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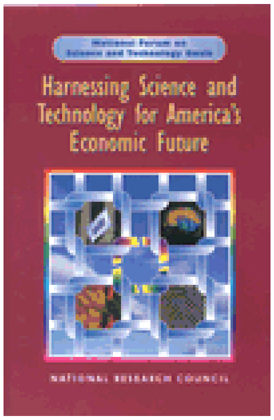

Harnessing Science and Technology for America's Economic Future: National and Regional Priorities

Committee on Harnessing Science and Technology for America's Economic Future, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

National Forum on Science and Technology Goals

Harnessing Science and Technology for America's Economic Future:

National and Regional Priorities

Office of Special Projects
Policy Division
National Research Council

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OFFICE OF SPECIAL PROJECTS

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Contents

PART I: COMMITTEE REPORT

PART II: SPEECHES, COMMISSIONED PAPERS, AND PRESENTATIONS FROM THE FORUM EVENT, FEBRUARY 2-3, 1998

APPENDIXES

PART I:
Committee Report

Executive Summary

If America is to achieve sustained economic growth and improved living standards in the next century, the creation and effective use of science and technology will be essential. To explore how the nation can best advance science and technology for improved economic performance over the next 10 to 20 years, the National Research Council (NRC) organized the National Forum on Harnessing Science and Technology for America's Economic Future, which was held in February 1998. On the basis of forum discussions and other materials, a committee of the NRC's Office of Special Projects developed this report, including its findings and recommendations.

America's ability to translate science and technology into new products and processes, wealth, and jobs is strong today. An outstanding research base, particularly the close linkage between research and education at U.S. research universities, is fundamental to this strength. A second essential element is the financial and cultural environment that encourages the formation and growth of companies based on science and technology. Both those elements will need to be sustained in the future.

The United States also must address serious deficiencies to ensure that science- and technology-based economic gains continue and extend to the broad mass of Americans in the form of good jobs and improved living standards. The most serious deficiency is in K-12 education. Working with local communities and industry, the science and engineering community can contribute to improving schools so that more Americans are prepared for careers in tomorrow's science- and technology-based industries. The United States also must ensure that fundamental research is funded adequately, particularly in fields important for future economic growth in which funding has been flat or industry and federal investment time horizons have shortened, such as information technology.

The steering committee has developed three long-term goals for the nation, and related policy recommendations.

Goal 1: *Over the next decade, achieve a sustained level of productivity growth that will allow rising living standards and noninflationary economic growth.*

Recommendations:

1. Increase investments in science and technology.
2. Develop new mechanisms for international research collaboration to advance fundamental knowledge, drawing on the experience of recent years.
3. Develop better metrics and understanding of science and technology trends and their connections with economic growth.

Goal 2: *Increase the number and proportion of Americans prepared for science and engineering careers, with a focus on underrepresented groups.*

Recommendations:

1. Scientists and engineers should work with local communities to improve K-12 education.
2. Create institutions and a supportive culture that facilitates lifelong learning.
3. U.S. industry and wealthy individuals, particularly those who have gained great economic benefits from the high-technology boom, should focus effort and resources on improving education for a science- and technology-savvy workforce.

Goal 3: *Improve the domestic and global market environment for U.S.-generated innovations.*

Recommendations:

1. Adopt national standards for securities litigation and product liability.
2. Examine trade, antitrust, and intellectual property policies with a view to improving global market access for U.S.-generated innovations.

1

Introduction

The National Research Council (NRC) organized the National Forum on Harnessing Science and Technology for America's Economic Future in order to catalyze a broad national discussion of how science and technology can contribute to U.S. economic growth and living standards over the next 10 to 20 years. The forum was the second of two initiatives inspired by the report *Enabling the Future*, which recommended the establishment of a regular forum activity that would help to link science and technology with long-term societal goals.[1] The NRC organized the forum with support from the Carnegie Corporation of New York.

A steering committee co-chaired by William Spencer, chairman of SEMATECH, and Dick Thornburgh, former governor of Pennsylvania and U.S. attorney general, planned and convened the forum, which was held February 2-3, 1998 (see Appendix A for forum agenda). The forum was designed to elicit participation from a wide range of experts and from the interested public. The 260 forum attendees, representing government, industry, and university perspectives from 34 U.S. states and a number of foreign countries, participated in plenary sessions and focused breakout discussions. This report uses material presented at the forum and later inputs from steering committee members. The conclusions and recommendations represent a consensus of the steering committee. The report contains chapters reflecting the major components of the forum

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[1] See Carnegie Commission (1992). The first NRC forum activity focused on environmental goals. See NRC (1996a).

> *"This examination of the relationships between R&D investments and economic performance is long overdue. It is being forced upon us by the social disruption following the end of the Cold War, changes in high-technology industries, and dizzying advances in science."*
>
> —Representative George Brown

discussions. One exception is Chapter 5, "The University Role in Research," which is based on material provided by steering committee members after the forum.

The forum and follow-up discussions among the steering committee confirmed that this is an appropriate time for renewed national focus on the importance of science and technology for long-term economic growth, because of positive trends in the economic and political environment.

THE ECONOMY

In contrast with the situation of just a few years ago, when many U.S. industries were being seriously challenged, the United States is perceived to be experiencing a high-technology-based resurgence. In the overall economy, unemployment and inflation are at the lowest levels seen in a generation. U.S.-based companies are setting the pace in the fast-growing information technology and biotechnology fields. U.S. manufacturing has been revitalized. The United States is seen as a leader in commercializing research through the creation of new technology-based firms.

During a period when the U.S. economy in general and high technology in particular appear to be so strong, the need for increased national attention to the issues of science, technology, and economic development will not be obvious to all. But presentations and discussions at the forum raised several important reasons why current favorable economic trends should not be taken for granted.

Some forum participants questioned whether the United States as a nation is taking the appropriate actions needed to sustain science- and technology-based growth over the long term. Ensuring that the United States possesses the flexible, highly skilled human resource base required for science- and technology-based industries of the next century is one critical task. The importance of improving the quality of K-12 science and mathematics education is well recognized, but success also will depend on how we approach lifelong learning. It might be necessary to develop new institutions and policies that encourage Americans to upgrade their knowledge and skills over the course of their careers. And, despite current success in innovation and commercialization, some question whether the United States and other countries are making adequate investments in advancing the fundamental knowledge that will underpin future innovation.

Furthermore, some regions and groups in U.S. society have not benefited extensively from recent economic growth and new technology. The forum focused on the U.S. economy and how science and technology can contribute to improved living standards for Americans over the long term. Although recent advances in technology appear to have benefited Americans in their roles as consumers and shareholders, real wages for large segments of the U.S. population are only now beginning to rise substantially after a long period of stagnation. Ensuring that the opportunities and rewards of science- and technology-based growth are shared widely throughout U.S. society surely will remain a challenge.

Events of recent years have made it clear that complacency and hubris, for both countries and individual companies, can be dangerous in today's global economy. The current positive outlook for the United States can be reversed quickly. With competition among companies and industries increasing, winners and losers are not determined once and for all. For example, not many experts predicted the rapid emergence of Korea in microelectronics in the early 1990s, the prolonged economic slump in Japan, or the recent financial crisis in several Asian economies. The current superior performance of the U.S. economy should not be taken for granted.

THE POLITICAL CONTEXT

Science and technology policy debates of the mid 1990s have focused on two issues. The first is the appropriate federal government role in funding science and technology specifically aimed at enhancing economic performance; disagreement over this role has been reflected in heated partisan debate about the Department of Commerce Advanced Technology Program and other specific initiatives. The second is whether the United States possesses a post-Cold War rationale to justify high levels of investment in science and technology as a national priority.

Those issues are still important and received a great deal of attention in the forum. However, the political context surrounding the discussion has shifted considerably in a short time. A key contributor has been the unexpected, rapid progress toward eliminating the federal budget deficit. The favorable budget environment appears to have dulled the partisan edge of debate over some science and technology issues. At the same time, a more bipartisan spirit on the issues is emerging in Congress, where groups in the House and the Senate are seeking to capitalize on current trends and to ensure that the federal government increases long-term investments in science and technology.

THE TASK

A key task for the scientific and engineering community is to develop a vision of how science and technology can best meet the nation's future economic needs and to effectively articulate this vision to political leaders and the broader public. The science and engineering enterprise itself is a key component of the national economy. Strong public funding support can no longer be considered an entitlement, if it ever was. The current economic and political environment provides an excellent opportunity for the nation to take stock of what we have learned from the past decade and a half of responding to global competitive challenges in science- and technology-based industries, while looking to the future.

To be sure, other groups within and outside the NRC, National Academy Sciences, and National Academy of Engineering have recognized the importance of these issues and are making contributions.[2] The Council on Competitiveness and Massachusetts Institute of Technology (MIT), for example, convened an innovation summit not long after the forum event.[3] Groups in the Senate and House of Representatives also are studying options for the future of science and technology policy.[4]

The steering committee expects that the forum and this report will contribute to the debate by identifying key challenges that need to be met if growth is to be sustained into the first decades of the next century and by outlining suggested new approaches that take account of the roles and capabilities of various participants in the U.S. research and innovation enterprise, including government at the federal, state, and local levels, universities and research institutes, labor, and industry.

But perhaps of equal importance is communicating the message that the time for future study and debate is limited. The time for action is at hand. With the advent of the new millennium, no more appropriate starting point could be envisioned.

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[2] In particular, see COSEPUP (1999) and STEP (1999).

[3] MIT (1998).

[4] U.S. House of Representatives (1998).

2

Science, Technology, and Economic Growth

OVERVIEW OF ECONOMIC THINKING ON INNOVATION AND "NEW GROWTH THEORY"

The linkages between innovation and economic growth have been subjects of inquiry since economics emerged as an organized discipline.[5] In *The Wealth of Nations,* Adam Smith (1994) observed that invention, growth in capital per worker, and advances in industrial organization were all linked. Recent work in economics reflects a renewed appreciation of Smith's late 18th century insight. Another early economist, Thomas Malthus, predicted that population and progress ultimately would be limited by the scarcity of land. Although strides in agricultural productivity proved Malthus wrong, he did originate an important insight—that the economy and society can be influenced profoundly by different rates of innovation across sectors. Innovation was also a central concern of Karl Marx's, who predicted that competition and technological advance would lead to both rising unemployment and rising productivity.

Interest in innovation among economists, which had waned somewhat during most of the first half of the twentieth century, began to revive in the 1940s. Joseph Schumpeter's writing, particularly the 1943 book *Capitalism, Socialism, and Democracy*, marked the beginning of a stream of work exploring the links between innovation and industrial structure. Efforts by Solomon Fabricant, Moses Abramovitz, and John Kendrick to quantify the contributions of various factors to

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[5] This section draws on the paper by Richard R. Nelson, "Technical Advance and Economic Growth," in Part II of this report.

economic growth launched another important line of inquiry in the late 1940s. That work underlies a number of econometric studies of research and development (R&D) investments that have found that private returns on these investments exceed 20 percent and that social returns exceed 50 percent.[6]

Over the last three decades, empirical scholarship on innovation and growth has produced several important insights. First, technological innovation involves uncertainty in a fundamental way; winners and losers cannot be predicted, and efforts to plan or predict the outcomes of innovative activity are largely doomed to failure. Second, elements of the optimal environment for innovation—including industry structure, firm size, intellectual property regime, and government role—vary across sectors and over time within sectors. Third, rapid innovation is always linked tightly with underlying scientific or engineering research, although the nature of this linkage tends to vary.

Although empirical research has deepened our understanding of the innovation process, economists working in the field of neoclassical growth theory have begun only recently to incorporate those insights into their macroeconomic models. Their efforts to make technological advance an endogenous factor in the growth equation have been labeled "new growth theory." New growth theory and the economists associated with it are responsible for more closely relating the mainstream of economics with the actual experiences and concerns of entrepreneurs and others involved with high-technology industry.

One key idea associated with new growth theory is the concept of knowledge as a factor of production. Traditional production factors—capital, labor, and land—bring diminishing returns to scale, producing less output per unit as one factor is substituted for others. Some hold that knowledge on the other hand brings increasing returns to scale.[7] Research and discussion associated with new growth theory have renewed interest in the science and technology aspects of other fields of economics, such as labor-market economics. This new appreciation for the role of human capital in economic progress could have important policy implications for science and engineering education.[8]

In short, economists long have agreed that science and technology are essential to economic growth in developed economies, but new growth theory is contributing to wider appreciation and deeper understanding of this connection.

