase rather than decrease the percentage of foreign students and postdocs recruited to work on federally funded projects at U.S. universities—as seems already to have resulted from the recent doubling of the NIH research budget. The effects of increasing the R&D tax credit on levels of domestic demand for scientists and engineers would be indirect and quite difficult to assess.

The Special Workforce Concerns of Federal Science and Engineering Agencies, and Their Implications for National Security

In a widely cited working paper (included in the background readings for this workshop), Richard Freeman (2005) seeks to reconcile available quantitative labor market data with the “shortage” arguments. His discussion offers some useful insights into the special position of the federal workforce.

Freeman first notes the absence of any credible evidence supporting claims of “shortages”:

Since labor market measures show no evidence of shortages of S&E workers, is there any way to make sense of continued claims that the U.S. has a shortage of scientists and engineers and of calls for more young Americans to enter those fields rather than others? How can there be a shortage which does not show up on the job market—a shortage that is not a shortage?

His interpretation is that the sizable influx of foreign-born students and employees in science and engineering means that there is and has been no “shortage.” Yet he notes that there also is concern that relying so much on this source could be risky, leading to the calls for more U.S. students to go into these fields. Such concerns, he believes, though expressed in terms of workforce “shortages,” are really about the flow of U.S. entrants into science and engineering.

Unlike most other writers on this subject, Freeman goes on to note the potential contradictions inherent in such calls, which typically focus on enhancing supply without due attention to the demand side:

But many of the persons and firms who make these arguments do not face up to the potential trade-off issue: that to attract more U.S. citizens, earning and opportunities have to get better, which is difficult to effectuate as long as the country can attract many scientists and engineers from overseas at current wages and employment opportunities. (Freeman, 2005)

This key point, so frequently ignored in debates in this area, has particular importance for those who are specifically concerned with the federal science and engineering workforce and implications for national security. Put simply, personnel needs of DoD and other federal agencies (and their contractors) that require substantial numbers of scientists and engineers able to obtain security clearances may be quite markedly different from those in the civilian corporate and university sectors, in which citizenship and security clearances are usually quite unimportant.

DoD and similar agencies depend upon the flow of science and engineering graduates from U.S. universities. Meanwhile U.S. universities are free to recruit their science and engineering students and personnel either domestically or internationally, and, at the graduate, postdoctoral, and faculty levels, have increasingly been doing so internationally. U.S. civilian employers that are not large contractors for such federal agencies have lobbied, and quite successfully, for rights to large-scale international recruitment as well.

If the “trade-off” issue highlighted by Freeman is correct, such international recruitment by U.S. universities and civilian employers may be an important element of the explanation as to why domestic earnings and employment opportunities for scientists and engineers have not improved—indeed seem to have fallen behind other professions requiring substantial postgraduate education—thereby limiting their attractiveness at the margin for domestic entrants.

In Pursuit of Leveraged Approaches

Most of the recent reports in this domain, including the *Rising Above the Gathering Storm* report, have focused attention on the importance of reforming the U.S. K–12 system to produce more and better students aiming for further education and careers in science and math. There is nothing wrong with such recommendations. Indeed, as a set of general goals for public policy, improving the quality of K–12 science teaching is very attractive indeed. In the 21st century, everyone who claims to be “educated” really will need to acquire a good understanding of science, mathematics, and technology.

However, the argument in favor of improving K–12 science and math usually is framed more in terms of “filling the pipeline” for future scientists and engineers, and in this form is far less convincing. Those who are employed as scientists and engineers represent only a small fraction (on the order of 5 percent) of the U.S. workforce. Meanwhile, the evidence available shows that each year a rather high percentage of entering freshmen in U.S. colleges and universities already are intending to major in science, mathematics, engineering, and related fields. According to surveys of entering freshman reported by the Higher Education Research Institute at UCLA, such intentions are reported by 31 percent of white freshmen, 43 percent of Asian/Pacific Islander freshmen, and 35 percent freshmen in underrepresented minority groups. The percentages are generally higher among males (National Science Board, 2004, Chapter 2). The surveys show sharp increases in intended majors in computer fields during the late 1990s boom, followed by sharp declines since the bust in these fields beginning in 2001.

Yet of those expressing such intentions, less than half appear to complete degrees in these fields. The National Science Board’s excellent biennial data compendium *Science and Engineering Indicators* reports that about one-third of such intending freshman shift to other fields while still undergraduates, and about one-fifth of the intending group drop out and do not complete any degree. There is limited evidence that retention rates are higher in selective private institutions that also have Ph.D. programs, and lower among minorities and women (National Science Board, 2004, Chapter Two).

Do we understand why there is such a drop-off among the nearly one-third of entering freshman who report intentions to major in science, mathematics, engineering, and related fields? A number of alternative and speculative hypotheses might be offered:

- Inadequate science and math preparation in K–12?
- Less supportive cultures for undergraduates in university science/math departments than in other fields?
- Poorer quality of undergraduate teaching in science, math, and engineering? (Romer, 2002, points especially to introductory science courses that he describes as “large, impersonal, and threatening. Students know them for what they are. They call them ‘weed out’ or ‘weeder’ courses.”)
- Student exposure as undergraduates to interesting fields not taught in secondary schools?
- Student knowledge of substantial differences in grading curves between science/math versus other fields, such that ambitious high achievers who are unsure about future career plans might differentially shift toward the latter (Romer, 2002; see also Parekh, 2002, and Bar and Zussman, 2005)?

We cannot at the moment confirm or reject any of these possibilities, but the large drop-off rates do suggest that there could be very high leverage from understanding which are most important, and then addressing them strategically. Successful measures to increase the proportion of intending freshmen who actually complete their majors in these fields could have major quantitative effects in relative terms, especially given that only a small percentage of any economy’s labor force is engaged in science and engineering occupations.

It is also wise to avoid overinterpreting the oft-reported cross-national comparisons of percentages of age cohorts or graduating classes that complete degrees in science, mathematics, and engineering. The system of U.S. higher education, unlike those of many other industrialized countries, is structured to allow students flexibility to shift their major interests after entry. Moreover the U.S. government does not determine the percent of university admissions devoted to science, math, and engineering; many other national governments do so.

Available evidence also suggests that relatively small percentages of students who do complete undergraduate majors in science and mathematics go on to graduate degree programs. Moreover (though the numbers here are very hazy), it also may be that even among those who do enter Ph.D. programs, the percentage completing the degree may be lower than might be expected from students who have already demonstrated both abilities and interest in these fields—especially if compared with the higher completion data for the MD degree. We know less than we should about this topic, but increasing our understanding might also offer rather highly leveraged opportunities for effective interventions.

One difficulty in assessing these issues, highlighted by RAND, lies in the substantial lags in labor market data for scientists and engineers. Available data commonly lag 2–3 years or longer behind reality. The disciplines and industries involved are dynamic ones, which make such data decidedly out-of-date to address the basic research workforce, and for some industries such lags may exceed even a full product life cycle. In response to such limitations, RAND has called for development of “flash data” on science and engineering labor markets—i.e., “provisional” estimates akin to those for overall unemployment and inflation produced regularly by federal statistical agencies. DoD could consider whether financing the creation of such preliminary but more up-to-date data might be a good investment, perhaps via interagency contracts with NSF and/or BLS.

Promising New Approaches to Graduate Science Education

Another approach with potentially high leverage would be to provide alternative pathways for the large fractions of U.S. students who are graduating with undergraduate majors in science and mathematics, but deciding against postgraduate studies in these fields. In part this may be due to the fact that postgraduate science pathways have increasingly concentrated on the Ph.D., and that many doctoral programs have become excessively lengthy—especially in fields in which a postdoc is the norm following completion of the Ph.D. degree itself. These trends increase the opportunity costs of such degrees, i.e., large foregone earnings while engaged in extended postgraduate studies at low levels of compensation (for a fuller discussion, see Teitelbaum, 2003).

In addition, these extended degree times make the standard Ph.D.-only tracks far more sluggish in responding to the shifts and fluctuations in labor market demand that have characterized many scientific fields in recent years. Finally, since most Ph.D. programs have been designed to produce highly qualified basic researchers suitable for academic employment, they may actually not be the most appropriate pathways for sophisticated graduate-educated scientists seeking careers in nonacademic environments.

The Sloan Foundation has been providing support over the past eight years for an additional track for graduate-level education for aspiring science professionals, known as *professional science master's* (PSM) degrees. Typically, these PSM degrees are two-year, course-intensive graduate degrees created and taught by science departments in major universities. Unlike the Ph.D.'s offered in the same departments, they are configured not for academic research careers but instead for science careers *outside* academe. Hence while they concentrate heavily on the graduate-level disciplinary courses required by employers of scientists, they also include a set of "science-plus" courses. These focus on the non-science skills emphasized as of critical importance by both corporate and governmental employers, such as the ability to work in multidisciplinary groups, to communicate effectively, to manage projects to budgets and timetables, and where appropriate to understand legal and regulatory issues.

There are now more than 50 U.S. universities offering PSM degrees, and over 100 such degrees in operation. A full listing may be found at the Professional Science Master's homepage (undated).

The emergence and growth of these PSM degrees offers another highly leveraged approach to concerns expressed by some federal agencies about whether sufficient U.S. citizen scientists and engineers are being produced by the U.S. educational system. In particular, PSM degrees have tended to attract higher percentages of U.S. citizen students than do related Ph.D. degree programs, and as two-year intensive graduate degrees, they also offer a potential "fast-track" approach to meeting recruitment needs of nonacademic employers including federal agencies.

The development of these PSM degrees has been welcomed or endorsed by many leading organizations involved in U.S. higher education and economic performance, including the Council of Graduate Schools and the Council on Competitiveness. It is therefore striking to note that no federal agencies apparently have yet been able to provide support for PSM programs or their students. Of course, large fractions of Ph.D. students and postdocs at U.S. universities receive funding from federal sources, but most of this support flows to them indirectly via research grants and contracts, rather than directly as fellowships or training grants. Since PSM students devote most of their time to graduate course work rather than to serving as research assistants on federal research grants and contracts, they typically cannot obtain

financial support from the federal funding streams that currently finance most graduate education in science.

DoD and other entities in the domain of security may wish to review the potential of PSM degrees and consider carefully whether existing or newly created degrees of this type might serve at least some of their future science personnel needs.

Summary

Objective analysts who have sought credible quantitative evidence of general “shortages” or “looming shortfalls” of scientists and engineers in the United States generally report negative results. Some find the opposite—i.e., evidence of excess supplies of scientists and engineers relative to labor market demand for their services.

Nonetheless, the large (and increasing?) percentages of foreign students, postdocs, and faculty recruited by U.S. universities may pose special labor market challenges for employers of scientists and engineers in the national security domain, where employment requires security clearances. The interests and concerns of such employers about domestic recruitment may differ markedly from those facing U.S. research universities, although in most cases the latter are responding in part to incentives presented to them by research funding from U.S. government sources. Similarly, corporate employers whose work requires security clearances face quite different hiring situations from those of U.S. employers without large security-related businesses.

There are a number of steps, with potentially high leverage, that DoD and other security-directed federal agencies could consider taking, both to reduce the haze surrounding the concerns about the U.S. science and engineering workforce and to deal creatively and concretely with the distinctive recruitment circumstances they face.

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Comments on the “Gathering Storm” and Its Implications for National Security

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Introduction

Rising Above the Gathering Storm outlines concerns regarding the U.S. competitive position and makes recommendations regarding ways to energize the U.S. system of innovation. Some of the recommendations are very supply-focused; others are demand-focused. In what follows, I comment briefly on some of the recommendations and make suggestions in several instances concerning ways to enhance the effectiveness of some of the recommendations.

The discussion is predicated on a number of findings regarding the science and engineering enterprise in the United States. These include the following points:

- The K–12 system of education in the United States is, if not broken, performing poorly, especially with regard to producing students with scientific and math literacy as well as students with a strong interest in pursuing studies in science, math, and engineering (STEM) and the necessary skills to be successful in this undertaking. Having a workforce that has a reasonable level of technical literacy could enhance innovation in the United States. Literacy helps in the adoption of new technology, but also, and perhaps more importantly, in using new technologies to create innovative solutions in the workforce. Students with the interest and capability of pursuing degrees in STEM are key if the United States is to grow its STEM workforce from within.
- Enrollment in graduate programs in STEM among citizens, especially among male citizens, has been on the decline. This is partly because of the deficiencies of the K–12 system, but not entirely because of these deficiencies. Many potential scientists, mathematicians, and engineers drop out of STEM majors in the process of getting undergraduate degrees.
- Signals play an important role in recruiting individuals into careers in science and engineering. These signals include (1) the availability of support while in undergraduate and graduate school; (2) the job prospects faced by fellow students, especially students who are several years ahead in training; (3) salary and working conditions available in other careers, such as those requiring a law, MBA, or MD degree; and (4) the opportunity to perform research. The latter point is important. A key issue for many students is the opportunity to do research. Salaries play an important role in science and engineering but the opportunity to engage in puzzle-solving work is also important. Take the prospect of doing research away from someone trained in science and engineering, or contemplating a career in science and engineering, and interest wanes among many.

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- Research productivity is affected by the environment in which scientists and engineers work and the conditions of their employment. For example, access to equipment and colleagues clearly affects productivity. Productivity is further enhanced by researchers having a certain amount of autonomy. Moreover, a research horizon, facilitated by job security or the stability of funding opportunities, encourages scientists to choose more risky projects than they might otherwise choose.
- It doesn't hurt to be young. Research consistently finds evidence of a relationship between age and productivity. (For a discussion of the relationship between age and scientific productivity, see Stephan and Levin, 1992, 1993; Jones, 2005; and Turner and Mairesse, 2005.) For what we might call journeymen scientists, the relationship is not that pronounced. But for prize-winning research, there is considerable evidence of a strong relationship. While it does not require extraordinary youth to do prize-winning work, the odds decrease markedly by mid-life.
- Signals are not only important to individuals. They also play a major role in the development of programs and buildings. The recent dramatic increase in research space dedicated to the biomedical sciences at universities is the best example of this in recent times. Faced with a doubling of the NIH budget, universities undertook to build a substantial number of new research facilities in the biomedical sciences. NSF (Christovich, 2005), for example, reports that 56 percent of construction that was undertaken on campuses in FY 2002 and FY 2003 was for the fields of biological and medical sciences. Moreover, as buildings came on line, faculty positions grew as well. The American Association of Medical Colleges faculty roster data show that the number of first assistant professor jobs at medical schools grew by 38.4 percent between 2002 and 2003.
- Stop-and-go funding, where federal agencies have received big increases in certain years (sometimes as high as 20 percent) followed by real cuts or modest increases, is not healthy for the scientific enterprise. Rapid increases, for example, lead to responses, both at the institutional level and individual level that cannot be sustained in the long run. The doubling of the NIH budget between 1998 and 2003 did much for research, but putting on the brakes is causing shock waves throughout the research system that may be felt for years to come and have significant unintended consequences. Universities responded to the doubling by building new facilities and hiring new faculty. Not surprisingly, the number of grant applications increased dramatically. But, with flat budgets since 2003 the likelihood of receiving NIH funding has declined considerably. At the National Institute of General Medical Sciences (NIGMS), by way of example, success rates for R01 grants fell from a high of 38 percent in the early 2000s to 25 percent by 2005. They are expected to fall further in 2006. Universities must now rethink how to cover the costs of facilities that were built on the expectation that NIH opportunities would remain strong; and faculty hired into these new positions are quickly learning that their jobs may be short-lived or precarious at best. Moreover, postdocs and staff scientists may be let go as faculty scramble to get funding to cover the costs of their labs.
- The uncertainty associated with stop-and-go funding can also weaken the U.S. scientific enterprise. It encourages scientists to pursue projects that are safe and to ignore risky projects with potentially higher payoffs. The absence of long-term funding also makes scientists less likely to undertake projects with distant payoffs.
- The academic job prospects of scientists and engineers have been relatively bleak in recent years. One exception to this was the upsurge in hiring that occurred in the biomedical

sciences in response to the NIH doubling. Universities are increasingly hiring more part-time and non-tenure-track faculty; they employ more and more postdoctorates and staff scientists. If we, for example, only focus on Research One institutions, we find that the ratio of full-time non-tenure-track faculty to full-time tenure-track faculty has grown considerably during the past 15 years. Ehrenberg and Zhang (2005, Table 3A.1) document that, for public Research One institutions, the ratio was 0.245 in 1989 but had climbed to 0.375 by 2001. In private institutions, where it was 0.312 in 1989, it had climbed to 0.434 by 2001. Several factors have led to this situation. First, cutbacks in public funds and lowered endowment payouts during the recession years have affected hiring. Second, salaries of tenure-track faculty are higher than those of non-tenure-track faculty and research shows that this leads to a substitution away from tenure-track positions. Third, funding for non-permanent positions, such as staff scientists, is available in research grants. The high cost of start-up packages also plays a role in explaining these trends.