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[6] For a tabulation of various studies, see Council of Economic Advisors (1995).

[7] Romer (1990). Experts in management also have pointed to the importance of knowledge at the firm level. For example, see Nonaka (1991).

[8] Some argue that the newer macroeconomic work needs to go further to incorporate insights generated by empirical work. See Nelson (1998).

CONCEPTS OF INNOVATION FOR POLICY MAKING: THE LINEAR MODEL AND PASTEUR'S QUADRANT

At the same time that economists have gained greater understanding of links between innovation and economic growth, the conceptual models used to guide policy making in the science and technology arena have remained rather static. Before World War II, the federal government played only a small role in science and technology. During the war, the United States enjoyed great success in harnessing its science and technology enterprise to develop new weapons and meet other military needs. At the end of the war, Vannevar Bush, who oversaw the wartime R&D effort, put forward his vision of a science and technology policy that would serve peacetime needs. In *Science, the Endless Frontier*, Bush (1990) proposed changes in government organization aimed at providing sustained federal support for science and technology. Although several of his specific policy recommendations were never enacted, the model implicit in the plan, picturing innovation as a linear process moving from basic research to applied research to development to production and operations achieved pervasive and lasting influence (see Figure 2-1).

With the end of the Cold War, the high-technology success of Japan and other economies that were not performing basic research on a large scale, and other factors, the linear model has come to be seen as less descriptive of real-world relationships, and therefore less useful. Donald E. Stokes has developed a matrix that categorizes R&D activities according to motivation (see Figure 2-2). Stokes was motivated by his observation that many worthwhile advances in fundamental knowledge are generated with some end in mind, contrary to the linear model.

In the Stokes matrix, research that is conducted to advance fundamental knowledge with no thought of practical use, even if insights eventually are utilized, fits in Bohr's Quadrant (BQ), named for the Danish physicist who modeled the basic structure of the atom. Today's research in high-energy physics, astronomy, and mathematics is representative of BQ research. It is conducted mainly in universities and research institutes and funded by the governments of developed countries. BQ appears to be a fertile area for expanded international cooperation. Although progress in this direction has been made in fields such as astronomy, the failure of the United States to develop international support for the Superconducting Supercollider some years ago shows that such efforts are not straightforward or easy.

Work conducted to achieve some practical benefit without consideration of advancing the frontiers of knowledge fits in Edison's Quadrant (EQ), named for the prolific American inventor. The work of most high-technology start-ups and indeed most industrial research today falls into this category. Intellectual property protection appears to be very important for EQ research.

Research conducted to advance knowledge while achieving a practical result is placed in Pasteur's Quadrant (PQ), named for the French pioneer in microbiol-

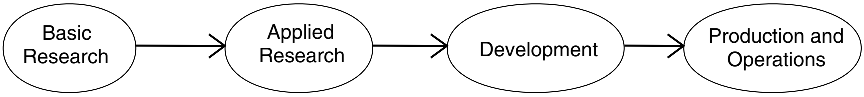

FIGURE 2-1 The Linear Model of Innovation

Research is Inspired by:

Considerations of Use?

		No	Yes
Quest for Fundamental Understanding?	Yes	Pure Basic (Bohr)	Use-inspired Basic (Pasteur)
	No		Pure Applied (Edison)

FIGURE 2-2 Stokes Matrix Model
Source: Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation,* Washington, D.C.: Brookings Institution Press, 1997.

ogy and public health. It is the absence of this category from Bush's linear model that Stokes was seeking to rectify in developing his matrix. Government funds much of the work in PQ, but the invention of the transistor at Bell Laboratories by Shockley, Bardeen, and Brattian is a good historical example of industrial work. Although the largest industrial laboratories—such as IBM, Du Pont, and Xerox—have done important work in PQ and even BQ, they are shifting their emphasis to EQ.[9] These trends and their implications are explored further in Chapter 3.

Figures 2-3, 2-4, 2-5, and 2-6 show broad trends in funding for research. Figure 2-3 shows the U.S. share of world gross domestic product (GDP) for 1950 and 1994, and the U.S. share of world R&D spending for 1960 and 1994. The U.S. share of each has declined over the years, and now, most of the world's R&D is performed outside the United States. Whether investments in fundamen-

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[9] Rosenbloom and Spencer (1996a).

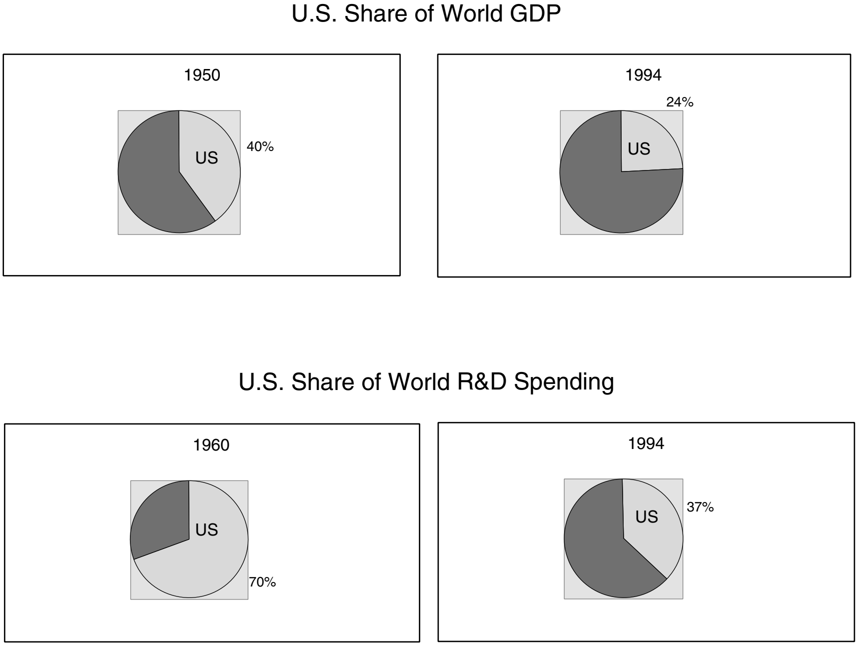

FIGURE 2-3 Changes in U.S. share of world GDP and R&D spending
Source: U.S. Department of Commerce, Office of Technology Policy, International Plans, Policies & Investments in Science and Technology, 1997.

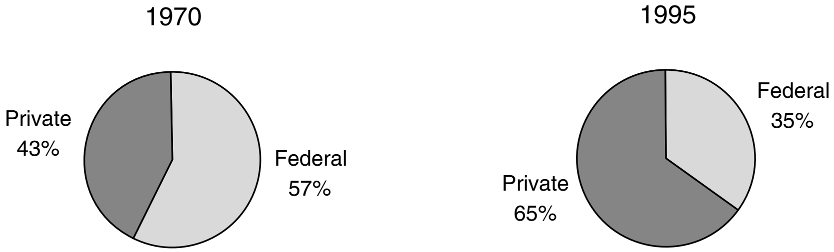

FIGURE 2-4 Federal and private funding of U.S. R&D
Source: National Science Board, *Science & Engineering Indicators, 1998*, Arlington, Va.: National Science Foundation, 1998.

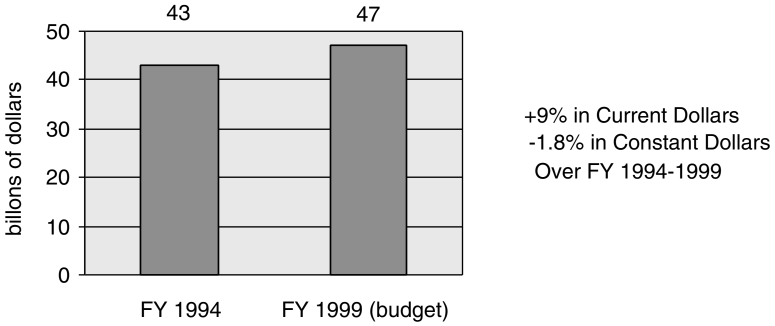

FIGURE 2-5 Trends in the Federal Science and Technology budget (FS&T)*
*Note: This figure is based on a measurement for the federal investment in science and technology proposed by the National Academy of Sciences. This measure, an alternative to the standard reporting of federal R&D spending, includes all federal R&D except for advanced development, testing and evaluation work in DOD and DOE.
Source: Observations on the President's Fiscal Year 1999 Federal Science and Technology Budget, National Research Council.

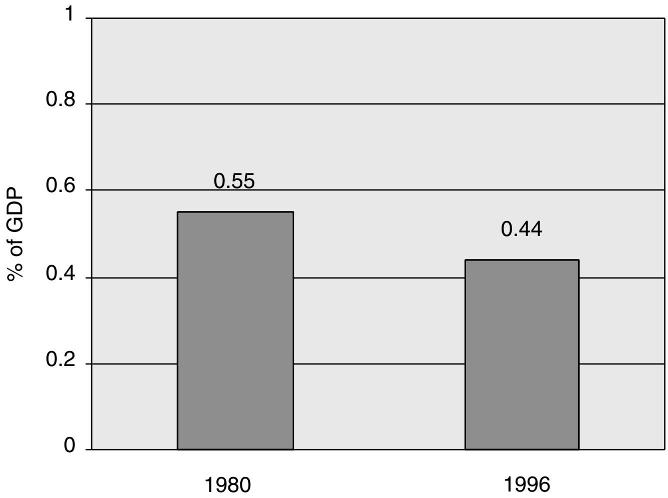

FIGURE 2-6 Federal nondefense R&D as a percentage of GDP
Source: National Science Board, *Science & Engineering Indicators, 1996,* Arlington, Va., National Science Foundation, 1996.

tal research (PQ and BQ) are adequate to sustain a global science and technology base for innovation depends not only on the United States but on other countries.

Figure 2-4 shows the trends in government and private support of U.S. R&D. Private support is now predominant. Figure 2-5 shows trends in the federal science and technology (FS&T) budget from 1994 to the proposed 1999 budget. Although spending has increased in current dollars, there has been a slight decline when inflation is taken into account. Finally, Figure 2-6 shows the longer-term trend of decline in federal nondefense R&D funding as a percentage of GDP. Industry and federal funding trends are discussed in more detail in chapters 3 and 4. A key question raised by the broad trends is whether enough long-term investment is being made in PQ work, particularly as industry's focus becomes increasingly short term, and FS&T investments remain relatively flat.

ISSUES AND CONCERNS

There is wide recognition that science and technology are fundamental wellsprings of economic growth, and the U.S. economy is turning in an excellent performance at the macro level—solid growth and low inflation. However, economists and other experts hold widely different views about key elements of the current economic environment and future trends. Technology is increasingly central to mainstream economic debates about several key issues.

One issue that has received a great deal of attention is the productivity paradox.[10] Labor productivity is a measure of output per unit of labor and reflects improvements in capital, technology, and skills. Productivity growth ultimately translates into improvements in real incomes and living standards. Growth in U.S. labor productivity, which averaged almost 3 percent per year during the 1950s and 1960s, slowed to less than half that on the average over the 1974-1997 period. In particular, productivity growth in service industries has been notoriously slow despite large investments by service industry companies in information technology. The Conference Board (1997) reports that labor productivity has increased substantially in manufacturing sectors that use computers intensively but has grown less rapidly in service industries and manufacturing industries that do not use computers.

Some economists argue that mismeasurement of price changes and output makes productivity performance look worse than what it is, especially in the service sector. Others (Roach, 1998) believe that the increase in working hours of salaried employees over the last several decades, which is not accounted for in the statistics, could offset some or all of the sources of possible downward bias in productivity statistics.

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[10] For a comprehensive discussion of this issue, see Lester (1998).

A second economic issue of long-term concern is the growth in wage inequality in the U.S. economy over the last several decades. According to some economists, the introduction of technology has played a major role in widening income gaps as technological advance leads to higher returns to education and experience. Under this formulation, the demand for educated workers has gone up and driven up wages in this group because of increased utilization of technology; at the same time, less-skilled workers have seen their wages stagnate. Other economists argue that although technology plays a major role in the skill upgrading of the workforce over the long term, skill-based technological change has not been the primary cause of increased wage inequality during the 1980s and 1990s.[11]

Despite the current economic environment of relatively low inflation and unemployment, the U.S. economy faces continuing challenges in delivering sustained growth in living standards for the majority of Americans. Reflecting different perspectives apparent in today's economic debates, experts put forward widely varied visions of the future. Some believe that we are entering a long period of science- and technology-led growth—a rise in living standards in the United States and around the world unprecedented in human history (Schwartz and Leyden, 1997). Others see the U.S. economy providing enormous opportunities to skilled entrepreneurs but middle-class American families increasingly being squeezed by inexorable forces of "the new economy" because stable, high-wage employment accompanied by benefits is harder to come by.[12] The contribution of science and technology to economic growth must be sustained and enhanced if the actual future is to approximate the first vision more closely than the second.

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[11] Mishel et al. (1997). Other possible causes for the growth in wage inequality include trade, industry shifts, immigration, deunionization, and low real growth in the minimum wage.

[12] These issues are treated in the documentary series *Surviving the Bottom Line,* produced by Hedrick Smith Productions, which aired on PBS in January 1998.

3

The Private-Sector Environment for Innovation

RESEARCH AND DEVELOPMENT INVESTMENT TRENDS: WHERE WILL TECHNOLOGY COME FROM?

The National Forum was organized in the context of an ascendant U.S. economy. The buoyant outlook of early 1998 stood in sharp contrast with the mood of a decade earlier, when key U.S. manufacturing industries, such as automobiles and semiconductors, seemed to be failing in the face of daunting international competitive challenges.[13] Although many factors fostered the turnaround, including effective national monetary policies, strong support for entrepreneurship in U.S. institutions and culture, and more focused management of U.S. industrial firms, robust technological innovation clearly has been a central contributing factor. One of the tasks of the forum was to look to the future and ask whether the U.S. technological resurgence is sustainable over the next 10 to 20 years and from whence tomorrow's technology will come.

Innovation in two broad, science-based industrial sectors has contributed to U.S. innovative success in the 1990s. The first is information technology, including semiconductors, computers, software, communications equipment, and information technology services. The second is the complex of industries that feed new technology into health care, including biotechnology, pharmaceuticals, and medical devices. Among the 50 U.S. firms with the largest research and development (R&D) budgets in 1994, the 20 with the highest ratio of R&D spending to

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[13] This section draws heavily from the background paper by Richard Rosenbloom, "Sustaining U.S. Innovation: Where Will Technology Come From?" in Part II of this report.

> *"In these two industrial sectors (information technology and health care), especially, the United States has developed distinctive, and superior, capabilities, which have been translated into growth and competitive advantage on a global scale."*
>
> —Richard Rosenbloom

sales were all in either the information or health care sectors. The increasing focus of private-sector R&D investments in these fields is a powerful illustration of their promise.

As pointed out in chapter 2, the process of harnessing science and technology for economic growth is complex and not adequately understood. Many economically important innovations are either imitative or represent incremental improvements of current practice. For example, through a series of individually minor incremental changes during the first 60 years after the introduction of insulin, impurities were reduced from 50,000 parts per million in 1930 to 1 part per million in 1980. Other innovations constitute important discontinuities in which radical changes usher in new categories of products or services, such as the introduction of magnetic resonance imaging. Although the discontinuities often flow from new science and technology, they also can result from the creative combination of already-available technologies, such as innovations in express delivery.

A key comparative strength of the United States has been the ability to initiate and rapidly exploit innovative discontinuities that stimulate economic growth, by transforming existing industries or giving birth to new ones. Several important changes appear to have occurred in U.S. innovation during the 1990s that will affect economic and industrial performance in the future. First, a recent analysis of U.S. patents issued to inventors from all over the world shows a dramatic increase in the reliance of inventions on recent science (Narin et al., 1997). The trend is especially pronounced for U.S. inventions in the medical and chemical fields. A large percentage of the scientific citations in recent patents resulted from work in universities and government laboratories.

A second trend concerns corporate research.[14] In contrast with government, which funds research to advance national interests or the missions of particular agencies, companies fund research to gain proprietary advantage. Corporate research laboratories first emerged about a century ago and flourished during the post-World War II period. The corporate laboratories of companies such as Du

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[14] Points in this paragraph are developed by Rosenbloom and Spencer (1996b).

TABLE 3-1 Basic and Applied Research Conducted by Industry (billions of Constant 1992 Dollars)

Year	Total	Industry
1991	67.1	35.3
1994	62.4	28.1
1997*	68.6	33.9

*Note: 1997 figures are preliminary.
Source: National Science Board, *Science & Engineering Indicators—1998* (Arlington, Va.: National Science Foundation, 1998).

Pont, AT&T, IBM, and Xerox grew to become important sources of fundamental technologies. Deregulation and the rise of global competition have led companies to put more focus on short-term results. One result is that investments in research, particularly longer-term or speculative research, have come under increased pressure and scrutiny. In aggregate, as Table 3-1 shows, the level of basic and applied research in industry declined by 20 percent in real terms between 1991 and 1994 and, despite recent increases, had not regained the 1991 level by 1997 (NSF, 1998). The changes have been extensive among the companies that had been most prominent in their fundamental research capabilities, such as IBM and AT&T. Although some newer companies, such as Microsoft, are boosting their investments in longer-term research, many newer information technology companies appear to focus their research exclusively on Edison's Quadrant (EQ) and near-term product development.[15] Other firms that require access to fundamental research—such as Intel, Motorola, and Texas Instruments—are pooling funds to support work in universities, but they perform relatively little in-house research.

The United States appears well positioned to profit by continuing to push incremental technological progress, but where will tomorrow's radical discontinuities come from? Important innovations increasingly are characterized by an extensive research base and an R&D environment in which institutional flexibility is tolerated and even encouraged. Information technology and biotechnology (including pharmaceuticals), the two most promising fields for the future, display those characteristics, but institutional relationships and funding trends differ between the two fields. In biotechnology, extensive collaboration between universities, start-up firms, and larger companies provides fertile ground for radical innovation; the current situation and trends in this field are encouraging. In information technology, however, there are grounds for concern. As noted earlier, firms are increasing their R&D spending but appear to focus more on short-term

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[15] For an explanation of EQ, see the discussion of innovation models in Chapter 2.

results. It is unclear whether the products of emergent new institutional relationships in combination with diminished effort within research labs of large companies will suffice to sustain the flow of radical innovations in information technology.

THE GLOBAL PICTURE

An assessment of U.S. prospects for building the science and technology foundation for future economic growth must recognize global developments and their implications.[16] As noted in Chapter 2, the U.S. R&D enterprise, although still by far the largest in the world, accounts for a much smaller share of the world total than it did in the 1960s. Despite the growth of scientific and technological capabilities outside the United States and the growth of international R&D interdependence through investments by multinational corporations and other mechanisms, national policies and innovation environments are still important. National governments still provide a substantial share of R&D funding in most countries, particularly in support of key institutions, such as research universities. Governments increasingly are pressed to deliver tangible economic benefits of R&D investments to citizens. International linkages have resulted in closer and more complex relationships between trade policy, regulation, technology policy, and competition policy.

The terms of domestic U.S. debate about the desirability of international R&D have undergone a number of shifts over the years. During the 1960s, increased investments in offshore R&D by U.S. companies raised concerns over loss of employment and other technological opportunities associated with the domestic performance of R&D. In the 1980s, as foreign investment in the United States grew rapidly, critics argued that foreign firms were creating mainly low-wage, low-skill employment and were not locating high-value-added activities, such as R&D. In the early 1990s, as the U.S. R&D investments of foreign companies grew, concerns were raised that these investments were a means of “cherry-picking” the fruits of government-funded R&D.

Although trends in the internationalization of R&D activities are not easy to track because of inadequate data, it is possible to formulate several generalizations based on existing information and analysis. First, some components of the innovation process, including product development and manufacturing, are much more international than are activities aimed at technology creation. Although multinational corporations still largely generate their inventions and basic technologies in their home countries, they are more likely to develop and manufacture technology-intensive products by using the capabilities of foreign subsidiaries and strategic alliance partners.

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[16] This section draws heavily on the background paper by David Mowery, “The Global Environment of U.S. Science and Technology Policies,” in Part II of this report.

A second generalization that can be supported by available evidence is that international flows of R&D investment are attracted to national or regional economies that can nurture specific technology-based capabilities. Even as the nationality of firms is blurred, the innovation environment in specific nations or regions, including supporting policies, becomes more important.

How do U.S. science and technology policies compare with those of other countries? A detailed look at U.S. policies is provided in Chapter 4, but a summary comparison of basic elements of science and technology policies between the United States and other developed countries shows some important similarities and convergences. In the United Kingdom, France, Japan, and Germany, the share of R&D financed by government has declined, as it has in the United States. The share of R&D performed by government laboratories also has declined in developed countries except Germany, and the German trend reflects the influence of reunification.

At the same time, U.S. science and technology policies remain distinctive in several important respects. For example, the share of R&D aimed at defense needs remains considerably higher in the United States than in other countries of the Organization for Economic Cooperation and Development, although the U.S. defense-related share has been declining as well. Note also that a significant amount of R&D spending by the U.S. Department of Defense supports broadly applicable work in fields such as computer science, materials science, and engineering. Within civilian-oriented government R&D, the United States directs larger shares of its funding toward health and space-related research and a smaller share toward research aimed at general economic development than other developed countries.

U.S. policies for the future must recognize that scientific and technological excellence will be distributed broadly throughout the world and that cross-border flows of R&D investment and technology will increase. For the United States to remain an attractive platform for R&D and related investments by U.S. and foreign-based firms, continued strong public investment in the R&D infrastructure will be required. However, U.S. policies also must be based on a realistic conceptualization of the sources of economic benefit associated with innovation.

> *“The U.S. policy posture toward these changing circumstances needs to proceed from the premise that the rapid and efficient adoption by U.S. firms of new technologies from foreign or domestic sources, rather than their creation, is the primary source of economic benefit.”*
>
> —David Mowery

Rather than restricting foreign access to the results of publicly funded R&D, it might be more productive to focus on improving the domestic adoption and implementation of new technologies from both domestic and international sources.

Forum participants wondered whether the tendency of national governments to invest in research with identifiable payoffs will lead to underinvestment in research in Bohr's Quadrant (BQ), or work aimed at advancing fundamental knowledge.[17] Some have argued that expanded international cooperation could help to leverage scarce resources (Government-University-Industry Research Roundtable, 1998a). Although international collaboration at the scientist-to-scientist level often works well, large projects that require extensive coordination between national governments have had mixed results. Still, the international space station and other projects illustrate that cost and other pressures will continue to provide governments with strong incentives to seek international cooperation for large-scale research. After the forum, steering committee members suggested that much work needs to be done by the United States and other countries to build an appropriate institutional framework for expanded cooperation in international science and engineering research. Although this is an important task for the federal government in coming years, the committee is cautious about how much can be expected in the near term.

THE BUSINESS ENVIRONMENT FOR INNOVATION

Excellence in R&D is a necessary but insufficient condition for creating wealth through the development of science- and technology-based industries. Nations and organizations must also possess mechanisms and infrastructure needed to transform science and technology into products and services that are competitive in global markets. At the forum, participants focused on an aspect of the innovative infrastructure in which the United States appears to be enjoying considerable success—fostering an environment that encourages the formation and growth of science- and technology-based companies.[18]

It was noted that the launch of high-technology ventures has been concentrated in specific regions, with Silicon Valley in Northern California being the most notable. Silicon Valley's strong infrastructure for creating and sustaining high-technology businesses has developed over many years. In addition to the role of Stanford University as a source of talent and know-how, several serendipitous events have contributed to the growth of Silicon Valley. Perhaps transistor coinventor William Shockley's decision to move to Palo Alto was a key

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[17] See the discussion of innovation models in chapter 2 for a description of BQ.

[18] This section draws heavily on the remarks by Charles Geshke and John Shock on "The U.S. Environment for Venture Capital and Technology-Based Start-ups," at the forum.

determining event. Several managers of Shockley Semiconductor, including Gordon Moore and Robert Noyce, left to start Fairchild. Fairchild spawned a group of start-ups, including Intel. Xerox's Palo Alto Research Center was an important source of talent and ideas for software-related start-ups in the 1970s and 1980s.

Several elements of infrastructure are essential to Silicon Valley's continued success. First is access to scientific and technological talent. Second is access to businesses and professionals (e.g., lawyers, accountants, executive search firms) that cater to the needs of start-up companies, in areas such as equipment leasing, legal help, and so forth. Third is a business culture that encourages people to strike out on their own. Failure is not welcome but is tolerated. In fact, venture capitalists seem more willing to invest in someone who already has failed than in a first-time entrepreneur.