- Compared to other countries, a large number (and percent) of scientists and engineers work in industry in the United States. This is particularly striking at the Ph.D. level; fully a third of all S&E doctorate-holders work in industry.² This stands in marked contrast to the situation in other parts of the world. The research intensity of U.S. industry clearly contributes to innovation in this country. Moreover, the ability of industry to create work environments that appeal to scientists and engineers contributes to recruiting strong researchers to work at firms.

Comments on Action Items Recommended in *Rising Above the Gathering Storm*

With this for background, in what follows I comment on seven of the action items recommended in *Rising Above the Gathering Storm*.

Action A-1: Annually recruit 10,000 science and mathematics teachers by awarding 4-year scholarships of \$20,000 a year, which require a commitment to five years of service in public K–12 schools. This supply-focused recommendation could provide strong incentives for individuals to follow a course of training in science and math in college and have an impact on math and science education at the K–12 level. The recommendation, however, stops short when it comes to retaining the newly recruited teachers. Research shows that it is often the best teachers who leave the classroom to pursue careers elsewhere (See, for example, Murnane and Olsen, 1990, which shows that teachers with high opportunity costs, as measured by test scores and subject specialties, stay in teaching for shorter periods than other teachers do.) Salary and especially working conditions play a large role in this response. If we want to improve K–12 math and science education in the United States, in addition to training new teachers we need also to explore what can be done to retain good teachers. There is a place for policies that focus on demand, such as providing teachers bonus pay and exploring ways to enhance working conditions. As an aside, it is not clear that the United States' proclivity to test students enhances

² This figure comes from National Science Board (2006, Appendix Table 3-9). The percent excludes those who are self-employed or working in the nonprofit sector.

working conditions. Too much is at stake to leave policies related to retention entirely to the local level.

Action B-1: Increase the federal investment in long-term basic research by 10 percent each year over the next seven years through reallocation of existing funds or, if necessary, through the investment of new funds. Although the federal investment in basic science is relatively small, standing at \$36.1 billion in 2004 (National Science Board, 2006, Table 4-1), it is critical, representing 62 percent of the United States' investment in basic science. The proposal would lead to a doubling of federal funds for basic research in a seven-year period. The growth would enhance research opportunities and is critical, especially given the trend of industry to focus increasingly on the applied areas. Care must be taken, however, to provide for a "soft" landing when the doubling ends. Much could be learned by examining the recent NIH experience. It will also be important to ensure that funds are not taken away from successful initiatives, such as NIH.

Action B-2: Provide new research grants of \$500,000 each annually, payable over 5 years, to 200 of the nation's most outstanding early-career researchers. The goal of this recommendation is commendable. Providing research support to individuals at a critical time in their careers could prove crucial in retaining those with a strong potential in science, but who face poor prospects of becoming independent researchers in academe given the current softness of the academic labor market. The award also signals that research possibilities exist for aspiring early-career scientists. The challenge is that the small number of awards (the 200 represents less than 0.2 percent of the eligible pool) could lead an initiative that is designed to have a positive impact to create a negative signal instead. Witness what appears to be happening with what are euphemistically called NIH kangaroo grants, or more formally, K99/R00 awards.³ Several years ago, as concern mounted that researchers in the life sciences were less and less likely to get research support in their early to mid-30s, the National Research Council, at the request of NIH, launched the study *Bridges to Independence* (National Academies, 2005). The upshot of this was the recommendation that NIH create a four- to five-year bridge grant formally known as "Pathways to Independence." The award works as follows: The initial one to two years provide mentored support while the principal investigator is in a postdoctoral position. The second, independent, phase occurs in years 3 through 5 and is designed to allow awardees to secure an assistant professorship or equivalent position to establish their own research program and successfully apply for an NIH investigator-initiated (R01) grant. The program was implemented in the spring of 2006. The response has been exceedingly strong—so strong in fact that, given the number of available awards, it is possible that the success rate will be considerably under 10 percent—at least in some NIH institutes. This does not send a positive signal to a community that has anxiously awaited some positive news for early-career researchers. Indeed, the possibility exists that the low success rate will be perceived as one more signal that research positions—at least research positions in academe—are not readily available and will discourage individuals from pursuing this track.

³ For a description of the award see National Institutes of Health (2006).

Action C-1: Increase the number and proportion of U.S. citizens who earn bachelor's degrees in the physical sciences, the life sciences, engineering, and mathematics by providing 25,000 new four-year competitive undergraduate scholarships each year to U.S. citizens attending U.S. institutions. Previous research shows that students respond to financial incentives in choosing their field of study. Moreover, and as noted earlier, the STEM pipeline leaks considerably during the college years. The rate at which STEM students switch to alternative fields of study at the undergraduate level is substantial. This recommendation has the potential to address this leakage and thereby augment the supply of individuals choosing to major in science and engineering fields as undergraduates. My enthusiasm for the recommendation is enhanced because it comes in concert with demand-focused recommendations such as D-2 and D-3.

Action C-2: Increase the number of U.S. citizens pursuing graduate study in "areas of national need" by funding 5,000 new graduate fellowships each year. This recommendation, with its \$30,000 recommended stipend, could prove extremely effective in recruiting U.S. students into graduate programs, much as the National Defense Education Act of 1958 did in recruiting U.S. students into key fields. Moreover, the portability of the proposed fellowships means that students could "vote with their feet" and not be tied to the research agenda of one faculty member, as is often the case. The success of this initiative hinges, as in the above case, on ensuring sufficient demand so that students will find good and productive job matches upon graduating.

Action D-2: Enact a stronger research and development tax credit to encourage private investment in innovation and Action D-3: Provide tax incentives for U.S.-based innovation. One strength of *Rising Above the Gathering Storm* is that it does not put all of its emphasis on supply-side initiatives—as is often the case—but instead also stresses measures that would enhance the demand for innovation and, by extension, the demand for STEM workers. This is extremely important. Supply-side initiatives are often successful in growing the workforce. But, without sufficient demand (from industry, government and academe), the initiative can lead to an increase in scientists and engineers with high hopes and poor job prospects, a perfect recipe for discouraging the next generation from entering careers in science and engineering.

Discussion

In closing, let me comment on an area not touched upon by the report but which I believe threatens the viability of the STEM workforce and thus the science and engineering enterprise. To wit, university research labs are overwhelmingly staffed by "temporary" workers in the form of graduate students and postdocs. This practice stands in marked contrast to that of many other countries, where there is a larger role for what could be thought of as permanent research scientists. The U.S. practice of using "temporary" workers to staff labs is based on the funding mechanism for research, which provides support for graduate students and postdocs, as well as on a preference of researchers to staff their labs with early-career individuals who have fresh ideas but who also can easily be dismissed if funding becomes an issue. It has much to recommend it and it has been the cornerstone of the way in which scientists and engineers are trained in the United States. However, this staffing pattern creates special challenges for

the United States because students and postdocs educated in such a system often seek to duplicate the career pattern of their mentors, striving to get an academic appointment and become principal investigators in their own labs. This is increasingly not possible. Tenure-track jobs have not been forthcoming and students hang on to temporary jobs in academe or eventually leave to take jobs in government and industry with a sense of failed expectations. It is time to rethink how we as a nation staff labs in academe. There is a place for permanent research scientist positions that provide a degree of autonomy. Many early-career scientists would find such positions rewarding in light of the alternatives. We must also rethink how we provide training to students to go sooner, rather than later, to productive research careers in industry and government

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Comments at a Meeting on the “Gathering Storm” and Its Implications for National Security

Thomas L. Magnanti¹

As Charles M. Vest wrote in a report to the MIT community while serving as its president,

The ability of our nation to remain secure in the face of both traditional military threats and international terrorism while maintaining the excellence and pace of American science and technology requires a delicate balance. It depends first and foremost on effective dialogue and joint problem solving by those responsible for maintaining our security and those who lead our scientific, engineering, and higher education communities. (Vest, 2003)

Needless to say, our deliberations today on these issues are important to all of us. I am very pleased to have the opportunity to join you in this forum.

By way of background, I am the dean of Engineering at MIT, where I have been a faculty member for 35 years. Many of my activities before becoming dean involved developing professional master’s programs at the interface of engineering and management. Since becoming dean nearly eight years ago, I have focused much of my attention on improving undergraduate education at MIT, including initiatives using innovative technology, and on technical entrepreneurship and innovation. I have also served as the chair of a working group on workforce skills convened by the Council on Competitiveness as part of its National Innovation Initiative.

Clearly, economic security and national security go hand in hand. We know how vital creating new technologies and products is to the economic well-being of a nation. An MIT faculty member and Nobel laureate in economics, Robert Solow, has estimated that 50 percent of this nation’s economic growth since World War II can be attributed directly to technology. I think it bears stating, too, that through the development of new technologies, products, and services, universities contribute in very significant ways to the nation’s economy. As an example, a 2003 report, *Engines of Economic Growth*, stated that in the year 2000 alone, Greater Boston’s eight research universities provided a \$7.4 billion boost to the regional economy (Association of Independent Colleges and Universities of Massachusetts, 2003). MIT itself makes new invention disclosures at a rate of one to two per day and, in fiscal year 2005, had 133 new U.S. patents and over 100 new license agreements, and it launched 20 new companies. Silicon Valley and the Research Triangle in North Carolina provide other powerful examples of how universities impact the regional and the national economies.

I could amplify in great deal on these brief comments and further illustrate the importance of investments in basic and applied research at our universities as well as comment in great detail about the novel research and educational programs that universities are undertaking across the nation. Simply stated, university research and education are essential for main-

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taining the nation's posture in the evolving world's innovation economies and for the resulting long-term health and security of our nation.

However, making this case is not my major purpose today. (Indeed, I suspect that this perspective would be well understood by those of us assembled here.) After making a brief remark or two about certain elements of STEM education, something that all of us at this meeting are concerned about, I'd like to speak to the critical importance of openness and illustrate it with a successful model, MIT OpenCourseWare.

Science, Technology, and Mathematics Education

A comment from another of the co-authors of the *Rising Above the Gathering Storm* report is worth noting. Last year during a congressional hearing, Rep. Ron Kind asked Norm Augustine, Retired Chairman and CEO, Lockheed Martin Corporation, "If you had to assign a grade to our country right now in terms of what we're doing to get ready for the competition in the global marketplace, and more specifically in the math, science, and engineering fields, what grade would you give us on an A to F scale?" After first qualifying his comment by pointing out that our current system is "bi-modal," in which "the best is very good and the rest is very poor," Mr. Augustine gave an overall grade of between D+ and C-.

We can all recite the many troubling statistics and reports that have been written about international test scores, student enrollments and retention and enrollment of women and minorities, especially as compared to other nations, and our nation's investments in research in engineering and the physical sciences. The National Academies' *Rising Above the Gathering Storm* and the Council on Competitiveness's *Innovate America* (2004) reports both articulate many of these, and I won't try to repeat them here.

While keenly aware of these sobering facts, there is still much we could talk about concerning science, technology, and mathematics education, both in lower and higher education, how these affect research and innovation, and the implications for our nation's future. I could, for example, enthusiastically join with others in endorsing the important recommendations made in both the cited reports. I could repeat the commentary I made last year in testimony before the congressional Subcommittee on 21st Century Competitiveness (the Committee on Education and the Workforce) and those I made in February before the Commission on the Future of Higher Education.

Openness

Today, however, I would like to focus on the critical importance of openness: intellectual openness as vitally necessary to universities and research and openness as a gateway to raising the level of education in our country. Of course, we need to take measures to ensure our nation's security, but in engineering and science, we need to sustain an environment of openness to productive collaborations across disciplines and across institutions and organizations in the public and private sectors. We also need to maintain an intellectual openness to the flow of international students and scholars who contribute so much to our universities and economy. As examples close to home:

1. Of the 12 living MIT faculty who have been awarded the Nobel Prize (8 current and 4 emeritus), 4 were born outside the United States.²
2. I chair the Engineering Council at MIT, an advisory/governance body made up of leaders of our engineering departments and divisions. Of the 14 members, all but six are foreign-born.
3. Among MIT engineering faculty age 40 and under, 50 percent are foreign-born, while that percentage is only 28 percent for faculty over 60.

Nationally, 8 percent of bachelor's degrees, 46 percent of master's degrees, and 55 percent of doctoral degrees in engineering in this country are now granted to non-U.S. students. As the economies and higher educational institutions of other countries develop, there is a need, and indeed a significant challenge, for us to continue to attract and retain this critical talent flow.

Openness is also a powerful way to raise the quality of education in our country at all levels. Simply put, my proposition is this: *technology and openness make a difference in higher education and, by extension, to our nation.* To tell you why I feel so confident in making that statement, I will share some experiences and data from my home institution's continued experiment in open sharing—MIT OpenCourseWare, an important model for how one might use the Internet to disseminate information and to provide wide access to it.

MIT OpenCourseWare

In April 2001, MIT announced that it would make all the course materials used in the teaching of its undergraduate and graduate subjects available on the World Wide Web free of charge, to any user anywhere. Five years later, this MIT OpenCourseWare (OCW) project has put online 1,550 courses, and the OCW materials, including on translation sites, currently attract more than 1 million monthly visits, a 56 percent annual increase.