The final element, which deserves some detailed comment, is the availability of financing for science- and technology-based ventures. Start-up financing is available from several sources in several forms. Organized venture capital is only one of these capital sources. Of the total amount of venture capital disbursements, about $10 billion in 1997 (National Venture Capital Association, 1999), roughly 60 percent goes to high-technology companies. The rest goes to other private equity investments, such as shopping centers and other real estate projects. Of the venture capital that goes into high technology, perhaps half or less goes to support technology development. This amount, about $3 billion in 1997, is not even as large as the $5 billion R&D budget of IBM.

Another source of financing for start-ups is corporate investment. For example, Adobe Systems started a venture capital fund several years ago aimed at allowing it to make superior returns on its cash reserves while providing a window on new technologies; the fund has been relatively successful so far. There are also "angels," wealthy individuals interested in investing in start-ups, who often have achieved success as entrepreneurs themselves. Angels constitute an important and growing source of financing for start-ups.

Note that the venture capital industry historically has been highly cyclical. The high returns of recent years have attracted more investment capital, so more money has been aimed at roughly the same number of potential ideas and entrepreneurs. If history is any guide, this ultimately will lead to lower returns and less money flowing into venture capital. Also, venture capital might be more or less available in different regions or for companies in different stages of development (e.g., seed capital versus capital for expansion).

Nevertheless, today's environment of relatively abundant capital has provided opportunities for other regions around the country to build infrastructure for supporting science- and technology-based start-ups patterned on Silicon Valley's success. The Boston area long has been a fertile region for start-ups, and other well-known areas of high-technology activity, such as Austin, Texas, and the Research Triangle region of North Carolina, have been building the necessary infrastructure for many years. Other emerging high-technology regions include Seattle, Washington; Salt Lake City, Utah; Northern Virginia; and Southern California.

The health of start-up activities is only one of several factors that will determine the U.S. high-technology future; maintaining and enhancing the positive environment that exists today will be important as well. A number of forum participants mentioned the importance of avoiding actions that could damage today's strong infrastructure and incentives to launch science- and technology-based ventures.

Four specific critical issues were discussed extensively at the forum. The first is the availability of scientific and engineering talent to fuel the growth of start-ups. Several recent reports by government agencies and industry associations state that there is a severe shortage of high-technology workers, particularly in information-technology. One way to address the problem in the short term is to increase the number of visas available for foreign scientists and engineers to work in the United States. Over the longer term, it might be necessary to expand the pool of Americans capable of filling these jobs if the United States is to remain an attractive location for high-technology activities. This issue is explored further in Chapter 6.

The second issue is the effect of securities litigation. The stock price of high-technology companies tends to fluctuate a great deal, and the risk for investors can be high, particularly for undiversified investors over short periods. If business results fail to meet expectations and its stock price falls sharply, a company can be vulnerable to securities-fraud lawsuits by shareholders. Recent federal legislation is seen as upholding the rights of shareholders to bring class-action lawsuits for genuine fraud while limiting the scope of less meritorious suits. However, suits increasingly are being filed in state courts, and this has led many in the high-technology community to call for legislation that would establish national uniform standards for securities class actions.

The third issue is intellectual property protection. For small science- and technology-based start-up companies, intellectual property can be one of the primary corporate assets. Particularly in the software and healthcare fields, U.S. firms often lose out on revenue because of various forms of infringement on intellectual property rights (IPR). Because markets outside the United States will represent the lion's share of new growth opportunities in coming years, intellectual property-intensive businesses have an interest in steps that increase the effectiveness of IPR protection around the world.

Finally, concern has been expressed about abuses in the civil justice system that have raised the costs of doing business and created impediments to product innovation through the application of science and technology expertise. Frivolous lawsuits and excessive punitive damage awards have made many technology-oriented businesses less willing to undertake cutting-edge R&D for fear of being sued unjustly by product users. The problem is compounded by the prevalence of so-called “junk science” testimony offered by experts engaged by litigants in these often complicated proceedings. Several participants in the forum remarked that product liability reform legislation such as that passed by the Congress but vetoed by the president in 1996 would relieve some of the concerns of those engaged in these enterprises and further free up the productive forces that have made the United States a leader in efforts to capitalize in the marketplace on our science and technology resources.

4

Government Roles and Priorities

THE FEDERAL ROLE

Discussions of U.S. science and technology policy have tended to focus on the federal government. The forum was intended to develop national goals and action items, so it gave equal weight to other participants in the U.S. research and innovation enterprise, including industry, universities, and state and local governments. Nevertheless, the forum participants recognized that the federal government will continue to be pivotal and that decisions made in the 1990s will probably influence federal policies for years to come. The forum was able to draw on the recent work of several other expert groups who have examined federal science and technology policies in recent years (Branscomb et. al., 1997; Council on Competitiveness, 1996; NAS/NAE/IOM/NRC, 1995).

As noted in chapter 1, a strong federal role in support of science and technology is a relatively recent phenomenon in the United States, dating from the post-World War II period. Defense was the predominant target for science and technology. Substantial amounts also have been spent on research and development (R&D) related to space (especially during the Apollo program), health, and energy. Investments in science and technology not aimed at specific agency missions traditionally have been relatively small. During the 1980s that began to change, as such programs as the multiagency Small Business Innovation Research program, the Advanced Technology Program of the Department of Commerce, the SEMATECH consortium of U.S.-based semiconductor companies and the Department of Defense, and the Engineering Research Centers program of the National Science Foundation were launched. Taken as a whole, however, these civilian technology programs did not come close to the size of the federal investment in defense, health, energy, or space-related R&D.

Just as science and technology policy discussions tend to focus on the federal government, discussions of the federal role tend to focus on support of R&D in the budget. Yet the federal government made several other important policy changes during the 1980s that were as important as the launch of new programs involving direct support of R&D. One set of changes was aimed at easing the flow of science and technology from government laboratories and academe to industry. The federal government also instituted a temporary tax credit for industrial R&D, which has been renewed periodically. Finally, a number of changes have occurred in regulatory, trade, and competition policies. The latter changes, taking the forms of legislation and court decisions, have had a major, sometimes unintended influence on U.S. innovation. The court-ordered breakup of AT&T in the early 1980s was one such change.

Federal science and technology policy has been politicized highly during much of the 1990s. At the start of the first Clinton administration, several technology programs aimed at enhancing economic performance and leveraging private-sector R&D investments to meet government goals were expanded rapidly. Those programs became a visible target for congressional Republicans seeking to reduce the federal role in the economy after their victory in the 1994 midterm elections. The large continuing federal deficit and the need for austerity heightened the stakes.

The situation has changed dramatically in the last year or so. Efforts to eliminate civilian technology programs in recent years have been unsuccessful, although growth has been flat. Although attacks on “corporate welfare” resonate among many in the electorate, legislators in both parties appear increasingly open to forging a new bipartisan consensus on a larger federal role in science and technology. Finally, the dramatic improvement in the federal government’s fiscal position in recent years appears to have lowered the political heat related to debates over specific programs.

What will the emerging consensus on federal science and technology policy look like? Several common themes emerge from the forum discussions and recent reports from various groups. There is broad recognition that industry will play the dominant role in funding U.S. R&D, particularly civilian R&D not linked to particular agency missions. Therefore, the federal government must act more as a partner and facilitator than as a contractor or enforcer. In addition to forging effective science and technology partnerships across agencies, this will involve working closely with industry, academe, and state and local government. In playing the role of partner, the federal government has numerous tools besides direct R&D support, such as extension programs and dissemination of information about global science and technology developments. A continuing challenge will be to restructure the federal laboratories so that they are able to contribute effectively to U.S. innovation in a changing environment.

The federal role in science and technology, although subsidiary to industry's, is no less crucial. The federal government will continue to carry the primary responsibility for funding fundamental research in science and technology, including sustaining the infrastructure of institutions and facilities that perform excellent research and play a critical role in educating and training the next generation of scientists and engineers.[19] Support of fundamental research and broadly relevant, use-oriented research in a number of engineering and technology fields is of current concern because of cutbacks by the Department of Defense and industry central laboratories in some fields. For example, most of the federal support of university research is now health related, and it will be important to ensure that other fields receive sufficient funding to take advantage of opportunities and produce the human capital needed to sustain U.S. leadership. The federal government also will need to refine mechanisms for funding use-oriented research in partnership with private entities. In principle, government should not fund research that industry would fund on its own or research that would deliver disproportionate benefits to specific companies unless an important non-economic mission is being advanced. A federal government commitment to double science and technology spending within a limited period, which is being debated, could be an important first step toward revitalizing the federal role in promoting science and technology for economic growth.

STATE, LOCAL, AND REGIONAL INITIATIVES

One of the truly important developments in the use of science and technology resources in aid of economic development during the 1980s and 1990s was the proliferation of state-sponsored partnerships among government, universities, and the private sector. The states were testing and demonstrating new approaches to link R&D with industry.

The ability to capitalize on university resources has evidenced itself over the last few decades in Massachusetts's Route 128 complex, California's Silicon Valley, and North Carolina's Research Triangle Park (RTP). More recently, however, with the advent of severe economic downturns in the former "Rust Belt" states during the 1970s and 1980s, more and more attention was focused on state governments' need to use partnerships between sectors to create new bases for growth. Typical of these programs were Pennsylvania's Ben Franklin Partnership and Ohio's Thomas Edison Program, each designed to use state funds as a catalyst to mobilize university and entrepreneurial resources to create new sources of economic growth and revitalize existing industries. Those pioneering efforts pro-

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[19] This is not meant to minimize the contributions of other sectors. For example, state and local governments provide most of the funding for construction and repair of science and engineering research space at public institutions. See National Science Board (1998, p. 5-16).

vided a model for other states, localities, and regions to follow. Today, most states are undertaking some partnership activities in science and technology as are many localities and regions, including metropolitan areas (Coburn, 1995).

The states can be divided into several groups. One group includes states in which active government science and technology programs have aided economic development, such as North Carolina, New York, Pennsylvania, and Ohio. A second group boasts strong high-technology growth aided by state spending on infrastructure (e.g., on research universities), where focused programs on innovation have not played as important a role, such as California, Texas, and Massachusetts. A third group includes the states involved in the Experimental Program to Stimulate Competitive Research program, with lower economic growth and less science and technology activity.

What lessons can be learned from the experiences of state, local, and regional initiatives? Many forum participants have personal involvement with these initiatives and provided important insights. The case of northeast Ohio was covered in detail.[20] Over the past decade and a half, the region has been developing new approaches to harness science and technology for economic growth. The main mechanism is a system of technology intermediary organizations.[21] A Technology Leadership Council links these organizations. Several industry-technology areas have been identified as particularly important, including automotive, aerospace, biotechnology, advanced materials, and information technology. The region also has developed several financing vehicles that provide capital for new companies and related infrastructure.

Although the precise effect of such efforts is difficult to quantify, several indicators and trends attest to the value of collaboration among government, university, and industry to enhance science- and technology-led growth in regional economies. For example, manufacturing employment in northeast Ohio has stabilized, and the Great Lakes Manufacturing Technology Center receives $5 million in annual project funding from area companies. Incubator tenants in the region have returned state investments in the form of payroll taxes. The northeast Ohio biomedical research base has tripled in recent years, and company formation is improving. Companies launched during the past 15 years are contributing to the regional economy.

One important trend that emerged in the discussions is the growing importance of federal funding for state, local, and regional science and technology efforts. For example, in 1985, northeast Ohio's technology intermediaries had a collective annual budget of less than $1 million, of which 58 percent came from

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[20] This section draws on the presentation by Dorothy Baunach on "The Northeast Ohio Experience" at the forum.

[21] These intermediary organizations include the Cleveland Advanced Manufacturing Program, the Edison BioTechnology Center, the Edison Polymer Innovation Corporation, the Great Lakes Industrial Technology Center, and the Ohio Aerospace Institute.

the state government and 41 percent from industry and foundations. In 1997, the collective annual budget of a larger group of organizations was $57 million; 60 percent came from the federal government, 22 percent from state government, and 18 percent from industry and foundations.

In 1995, the White House Office of Science and Technology Policy created a task force to recommend ways of improving the state-federal science and technology relationship, with particular regard to maximizing the economic benefits of greater cooperation. The task-force report called for presidential leadership to create a truly national, as distinct from federal, science and technology policy, taking into account the roles and contributions of states, localities, and the private sector (State-Federal Technology Partnership Task Force, 1995). It specifically recommended that a high-level mechanism be established to involve the states in policy development; that each state fashion its own science and technology strategy; that a national strategy be implemented to catalyze private-sector investments in technology; and that special emphasis be given to using technology to promote excellence in manufacturing.

Out of those recommendations came the creation in 1996 of the U.S. Innovation Partnership (USIP) by agreement between the White House and the National Governors' Association. USIP is intended to serve as the policy-making mechanism to foster coordinated development of national science and technology policies. At the same time, the State Science and Technology Institute, based in Columbus, Ohio, was formed to provide a focus for activities at the state level and a clearinghouse for the exchange of information on best practices and experiences among state officials and with their federal counterparts.

As the time-honored laboratories of democracy, state governments can play an increasingly important role in the effort to capitalize on our vast science and technology resources. The progress made during the past decade in furthering coordination between federal and state programs is promising and should be capitalized on to the greatest possible extent. One possibility is a program of matching grants to industry-university partnerships with local and state governments to harness science and technology for economic development. USIP could play a key role in undertaking such a program, which might be supported by federal, state, and local funding.

FOREIGN GOVERNMENT POLICIES AND PARTNERSHIP EFFORTS

The discussion of the global context in Chapter 3 provides some comparative information on science and technology policies in the United States and other developed countries. In assessing trends in U.S. government policy, note that other countries and regions are focused on harnessing science and technology for economic growth (Government-University-Industry Research Roundtable, 1998a).

One example of a successful foreign government-university-industry initiative discussed at the forum is the Hsinchu Science-Based Industrial Park in Taiwan (HSIP).[22] HSIP was founded in 1980 to attract investment in high-technology industries. Taiwan's government has since invested over $520 million in land acquisition and infrastructure. The park capitalizes on the proximity of Chiao Tung University, Tsing Hua University, and the Industrial Technology Research Institute. HSIP includes factories, laboratories, and residential areas.

As of 1996, there were 203 companies operating in HSIP, of which 36 were foreign owned and 167 were domestically owned. Many of the companies were founded by returning expatriates. Park tenants had combined revenues of over $11 billion in such industries as semiconductors, computers and peripherals, telecommunications, optoelectronics, precision machinery, and biotechnology. HSIP firms invested over $500 million in R&D in 1996. Of the 54,806 people employed in HSIP, 59 percent possessed at least a junior college or technical college degree.

By 2006, the number of companies and the number of employees in the park are expected to double, and the total value of goods is expected to increase to $58 billion and R&D expenditures to $2.5 billion. The government has acquired additional land for expansion. The HSIP model is seen as so successful that the government is taking steps to build a similar science-based industrial park in southern Taiwan.

HSIP is an outstanding example of the initiatives that foreign economies are pursuing to promote science- and technology-based growth. HSIP's focus on the generation of jobs and revenue, including the specification of goals to be reached over a 10-year time horizon, is striking. Perhaps the closest U.S. analogy to HSIP is RTP in North Carolina. It was founded in 1959 and almost 40,000 people work there. About three-fourths of the 133 organizations in RTP are doing research-related business.

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[22] Most information was obtained at the HSIP World Wide Web site, at www.sipa.gov.tw. See also Mathews (1997).

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The University Role in Research

OVERVIEW OF ACADEMIC RESEARCH AND TRENDS

The U.S. research university is the benchmark for the rest of the world. Facilities, faculty, research funding, and the ability to attract the best students are all key success factors. This leadership position has been established during the twentieth century. The immigration of talented scientists and engineers to the United States, stable and increasing funding from the state and federal governments, particularly after World War II, and an expanding job market for graduates have contributed to the preeminence of U.S. research universities. During the 1980s and the first half of the 1990s, the academic sector played an increasing role in U.S. R&D performance, with its share rising from 9.8 percent to 12.6 percent of the total.

However, U.S. academic research faces major challenges. Federal funding, as well as state funding of many public universities, has been flat or declining in real terms since the early 1990s. In a number of science and engineering fields, foreign students make up most of the enrollment at the Ph.D. level. Doctoral recipients in some fields have experienced difficulty in finding attractive positions, whereas universities are finding it difficult to fill tenure-track positions in other fields where there is strong industry demand for talent. University administrations, with their government and industry partners, must address these pressures to maintain the strong position of U.S. academic research.

Today, most basic research is performed in universities, and most university basic research is supported by federal agencies.[23] This federal support is concentrated in three agencies: the National Institutes of Health (53 percent), NSF (15 percent), and the Department of Defense (12 percent).

Federal research support is one important mechanism for financing science and engineering education, and its importance grows at the most advanced levels. In 1993, 27 percent of all full-time graduate students in science and engineering received primary support from research assistantships, roughly half of which were federally funded. At the doctoral level, about 38 percent of academic doctoral scientists and engineers reported receiving federal support in the spring of 1993. Life sciences (53 percent) and environmental sciences (52 percent) had the highest support rates; mathematics (21 percent) and the social sciences (15 percent) had the lowest.

After the federal government, the academic institutions performing research and development (R&D) provided the second largest share of academic R&D support. Much of this funding comes from state governments but is counted as institutional funding because the university has discretion over whether it will be spent on research or in other ways. From 1980 to 1995, the institutional share grew from 13.8 percent to an estimated 18.1 percent of academic R&D expenditures.

Industrial R&D support of academic institutions has grown more rapidly than support from other sources since 1980. In constant dollars, industry-financed academic R&D increased by an estimated 250 percent from 1980 to 1995, as industry's share grew from 3.9 percent to 6.9 percent. Although industry has expanded its share of support for academic research, it is still much lower than federal or state support.

More and more academic institutions are receiving patents. The 100 largest research universities, which account for roughly 80 percent of total academic R&D expenditures, received about 90 percent of all academic patents. In 1994, patents awarded to U.S. academic institutions continued their rapid increase—1,761 patents awarded, compared with 434 a decade earlier. The academic sector's share of all U.S. patents rose to 3 percent from less than half that in 1991 and from 1 percent in 1980. The biomedical area is a particular focus for academic patenting, with three patent use classes in the biomedical area accounting for 25 percent of all academic patents.

UNIVERSITY-INDUSTRY INTERACTIONS

Research universities benefit from interacting with industry in many ways; this is most important, perhaps, because such interaction improves the capacity of

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[23] According to preliminary data for 1997 from the National Science Foundation (NSF), total funding for U.S. basic research was $31.2 billion, of which $16.1 billion was performed at universities and colleges.

universities to obtain funds to strengthen their basic research and graduate training programs and to support the facilities that make those programs possible. Research sponsored by industry provides students and faculty with exposure to real-world problems and with an opportunity to work on intellectually challenging puzzles whose solution might be of immediate importance to society at large. Faculty researchers also report that industry money typically involves less bureaucracy than government money and that the reporting requirements are not as time-consuming. At the same time, some government funds for research are tied to joint efforts between universities and industry, and so, research collaborations with industry could become increasingly vital to obtaining more government support for research and graduate education at universities.

Universities are being called on to perform more long-term use-driven research of the type that in the past has been conducted in industry central laboratories, as companies increasingly focus on short-term product needs, as described in chapter 3. Although long-term research in industry has never constituted a large share of U.S. R&D, it has produced some of the most economically important inventions of the last 50 years. A dearth of this kind of funding could lead to a future dearth of important inventions.

In addition, the nature of technology-based competition is changing; there is a greater emphasis on the development of components and subsystems, architectures and designs, software, and computing standards, as opposed to complex manufacturing and assembly, a key source of Japan’s competitive advantage.[24] In the new environment, competitive positions are defended as much by staking out intellectual property rights, technology adaptation, or broad market acceptance of company standards as by production skill. As a consequence, a more intimate relationship is required between the source of the technology—whether it be a university, a company, or a government laboratory—and the user of the product that incorporates the technology. The university, as a source of science and engineering, thus changes from being at one end of a funnel to being part of a circle, which involves continuous interaction with the marketplace.

That the technological requirements of industrial customers increasingly call for solution of fundamental scientific puzzles means that faculty are increasingly attracted to this sort of use-oriented research on their own; in addition, graduate students involved in research now are trained in science and engineering practices that can lead to employment in industry just as easily as employment in academe. Research agendas already are changing to reflect the new realities. Therefore, universities must be vigilant about safeguarding the open academic

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[24] Of course, manufacturing is still an important ingredient in competitiveness, and the resurgence of U.S.-based companies in industries such as automobiles, data storage, and semiconductors is due to improved manufacturing. See STEP (1999).

environment and protecting student research agendas from undue commercial influence.[25]

Freedom to publish and discuss research results is a hallmark of the university. Academic research generally is aimed at fundamental, long-term problems, not at meeting short-term product needs, although some university breakthroughs are commercialized quickly. These characteristics of university research can conflict with industry's interest in short-term contributions to the development and production of specific products, and with industry's need to protect information until patents or products are realized from research results.

Industry and universities have made progress in developing mechanisms for cooperation that reconcile different outlooks and time horizons. However, further learning and adaptation on each side will be required to bring about expanded industry support for university research consistent with the core values of academe. A 1996 report suggests that increases in industry funding are not compromising the basic integrity of university research, as some critics have charged (Blumenthal et al., 1996). However, the report did find that industry-sponsored scientists tend to be more secretive about their work and more likely to choose research topics with commercial appeal.

The role of people in knowledge transfer raises important issues. One of the most effective mechanisms for applying the results of university research in industry is the movement of people. Industry hiring of graduates and the participation of faculty and graduates in forming new companies based on results of university research are important. Tensions between university and industry roles can arise here. Education remains the primary mission of the university, and research that supports the educational process must have the top priority in the university research agenda. Some voices call for educational programs to be targeted more sharply on industry needs, but industry must adjust its own approach to human resources development in order to work more effectively with academe.

For example, it might be necessary for larger numbers of company employees with a wider variety of corporate functions (manufacturing and design, as well as research) to spend extended periods of time on campus than has been the case in the past. That type of interaction would enhance the educational mission of universities and help to renew industry's technical knowledge base. Yet, because of the high degree of mobility among scientists and engineers in U.S. industry, today very few companies and individuals have the incentive to support or participate in such extended stays. Employees are concerned that extended time away from the company can hurt their career prospects, and companies

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[25] Recently there has been renewed discussion of openness and secrecy issues in academic research. See Alberts et al. (1998) and Government-University-Industry Research Roundtable (1998b).

trying to remain as lean as possible are reluctant to do without employees who can contribute to meeting immediate needs for extended periods.

Universities will need to make adjustments as well, accepting medium- and long-term visitors who do not possess a significant publication record. Universities also might need additional flexibility to allow faculty and students the scope to move into industry on a temporary basis in order to do the final work on promising ideas (Spencer, 1990).

How can universities and industry develop new mechanisms that provide each side with the incentives necessary to expand cooperation? The semiconductor industry might provide important lessons for other sectors. The Semiconductor Industry Association engages in a road-mapping activity that identifies appropriate topics for research with time horizons of up to 15 years, and for many years companies have pooled resources through the Semiconductor Research Corporation to support academic research and advanced education. The SEMATECH industry research consortium also supports research on future manufacturing processes. Two recent initiatives by the industry are academic research centers at two leading universities working on design and interconnect issues for future semiconductor products (Nelson et al., 1996). Other industries might adapt such activities to their own circumstances.

Universities and government have also been developing initiatives. For example, the University of California recently announced its new Industry-University Cooperative Research program, a competitive-grants research program designed to help the state's economy by boosting productivity and creating jobs. The program focuses on applications of basic research that show the most promise for the development of new products and processes, allowing the university to accelerate the transfer of ideas from the laboratory to the marketplace. Funding for this initiative will be phased in; it will eventually attract $15 million per year in state support, a targeted $20 million per year in industry funds, and $5 million per year in university funds. The new program builds on existing efforts at the University of California to promote expanded research collaboration with industry in microelectronics, computers, and biotechnology.

With a favorable environment for entrepreneurial activity, the research university is a major U.S. asset in creating and applying new science and technology for economic growth. More extensive industry-university collaboration on long-term issues of interest to industry could help to alleviate the funding pressures being faced by universities and ensure that U.S. innovation has access to a strong stream of inventions, ideas, and skilled people in the next century. Universities and industry will both need to adapt if they are to ensure that collaboration delivers maximum benefits to each.

6

Education and Human Capital

THE EDUCATION CHALLENGE

The performance of the U.S. education system over the next several decades will play a major role in determining how well the United States is able to use science and technology for economic growth and other important national goals. Superior capabilities and skills will be needed to perform in technologically complex occupations and workplaces. Even those who do not go into careers that require advanced education in science and engineering will need basic scientific and technological literacy to function as effective citizens.

Discussion at the forum touched on reports of current shortages of science and technology workers, particularly information technology workers. Immigrant scientists and engineers have been and will continue to be important in addressing needs for talent. However, enabling greater numbers of native-born Americans, particularly members of underrepresented minorities, to enter these careers is a difficult and important long-term challenge.