With plans to offer materials from 1,800 MIT courses by 2008, OCW has contributed to higher education in remarkable ways, evident from these statistics:

- 95 percent of users report that MIT OCW has or will help them to be more productive and effective (49 percent of visitors are self-learners, 32 percent students, 16 percent educators).
- 46 percent of educators have adopted MIT OCW content to improve their own teaching.
- 38 percent of students use MIT OCW materials to complement a course they are taking; 34 percent use MIT OCW to learn about subjects outside of formal classes.
- 56 percent of self-learners use MIT OCW to enhance personal knowledge; 16 percent use MIT OCW to stay current in their chosen field.

These statistics only begin to tell the story: the chairman of a high school science department in Toms River, New Jersey, now utilizes OCW materials, and the video lectures of MIT Professor Walter Lewin about electricity and magnetism, to get his students excited about physics. Kenn Magnum, a high school computer science teacher in Chandler, Arizona, has utilized

² Ketterle (Germany), Khorana (India), Molina (Mexico), and Tonegawa (Japan).

materials from several OCW computer science courses to educate himself and his students. With more than 100 course offerings from the MIT Department of Electrical Engineering and Computer Science, Magnum sees MIT OCW as an invaluable professional development tool. And he is referring students in his after-school Artificial Intelligence Club to OCW courses on artificial intelligence and electric power systems. In Colorado, a father is using the lectures and course materials of noted MIT mathematics professor Gilbert Strang to teach his 10- and 12-year-old daughters. We have hundreds of stories from around the United States (and the world) about the impact OCW is having.

Let me interject another point here: As a powerful tool for accessing information, OpenCourseWare also broadly serves our national security interests more directly. For example, Captain Kevin Gannon, a Leadership Trainer at the U.S. Navy's Southwest Regional Maintenance Center at the San Diego Naval Station, has used OCW materials to train the 3,000 sailors and civilians under his command; and VR Bill Humes, a U.S. Navy Aerospace Engineer and Researcher at Patuxent River Naval Air Station in Maryland, has made fighter canopies stronger and safer using information from the site. These are but two illustrations of the considerable and growing use of OCW by those in our armed forces that we are seeing: nearly 21,000 hits last year. In fact, the U.S. Navy ranks number 1 among users of OCW outside of Internet service providers; the U.S. Air Force, number 3; and the U.S. Army, number 6.³

At MIT, we have demonstrated that the OpenCourseWare model is an affordable and accessible way to transform education, and our global audiences of users hold MIT accountable to create and share high-quality materials. Judging by our experience working with and talking to users from around the world, we believe there are tremendous positive implications to open sharing of educational materials for the U.S. workforce.

Can we leverage what is happening on our college campuses to benefit the lives of *all* Americans, and close the education gap that is of grave concern today? History has proven that education and discovery are best advanced when knowledge is shared openly, and the promise of OpenCourseWare is an opportunity that I would argue we should not miss.

OpenCourseWare is an important initiative unto itself; but it is also an important illustration of the power of openness and, at least to me, serves as a symbol for what openness is and should be.

Recommendations

Driven by the prescriptions of openness that I have alluded to and that others have discussed here today, I would like to offer several recommendations: one directly related to OpenCourseWare, but others of a more general nature. These recommendations provide comprehensive approaches that could go a long way in addressing needed changes and ensuring our nation's continuing leadership, prosperity, and security:⁴

³ In 2005, U.S. Navy: 8,388 visits (unique users) to the OpenCourseWare Web site; U.S. Air Force: 6,436; and U.S. Army: 5,405.

⁴ The first two of my recommendations, without a specific reference to DoD, have been embraced by leaders from industry and the academy (see Council on Competitiveness, 2004).

1. Create a National Innovation Education Act, including an “NDEA for our times,” with government-supported, and particularly DoD-supported, portable graduate fellowships for students in math, science, and engineering.
2. Develop laws and policies to attract and retain international talent. To harvest our national investments, DoD should work with DHS/U.S. Citizenship and Immigration Services to automatically provide every foreign-born Ph.D. graduate in the United States in science and engineering with an automatic green card.
3. Launch an OpenCourseWare for secondary education focused on science, engineering, and mathematics that would help close the achievement gap in science and engineering education in the United States that concerns us all. Let’s assemble and provide open access to the best possible science and mathematics educational materials, including laboratories at a distance and other educational innovations and resources; and let’s add engineering content to secondary education to help motivate and stimulate science and mathematics education and to fuel an innovation economy. Let’s do so by creating a government-industry-educational partnership, that includes DoD, to develop and sustain such a project.
4. Increase DoD and other government investments in basic research in engineering and the physical sciences, as well as funding for research on “next generation” technologies. Although I have only briefly alluded to the benefits of this research, I believe that these investments are among the most important that the government can make in the nation’s long-term economic health and in U.S. national security.

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Some Thoughts on the “Gathering Storm,” National Security, and the Global Market for Scientific Talent

Paul Oyer¹

Introduction

The *Rising Above the Gathering Storm* report from the committee assembled by three prestigious academies of scientists certainly makes for provocative reading. Coming, as it does, at a time when Americans feel particularly vulnerable in terms of national security, it is likely to touch a nerve with many of its readers. In this note, I would like to provide a little context for the *Rising Above the Gathering Storm* report from work by labor economists and by thinking of the issues from the perspective of organizational economics and business strategy. I will consider some of the costs and benefits of the *Rising Above the Gathering Storm* recommendations and suggest a few thoughts on which proposals might be relatively higher priority. Overall, I believe that the recommendations in the *Rising Above the Gathering Storm* report are in the nation’s best interests, though I am not generally convinced that we need to do a better job than we are doing to *create* scientists.

The rest of this paper will focus on three issues in assessing the relationship between production of scientists and national security. First, I will think of the American economy as a large organization (similar to a large corporation) facing a “make or buy” decision with respect to a key “factor of production” (technology and/or security) and then take it down another level in the “supply chain” to think about whether we should make or buy a key input to technology (that is, scientists). Second, I will discuss the importance of general macroeconomic health in ensuring that the United States continues to be a relatively attractive place for leading scientists to do their work. Third, I will briefly review the historical success of predictions of labor shortages in specific occupations and how that should affect related policy.

Should We “Make” Scientists Or “Buy” Them?

Think of the United States government as one large corporation trying to maximize its shareholders’ value like any other large company. The people who run corporations should, for the most part, be trying to maximize the discounted value of cash flow to shareholders. It works a little bit differently when we think about people running a superpower, but the goal isn’t all that different. A reasonable hope is that our leaders would do something along the lines of trying to maximize the discounted present value of American economic activity. Unlike a corporation, the government should be willing to give up some level of wealth in order to distribute resources more evenly. This “fairness” idea is important and relevant, so I will return

¹ Stanford University Graduate School of Business and National Bureau of Economic Research. I thank Susanna Loeb, Scott Schaefer, and Brian Viard for useful input and discussions.

to it later. But, for now, think of the government's job as simply to maximize the size of the economy.²

Almost all corporations have to consider the potential effects of competitors on their economic fortunes and take these effects into account when they make decisions. Competitive considerations are even greater for governments making decisions, however, because of issues of national security. While American corporations are largely insulated from physical attack by outside parties, the U.S. government has to ensure physical security as a first step in its policy making. National security makes the standard "make versus buy" issues faced by corporations somewhat noncomparable to the make versus buy decision faced by the U.S. government. Dell, Inc., or General Motors can buy virtually any input from a supplier if the supplier can produce the good more efficiently. But, simply put, we cannot "buy" national security. If we ever relied on a foreign entity to provide our entire army or any critical weapons system, we would face the possibility of that entity threatening much of our wealth.

Because of this, and despite the fact that the U.S. military is hardly known as a model of efficiency, the U.S. government runs the Army and directly procures all major weapons systems. That is, we "make" key national security components such as the military and advanced weapons systems.

Dell and GM have made comparable decisions and they make computers and automobiles, respectively. The strategic decisions and processes underlying their decisions are very different from those that drive U.S. national security, but the final decision is the same—they will make the final product. However, both of these corporations buy, rather than make, some of the key inputs to these final products. Dell buys processors from Intel Corporation and Advanced Micro Devices, Inc. GM buys tires, engine systems, and parts for almost every area of cars and trucks from a large set of suppliers.

Historically, the United States has also used a "buy" strategy for one of its key *inputs* for national security—scientific talent. Consider, for example, the production of the atomic bomb, the hydrogen bomb, and the early space program. All of these were considered important national security programs and were backed by considerable government resources. The Manhattan Project, which developed the first atomic bombs in laboratories in Los Alamos, New Mexico, was overseen by a General (Leslie Groves) and a scientist (Robert Oppenheimer) who were born and educated in the United States. However, using the very imperfect measure of all scientists mentioned on *Wikipedia's* "Manhattan Project" page as having contributed to that project, a little over half of the key scientists involved were not born in the United States.³ The two scientists that were clearly most important to the development of the United States' hydrogen bomb were Edward Teller, who was raised in Hungary and moved to the United States at the age of 27, and Stanislaw Ulam, who was raised in what is now the Ukraine and emigrated to the United States at the age of 29. After these early nuclear weapons advances, the next major science-oriented security challenge came from Sputnik 1 and the onset of the "space race." The United States turned to Wehrner von Braun. He was born in what is now Poland, developed rockets for the Germans during World War II, and went on to become

² Keep in mind that I am talking about the discounted value of all future economic activity. This means that good policies would include making responsible choices about the environment for the sake of future generations and decisions that involve giving up short-term consumption in favor of consumption by future generations.

³ The Manhattan Project was, to some extent, a joint project with Great Britain and Canada. However, none of the key scientists were born in either of those two countries.

known as the “father of the U.S. space program.” In 1961, the first American to visit space flew in a ship designed by Max Faget, who was born in what is now Belize (though his parents were American).⁴

These examples do not by themselves ensure that the United States can continue to rely on foreign-born scientists. But they do point out that national security is not, by definition, a function of domestic scientific talent.⁵

“It’s The Economy, Stupid”

So then, how do we ensure that the very best scientists (that is, the ones who will make breakthroughs that are truly critical to national security) will work in the United States? We could make sure that we train the very best scientists and then somehow insist they do not leave the country (after all, this sort of worked for the Soviet Union for a while). Alternatively, we could make the United States an attractive place for scientists, whether born here or not, to work.

As James Carville famously said about the 1992 presidential campaign, “It’s the economy, stupid.” That mostly means the economy overall, but it also means the environment for scientists more specifically. The United States will be an attractive place to work if scientists expect the most “utility” from working here. Scientists, like almost everyone else, get utility from more money and consumption goods. So, a vibrant economy overall will attract scientists just like it attracts any other immigrant. But scientists also get utility from a good research environment. This includes first-class universities, other research institutions (including R&D groups at corporations), and other great scientists. Here’s where we are lucky in the United States. We already have all those things. There is a “network effect” in the location of scientists, meaning that a great scientist is likely to want to work where other great scientists work because this will enable collaboration and the sharing of ideas. Scientists are a “complementary” good, meaning that the marginal value of one is increased by having others nearby. As King (2004), May (1997), and others have shown, by any measure, the United States has a large absolute advantage in the production of scientific research.⁶ Though these same articles indicate there is some sign that this absolute advantage is slipping a bit, the rate of decline appears to be slow and is only to be expected given the enormous differences. The large advantage and the network effect give the United States a great combination. Unless we do something to make the country much less attractive to scientists, the advantage is likely to be self-sustaining.

So what could we do to mess things up? One possibility is to set such strict immigration policies that highly skilled workers choose to move elsewhere or stay in their home country.

⁴ The historical facts are based on *Wikipedia’s* “Manhattan Project,” “Edward Teller,” “Stanislaw Ulam,” “Wehrner von Braun,” and “Project Mercury” pages, as well as on Oberg (1995). Foreign-born scientists have also been central to major nonmilitary technical advances centered in the United States, including the development of the integrated circuit.

⁵ One might also ask the question of whether, in the current global security climate, scientific advances are the key to national security? Perhaps border inspection and forensic science advances will be critical, but perhaps just allocating conventional forces appropriately will be even more central. In any case, I will proceed under the assumption that we *need* cutting-edge technology for national security purposes.

⁶ This advantage is further self-sustaining in that America’s historical strength in science has made English the international language for communicating scientific research. Talented people have an incentive to learn English, which then makes moving to the United States to study or work that much more attractive.

There is anecdotal evidence that we have moved a bit in this direction since the events of September 11, 2001. Hopefully this will not be a long-term problem.

Another risk is that American universities could get worse. This strikes me as a threat worth worrying about, but not a likely outcome. American universities have proven to be a very good investment for the students who go to them, and many have large and growing endowments. Government aid is important to some areas at some schools, so a dramatic cutback in government generosity would present a problem. But there seems to be widespread support for continuing to fund universities at reasonable levels. Overall, I agree with Wooldridge's (2006) prediction that, "There is every reason to think that the absolute number of people from India and China who want to study in America will rise as those countries get richer."

I believe that the real risk to America's ability to attract and retain scientists comes not from the scientific community itself, but rather from risks to the state of the overall economy. That is, American universities and research institutions are doing well and, at this point, so is the American economy. But if universities ever become an island of success in a sluggish economy, then it will be hard to attract and retain excellent scientists. That's why the parts of the *Rising Above the Gathering Storm* report that I believe to be most important are those parts aimed at elementary and secondary education. There has been a lot written about the lackluster student achievement in the United States, as well as the variation in the quality of schools based on neighborhoods. See, for example, Gonzales et al. (2004) and Hanushek (2002). Spending on public schools in the United States has gone up consistently (see Hanushek, 2001), despite perceptions that school budgets have been tightened.

So why does it seem as though we are getting less for our money? Whether we are actually getting less or not is a matter of some debate, but it is surely the case that the cost of providing education in the United States has gone up over the last several decades. That is, providing the *same quality of education* in 2006 simply costs more than it did in, for example, 1966. This is because two of the largest parts of the cost structure of elementary and secondary education are salaries of college-educated employees and real estate.⁷ Relative to other goods, the costs of these two inputs have skyrocketed over the years. Consider salaries. In the Palo Alto Unified School District, 65 percent of total expenditures are salaries. This includes some people who do not have college degrees, such as bus drivers and janitors, but it does not include benefits. In the state of California, 40 percent of education expenditures are teacher salaries. This does not include salaries of others with advanced degrees such as principals and other administrators. So roughly half of education expenditures are on salaries for college-educated employees. Katz and Autor (1999) and Autor, Katz, and Kearney (2005) document that the average wage premium for a college education (relative to someone who leaves school upon high school graduation) has risen steadily since at least 1963 while the average wage discount for women (relative to men) has declined. Given that college-educated women are a primary educational input, these changes in the wage structure have added at least 10 percent to the cost of elementary and secondary public education. It is much harder to assess the effect of real estate on educational costs given that schools generally use public land and pay no rent. However, the implicit rent being paid for school buildings is an enormous and increasing cost (or at least opportunity cost) borne by taxpayers.

⁷ The idea that labor-intensive goods will become relatively more expensive over time dates back to at least Baumol and Bowen (1966). But the key point here is that the type of skill required to staff schools has become especially expensive in recent decades.