In contrast with other subjects of forum discussions, such as the strengths of the U.S. innovation system that have reemerged in recent years, the U.S. education system clearly is not performing at a standard adequate to meet our future needs. That is particularly true of K-12 education. Although the educational challenges were widely recognized over a decade ago, U.S. students still are performing at average or below-average levels in mathematics and science, compared with students in other countries (National Center for Education Statistics, 1999). A study of middle school students showed that around 40 percent were “disengaged” (Steinberg, 1996).

Improving K-12 education is a difficult, complex, long-term task. Most of the burden lies with states and localities; improving the performance of schools and school systems will require long-term partnerships with parents, communities, and industry. The federal government can play an important role in promoting high standards for students and teachers, and as a funder in specific fields, such as early education. Although the forum did not aspire to address all aspects of the topic, several important issues were raised and discussed extensively.

UTILIZATION OF INFORMATION TECHNOLOGY IN EDUCATION

One of the important questions facing U.S. education is that of the most effective use of information technology to enhance education while preparing students for the twenty-first century workplace. A recent report has called for a massive program to deploy computers in elementary and secondary schools (President’s Committee of Advisors on Science and Technology, 1997). Yet the forum discussions raised several caveats about whether a $13 billion investment in computers would yield the highest educational returns, as opposed to other potential uses, even assuming that this scale of investment is possible.[26]

When computers are applied in various fields of human endeavor, the first use generally is to automate a task that already is being performed. The value of computers is unlocked when they are used to reach the original goal in a profoundly different way. Today, the underlying model for using technology in education is still automated drill, which was developed in the 1960s. There is nothing wrong with automated drill; it can help to improve student performance. But this can be accomplished with devices that are much less expensive than today’s personal computer.

Educators around the United States are coming up with innovative uses of information technology to enrich educational experiences. One example in the humanities is the Valley of the Shadow archive developed by historian Edward Ayers, of the University of Virginia.[27] The archive contains detailed records on Staunton, Virginia, and Chambersburg, Pennsylvania, for the period before and during the Civil War. It is a potent educational tool that is very different from a traditional textbook. The author cannot control the order in which a student progresses through the information or the detours that he or she takes. The teacher engages the students in scholarship instead of rote learning. Students are encouraged and guided in their own research projects.

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[26] This section draws heavily on the talk by Wm. A. Wulf on “The Education Challenge” at the forum.

[27] See the Valley of the Shadow World Wide Web site at jefferson.village.virginia.edu/vshadow2.

> *"It seems to me that if we're serious about education, and we have to be serious about it, we need to step back and take a long view. We need to be willing to make fundamental changes, not just use technology to do what we are already doing a little bit better."*
>
> —Wm. A. Wulf

Information technology probably will challenge other traditional assumptions about how we educate. For example, the lecture format and the organization of courses in universities are designed to optimize faculty time and the use of buildings, rather than to maximize learning. New approaches that more effectively use student-to-student interactions and allow for flexible approaches to organizing classes can be developed with information technology. Nevertheless, the compartmentalized institutional model of education is likely to hold on for some time, even when the assumptions behind it are rapidly becoming obsolete.

Information technology undoubtedly will have a profound effect on education in the long term. In the meantime, the returns on investments in educational information technology and the opportunity costs should be assessed carefully.

PROMOTING A REVOLUTION IN K-12 SCIENCE AND MATHEMATICS TEACHING

Although America's educational problems probably are not amenable to a quick fix of massive spending on personal computers for schools, even if it were desirable, several long-term efforts could yield considerable dividends.[28] The scientific community already has been engaged in the education reform movement through the development of standards for science education, which state that science should be a core subject in every year of school starting in kindergarten, that science should be for all students, not just those who might become engineers or scientists, and that science education should focus on inquiry-based learning rather than rote memorization (NRC, 1996b). The National Academies and other scientific and engineering leaders also can play roles by supporting and disseminating best practices in science education.

Two issues particularly relevant to improved K-12 science and mathematics

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[28] This section draws heavily on the talk by Bruce Alberts on "Meeting the Education Challenge" at the forum.

education were identified during the forum discussions: attracting superior talent to the teaching profession and improving science and mathematics curricula.

Today, there is an opportunity to attract young scientists and engineers to nonresearch careers. It will be important to create new pathways for talented young people to enter teaching and to change the academic culture in which advisers tell their students that they are failures if they do not go into academic research. One innovative program discussed at the forum is Teach for America, a nonprofit program that selects 500 young people per year with nontraditional backgrounds to teach for two years in urban and rural schools.[29] The prospective teachers are given 5 weeks of training in a “boot camp” setting the summer prior to their assignment.

Launched in 1989, Teach for America has a track record of improving education. At any time, 1,000 teachers in the program are having an influence on the lives of 100,000 young people. Although the program has been criticized by some in the education establishment, there is considerable competition for Teach for America positions, and the program attracts $5 million per year from corporations, foundations, and individuals. Participants are expected to teach for 2 years, but many decide to stay in the field.

A second task taken up in the forum discussions is improving science curricula. All over the country, curricula are being developed in accord with the National Science Education Standards. Many worthwhile examples are aimed at elementary school students. One example is the curriculum developed by the National Science Resources Center, a joint activity of the National Academy of Sciences and the Smithsonian Institution. Other organizations, such as the Lawrence Hall of Science, are producing similar curricula, many of which are available on the Internet.

At the middle school and high school levels, textbooks are being written to meet state specifications that are too detailed; the results are often dull and even scientifically incorrect texts. However, here too, local grassroots efforts by individual teachers and nonprofits to develop better curricula are beginning to blossom. The Internet is facilitating exchange and mutual reinforcement among these efforts. Major experiments are under way in asynchronous learning networks: high school teachers are putting courses up on the World Wide Web and using them to teach students all over the country. The National Academies and other scientific and engineering leaders can play roles by encouraging such efforts and convening networks.

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[29] See the Teach for America World Wide Web site at www.teachforamerica.org.

LIFELONG LEARNING FOR A TECHNOLOGICALLY SOPHISTICATED WORKFORCE

In addition to educational foundations, improving America's human resource base for science- and technology-led economic growth will require the spread of a new culture that values lifelong learning and continuing education and the institutions to support them. Educational institutions are changing to meet the needs of a changing body of students, including pursuit of innovative, market-oriented strategies. For example, the private, for-profit University of Phoenix addresses the specific needs of major employer groups which can partner with them in planning and designing their educational offerings. Such partnership keeps educational institutions in tune with changing markets and needs. Although most of the University of Phoenix's offerings are business-oriented, as opposed to scientific and engineering, it serves as an interesting new model and a challenge to the education orthodoxy.

The National Technological University (NTU) is another useful example. NTU give engineering courses to working professionals through distance learning technologies. Close links with industry customers allow NTU to stay current in industry trends and current educational needs. The use of distance learning technologies makes it possible for courses to be flexibly scheduled.

A number of U.S. research universities already have substantial lifelong learning programs, such as the School of Continuing Studies at Johns Hopkins University. Other universities seeking to establish or expand continuing education programs can learn from these examples.

In summary, the United States must invest in the future workforce by providing students with a firm understanding of science and mathematics in addition to a command of oral and written communication skills. Advances in science and technology have created new resources for improving K-12 education and have made possible new types of educational institutions to meet changing needs.

> *"[We need to strengthen] education of technical people once they enter the workplace. Here the focus should be on lifetime learning, and on iterative programs that take employees through university courses—either in specific geographic locations or on the Web. For large transnational organizations, this may evolve to situations where corporations—not individual students—are the prime university customer."*
>
> —Forum participant

7

Conclusions and Recommendations

The forum steering committee has taken the various inputs of the forum event, follow-up discussions, and complementary work by other groups to formulate the long-term goals that it believes America should work toward to sustain and enhance its ability to harness science and technology for economic growth.[30] The long-term goals are presented below with a number of specific action items.

Long-Term Goal 1: Over the next decade, achieve a sustained level of productivity growth that will allow rising living standards and noninflationary economic growth.

In its 1993 report to the president and Congress, the Competitiveness Policy Council (CPC) set out the objective of raising productivity growth to 2 percent per year, roughly the rate achieved by the U.S. economy during the period 1947-1973. During the period 1973-1995, productivity growth was much lower, about 0.4 percent, but we have seen a sharp upturn in the past few years. Notwithstanding debate of measurement issues, discussed in chapter 2, the steering committee believes that productivity growth of at least 2 percent per year, as called for by the CPC, is an appropriate long-term target.

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[30] In particular, see COSEPUP (1999), STEP (1999), and U.S. House of Representatives, Committee on Science (1998).

General Recommendations and Specific Action Items

1-A **Increase investments in science and technology as a top national priority:**

- Federal investment is still a necessary ingredient for sustaining U.S. capabilities. We endorse the bipartisan effort to pass legislation calling for substantial increases in federal science and technology investments as a good start after a number of years of low real growth in the science and technology budget. Particular attention should be paid to emerging fields of science and technology in which cuts in long-term industrial research and Department of Defense basic research spending have had a severe impact.
- Although industry funds two-thirds of all U.S. research and development (R&D), only about 7 percent of academic research is funded by industry. U.S. industry, universities, and government should work together to raise this proportion to 20 percent over the next 10 years. The role of new incentives, such as tax incentives, should be explored.
- Industry-university partnerships with all levels of government should be encouraged, with flexible design and implementation. Working through the U.S. Innovation Partnership, federal, state, and local governments should establish a program of matching grants for state and local government partnerships with industry and universities to harness science and technology for economic development.
- To encourage private-sector R&D investment, the R&D tax credit should be made permanent. Federal, state, and local governments should institute similar tax incentives for R&D investment and industry collaboration with universities.

1-B **Undertake policy restructuring to improve effectiveness and leverage of investments:**

- The federal government should lead in structuring international research cooperation that advances fundamental knowledge, building on the lessons of recent years.
- The 1995 report *Alternative Futures for the Department of Energy National Laboratories* remains an appropriate blueprint for national laboratories (Task Force on Alternative Futures, 1995).

1-C **Develop better metrics and understanding of science and technology trends, and connections with economic growth:**

- Inspired by Motorola and the semiconductor industry, a number of industries and companies are conducting technology road-mapping activities. These should be continued with expanded efforts to share perspectives across fields and sectors.

- We have made progress over the years, but we still need to better understand how science and technology are translated into economic growth. We also need to continue work on measuring productivity.

Long-Term Goal 2: Increase the number and proportion of Americans prepared for scientific and engineering careers, with a focus on underrepresented groups.

Intellectual capital and well-trained people are key to delivering sustained benefits of science and technology to all Americans. If we attack our educational problems effectively over the next decade, we should be able to raise the proportion of Americans versed in technology and its applications. Improving the participation rate of underrepresented groups should be a particular focus. One metric is the number of Americans receiving scientific, engineering, and technology training at various levels. For example, fewer than 40 percent of the engineering doctorates awarded by U.S. institutions are earned by Americans. One possible goal would be to increase this proportion to over 50 percent in the next 5 to 10 years.

General Recommendations and Specific Action Items

2-A **Continue and extend efforts to improve K-12 science and technology education:**

- Problems in K-12 education are fairly well understood, and most of the work will need to be done at the state and local levels. The National Academies and other scientific and engineering leaders should continue efforts to work with states and localities to set standards, promote best practices, and improve overall science and technology literacy.

2-B **Create a supportive culture and new institutions that facilitate lifelong learning:**

- Information technologies can play a major role. The University of Phoenix and the National Technological University are examples.

2-C **Enable more Americans to enter scientific- and engineering-oriented careers, especially underrepresented groups.**

- Although use of foreign science and engineering talent has been and will be an important aspect of filling our need for human resources, high-technology industries need to improve and broaden the science and engineering human resource base among American citizens. Corporations and individuals that have gained great economic benefit from the high-technology boom have a responsibility to invest time and resources in local schools and in programs such as Teach for America and groups such as the National Action Council for Minorities in Engineering. Developing metrics on the level of private giving to these initiatives and future goals would provide a better picture of trends.

Long-Term Goal 3: Maintain and improve the domestic and global market environment for U.S.-generated innovations to allow us to prosper in a global economy.

3-A **Adopt national standards for securities litigation and product liability.**

3-B **Continue to examine trade, antitrust, and intellectual property policies with the aim of opening markets globally for U.S.-generated innovations.**

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PART II:
Speeches, Commissioned Papers, and Presentations at the Forum on Harnessing Science and Technology for America's Economic Future

National Academy of Sciences Building
Washington, D.C.