Combining these basic statistics implies that, over time, we need to be willing to increase expenditures on education as a share of the total economy just to ensure that the quality of education does not deteriorate. Education has gotten costlier, and if predictions of further increases in the wage premium for skilled workers pan out, it will get more costly still. Why is it worth the cost? There is a huge economics literature studying the returns on education. A reasonable consensus estimate from this work is that a typical person will increase his or her earning power by about 8 percent for the rest of his or her career by obtaining an additional year of education and that there are nontrivial benefits of this additional education over and above the monetary value. Thinking of this in terms of an underlying economic equilibrium (that is, assuming that, over the long run people get paid, on average, the value of their labor), it must be the case that an extra year of education increases a person's productivity and contributions to the economy by 8 percent. So, suppose we were to freeze expenditures on education at their current levels and the relative costs of educational inputs continue to rise. Then the quality of new high school graduates' education would deteriorate.

Suppose that high school graduates at some future date learned as much as current graduates learn in their first 11 years in school. Then the value of a high school degree would drop by the value of one year of education, or about 8 percent. If this happened to all American students, we could expect a long-run negative effect of up to 8 percent in terms of total GDP.⁸ This strikes me as the biggest potential threat to the United States' ability to attract top scientific talent from abroad. If the size of our economy dropped by 8 percent (or, depending on educational investments, somewhat more or less), that would make the United States a much less attractive place to pursue a scientific career. I believe a bigger threat to our ability to attract and retain scientists lies in this indirect threat to the economy than in the more direct threat of not producing those scientists ourselves.

My argument that it is education, rather than scientific education, that will drive our ability to ensure a healthy supply of scientists leads me to take issue with one recommendation in the *Rising Above the Gathering Storm* report. While I support recommendation C ("Make the United States the most attractive setting in which to study and perform research so that we can develop, recruit, and retain the best and brightest students, scientists, and engineers from within the United States and throughout the world"), I do not think that the more science-specific "implementation actions" are warranted. I see no reason to think that the market for higher education inefficiently encourages people to focus on social sciences, the humanities, or professional studies rather than the physical sciences. We need educated, literate people. Communication and logic skills are just as important as science skills. I believe the job market provides the right incentives for people to invest in whatever set of skills they find fit their financial goals and their enjoyment of work. While the very elite scientists who design weapons and instruments that ensure national security provide "public goods" that we should encourage through public policy, the vast majority of people should invest in skills that take advantage of their individual comparative advantages.

Note, by the way, that the deterioration of elementary and high schools would threaten national security directly because we need these schools to educate the people who will lead our military. Though military leaders born outside the United States are not unheard of, the case for "making" military leaders seems much stronger than the case for making scientists

⁸ I say "up to" 8 percent because some of the value of education is probably due to moving up in relative skill rather than absolute skill. This part of the value of education would not be lost if everyone's skill level dropped.

due to American-specific military education and the fact that, all else equal, American soldiers probably respond better to American commanders. So, from a national security point of view, we need good basic education to ensure high-quality military leaders.

A final consideration, when thinking about the broad economic issues, is potential problems that can arise from income inequality. Income inequality has increased fairly dramatically over the last few decades (see Katz and Autor, 1999) and this trend shows no sign of slowing down (Wooldridge, 2006). While increasing inequality is a global phenomenon, it is more exaggerated in the United States. To the extent that scientists value living in a relatively equal society or that inequality leads to social unrest in the United States, this could make attracting top talent here more difficult. However, a more likely effect is that the relatively privileged position of top talent within the United States will make this an attractive place for top scientists and others with very specialized skills.

The Reliability of Projections of Labor Shortages

Being proactive about thinking through the skills we will need for future security challenges is an admirable idea and I applaud the Academies for bringing attention to this issue. However, I think the potential shortage of scientists, and the potential shortage of “talent” more generally, should be considered in the historical perspective of past projections of sector-specific employment trends. Freeman (2006) highlights several examples where, even over a period of just a few years, economic or other factors switched labor shortages to gluts or vice versa. He notes, “The wide variation in the number of workers projected in computer and mathematical sciences reflects the difficulty in foreseeing future demands in an occupation subject to volatile demand from different economic factors.”

Freeman (2006) goes on to note the error in his own scientifically grounded 1976 projection of a surplus of college graduates. He also notes that projected labor shortages in Europe and Japan over the last 10 to 15 years have not materialized.

Perhaps the most relevant past projection is the early 1980s predictions of a large shortfall of scientists in the United States. This encouraged too many people to pursue science Ph.D.’s, which, combined with an influx of scientists after the crumbling of the Soviet Union, has led to an oversupply of physicists, mathematicians, and Ph.D.’s in other sciences. Just as an unpredicted event such as the falling of the Berlin Wall spoiled prior predictions, there are many possible events that could doom current projections. Political turmoil in Asia involving China, major new challenges in the Middle East, or some shocking new discovery about the challenges of climate change strike me as possible (though hopefully unlikely) events that could have a major effect on either the supply or demand for scientists and other highly skilled people.

Again, this does not mean that we should not plan ahead or take seriously the issue of how we can ensure we get more than our fair share of major technical advances. But the unreliability of forecasts of shortages or surpluses in specific labor markets makes me hesitant to devote too many resources to a problem that might well never develop (or that might pale in comparison to some currently unforeseen problem.)

Summary

I believe that a strong national economy is our best strategy for promoting a scientific community strong enough to ensure U.S. national security. That is, to the extent that we devise policy to address the science-security relationship, it should be focused on general economic health and making this a desirable place for scientists to study and work. I have emphasized the importance of elementary and public education, but there are other policy issues that are clearly of paramount importance. Keeping the national debt under control, for example, seems like an important and (indirectly) related goal. We also need to focus some policy attention on the health care system in the United States. Just as wage structure changes have made education more expensive, changes in the wage structure and in demographics have made health care more expensive. Unlike education, which is, in effect, rationed through the public school system, health care is neither rationed nor "priced" such that decision makers bear the cost of their health care consumption choices. Addressing this, either through some form of rationing or more efficient employment of a market-based system, would help ensure the economic future and, by extension, the attractiveness of the United States to scientists. Perhaps the Academies can convene their next committee around this challenge.

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Summative Evaluation of Personnel Management and Compensation Initiatives

Brigitte W. Schay¹

Background

Various high-level reports issued over the past five years argue that the United States is losing its competitive edge in science and technology. The most recent report, *Rising Above the Gathering Storm* (National Academy of Sciences et al., 2006), pointed to the increase in research and development in major developing countries; the rapid transmission of new technologies throughout the global economy; the increase in the number of doctoral students in China and India; the seemingly small number of U.S. students entering science, technology, engineering, and mathematics (STEM); and the rising return home of foreign graduate students who trained in the United States. Among its recommendations, the report calls for increased federal investments in STEM research facilities and funding, graduate stipends, and steps to increase the number of qualified STEM teachers down to the K–12 level. However, there does not appear to be a consensus on whether there is or will be an inadequate supply of STEM talent in the United States.

This paper contributes to the discussion by examining results of federal personnel management demonstration projects designed to improve recruitment and retention of high-quality scientists and engineers. Since 1980, five major demonstration projects have tested integrated approaches to compensation, classification, and performance management by implementing broadbanded pay systems and a variety of pay-for-performance systems that replaced the traditional longevity-based pay systems prevalent in the civil services (“China Lake,” National Institute of Standards and Technology (NIST), Commerce, DoD Acquisition, and DoD Laboratory Demonstration program). These projects were driven in part by pay problems caused by an outdated federal job classification and compensation system.

Federal Job Classification and Compensation

The federal job classification system is based on the 1923 Classification Act and was further reinforced by the 1949 Classification Act. It establishes pay grades linked to compensation schedules based on “duties classification.” This approach reflected the “scientific” management period by formalizing the “rank in position” principle of classification, rather than the European practice of “rank in person.” Jobs were narrowly classified based on duties and responsibilities, and flexibility and discretion were limited whenever possible (Ingraham and Rosenbloom, 1990).

¹ U.S. Office of Personnel Management. Any opinions expressed in this paper are those of the author and do not represent official OPM policy.

This worked when the federal government was primarily a “government of clerks,” but now, more than 50 percent of federal jobs are professional and technical. James Q. Wilson, in his book *Bureaucracy*, describes the resulting dilemma as the choice between a bureaucratized and professionalized service (Wilson, 1989). “The former consists of a set of rules that specify who are to be hired, how they are to be managed, and what they are to do; the latter consists of rules that specify who are to be hired but that leave great discretion to the members of the occupation, or to their immediate supervisors, to decide what they are to do and how they are to be managed.” According to Wilson, the biggest struggles in the federal personnel system have been over autonomy, allowing local managers to make decisions and allowing professionals to do their jobs. Under the pay-for-performance demonstration projects, more discretion and authority over human resource decisions have been delegated to federal managers who try to maintain the delicate balance between rules and discretion.

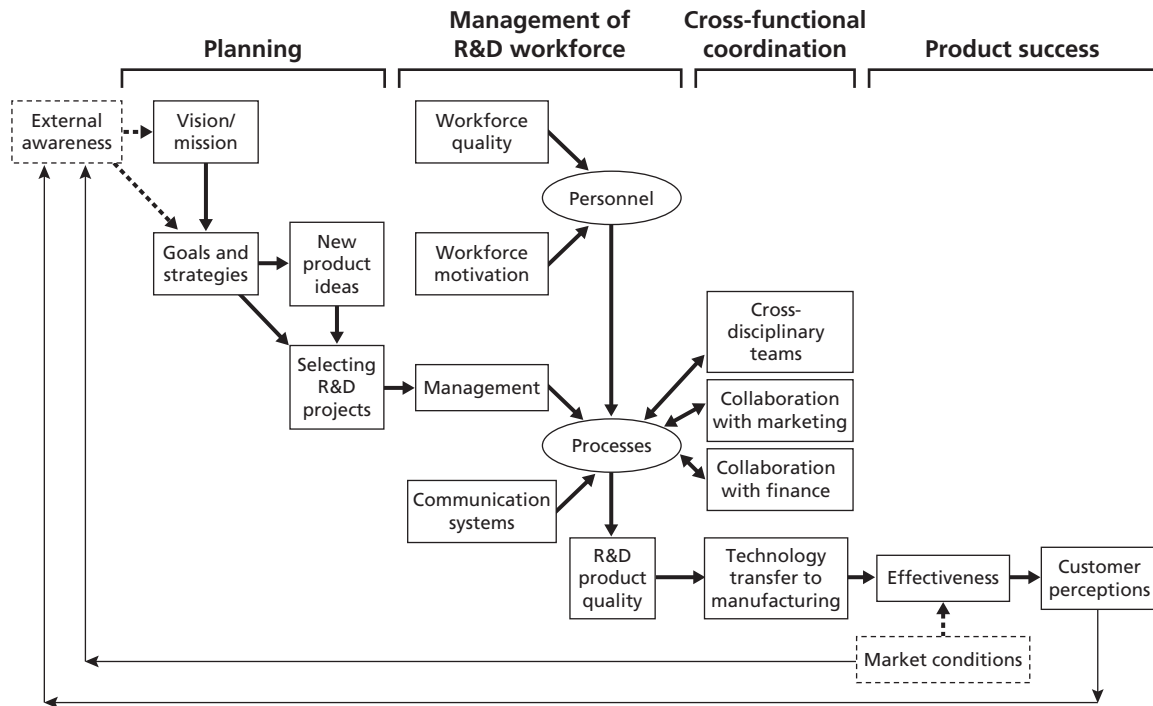
In the demonstration projects, the 15-grade job classification system was replaced with a system of broad bands using simplified, automated classification procedures. Under pay-banding, jobs are typically classified based on three to four levels: entry/developmental, full performance, and senior expert. This has eliminated much of the conflict between managers and classification experts, since managers had to spend a lot of time and effort arguing minute distinctions between grade levels in order to upgrade positions to obtain more competitive pay levels for recruitment and retention, especially for difficult-to-recruit positions in science and engineering. Since job classification drives pay in the federal government, the only way to increase pay is to upgrade the position.

Demonstration Projects and Alternative Personnel Systems

The idea of broadbanding, accompanied by streamlined job evaluation procedures and new performance management approaches, was pioneered in 1980 by a demonstration project in two naval research and development laboratories at China Lake and San Diego, California. This first demonstration project has become known as the “China Lake” demonstration project. The two Navy labs were the first to take advantage of a provision of Title VI of the Civil Service Reform Act (CSRA) of 1978 to experiment with alternative personnel systems under waivers of law and regulation granted by the U.S. Office of Personnel Management (OPM). The two Navy labs implemented pay-banding and pay for performance in order to improve recruitment and retention of scientists and engineers, but also extended the demonstration project to administrative, technical, and clerical positions in order to ensure a common culture for their organizations.

Fortunately, Title VI of CSRA also requires rigorous evaluation of the results of these projects to allow policymakers and Congress to decide whether the outcomes are beneficial and warrant legislative changes. Summative evaluation reports have been issued on this and subsequent demonstration projects. To date, two of the projects, “China Lake” and NIST (implemented in 1988), have been made permanent by Congress based on their positive results in streamlining HR processes and improving recruitment and retention (Schay, 1996). Three more projects are continuing under various authorities (DoD Lab Demo and DoD Acquisition Demo), or have been granted extensions (Commerce, implemented in 1998 and extended until 2008). These projects also provided the basis for moving forward with agency-wide pay-

Figure 1
Model of R&D Organizational Performance



RAND CF235-13.1

banding and pay-for-performance systems in DoD (i.e., the National Security Personnel System [NSPS]) and the Department of Homeland Security. However, successful court challenges by the unions have limited implementation to non-bargaining unit employees in DoD, and DHS is reconsidering its approach and will start with a more limited pilot in 2008 before expanding broadbanding and pay for performance to the entire workforce.

There are a number of other, independent alternative personnel systems, authorized by Congress, that have implemented pay-banding and pay for performance, but these are outside of Title 5 USC and not under OPM oversight (Federal Aviation Administration, Internal Revenue Service, Government Accountability Office, Office of Thrift Supervision, Office of the Comptroller of the Currency, National Credit Union Administration, and Federal Deposit Insurance Corporation). Since there are no evaluation requirements for these projects, limited information is available about their results. According to a 2005 report by OPM, demonstration projects (ongoing and permanent) cover about 53,000 employees, while the independent systems cover about 32,000 employees.

The objectives of the pay-for-performance systems are very similar. For the sake of simplicity, the objectives of the largest ongoing demonstration program, the DoD S&T Laboratory Demonstration program, will be cited here as representative:

- Improve the effectiveness of DoD laboratories through a more flexible, responsive personnel system.
- Increase line management authority over human resource management.
- Recruit, develop, motivate and retain a high-quality workforce.
- Adjust workforce levels to meet strategic program and organizational needs.

These are ambitious objectives and it should be remembered that human resource management involves only one component of organizational effectiveness (see Figure 1, “Model of R&D Organizational Performance”). This model has guided the evaluation of the DoD Laboratory Demonstration and illustrates the four organizational effectiveness components for R&D organizations: strategic planning, management of the R&D workforce, cross-functional coordination, and product success.