February 2-3, 1998

Keynote Address

Honorable Jeff Bingaman
U.S. Senator from New Mexico

I am very pleased to be here this morning in front of such a distinguished audience. This meeting is very timely. We need to have a national conversation on how to meet the challenges of the twenty-first century, the next American Century, through science and technology. I congratulate Governor Thornburgh and Bill Spencer for putting together what promises to be a very substantive two-day program.

For the past 100 years, science and technology have been vigorous engines for U.S. economic growth. In the past 50 years, as Vannevar Bush foresaw, the Federal government has become the primary steward of the health of science and technology in this country. What Vannevar Bush did not foresee, when he wrote *Science: The Endless Frontier*, is that our system of research and innovation has become vastly more complicated and nuanced than the simple linear model of R&D laid out in his report.

What actions should the federal government, as a good steward, take to keep our system the most robust and beneficial in the world?

I believe that the federal government must remain very broadly involved in ensuring the overall health of our research and innovation system. Our society's continued ability to create and harness the fruits of research and innovation will probably be the single largest determinant of our future quality of life and standard of living.

- We already live longer, healthier lives as a direct result of advances in medical science and public health. The revolution in molecular biology promises to increase our knowledge of the basic mechanisms of disease by orders of magnitude.

- Environmental science and our technological responses to its warning may largely determine the type of world we leave to our children. For example, if we do not innovate our way out of increased greenhouse gas emissions by improving our energy efficiency and by developing new energy sources, our children and we will be paying our way out of the consequences.
- Our standard of living has been lifted by growth in productivity and wages throughout our economy. Economists generally agree that, in this century, roughly 25 to 50 percent of our productivity growth—which is the engine of wage growth—has been created by new technology. These new technologies have boosted our economy and created jobs not just through their sale, but through the efficiencies they have made possible throughout the economy.

It is important to realize that if we are a healthier, safer, or wealthier society today than in the past, it is not because we are inherently smarter than our ancestors. Nor do we dominate the world economy because we are inherently smarter than the rest of the world. Our success is due to our society's uniquely powerful system for creating new knowledge and putting it to work for everyone's benefit.

How does our system work today, and what are some of its strengths and weaknesses? To gain some insight into this, it is useful to look at three examples:

First, the integrated circuit (IC) was first reduced to practice in two companies, Texas Instruments and Fairchild, which were initially outsiders in the solid-state devices industry. They used their own funds to spur the initial development of ICs. The managers of the Minuteman and Apollo programs in the Department of Defense (DoD) and the National Aeronautics and Space Administration needed ICs and became the first to use them widely. As continued innovation led to increased circuit density and lower prices, new markets opened up in the commercial world. By the late 1970s, the DoD was roughly only 10 percent of the market for ICs. Integrated circuits were at the heart of the personal computers that sat, somewhat isolated, on our desktops in the early 1990s.

As a second example, while the IC was moving from the defense world into the commercial world in the late 1960s and early 1970s, the Defense Advanced Research Projects Agency (DARPA) was pushing the creation of the ARPANET at universities, firms, and nonprofits. DARPA's objective was to share expensive research computers economically. Unexpectedly, researchers started using the ARPANET as a communication medium within the scientific community. Eventually, the National Science Foundation became the primary sponsor of what came to be called the Internet. Various pieces of software were developed to exploit this new medium, though they were not particularly easy to use. Then, off in Geneva, some high-energy physicists invented and started using the World Wide Web as a practical way to share data via hypertext. This Web idea was picked up by graduate students at a federally funded center at the University of

Illinois. They added graphics to create a user-friendly program called Mosaic, which quickly spread among all those previously isolated desktop computers. The developers of Mosaic founded Netscape, and the Web and the Internet exploded into homes and businesses across America and the world.

A third example of innovation that I want to talk about is a device that I saw on a recent trip to New Mexico. A scientist at Los Alamos National Laboratory, Bob Hockaday, got an idea for a thin-film fuel cell that would produce electricity from methanol and that would be sufficiently compact that it could replace batteries in hand-held devices such as cellular telephones. He quit the lab to work on the idea in his basement, living off the income earned by his wife. As he hit snags in the development of his idea, he used a Cooperative Research and Development Agreement (CRADA) with the lab to tap into its fundamental research expertise. When he was far enough along to have a promising story to tell investors, the lab helped him to contact potential sources of capital to move to the next step of prototyping. He presented his invention to 35 different potential investors before finding one who would put up $1 million to move to the next stage. I was at the ceremony two weeks ago at which the lab turned over its intellectual property rights for commercialization to Dr. Hockaday and his investor.

What do these examples tell us about our present research and innovation system?

- First, we don't see the simple linear progression, of basic research to applied research to development and then to products, that we read about in books. Nor do we see smooth and predictable handoffs between institutions that we read about in strategic plans. The real world of research and innovation features an amazing diversity of institutions, motivations, timescales, and pathways to success.
- Second, the marketplace to which innovation responds often displays a form of competition that economist Joseph Schumpeter termed "creative destruction." In the technology marketplace, firms do not merely try to be a little better than their competition. Sometimes they seek to radically transform the struggle by inventing new products and forms of organization that will make their competitors obsolete and extinct. The personal computer, which had caught the mainframe unawares and largely displaced it, is now challenged by the idea of the net computer. I expect we'll see more and more of this sort of competition in the next century. To survive in that kind of marketplace, one has to constantly innovate, constantly evolve, or the market will pass you by.

The picture that emerges from this description sounds almost biological. We have a rich, vigorous "ecosystem of innovation" in our country. Our research and innovation system is not dominated by a simple, mechanistic process, but by an Amazonian rain forest of complex webs and connections. It features an incredible diversity of actors and is marked by chance, chaos, competition, and cooperation.

I should note that the people at the Santa Fe Institute are studying the field of complexity and trying to understand what they refer to as "adaptive systems." We may conclude that in many respects our system for creating and using new knowledge and technology is a type of adaptive system.

While our innovation system has great strengths, it is also marked by some important gaps. For example, what would have happened to Bob Hockaday's invention if he hadn't had a spouse with a good job? Or if he had given up after being turned down by the fifteenth investor he contacted?

Now, the federal government is the primary steward of the health of this ecosystem of innovation. If we are to prosper as a society in the next century, we need to build on the strengths and fill in the gaps in our research and innovation system. We have to move from *having* an innovation system to *being* an innovation society.

I believe that focusing on the innovation society as a goal for the twenty-first century can help us to both open up and organize our thinking about what we need to do. I'd like to lay out at least two characteristics of an innovation society.

First, as I see it, an innovation society values and encourages the search for new knowledge and technological capabilities across a broad range of disciplines and across broad time frames of possible use. Such a broad focus can help us to overcome the false split between so-called curiosity-driven research and so-called problem-driven research. For example, in DoD, we currently use rigid categories of research based on an obsolete linear model of innovation (e.g., 6.1, 6.2, 6.3A). This structure entails a lot of bureaucratic effort to classify and control projects and dollars within individual stovepipes. Is this structure really necessary? What does it really buy us? Couldn't a more holistic view of research and innovation lead to a better, less bureaucratic way of managing these programs?

A second characteristic of an innovation society is that it develops a wide variety of incentives and mechanisms to disseminate and use new knowledge quickly because it is in its use that the largest social benefits come. In the past, we have experimented with CRADAs and other forms of partnership arrangements between knowledge generators and users. A focus on an innovation society might lead us to make greater efforts in the future to develop other forms of enhanced technical cooperation and dissemination.

A focus on the societal aspects of the innovation society metaphor might lead to new insights into the roles that each of our social institutions will have to play in creating and sustaining innovation in the next century. For example:

- Elementary and secondary schools, already making efforts to provide higher-quality math and science education, might be encouraged to try to nurture the creative spark in all its manifestations. The quality of our education in every respect must be second to none.
- Universities, where our most fundamental discoveries are made, must be free from administrative requirements that stifle creativity and better linked to the most difficult problems we face.
- Federal laboratories, already repositories of unique skills and facilities,

might be encouraged to grow even closer to potential users of their assets in order to speak their language effectively and to partner with them in innovation.

- Businesses, the primary force in embodying new knowledge into products and services, might be encouraged to look for new ways to integrate their activities with studies of the fundamental phenomena and processes underlying their products. This would improve their ability to exploit the opportunities for fundamental market shifts that new knowledge can provide.
- State and local governments might be encouraged to take on an enhanced mission of helping to disseminate new knowledge and techniques to smaller businesses, to assist them in innovation.
- All levels of government might be encouraged to consider how their policies create an overall business climate conducive to, or hostile to, innovation.

I think the time is ripe to develop a bipartisan consensus on the future federal stewardship of our research and innovation system. We went through a tough period in the 1980s, but the competitiveness crisis of those years provoked some serious thinking about innovation. More recently, there was also a great deal of heated argument—some of it useful—in response to the Clinton administration's technology initiatives.

I believe that we are now in the eye of the storm. Most of the acrimony about federal technology programs has died down. R&D funding, both in industry and the federal government, is up this year in real terms. The President has announced that his next budget will increase civilian R&D considerably. Our overseas competitors, particularly in Asia, are down on their luck at the moment. And the U.S. economy as a whole is the best it's been in a generation, and is currently the envy of the world.

But none of these trends is likely to last very long. We should take full advantage of the reprieve that we've been given to develop a new bipartisan consensus and understanding that will guide us when times get tough again. I see a number of hopeful signs that we are doing just this. One is the major study of science and technology policy being conducted by the House Science Committee. I look forward to seeing what emerges from its work. Another is a bipartisan bill in the Senate that would double the R&D budgets of the civilian agencies over the next 10 years. I am a cosponsor of that bill, S. 1305, along with Senators Gramm, Lieberman, and Domenici.

Your discussions over the next two days will be a source of valuable input to us in the Senate as we continue our discussions. You've picked all of the right topics to focus on, in my view. I am looking forward to the results of your deliberations.

Keynote Address

Honorable George Brown
U.S. Representative from California

I want to thank you for inviting me to join with you today at the start of two days of discussion on how science and technology (S&T) can contribute to U.S. economic performance in the next century and what national policies are needed to support that effort. This forum is tackling a very difficult set of issues and is trying to map a policy course at a time when predicting international economic directions, or S&T breakthroughs, seems to have become a game of chance. Now I was going to say that your chances of finding the right S&T policy for these times was about the same as your buying a winning lottery ticket, but after Chairman Sensenbrenner's recent outstanding performance in beating the lottery, the metaphor does not work.

Much of your discussion over the next two days is likely to center on the contribution that S&T makes to the economy and how to maximize the economic impact of our public investment in research and development (R&D) programs. In my remarks today, I would like to examine a broader set of issues that become linked to S&T policy when we look to economic performance as an outcome of public R&D investments.

However, this examination of the relationships between R&D investments and economic performance is long overdue. It is being forced upon us by the social disruption following the end of the Cold War, changes in high-technology industries, and dizzying advances in science. As an indicator of the magnitude of the change that surrounds us, I cannot let pass an observation that today's National Academy of Sciences conference on linkages between federal R&D and national economic goals is exactly the kind of conversation I sought to initiate some years ago. My goal then, and now, is to encourage these discussions in order to counteract an attitude that I perceive among some in the S&T community that their work is entitled to large and growing public support without any demonstration of the contribution of such work to national economic or other goals. Perhaps more important has been a reluctance on the part of the S&T community to join in the process of defining and prioritizing public goals during a time of rapid global economic, social, and political change, largely due to the impacts of S&T applications.

Although I believe in the importance of expanding human knowledge and its application to human needs as a matter of faith, most of those whose duty it is to decide on how public funds are spent require a more tangible demonstration of how their decisions will play out than mere faith.

My call to arms was an effort to strengthen the position of S&T in the decision-making process, not weaken it. Yet when I raised this issue a few years ago, some of you thought I was off my rocker or had abandoned my support for S&T. Now that the debate is progressing so well, as evidenced by this forum and other similar explorations, my challenge today is to see if I can help to move the boundaries of the discussion yet further out.

In the past, our economy, even the high-technology parts of it, operated in a much different environment. We were in a national security competition with the former Soviet Union and an economic competition with most of the rest of the world. Many high-technology advances came from defense spin-offs and moved from defense labs to the marketplace. Product life cycles were measured in years, allowing ample returns from industrial research investments. The financial markets were relatively patient and looked at a wide range of factors in determining a company's health. Federal R&D investments seemed to be on a stable growth path and, at their high point, constituted about two-thirds of total national R&D funding.