Results

As would be expected, the measurable impact of the demonstration projects on organizational effectiveness has been modest but positive. In examining data for the DoD Lab Demo on laboratory effectiveness, a number of measures were used (strategic planning, efficiency of personnel processes, workforce quality, cross-functional coordination, patents and patent income, customer satisfaction, and perceived impact of demonstration on organizational performance). While no significant differences were found on most of the organizational performance measures when comparing demonstration and comparison labs over time, workforce motivation improved only in the demonstration projects and the demonstration labs reported a positive impact on their organizations’ programs and operations in their surveys.

All demonstration projects were successful in improving their personnel processes by streamlining and simplifying classification and integrating it with compensation and performance management to give managers more flexibility in rewarding performance and attracting and retaining high-quality employees. The second objective, to increase line management authority over human resource management, has been successfully achieved in all demonstration projects, and this increased managerial discretion has not had a negative impact on employee morale. Job satisfaction either remained unchanged or even increased in the demonstration projects.

The third objective, recruitment, motivation, and retention of a high-quality workforce, has been affected by the fourth objective, continuous downsizing in DoD. But overall results show increased retention of high performers (Adams-Shorter et al., 2002; Schay, 1996). The flexibility to pay higher starting salaries and reward high performers has also been helpful in attracting and retaining talent. As stated earlier, actual increases in individual effort and motivation were found in the DoD Lab Demo.

Workforce quality was measured by the percentage of the workforce with advanced degrees, GPA of new hires, number of postdocs, professional society memberships, and refereed publications. Due to limited hiring and ongoing downsizing during the demonstration period, the results indicated no change in most of the hard measures. However, the demonstration labs slightly increased their proportion of scientists and engineers with advanced degrees relative to the control group. Survey results also show that managers in the demonstration labs were significantly more satisfied with the competence of newly hired scientists and engineers, and were more likely to agree that they were able to attract high-quality candidates and that newly hired candidates were a good match for the job. The same positive trends were found in the Commerce and Acquisition demonstrations.

Our research on demonstration projects has shown that changing from an entitlement culture with longevity-based pay to a performance culture, in which performance drives pay, can take five years to take hold in the majority of the workforce. The original “China Lake”

project took five years to gain support from more than 50 percent of its employees, compared to three years for NIST. Our 2002 summative evaluation report of the DoD Laboratory Demonstration included five-year data through 2001 (pre- and post-demonstration) but at the time none of the labs had completed five full years under their demonstrations. Implementation was phased in over a period of five years from 1997 to 2002. By 2004, when a follow-up pulse survey was conducted with most of the labs, all but two of the nine projects had been going on for at least five years and all but two of the labs had reached more than 50 percent support from the participants. Demonstration project support reached over 66 percent in the most successful projects: “China Lake,” 71 percent; NIST, 70 percent; Air Force Research Laboratory (AFRL), 80 percent; and the Army’s Aviation Missile Research Development and Engineering Center (AMRDEC), 70 percent.

The success of the demonstration pay systems has been evaluated against seven criteria cited by compensation expert Ed Lawler as prerequisites for effective pay-for-performance systems (significant rewards linked to performance, adequate communication about rewards, supervisors’ willingness to explain the system, variance of rewards based on performance, meaningful performance feedback, objective performance measurement or trust if criteria cannot be entirely objective). The original “China Lake” and NIST demonstration projects met most of the seven criteria (Schay, 1997), as did at least three of the DoD labs (AFRL, AMRDEC, and NUWC Newport) based on results through 2004.

In order for pay for performance to be effective, employees have to perceive the link between their performance and pay. Although demonstration project support in the DoD labs varied from a low of 26 percent to a high of 80 percent, there were increases in all labs over time in the actual and perceived pay-performance link and pay satisfaction. Lower support was correlated with lower ratings on communication, trust, and procedural justice (perceived fairness of ratings, reconsideration procedures, and pay administration). This indicates that the labs have been successful in establishing the link between pay and performance while for the most part ensuring procedural justice.

Since rising salary cost is of concern to Congress, salary analyses were conducted comparing the cost under pay-banding to the General Schedule. Historic results of previous demonstration projects (“China Lake” and NIST) show different trends, a salary difference of 8.9 percent for NIST after eight years and 2.8 percent for “China Lake” after 14 years. Translated into steps of the General Schedule system, where one step is equivalent to about 3 percent, differences have ranged from one to three steps more than under the General Schedule. The results for the DoD Lab Demo are similar, with slightly higher cost under most but not all the demonstration pay systems. The average difference in pay progression over a six-year period was slightly more than one step. In some cases, pay progression was slower than under the General Schedule due to below-average funding of pay pools, and, in some cases, almost three steps more. AFRL’s contribution-based pay system, with its flexible open-banding system that allows promotion to a higher band based on performance, has performed extremely well by keeping down overall salary growth and redistributing pay based on performance contribution. Under AFRL’s contribution-based system, performance expectations rise with pay, slowing down pay progression at the higher levels but facilitating rapid upward movement for high performers in the lower bands.

Regression analyses for cohorts of employees were conducted in three demonstration projects (“China Lake,” NIST, and DoD Lab Demo) to examine the impact of performance (performance ratings and promotions) and nonperformance factors (e.g., tenure, gender, race)

on pay progression over time. The results show that over time, performance became an increasingly significant predictor of pay progression in the demonstration systems, without showing any systematic bias due to gender or race. The effect of performance on pay was small or non-existent in the General Schedule comparison group.

The fourth objective, to adjust workforce levels to meet strategic program and organizational needs, was met to the extent that labs continued to downsize as the demonstration projects were implemented. Another BRAC (Base Realignment and Closure Act) is under way. This indicates that laboratory missions are being realigned, and it remains to be seen what the demand will be for scientists and engineers in the federal research laboratories, although it is clear that significant proportions of the aging workforce of baby boomers will have to be replaced.

Not all demonstration projects were equally successful in implementing their programs and gaining employee support. Success was determined as much by the design and structure of the new human resource management systems as the way they were implemented and managed. Critical success factors include effective performance management practices, good communication by managers, and procedural justice. These result in trust in management and employee and union support. Unions tend to be opposed to pay-for-performance projects because of their lack of trust in management. Based on 2004 survey results, trust levels ("I have trust and confidence in my supervisor") actually increased in four of six DoD labs participating in the survey and ranged from 55 percent to 76 percent, while remaining statistically unchanged in two. Trust also increased in the Commerce Demonstration, from 59 percent to 70 percent over seven years, and in the Acquisition Demonstration, from 63 percent to 66 percent over five years.

Implications

While adequate pay is important to attract quality candidates, employees in the federal science labs accept and remain in their jobs for reasons other than pay, including job challenge and learning and development opportunities. Developmental opportunities can enhance retention of younger employees, which is especially important in view of the increasing retirements of baby boomers. At the same time, it is critical that candidates for leadership positions be carefully selected based on their leadership competencies, or emotional intelligence (EQ), and not just based on their technical competence (IQ). Research by the Hay Group has shown that EQ assumes increasing importance at higher-level leadership positions. Given the same IQ level, those with a higher EQ level are more likely to succeed as leaders.

Three of the most consistent findings in climate surveys and focus groups across the federal government are: (1) complaints about managers who lack leadership competencies, (2) too much red tape and bureaucracy, and (3) lack of creativity and innovation. These factors are particularly demotivating to professionals in STEM occupations and are reasons for leaving the government. Another trend that will result in the loss of talent is increased contracting out. Scientists and engineers, especially those with advanced degrees, are not likely to be motivated by the prospect of contract management when they have spent years in graduate school preparing for their professions. As the federal government attempts to recruit and retain top talent in STEM occupations, minimizing red tape and selecting leaders who can foster innovative

thinking and autonomy would help to achieve that goal and contribute to continuing scientific and technical advances.

Focusing on the number of individuals in the STEM workforce should not obscure the fact that the quality of those individuals is what determines ultimate outcomes and advances in science and technology. Variance in performance tends to increase with the complexity of the job, and if talent is defined as the ability to solve complex problems and invent new solutions, the recruitment and selection of STEM talent needs to focus on quality.

Future shortages of STEM professionals in the federal government can be addressed in a number of ways: (1) structuring work, not just HR processes, to minimize red tape and make the work more attractive to professionals; (2) growing our own talent by offering student career (co-op) appointments that allow students to work and continue graduate study (including seeking out women and minorities who are underrepresented in STEM positions); (3) providing career intern programs that offer development opportunities on a faster track; (4) offering student loan repayment; (5) obtaining direct-hire authority for non-citizens in difficult-to-recruit STEM occupations (e.g., NRL demonstration project); (6) implementing pay-banding and pay for performance with dual career ladders where senior experts earn the same pay as first-line supervisors to provide incentives for talented STEM professionals to continue their work rather than seek supervisory positions in order to earn higher pay; (7) selecting and developing better leaders to nurture and retain STEM talent in the federal government.

Finally, while the government cannot compete on pay with the private sector, it still offers a good employment value proposition: challenging work, important mission, better benefits than most private-sector companies, greater job security, and programs to ensure work-life balance that are particularly attractive to younger employees with childcare responsibilities.

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The Economic Complexities of Incentive Reforms and Engineers in the Federal Government

Beth J. Asch¹

Introduction

High-level reports, such as the National Academies' report *Rising Above the Gathering Storm*, have raised concerns about the ability of the United States to maintain its leading edge in science and technology. Part of the concern stems from the leveling effects of globalization that erode the preeminence of the United States and puts it in direct competition with other countries. Consequently, to maintain its edge, the United States must be quicker, more agile, and even more innovative. Part also stems from concern about the size of the U.S. science and engineering workforce and reports of potential shortages in these fields.

In the context of national security, the Department of Defense (DoD) relies heavily on scientists and engineers to develop, test, and evaluate a wide array of systems, both hardware and software, that support its national security strategy. This workforce consists of federal employees as well as civilian contractors (so-called *beltway bandits*), and national security concerns prompt a demand that a subset of this workforce be U.S. citizens. Thus, reports of shortages of scientists and engineers and the need for them to be the best, the brightest, and the most innovative call into question DoD's ability to meet its national security goals.

Despite these concerns, available evidence suggests that, in fact, the supply of scientists and engineers is adequate (Butz et al., 2004; Freeman, 2005). The U.S. share of engineering and science graduates has declined, but apparently in response to the lack of attractive opportunities for these graduates relative to their competing opportunities in such fields as law and business, and to the high costs (both the direct and opportunity costs) of attaining a science doctorate or postdoctorate degree. The challenge for DoD personnel managers then is how to attract and retain the best and the brightest to engineering and science careers and motivate strong performance over those careers given their excellent opportunities elsewhere.

A common criticism of the current Title V federal personnel and compensation system is that it is invariant to good performance and overly compresses pay. To some extent, DoD has been able to waive the civil service system—by establishing a series of demonstration projects for some of its science and engineering workforce. More recently, it has received congressional approval to launch a replacement to the civil service system, called the National Security Personnel System (NSPS), which will be implemented in stages over the next several years. In general, these new systems have converted the current civil service pay table into broad pay bands. While the specifics differ substantially across sites, at the heart of these efforts is the concept of pay-for-performance and putting some compensation at risk based on assessments of performance. Incentives for performance are also at the heart of other efforts throughout the

¹ RAND Corporation.

federal government to raise performance, such as the 2002 President's Management Agenda. Key questions are how should pay-for-performance be implemented, and what are the pitfalls of such a system?

This paper summarizes lessons from the economics and management literature on improving incentives for performance in the context of the science, engineering, and technology workforce drawing from an earlier paper (Asch, 2004). It is intended to help government leaders and federal managers as they move ahead with efforts to improve incentives in the federal government for this workforce. It summarizes the evidence on pay in the federal government for scientists and engineers, then highlights the issues that must be resolved and the problem of unintended consequences that may arise in pay-for-performance systems, discusses subjective evaluation, and summarizes alternative approaches to explicit pay-for-performance systems. The paper does not address the contractor workforce, though some of the ideas would be relevant to that workforce as well.

Overview of Evidence

Although the current federal civil service system has been highly criticized for the inability to reward strong performers or to be responsive to market forces, the available evidence is somewhat mixed on the recruiting and retention outcomes of the system for scientists and engineers. Gibbs (2001) examined trends in the workforce outcomes of scientists and engineers who worked in laboratories in DoD in the 1980s and the first half of the 1990s, a group including many individuals with advanced degrees. Among those who were not part of the demonstration projects, he found little evidence that DoD suffered a declining trend in the quality of its science and engineering laboratory workforce, though it did not find evidence of an increase, either.

Studies comparing the pay of federal and private-sector employees in general with similar "human capital" in terms of age, education, region, and so forth found that federal pay exceeded private-sector pay from the mid-1970s to 2000, though the gap declined somewhat for males (Gyourko and Tracy, 1988; Krueger, 1988; Moulton, 1990; Borjas, 2002). However, the structure of compensation in the federal sector relative to that in the private sector became more compressed, calling into the question the ability of the federal sector to attract and retain high-quality personnel in the future (Borjas, 2002). Gibbs (2001) found a similar compression of the pay structure for scientists and engineers within the DoD civil service.

Regarding the demonstration projects, they seemed to have shown promise but have not always lived up to their potential. Gibbs (2001) studied the outcomes of DoD laboratory scientists and engineers and found no evidence that these other pay plans provided greater flexibility in personnel management. The Naval Research Advisory Committee report on the defense science and technology community, which described reviews of the studies of these demonstration projects at various defense laboratories, concluded that the results of these projects could have been much better than they were and that many of the most promising initiatives for improving the civil service system were dropped due to problems in getting organizational approval (U.S. Office of the Assistant Secretary of the Navy, 2002).

It is useful to note that in the private sector, a common finding is that time on the job, such as hours worked, is a stronger predictor of pay than are metrics of performance (Lazear,

2000a; Parent 1999; Medoff and Abraham, 1980; Baker, Murphy, and Jensen, 1988). The next section discusses the purpose and some of the drawbacks of pay-for-performance systems.

Purpose and Drawbacks of Pay-For-Performance Incentives

Pay-for-performance is intended to solve the employer's twin problems of motivating high performance and attracting and retaining talented personnel when individual employee effort or ability is not readily observed. The potential for incentive problems to arise in the federal government seems great. Effort and output are often difficult to measure, because the nature of the work is generally complex, unique, and service oriented. Output is often a result of team effort, and disentangling an individual's effort may be difficult. Whether or not an employee has characteristics that are particularly important for productivity (e.g., honesty, diligence, creativity, adaptability, entrepreneurship, collegiality) is often difficult to discern from entry test scores or a resume, and the civil service system may inadvertently attract applicants with undesirable characteristics. Finally, the role of random factors in determining performance may be particularly important in some situations, because civil service projects may be "one-of-a-kind," thereby preventing the use of "benchmarks" to compare performance.

The classic solution to the incentive problem is a piece-rate or system that sets pay in direct proportion to either a metric of output (e.g., number of articles published, patents issued) or the dollar value of an output (e.g., commissions on sales). This approach solves the incentive problem in that workers who cut their effort also cut their pay. Such systems also attract and retain better workers, because more-talented individuals prefer pay systems that explicitly reward them for their talent. They also induce the most talented individuals to apply for employment and the least talented to leave. The available evidence from private-sector organizations that use commissions and piece-rates supports this result (Lazear, 2000b; Prendergast, 1999).

One disadvantage of explicit pay-for-performance systems is that they expose employees to earnings variability caused by factors that are beyond their control. For risk-averse employees, the greater the random factors are, the more it makes sense to weaken the incentives for performance and increase the fixed component of compensation.

Measurement Costs

In actual practice, few organizations allow a large part of earnings to directly depend on performance. The reasons have to do not just with risk aversion of employees but the unintended consequences that occur when large parts of compensation are at risk and dependent on metrics of performance. The discussion first highlights issues related to measurement costs, then multiple principals or employers, multiple objectives, and, finally, subjective evaluations.

Multidimensional Performance. The simplest and arguably the best setting for pay-for-performance is one that has a single, easily measured output. The problem posed by multiple-dimensioned output is that employees can reallocate their efforts toward those tasks that are measured and rewarded and away from those that are not (Holmstrom and Milgrom, 1991). For example, when pay is based on quantity, such as number of articles published, and not quality, too little quality is produced, i.e., an unintended consequence. Much empirical evidence supports this result (Polich, Dertouzos, and Press, 1986; Asch, 1990; Courty and Marschke,

1997). In these situations, the greater the problems caused by unintended consequences, the weaker the link should be between pay and performance, and alternative approaches to providing incentives that reduce these consequences should be used.

One approach that reduces the problem of unintended consequences is to strategically design how job characteristics are bundled and assigned to workers (Holmstrom and Milgrom, 1991). For the government setting, specialists could be employed for narrowly defined task sets (see Dewatripont, Jewitt, and Tirole, 1999). The use of pay-for-performance is then more feasible, because the workers have limited ability to reallocate their efforts in unproductive ways.

Team Production. Problems with pay-for-performance systems can also arise when performance is the result of teamwork, and the contribution of each individual is thus difficult to identify. One approach is to base pay on group performance. An advantage of this scheme is that it fosters cooperative behavior among team members. But “free-riding” is also possible (Holmstrom, 1982). If each employee’s share of the team-based reward is small relative to the difficulty of the work (or the cost of effort) and if effort is difficult for the employer to observe, each individual on the team has an incentive to free-ride on the efforts of others, so overall team output is less. Several studies have documented such free-riding behavior (Prendergast, 1999). One approach to reducing free-riding is to encourage peer pressure or “mutual monitoring” among team members (Kandel and Lazear, 1992). Similarly, an organization that can successfully create a “corporate culture” of hard work and intrinsic motivation can ameliorate the free-riding issue.

Clearly, the output of defense laboratories reflects team effort. Performance and accountability measures that base rewards on metrics of team performance will run up against the free-rider problem. A lab or installation can attempt to counteract this behavior by adopting a “high performance” corporate culture. Alternatively, if it is feasible to do so, the laboratory can combine team-based incentives with individual incentive mechanisms. By using a complementary incentive scheme that rewards individual performance, the organization offsets the negative effects of free-rider behavior while fostering the positive effects that team-based incentives have on cooperation.

Multiple Principals or Multiple Objectives

Public-sector organizations are often large and usually have multiple principals with somewhat divergent objectives. For example, in the case of a middle manager in an Army laboratory, the principals might include the Army, the Office of Personnel Management (OPM, the organization that oversees federal civil service personnel management), and different interest group constituencies, such as civil service unions. The problem posed by multiple principals is, again, one of unintended consequences: Efforts on behalf of one principal can divert efforts on behalf of other principals. The 1990s reform efforts in the DoD laboratories offer an example (U.S. Office of the Assistant Secretary of the Navy, 2002).

The purpose of the reforms in the 1990s was to allow the DoD laboratories to waive Title V requirements and to develop personnel and compensation systems that embedded more management flexibility and greater performance incentives. These reform efforts often conflicted with other reform efforts occurring at the same time, such as the National Performance Review initiative, which was being carried out throughout the federal government, and the Defense Management Review, which was being carried out within DoD. According to the

Naval Research Advisory Committee Report, these other initiatives were often given preference. Furthermore, the laboratories required extensive justification by OPM before the Title V requirements were allowed to be waived.

The optimal incentive scheme when multiple principals have conflicting rather than complementary goals is one that weakly links pay with performance for any given activity (Dixit, 2002). The weaker link reduces the incentive to divert effort toward the goals of one principal at the expense of the goals of the others. Furthermore, the more that the efforts of the agent for the different principals are substitutes, so that effort on behalf of one principal takes away effort on behalf of another principal, the weaker the optimal link. Put differently, pay should be only loosely linked to metrics of performance tied to the specific objectives of different principals when those objectives cannot all be measured.

Obviously, having multiple principals is not a problem if the principals have common or complementary goals. And even when goals are not complementary, it may be possible to bundle the agent's tasks so as to limit the number of principals with an interest in any given set of tasks. For example, if divisions within a laboratory were "bundled" according to mission, the use of pay-for-performance incentives would become more feasible, because employees in each division would have less scope to redirect their efforts to the missions of other principals.

Multiple Objectives. The objectives of public-sector organizations are more diverse than those of most private-sector businesses. The very reason why the activity is provided by the government may be motivated by the idea that profit maximization by itself will not result in the socially optimal allocation of resources. Public-sector organizations often care about the outcomes *and* the processes of their activities. Thus, governmental organizations may have not only multiple principals, but multiple objectives as well (Tirole, 1994; Dixit, 2002; Wilson, 1989).

The problem with multiple objectives is similar to the problem of multiple dimensions. If only some objectives are measured and rewarded, pay-for-performance may lead to unintended consequences, especially if those objectives are not complementary. Related to the issue of multiple objectives is the concept of "fuzzy missions," which introduce uncertainty about what objectives agents are to pursue. As discussed by Wilson (1989) and developed more fully by Dewatripont, Jewitt, and Tirole (1999), vague objectives rather than clear missions result in lower performance because the uncertainty of the mission creates more uncertainty about the effects of effort, or worker talent, on performance.

Subjective Evaluations

Performance metrics can be quantitative, or *objective*, and/or qualitative, or *subjective*. (A subjective measure might be the ranking of an employee's performance based on a supervisor's expert opinion and experience.) The NSPS and demonstration projects use supervisor assessments or subjective evaluations to assess performance. The issues of measurement costs, multiple principals, and multiple objectives also arise to some degree when performance is assessed using subjective metrics. Subjective assessments do have the advantage over objective assessments in that evaluators can account for ill-defined dimensions of performance, such as collegiality. On the other hand, the accuracy of subjective assessments based on ill-defined dimensions cannot be fully verified by outsiders (Baker, 1992).

Subjective performance assessments are valuable only if supervisors have an incentive to give assessments that are consistent with their organization's mission. In a highly competitive labor market, employers might prefer to reduce their company's wage bill and deny that their workers performed well to avoid paying higher wages (Landy and Farr, 1980).² In organizations such as the federal government, supervisors are not residual claimants: Claiming poor performance and denying workers increases does not increase the pay of the supervisors. In fact, just the opposite problem may occur. Supervisors may have an incentive to be lenient and give overly positive assessments so as to minimize complaints or maintain morale among employees (Milgrom, 1988; Milgrom and Roberts, 1988). Supervisors may have a fixed budget from which to allocate raises, so a higher raise for one employee ultimately has to be offset by a lower raise for another. In this case, employees have an incentive to lobby the supervisor for a better assessment, thereby diverting their time away from productive activities and toward unproductive (from the standpoint of the organization) lobbying activities.

The federal government has traditionally relied on subjective performance assessments. The problem is that the overwhelming majority of employees in the federal government receive an acceptable rating, and the subjective performance assessments indicate little difference in employee performance. This problem is not limited to the federal government. Ratings tend to be compressed in the private sector, and the compression becomes more severe as the ratings become more important for setting pay (Prendergast, 1999).

As part of the move toward increased accountability, various federal organizations are using scorecards that rely on metrics of productivity. However, a key question is whether there is any reason to expect supervisors to behave any differently than they have in the past. For scorecards to be effective, supervisors must have the incentive to resist inflating the performance scores to minimize complaints from their subordinates, thereby maintaining the integrity of the accountability of the metric system.

In sum, the use of subjective evaluation is subject to the problem of "grade inflation," while the use of objective metrics is subject to the problem of measurement cost associated with job complexity and the inability of managers to credibly specify all actions to be taken in all circumstances. Given these limitations, the simultaneous use of both approaches—each imperfect but still informative about performance—may be a good strategy. Another approach is to require evaluations from multiple sources. For example, in the so-called 360 reviews, evaluations are solicited from both supervisors and subordinates.

Additional Approaches to the Provision of Incentives

There is no magic cure for the problem of unintended consequences. Instead, there are alternative approaches to the provision of incentives that can be effective in different circumstances. Highly technical workforces such as scientists and engineers have "flat" careers in the sense that employees enter at a high pay grade, reflecting their advanced education, and then spend most of their long career in just two or three grades, rather than rapidly climbing a promotion ladder as someone on a management track might. The following sections summarize how seniority or career-based systems and promotion systems can work in providing incentives.

² This is a short-sighted strategy, however. An employer that cares about its long-term reputation in the labor market as a caring employer would eschew this strategy, and the competitive equilibrium would involve higher wages.

Seniority-Based Incentives

Seniority-based incentives recognize that employees often stay with the same employer for long periods. When employees stay with one organization for much of their career, employers can motivate high performance by offering a reward later in the employee's career that is contingent on current levels of effort.

Seniority-Based with a Pay Band. One approach to incentives is to vary pay within the band in such a way that employees are initially underpaid *relative to their productive worth* during the initial phase of their career and overpaid relative to their worth later in their career if they demonstrate high performance in the initial phase. Thus, there is a “speed bump,” or control point, within the pay band, beyond which an individual does not advance without displaying adequate performance. The financial incentive for performance is a “carrot-and-stick” approach, with the promise of future overpayment within the band for those who perform satisfactorily, and no overpayment, and possible dismissal for those who do not. Over the course of a career in the band, the underpayment and overpayment cancel each other out, and expected pay equals the discounted value of productive worth. Thus, pay within the pay band grows faster than productivity, but only high-performing junior employees receive the overpayment when they become more senior employees.³ An advantage of this approach is that performance can be assessed periodically, thereby saving measurement costs, given that these are long-term employees. Available evidence suggests that private sector organizations do offer such career paths (Kotlikoff and Gokhale, 1992; Lazear and Moore, 1984; Medoff and Abraham, 1980; and Spitz, 1991).

Career Concerns. Another approach recognizes that employees have career concerns and care how their performance in their current job influences their ability to get a future job in the internal or external market. If good performance on the current job leads to better future job offers from the external market or from other work groups in the internal market, employees have an incentive to work hard, even in the absence of pay-for-performance contracts based on metrics of output and even if they do not end up eventually changing jobs (Fama, 1980).⁴

The employee's reputation for good or poor performance plays an important role in facilitating strong incentives for performance. Employees who gain a reputation for poor performance reduce their chances of getting a good job in the future. By the same token, organizations can earn a bad reputation for reneging on pay or treating employees poorly, thereby hurting their ability to hire high-performing workers in the future. If hiring high-quality employees is important, the organization has an incentive to refrain from such behavior.

³ One problem with this incentive scheme is that employees have no incentive to separate or retire when they are senior employees, because they are being paid more than their productive worth. Lazear (1979, 1983) discusses how mandatory retirement and nonactuarially fair pensions are important mechanisms to induce employees to retire involuntarily (as in the case of mandatory retirement) or voluntarily (as in the case of nonactuarially fair pensions).

⁴ As discussed in Holmstrom (1982) a problem with using career concerns as part of an incentive mechanism is that junior employees will work too hard (when the external market is still making judgments about the performance of workers and their entire career spans before them) and senior employees will work too little (because the market has already made its judgment and these workers have little of their career left before retirement). Gibbons and Murphy (1992) show that the optimal incentive scheme over workers' careers will involve a heavier reliance on career concerns and nonexplicit pay-for-performance schemes for junior and mid-career workers, but a weaker reliance on career concerns for senior workers. In fact, the optimal scheme for senior workers will rely more heavily on explicit pay-for-performance incentive schemes, because career concerns are less relevant when there is little concern about external job opportunities.

Promotion-Based Incentives

To the extent that scientists and engineers are promoted, promotion-based incentives rely on a pre-specified pay table or pay band in which promotions to the higher grades or band are based on performance assessed over several time periods (Lazear and Rosen, 1981). The financial incentive to supply effort is affected by the probability of promotion and the financial return to promotion, given a promotion occurs. An increase in the return induces more effort, all else being equal. Increases in the probability of promotion (and therefore the expected return) raise effort up to a point. Beyond that point, there is a high probability that additional effort has little effect. In the extreme case, where the probability equals one and the return is received with certainty, there is no effort incentive. Promotion-based systems can be equally as powerful as explicit pay-for-performance systems in terms of the incentives for performance they provide.

Promotion systems address some of the problems posed by explicit pay-for-performance methods. First, measurement costs are often much lower. The supervisor has to determine only who has the best performance, not the exact level of performance of each employee. So, when some dimensions of performance are ill defined, the best approach to providing incentives is likely to involve the use of supervisor rankings, often together with subjective evaluations. Second, promotion systems can reduce the variability of employee earnings caused by random external factors, such as a weak economy, if those factors common to all workers are important relative to those factors specific to individual employees. Third, the common pay scale that forms the foundation of the promotion system helps ensure the transparency and credibility of the compensation system. Since the pay table is common knowledge, the employer cannot secretly renege and fail to pay workers and, similarly, employees cannot falsely claim that the employer reneged on its payments. The issue of reneging is a potential drawback of explicit pay-for-performance systems. It is also a criticism of pay-banding, since managers have discretion over pay within the band and, in the absence of effective oversight, can engage in favoritism and other types of misbehavior (Prendergast and Topel, 1996).

For promotion systems to provide meaningful performance incentives, it is imperative that the organization maintain the integrity of the promotion system. Workers have an incentive to try to influence the outcome of promotion “contests” by lobbying the supervisor who makes the promotion decision or by sabotaging (or spreading incorrect rumors about the performance of) competitors. The greater the expected return from promotion, the greater the incentive to engage in these activities. The U.S. military solves the problem of influence activities among mid-grade promotions by relying on anonymous national selection boards. The problem of sabotage is ameliorated because service members compete against “the field,” which is made up of all eligible members, who are mostly anonymous and are scattered throughout the world.

But in organizations such as defense installations where supervisors at the local work site make the promotion decisions, and those who make up an employee’s group of competitors consist of individuals working at the same site, the problems of influence and sabotage activities are more likely. If promotion is based on subjective performance assessments, supervisors can bias their assessments toward some individuals. Furthermore, supervisors may use promotion to solve personnel problems unrelated to promotion. For example, supervisors may recommend employees for promotion because they were difficult to work with, and promotion was a way to remove them without having to fire them. Or promotion might be the only feasible way

to provide a large enough pay raise to meet a competitor's outside offer, because other methods of raising pay are constrained. Such behavior compromises the integrity of the system and undermines employee confidence about its fairness and accuracy.

An important policy implication of the economics literature regarding the structure of compensation in organizations such as the civil service and the military, where promotion-based incentives are used, is that the pay structure must be "skewed," with the differences in pay across grades rising with grade level (Rosen, 1982a, 1982b). For example, the difference in pay between the top two grades should be larger than the difference in pay between the two grades just below them. There are three reasons for this structure. First, the pay gain associated with each successive promotion must rise to maintain the same expected financial incentive, given that individuals have fewer promotions as they climb the promotion ladder. Second, the pay gain associated with promotion must rise at higher grades because the probability of promotion tends to decline with grade. Third, the pay gain associated with each promotion must increase to induce the most talented workers to stay in the organization and to seek advancement to the senior ranks, where their ability is valued most.

The federal government's pay structure is not skewed relative to that of the private sector for similarly skilled workers (Gibbs, 2001; Borjas, 2002; Katz and Krueger, 1991), implying that the government's promotion ladders do not provide as much financial incentive for performance as those in the private sector do. On the other hand, the degree to which the lack of skewedness has hurt retention and recruiting is unclear, as discussed earlier. Furthermore, one important factor that diminishes the desired amount of skewedness in the federal sector is cooperation among employees. Reduced financial incentives associated with promotion in the upper grades can help engender a work environment or culture of public service (Lazear, 1989).

Incentives to Attract and Retain Talent

The most efficient approach for achieving a high level of performance may involve structuring a pay system or using personnel policies to induce talented individuals to self-select or sort into the organization—seek employment and stay in the organization—rather than hiring a workforce of average quality and then devising a pay system that makes that workforce perform better.

There are a few approaches to induce the self-selection of talented workers. One approach, discussed earlier, is to directly tie pay to performance. Talented workers are attracted to pay-for-performance systems because they can expect higher-than-average earnings. Another approach is to use apprenticeship or internship programs (Guasch and Weiss, 1981; Lazear, 1986). During the apprenticeship program, pay is set far below the apprentice's productive worth to discourage poorly qualified applicants. In the postapprenticeship career, pay is set high enough to offset the low pay earned in the apprenticeship period for highly qualified applicants. The civil service has a career intern program that serves this role. It could be expanded as a way to expand the screening of qualified recruits.

Another approach is for the organization to set pay higher than that of the average external alternatives of employees, thereby increasing the size and average quality of the applicant pool from which it can draw (Weiss, 1980), as well as the average quality of the personnel it retains. Arguably this has been the approach used by the federal civil service since the mid-

1970s. Borjas (2002), Gibbs (2001), and Katz and Krueger (1991) all argue that the compressed structure of earnings among those in the federal civil service relative to those in the private sector will likely hurt the federal sector's ability to recruit and retain highly talented personnel in the future.

Conclusions

DoD is expanding the demonstration projects' scope by implementing the NSPS. At the core of both NSPS and the demo projects are pay bands and pay-for-performance. Pay bands, whereby personnel spend large segments of their careers within single bands, are appropriate for the science and engineering workforce, given that this workforce typically follows a relatively horizontal career anyway with relatively few promotions, with most pay increases reflecting increasing technical proficiency. That said, the discussion in this paper makes clear that pay-for-performance schemes have a number of pitfalls having to do with the high cost of directly measuring output, or with multiple principals or multiple objectives. These issues lead to the problem of the unintended consequences. Subjective evaluations can address some of these pitfalls, but subjective evaluations also have their pitfalls, such as favoritism, "grade inflation," and unproductive lobbying of the evaluator. These issues suggest that the amount of money at risk and directly dependent on performance at a point in time for a given employee should be relatively small. But while smaller financial rewards imply weak incentives, even weak incentives can be meaningful, especially if they are linked to important strategic goals of the organization. They also suggest the value of using both subjective and objective metrics of performance, as well as subjective evaluations from multiple sources.

Career incentives should also be provided for the science and engineering workforce. In the context of pay bands, incentives can be provided by a seniority-based system in which pay is less than productivity until the employee hits the speed bump, at which point pay exceeds productivity. Pay rises faster than productivity within the pay band and the speed bump prevents low performers from earning the high pay. Alternatively, some scientists and engineers may enter the civil service to gain civil service experience that is valuable in the private sector. Their incentive to perform is based on their focus on external job opportunities, and their motivation for working hard is their concern for how their current performance will affect their future private-sector opportunities. Here, the incentive approach is to set pay high enough to attract and retain talent.

In sum, multiple incentive mechanisms should be used in tandem for the science and engineering workforce. Evidence from the private sector indicates that when mechanisms are used together, productivity increases more than when individual mechanisms are used alone (Lambert, Larcker, and Weigelt, 1993). A well-designed system of incentive mechanisms can enable DoD to attract, retain, and motivate top-notch scientists and engineers to meet its requirements.

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Agenda, List of Attendees, and Biographical Information

Agenda

Meeting on the Gathering Storm and Its Implications for National Security November 8, 2006 Washington, D.C.		
8:00–8:10	Opening Remarks	David S. C. Chu, Under Secretary of Defense, Personnel and Readiness
8:10–9:40	Scientific Wealth and Scientific Investments of Nations	Jonathan Adams
	Is America Losing Its Edge?	Adam Segal
	Summary of <i>Rising Above the Gathering Storm</i>	Deborah Stine
9:40–10:00	Coffee Break	
10:00–11:00	Panel: Retrospective on DSB 2000 Report on Globalization and Security	Bill Greenwalt, Kenneth J. Krieg, and Brian H. Wells
11:00–11:30	Knowledge and the Wealth of Nations	David Warsh
11:30–12:30	Lunch	
12:30–1:30	Innovation, Diffusion, and Trade	Jonathan Eaton and Samuel Kortum
	Endogenous R&D Spillovers and Industrial Research Productivity	James D. Adams
1:30–2:30	Does Globalization of the Scientific/Engineering Workforce Threaten U.S. Economic Leadership?	Richard B. Freeman
	Do We Need More Scientists?	Michael S. Teitelbaum
2:30–2:50	Coffee Break	
2:50–3:50	Summative Evaluation of Personnel Management and Compensation Initiatives	Brigitte W. Schay
	Economic Complexities of Incentive Reform	Beth J. Asch
3:50–4:50	Panel Discussion: Summing Up	Jonathan Eaton, Ray O. Johnson, Thomas L. Magnanti, Paul Oyer, Paula E. Stephan, and Rick Stephens
4:50	Closing Comments	David S. C. Chu

Presenters (in order of presentation)

- David S. C. Chu, Under Secretary of Defense for Personnel and Readiness
- Jonathan Adams, Director, Evidence Ltd.
- Adam Segal, The Maurice R. Greenberg Senior Fellow in China Studies, Council on Foreign Relations
- Deborah Stine, Director, Office of Special Projects, National Academy of Sciences, Policy and Global Affairs Division
- Bill Greenwalt, Deputy Under Secretary of Defense for Industrial Policy
- Kenneth J. Krieg, Under Secretary of Defense for Acquisition, Technology and Logistics
- Brian H. Wells, Principal Fellow, Raytheon Company
- David Warsh, Editor, *economicprincipals.com*
- Jonathan Eaton, Professor of Economics, New York University; National Bureau of Economic Research
- Samuel Kortum, Professor of Economics, University of Chicago; National Bureau of Economic Research
- James D. Adams, Professor of Economics, Rensselaer Polytechnic Institute
- Richard B. Freeman, Director, Labor Studies Program, National Bureau of Economic Research
- Michael S. Teitelbaum, Program Director for Research and Technology, Alfred P. Sloan Foundation
- Brigitte W. Schay, Director, Assessment Services, Office of Personnel Management
- Beth J. Asch, Senior Economist, RAND Corporation
- Ray O. Johnson, Vice President and Chief Technology Officer, Lockheed Martin Corporation
- Thomas L. Magnanti, Dean of the School of Engineering and Institute Professor, Massachusetts Institute of Technology
- Paul Oyer, Associate Professor of Economics Graduate School of Business, Stanford University
- Paula Stephan, Professor of Economics, Georgia State University
- Rick Stephens, Senior Vice President for Human Resources and Administration and Member of the Executive Council, Boeing Company

Attendees

- Barry D. Bates, Vice President of Operations, National Defense Industrial Association
- Anita K. Blair, Deputy Assistant Secretary of the Navy for Military Personnel Policy
- Carl Dahlman, Program Executive Officer for the Defense Human Capital Strategy
- Daniel Denning, Acting Assistant Secretary of the Army for Manpower and Reserve Affairs
- Duane Dimos, Director, Materials Science and Engineering Center, Sandia National Laboratories
- Leonard Ferrari, Provost, Dean of Research and Professor, Electrical and Computer Engineering, Naval Postgraduate School
- Jeanne Fites, Deputy Under Secretary of Defense for Program Integration

- Peter Freeman, Assistant Director, National Science Foundation for Computer and Information Science and Engineering
- Titus Galama, Physical Scientist, RAND Corporation
- Robert Goodwin, Acting Assistant Secretary of the Air Force for Manpower and Reserve Affairs
- Sharon Hays, Associate Director, Office of Science and Technology Policy
- Peter Henderson, Director, National Academies Board on Higher Education and Workforce
- Charles Hokanson, Chief of Staff, Office of Planning, Evaluation and Policy Development, U.S. Department of Education
- James Hosek, Senior Economist, RAND Corporation
- Steve Kaminsky, Vice President for Research and Director of Research Administration, Uniformed Services University of the Health Sciences
- Gail McGinn, Deputy Under Secretary for Plans
- Marc Mossburg, Senior State Liaison, Office of Deputy Under Secretary of Defense for Military Community and Family Policy
- William S. Rees, Jr., Deputy Under Secretary of Defense for Laboratories and Basic Sciences
- John Salamone, Executive Director, Chief Human Capital Officers Council, Office of Personnel Management
- Robert Shea, Counselor to the Deputy Director for Management, White House Office of Management and Budget
- Nancy Spruill, Director, Acquisition Resources and Analysis, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics
- John J. Young, Jr., Director, Defense Research and Engineering, Office of the Secretary of Defense

Presenters' Biographical Information

David S. C. Chu, Under Secretary of Defense, Personnel and Readiness

David S. C. Chu was sworn in as the Under Secretary of Defense for Personnel and Readiness on June 1, 2001. A presidential appointee confirmed by the Senate, he is the Secretary of Defense's senior policy advisor on recruitment, career development, pay, and benefits for 1.4 million active-duty military personnel, 1.3 million Guard and Reserve personnel, and 680,000 DoD civilians and is responsible for overseeing the state of military readiness. Dr. Chu also oversees the \$15 billion Defense Health Program; Defense Commissaries and Exchanges, with \$14.5 billion in annual sales; the Defense Education Activity, which supports over 100,000 students; and the Defense Equal Opportunity Management Institute, the nation's largest equal opportunity training program. Dr. Chu received a B.A., magna cum laude, in economics and mathematics from Yale University in 1964 and a Ph.D. in economics, also from Yale, in 1972.

James D. Adams, Professor of Economics, Rensselaer Polytechnic Institute; National Bureau of Economic Research

James D. Adams is a professor of economics at Rensselaer Polytechnic Institute and a research associate of the National Bureau of Economic Research. Dr. Adams has held visiting appointments at the U.S. Bureau of Labor Statistics, the U.S. Bureau of the Census, and the George J. Stigler Center for the Study of the Economy and the State at the University of Chicago. His current research focuses on the limits of the firm in research and development, the measurement of scientific influence, the identification of alternative channels of knowledge externalities in the economy, the structure and meaning of scientific teams and collaborations, the speed of diffusion of scientific research, the interaction between investment in industrial research and development and investment in physical capital, and the determinants of research and teaching productivity in academia. He received a B.A. in economics from the University of New Mexico in 1967 and a Ph.D. in economics from the University of Chicago in 1976.

Jonathan Adams, Director, Evidence, Ltd., United Kingdom

Jonathan Adams is the lead founder and a director of Evidence, a knowledge-based company specializing in data analysis, reports, and consultancy focusing on the international research base. He was a member of the science policy staff of the Advisory Board for the Research Councils from 1989 to 1992 and was director of research strategy at the University of Leeds (1993–1997).

Beth J. Asch, Senior Economist, RAND Corporation

Beth J. Asch is a senior economist at RAND. Her research focuses on personnel supply and incentive issues in the U.S. military and federal civil service. Recent research has examined the effects of the federal civil service retirement systems and of buyout and early retirement programs on civil service retirement behavior. Other recent research has analyzed military recruiting policies, such as those targeted toward college-bound youth, and the effects of alternative military pay and retirement policies on military retention, retirement, and productivity. Her work also includes several co-authored papers on the relative efficiency of military conscription versus a volunteer force. She has taught undergraduate labor economics at UCLA and is currently a faculty member at the Pardee RAND Graduate School teaching a course on economic incentives and organization. She received a Ph.D. in economics in 1984 and a master's degree in economics in 1981, both from the University of Chicago. She received a bachelor's degree from UCLA in 1979.

Jonathan Eaton, Professor of Economics, New York University; National Bureau of Economic Research

Jonathan Eaton is a professor of economics at New York University and a research associate at the National Bureau of Economic Research. He is an editor at the *Journal of International Economics* and an associate editor at the *European Economic Review*. In 2003, Dr. Eaton served as vice president of the American Economic Association. His main areas of research include international trade and finance. Dr. Eaton was awarded the Frisch Medal with Samuel Kortum in 2004. Over the past 15 years, he and Dr. Kortum have received multiple grants from the National Science Foundation to study topics related to technology and globalization. He received an A.B. in economics, summa cum laude, from Harvard and an M.A. and Ph.D. in economics from Yale University.

Richard B. Freeman, Herbert S. Ascherman Professor of Economics, Harvard University; National Bureau of Economic Research

Richard B. Freeman holds the Herbert Ascherman Chair in Economics at Harvard University. He is currently serving as faculty co-chair of the Harvard University Trade Union Program. He is also director of the Labor Studies Program at the National Bureau of Economic Research, senior research fellow in labor markets at the London School of Economics' Centre for Economic Performance, and visiting professor at the London School of Economics. Dr. Freeman has served on five panels of the National Academy of Sciences, and has published over 300 articles dealing with a wide range of research interests, including the job market for scientists and engineers, the effects of immigration and trade on inequality, and the Chinese labor market. Dr. Freeman received a B.A. from Dartmouth College in 1964 and a Ph.D. from Harvard University in 1969.

Bill Greenwalt, Deputy Under Secretary of Defense for Industrial Policy

Bill Greenwalt is the Deputy Under Secretary of Defense for Industrial Policy. He is the principal advisor to the Under Secretary of Defense for Acquisition, Technology, and Logistics and the Deputy Under Secretary of Defense for Acquisition and Technology on all matters relating to the defense industrial base. Prior to joining DoD, he was a professional staff member of the Senate Armed Services Committee (Senator John Warner, chair). He was also a lead staff member for the Subcommittee on Readiness and Management Support and the Subcommittee on Strategic Forces, and served as a professional staff member on the Senate Governmental Affairs Committee (Senator Fred Thompson, chair). Mr. Greenwalt also served as a staff member for the Senate Subcommittee on Oversight of Government Management (Senator William Cohen, chair). Prior to coming to the Senate in 1994, Mr. Greenwalt was a visiting fellow at the Centre for Defence Economics, University of York, UK; worked for the Immigration and Naturalization Service in Frankfurt, Germany; and served as an evaluator with the U.S. General Accounting Office in Los Angeles, California. He graduated from California State University at Long Beach with a degree in economics and political science and received an M.A. in defense and security studies from the University of Southern California.

Ray O. Johnson, Vice President and Chief Technology Officer, Lockheed Martin Corporation

Ray O. Johnson is the Vice President and Chief Technology Officer of the Lockheed Martin Corporation. Dr. Johnson guides the company's technology vision and provides corporate leadership in the strategic areas of technology and engineering, which include more than 65,000 people working on more than 10,000 programs. Before joining Lockheed Martin, Dr. Johnson was chief operating officer for Modern Technology Solutions, Inc. (MTSI), of Alexandria, Virginia. Prior to that, he held a variety of increasingly responsible executive positions with Science Applications International Corporation (SAIC), including senior vice president and general manager of the Advanced Concepts Business Unit. In addition to executive leadership and management positions, Dr. Johnson has experience in strategic planning, program development, program management, and venture capital funding. He served on the board of two biotechnology companies. Dr. Johnson was a member of the Air Force Scientific Advisory Board from 2001 to 2005, where he chaired the 2003 Summer Study titled, Unmanned Aerial Vehicles in Perspective: Effects, Capabilities, and Technologies and co-chaired the 2002 summer study, "Predictive Battlespace Awareness." Dr. Johnson holds a B.S. in electrical engi-

neering from Oklahoma State University and M.S. and Ph.D. degrees in electrical engineering from the Air Force Institute of Technology.

Samuel Kortum, Professor of Economics, University of Chicago; National Bureau of Economic Research

Samuel Kortum is a professor of economics at the University of Chicago and a research associate at the National Bureau of Economic Research. His research interests include quantitative models of international trade, technology diffusion, and firm dynamics. Dr. Kortum was awarded the Frisch Medal with Dr. Eaton in 2004. Over the past 15 years, he and Dr. Eaton have received multiple grants from the National Science Foundation to study topics related to technology and globalization. He received a B.A. from Wesleyan University in 1983 and a Ph.D. in economics from Yale University in 1992.

Kenneth J. Krieg, Under Secretary of Defense for Acquisition, Technology, and Logistics

Kenneth J. Krieg was confirmed as the Under Secretary of Defense for Acquisition, Technology, and Logistics in 2005. He is responsible for advising the Secretary and Deputy Secretary of Defense on all matters relating to the DoD acquisition system; research and development; advanced technology; developmental test and evaluation; production; logistics; installation management; military construction; procurement; environmental security; nuclear, chemical, and biological matters; and logistics policy matters to assist the end-to-end logistics process of delivering to the warfighter. Prior to joining the Department of Defense, Mr. Krieg worked for International Paper, most recently as vice president and general manager of the Office and Consumer Papers Division. Before working in industry, he worked in a number of defense and foreign policy assignments in Washington, D.C., including positions at the White House, on the National Security Council staff, and in the Office of the Secretary of Defense. Mr. Krieg received a B.A. in history from Davidson College and a master's degree in public policy from the Kennedy School of Government at Harvard University.

Thomas L. Magnanti, Dean of the School of Engineering and Institute Professor, Massachusetts Institute of Technology

Thomas L. Magnanti is dean of the School of Engineering and one of 13 institute professors at MIT, where he has been a faculty member since 1971. He has devoted much of his professional career to education that combines engineering and management and to teaching and research in applied and theoretical aspects of large-scale optimization. Professor Magnanti served as a head of the Management Science Area of the Sloan School of Management and was a founding codirector of MIT's Leaders for Manufacturing and System Design and Management Programs. He is a past president of the Operations Research Society of America and the Institute of Operations Research and Management Sciences, and a former editor-in-chief of the journal *Operations Research*. He is currently president of the International Federation of Operations Research Societies. As dean, he has focused on educational innovation, industrial and international partnerships, technical-based entrepreneurship, diversity, and innovation in emerging domains such as bioengineering, tiny technologies, information engineering, and engineering systems. Professor Magnanti received an undergraduate degree in chemical engineering from Syracuse University and master's degrees in statistics and mathematics and a doctorate in operations research from Stanford University. He has received numerous educational and research awards and currently serves on several corporate and university boards.

Paul Oyer, Associate Professor of Economics Graduate School of Business, Stanford University

Paul Oyer is an associate professor of economics at the Stanford Graduate School of Business. He teaches the core human resources management class in the M.B.A. program, as well as a Ph.D. class in Personnel Economics. His current projects include papers focusing on how firms select and recruit workers, and he is looking at how software companies recruit teams of developers and how law firms use their law school-based networks to hire newly minted lawyers. Before moving to the Stanford Graduate School of Business in 2000, he was on the faculty of the Kellogg School at Northwestern University. In his pre-academic life, he worked for the management-consulting firm Booz Allen Hamilton, as well as for the high-technology firms 3Com Corporation and ASK Computer Systems. He holds a B.A. in math and computer science from Middlebury College, an M.B.A. from Yale University, and an M.A. and Ph.D. in economics from Princeton University.

Brigitte W. Schay, Director, Assessment Services, Office of Personnel Management

Brigitte W. Schay is a supervisory personnel research psychologist with the U.S. Office of Personnel Management and manages the Assessment Services Branch in OPM's Center for Talent Services. She leads a staff of personnel research psychologists who conduct individual and organizational assessment projects for agencies across the federal government, including leadership assessment, climate surveys, and program evaluation. For the past 25 years, Dr. Schay has conducted extensive research on the effectiveness of federal pay-for-performance demonstration projects and authored numerous technical reports, journal articles, and a book chapter on the results. She graduated summa cum laude with a B.A. in psychology from George Mason University, where she also received an M.A. in psychology. She holds a Ph.D. in social and organizational psychology from George Washington University. In 1994, she served as a congressional LEGIS Fellow in the 103rd Congress.

Adam Segal, Maurice R. Greenberg Senior Fellow in China Studies, Council for Foreign Relations, and Adjunct Professor at Columbia

Adam Segal is the Maurice R. Greenberg senior fellow in China studies at the Council on Foreign Relations. An expert on Chinese domestic policies, technology development, foreign policy, and security issues, Dr. Segal currently leads a study group on Asian innovation and technological entrepreneurship. Before coming to the council, Dr. Segal was an arms-control analyst for the China Project at the Union of Concerned Scientists. He was a visiting scholar at the Massachusetts Institute of Technology's Center for International Studies, the Shanghai Academy for Social Sciences and Quighua University in Beijing, and taught at Vassar College and Columbia University. Dr. Segal has a Ph.D. and a B.A. in government from Cornell University and an M.A. in international relations from the Fletcher School of Law and Diplomacy. Dr. Segal has written a book—*Digital Dragon: High-Technology Enterprises in China* (Cornell University Press, 2003)—as well as several articles on Chinese technology policy. His work has recently appeared in the *Washington Post*, *International Herald Tribune*, *Far Eastern Economic Review*, *Financial Times*, *Foreign Affairs*, *Los Angeles Times*, *Asian Wall Street Journal*, and *Washington Quarterly*.

Paula E. Stephan, Professor of Economics, Andrew Young School of Policy Studies, Georgia State University

Paula E. Stephan is a professor of economics at the Andrew Young School of Policy Studies at Georgia State University. Her research interests focus on the careers of scientists and engineers and the process by which knowledge moves across institutional boundaries in the economy. Dr. Stephan was recently appointed to serve a four-year term on the National Advisory General Medical Sciences Council, National Institutes of Health, and currently serves on the advisory committee of the Social, Behavioral, and Economics Program, National Science Foundation. She was a member of the European Commission's high-level expert group that authored the report, *Frontier Research: The European Challenge*. She has served on a number of National Research Council committees. Her research has been supported by the Alfred P. Sloan Foundation, the Andrew W. Mellon Foundation, and the National Science Foundation. Dr. Stephan graduated from Grinnell College (Phi Beta Kappa) with a B.A. in economics and earned both an M.A. and a Ph.D. in economics from the University of Michigan. She has published more than 50 articles in journals such as the *American Economic Review*, *Science*, *Journal of Economic Literature*, *Economic Inquiry*, and *Social Studies of Science*. She is the co-author of the book *Striking the Mother Lode in Science: The Importance of Age, Place and Time*.

Rick Stephens, Senior Vice President for Human Resources and Administration, Member of the Boeing Executive Council, Boeing Company

Richard (Rick) Stephens is senior vice president, human resources and administration, for the Boeing Company and member of the Boeing Executive Council. In a career with Boeing that spans 25 years, he has led a number of businesses, including Space and Communication Services, Reusable Space Systems, Naval Systems and Tactical Systems, Submarine Combat Systems, Space Shuttle, and a number of service and support-related programs. Mr. Stephens has been recognized for his long-standing leadership to local and national organizations regarding the use of science and technology education programs to develop the workforce of the future. He received a B.S. in mathematics in 1974 from the University of Southern California and an M.S. in computer science in 1984 from California State University, Fullerton.

Deborah D. Stine, Study Director, *Rising Above the Gathering Storm*, The National Academies

Deborah D. Stine is associate director of the Committee on Science, Engineering, and Public Policy; director of the National Academies Christine Mirzayan Science and Technology Policy Fellowship Program; and director of the Office of Special Projects. Dr. Stine has been working on various projects throughout the National Academies since 1989—most recently as study director of the National Academies report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. She has directed studies and other activities on a wide-range of issues including science and security in an age of terrorism, human reproductive cloning, presidential and federal advisory committee science and technology appointments, facilitating interdisciplinary research, setting priorities for the National Science Foundation's large research facilities, advanced research instrumentation and facilities, evaluating federal research programs, international benchmarking of U.S. research, and many other issues. Before coming to the National Academies, she was a mathematician for the Air Force, an air-pollution engineer for the state of Texas, and an air-issues manager for the Chemical Manufacturers Association. She holds a B.S. in mechanical and environmental engineering

from the University of California, Irvine, an M.B.A. from what is now Texas A&M at Corpus Christi, and a Ph.D. in public administration with a focus on science and technology policy analysis from American University. She has received the President's Award, Distinguished Service Award, and a Group Recognition Award for the "Policy Implications of Greenhouse Warming" study from the National Academies. In addition, she received the Mitchell Prize Young Scholar Award for her research on international environmental decisionmaking from the Mitchell Foundation and the Association for Women in Science–Bethesda Chapter Mentoring Award.

Michael S. Teitelbaum, Vice President, Alfred P. Sloan Foundation

Michael S. Teitelbaum is vice president at the Alfred P. Sloan Foundation in New York, and concurrently (2006–2007) the Edward P. Bass Distinguished Visiting Scholar at Yale University. He is a demographer, educated at Reed College and at Oxford University, where he was a Rhodes Scholar. His past positions include member of the faculties of Oxford University and Princeton University; staff director of the Select Committee on Population, U.S. House of Representatives; professional staff member of the Ford Foundation and the Carnegie Endowment for International Peace; commissioner (one of 12) of the U.S. Commission for the Study of International Migration and Cooperative Economic Development; first vice president of the Population Association of America, the scientific society of demographers; vice chair and acting chair of the U.S. Commission on Immigration Reform (known as the Jordan Commission). Dr. Teitelbaum is a member of the Council on Foreign Relations and an elected fellow of the American Association for the Advancement of Science. He is a regular speaker on demographic issues and has been a frequent invited witness before committees of the U.S. Congress. He is the author or co-author of seven books and publishes extensively in scientific journals, magazines, and national op-ed pages.

David Warsh, Journalist and Author, *economicprincipals.com*

David Warsh is editor of the online weekly *economicprincipals.com* and author of *Knowledge and the Wealth of Nations* (W. W. Norton, 2006). He covered economics for the *Boston Globe* and *Forbes Magazine* for 25 years and, earlier, reported from Saigon for *Pacific Stars and Stripes* and *Newsweek*. Mr. Warsh is a graduate of Harvard College (1966 and 1972) in social studies and a two-time winner of financial journalism's Loeb Award. He was the J. P. Morgan Prize fellow in spring of 2004 at the American Academy in Berlin.

Brian H. Wells, DD(X) Systems Engineering Team, Raytheon Company

Brian H. Wells is a principal engineering fellow within the Raytheon Integrated Defense Systems engineering organization. He is the technical director for the Future Naval Capabilities business organization. His role includes being the Total Ship System engineering lead for the DDG 1000 program and the chief engineer for the CVN-21 Warfare System. As a principal engineering fellow, Wells provides system engineering and architecture expertise to multiple programs. He is also an instructor in the System Engineering Technical Directors Program. In his DDG 1000 role, he is responsible for directing all national team system-engineering activities on DDG 1000. On both DDG 1000 and CVN-21, his responsibilities include defining system engineering processes, methods, and tools; planning for major reviews and milestones (SRR, PDR, Milestone B, and CDR); creating resolutions for design problems and conflicts; managing, on a technical level, system engineering and system design activities; and providing

team training for system engineering. Mr. Wells has a bachelor's degree in electrical engineering from Bucknell University and a master's degree in electrical engineering from the University of Illinois.

Editors' Biographical Information

Titus Galama

Titus Galama is a physical scientist at the RAND Corporation. With James Hosek, he is editor of this volume and organizer of the meeting on November 8, 2006, in Washington, D.C., that forms the basis of these proceedings. He holds an M.Sc. in physics (cum laude, 1995) and a Ph.D. in astrophysics (cum laude, 1999) from the University of Amsterdam, the Netherlands. Two of the discoveries presented in Dr. Galama's Ph.D. thesis were considered the fifth and 10th most significant scientific discoveries of 1997 and 1999, respectively, by the journal *Science*. He was awarded the Christian Huygens Award by the Dutch Royal Academy of Sciences for outstanding thesis in astrophysics. After completion of his thesis, he worked as a Fairchild Postdoctoral Prize Fellow at the California Institute of Technology, Pasadena. He is the author of more than 50 articles on astrophysics in scientific journals. Following his career in astrophysics, he earned an M.B.A. from INSEAD and worked as a senior strategy consultant for a global strategy consulting firm on a variety of strategy projects in health care and biotechnology for companies ranging from mature start-ups to global conglomerates. His current policy research interests are in education, science, technology, and innovation, and the economics of health and retirement.

James Hosek

James Hosek, editor of this volume and organizer of the November 8, 2006, meeting with Titus Galama, is director of the Forces and Resources Policy Center in the National Defense Research Institute at RAND and editor-in-chief of the RAND Journal of Economics, a leading journal on industrial organization, regulation, and contracts. He is a professor of economics at the Pardee RAND Graduate School. He has served as corporate research manager in human capital and as chair of the economics and statistics department at RAND. He was as chair of the Economic Advisory Council of the California Institute, a nonprofit organization informing California's congressional delegation on policy matters. Dr. Hosek holds a B.A. in English from Cornell University and an M.A. and Ph.D. in economics from the University of Chicago. His main research area is defense manpower, and his current work concerns the reform of military compensation and retirement benefits, the effect of deployment on the retention of service members, the supply of recruits to the reserves, and the competitiveness of U.S. science and technology and the adequacy of the supply of scientists and engineers.