Of course, all of that has changed over a very short period of time. We won the Cold War and have a new set of international economic conditions. Old competitive relationships have been replaced with cooperative business ventures on a global basis that defy any attempt to determine national ownership. Product life cycles are now frequently measured in months and, combined with crazed investment fixation on quarterly profit-and-loss statements, this has forced many in the private sector to shed their long-term R&D operations and move research toward a short-term, product development focus. And as federal R&D funding has flattened, a major reversal in funding sources has occurred with industry now providing two-thirds of the nation's R&D funding, albeit with this shorter-term, product-oriented focus.

Driving much of this shift are advances in S&T that bring new products to market almost as fast as cutting-edge research is published. We are now on the threshold of seeing yesterday's science fiction enter the marketplace: animal cloning, talking electronic road maps installed in automobiles, powerful computers as small as a pack of cigarettes, and so on.

As individuals, our view of ourselves is changed by these advances, with S&T getting both the credit and the blame. As members of institutions involved in science policy or the conduct of research, we are challenged to rethink the roles of our institutions in this constantly changing state and must even contemplate future scenarios in which our respective institutions might become obsolete. For political institutions, the situation becomes even more complex as the changing and expanding role of S&T encounters debates taking place in other parts of society.

That last point bears a little more detailed examination. It is not sufficient to debate the role of S&T in the nation's economic well-being without putting that set of variables into a larger and more complex social equation. Some of this work is under way in other policy discussions. Dr. Jane Lubchenco's Presidential Address at last year's annual meeting of the American Association for the Advancement of Science (AAAS), as reflected in the January 23 issue of *Science*, is a good look at this integration of debates as she calls for the development of a new social contract for science. The "Conversation with the Community" on the AAAS Web site is a fascinating debate under way on the relationship between science, technology, and society at the end of one century and the start of another. In Congress, Representative Vernon Ehlers is undertaking a review and update of our nation's science policy that will continue this debate throughout the year.

So, let's take a moment to look at some of the larger questions being raised by the focus of this conference.

First, what is this economic well-being that we seek? How do we define it? Economic well-being means one thing if we own stock in company X and has a different meaning if we are an hourly wage worker whose job is eliminated by company X's advanced technology product or a new and more efficient manufacturing process. Do we have a sufficiently complex definition to take into account all of these effects? How do we anticipate any negative effects of technological advance and how do we make appropriate adjustments to avoid or minimize them? Whose job is it to do this?

Next, since we are looking at "America's economic future" today, what measure do we use for the national economic performance that we seek? Do we want to use the same short-term measures that investors use, the ones that have forced industry to look at quarterly profit-and-loss statements instead of long-term economic sustainability? How can we measure the benefits to the U.S. economy from multinational partnerships that produce manufacturing jobs and corporate profits around the world? Are we using an outdated set of concepts left over from an earlier, simpler economic model?

This last point should prompt some discussion during this meeting. Our world view, our language, our legal and trade systems, our whole national perspective have been focused on global competition, but much of our current economy is based on global cooperative ventures that have a different perspective. These cooperative economic arrangements come into conflict with our competitive orientation that has its roots in the Cold War.

So, when U.S. computer companies seek to operate in the new world order, they must seek exemptions from the old-order trade laws in order to reimport components they sent to their Asian factories for assembly. When U.S. satellite companies seek to use the U.S.-Russian joint launch venture at Baikonur in Kazakhstan, they must frequently get special permission from the government to export their satellites. U.S. auto companies perform intricate import and assembly maneuvers to sell their essentially foreign-made cars as domestic automobiles. And when Department of Energy labs sign a Cooperative Reserach and Development Agreement with a U.S. consortium that may license extreme ultraviolet lithography technology to foreign companies, cranky U.S. congressmen want to know how this new economic arrangement fits within our old national policies.

On another front, our national economic progress raises issues of equity that must be addressed. While we are justified in our celebration of scientific and technological advance that moves the boundaries of human understanding further out, what do we do about the people left behind by those advances? In a rapidly changing world, we may strand those who are left standing still, those without access to the benefits of our technological advance. We cannot ignore these people. We cannot become a nation of technological haves and have-nots. This situation leads, on the one hand, to social unrest and instability, conditions that will threaten our continued economic well-being and that, in past ages, brought down the beauty that was Greece and the glory that was Rome. On the other hand, these people left technologically disenfranchised constitute underutilized human resources, people who could have been brought along through better education and training to perform the high-technology jobs that companies now seek immigrant scientists and engineers to fill.

Just as Edwards Deming revolutionized Japanese industry by bringing Total Quality Management to the factory floor and involving an even larger number of workers in improving quality throughout the system, we now need a new generation of Demings who will see the broader society as a system requiring quality improvements. And that new generation will include scientists, engineers, and political leaders with the vision to see and understand that a flawed society with distorted priorities and goals and underutilized human resources is a major economic burden on the productivity and stability of that society, and hence an impediment to its ability to survive and compete on a global basis.

Now I must point out that it is not the duty of every scientist and engineer, or every high-technology company, to anticipate and describe every potential social consequence, good or bad, of their work. Nor is it their job to solve these problems. A free and effective market system combined with an open and democratic political system should carry most of this burden. But it is incumbent upon all of us working in these areas during this period of such rapid and unpredictable change to identify potential stresses and inform the public policy process so that the public can make rational decisions about what they want to do, perhaps using tax and regulatory mechanisms where necessary. In these new public-private partnerships that you are discussing at this meeting, we need to look at changing responsibilities on both sides of the equation. As the government gives a little more support and assistance to the private sector, the private sector needs to be more sensitive to public policy issues that they encounter.

Here I must point out how much easier all of this would be if we still had a prudent technology assessment operation in this country, preferably imbedded in most of the major public and private institutions that impact on the future. Without such an entity, we are left to rely on the wisdom and good will of those of you involved in the process of discovery and commercialization. I hope that you accept this broader set of responsibilities.

I would like to make one last point in my attempts to stimulate discussion of a broader perspective. You should think about how each of you and your institutions will be transformed by the changed economic atmosphere and the changing set of relationships you are discussing. We would all like to think that our individual institution will emerge unchanged through any storm. As a Democrat in Congress, I can tell you where that lack of flexible thinking leaves you.

We need to examine those institutions that forgot to set their clocks ahead when the times changed. Research universities come to mind as a set of institutions that are struggling against change, or at least have not yet developed an effective transition strategy. It is unclear what the U.S. academic research system, our engine of discovery, will look like in the future. I know how much it has changed since I was a graduate student of physics 50 years ago. It will change at least as much again in the next 25 years. Like many other institutions whose identities were formed during the Cold War, and I will include in this group our national system of laboratories and much of our science policy apparatus, U.S. research universities still do not fully accept the transforming nature of the changes taking place today or their role in energizing these changes.

To help shape and guide these transformations, we may need to develop a new set of principles, perhaps even a new myth that will empower our efforts with a new sense of purpose. The goals that we seek as a society can be expressed through our economic undertakings, as shaped by S&T, if those activities are guided by an appropriately visionary set of principles.

What we are seeking is a free and open global society, within which we can harness the power of S&T for innovation and global economic gain. But that economic activity must be sustainable over the long run, broadly defined to include both intergenerational and resource sustainability. It must have a dynamic and adaptive stability that utilizes an appropriate level of technology assessment and has a reasonable predictive or forecasting capability. To be sustainable, it must be equitable and just and avoid alienation or polarization of society. It should allow for individuals and individual nations to profit, but not at inhumane or exploitative costs to other individuals or nations.

On the level of a guiding myth, we need to see ourselves and our current challenges as leading to a higher level of integration of human activity. Perhaps what we are moving toward is a new state of global relationships that constitute a "Noosphere," or a set of global interconnections that will define the Earth as a sphere of globally-shared knowledge and culture. Dr. Alberts writes about evolution in terms of an increasingly complex signaling process between biological entities, at every level of development. We can view this process as one that starts with simple biochemical signaling within cells, moving to simple signaling between cells to produce colonies of organisms, followed by more sophisticated signaling between cells leading to the evolution of multicellular organisms, and finally signaling between organisms allowing them to organize into herds, tribes, and eventually develop into human society and culture. Today we are using S&T to link the globe in a sphere of knowledge and understanding, a global web of interconnectedness for which the new satellite telecommunication systems such as Iridium and Teledesic are an effective metaphor. We have the universal language of mathematics and the increasingly universal nomenclature and reasoning of S&T. Can we be far from a universal mythology, or religion, or culture communicated through one verbal and written language?

Now I know that you will not rise to this level of discussion in only two days, but what I have sought to do in my remarks is to set your work in a broader context. You need to keep this context in mind if your deliberations are to have meaning outside of these halls and beyond the present.

I wish you well in your undertakings during this conference and I look forward to the results of your work. I hope that you can help to narrow the odds for success in the policy process and make the choices that face us look less like part of a game of chance. I, on the other hand, am going to check today's lottery number and see if I can follow Chairman Sensenbrenner's model for economic well-being. Thank you.

Technological Advance and Economic Growth

Richard R. Nelson
Professor, Columbia University

In this brief talk, I will touch on three themes. First, I shall make some observations about the history of economic thought on technical advance and economic growth. Then, I will identify a few salient features of technological change that research has highlighted, which seem highly germane to the present policy discussion. Finally, I will lay out several matters bearing on the connections among technical change, economic growth, and public policy, that I personally would stress.

First, some history of thought. Reflecting on what some early economists had to say about technological advance and economic growth seems valuable for at least two reasons. First, it brings out clearly that much of modern growth theory in fact has been the understanding of economists for a long time. Second, several very important elements of the earlier articulations have been repressed, or lost, in the more contemporary ones. They need to be brought back in. Adam Smith's *The Wealth of Nations*, written in 1776, is largely a book about economic growth. At the time he wrote it, the first industrial revolution was moving into full swing, and Smith, the keen observer, makes a number of insightful remarks about technical advance and economic growth. In reading Smith, one can see that the current emphasis on increases in capital per worker and on technological advance as sources of growth is no new conception:

> "Everybody must be sensible how labour is facilitated and abridged by the application of proper machinery.... I shall only observe, therefore, that the invention of all these machines by which labour is so much facilitated and abridged, seems to have been originally owing to the division of labour." (Smith, 1994)

But note that in Smith's account, growth of capital per worker and invention are not separate sources of growth, but are tightly connected. And both are related to the organization of industry. Modern growth theory has only recently been scrambling back to these important insights.

Thomas Malthus is another great classical economist whose central interest was economic growth. The "limits to growth" discussion often is regarded as a modern conception, but nearly two centuries ago Malthus raised the issue in his prediction that the fixity of land would, ultimately, limit population growth and economic progress. A key part of Malthus' analysis involved his proposition that technical change in manufacturing would be significantly greater than technological advance in agriculture. Historically, that has turned out to be wrong. But here, nearly two centuries ago, one can see economists recognizing that technological advance is unlikely to proceed uniformly across all areas of economic activity, and considering the implications. Unfortunately, much of this perception is missing in modern growth theory.

And, of course, technological advance was central in Karl Marx's analysis. In Marx technological advance is an essential element of the competition among firms. Under the force of competition, firms are inexorably driven to adopt new technologies that substitute capital for labor. The result for Marx was as much rising unemployment as it was rising productivity. One can see here the origins of the modern dispute about the effects of automation. By and large, technological advance seems not to have caused widespread unemployment. But the issue is repressed in most modern growth theory, which simply assumes full employment.

For a variety of reasons, toward the end of the nineteenth century, the interest of economists in economic growth diminished. While there are important exceptions, it is fair to say that strong interest in technical change and economic growth only returned to economics after World War II. Here one can recognize two quite different strands, which were then, and still are, somewhat at odds.

One was due to Schumpeter. Schumpeter was strongly influenced by Marx, at least in his insistence that technological innovation and industrial competition are closely intertwined. While Schumpeter's argument that innovation and change are central to economic activity goes back to his *Theory Of Economic Development*, written in 1911, his writing that has had the greatest influence on contemporary analysis is his 1943 volume, *Capitalism, Socialism, and Democracy*, where he made two important arguments.

The first is that technological change and economic growth involve disequilibrium in a fundamental way. Technological advance, and competition in industries where technological advance is important, proceeds through a process of "creative destruction." Schumpeter's second important contribution was to call attention to the relationship between industrial structure and technological advance. In particular, he called attention to the fact that, while innovation was a central form of competition in many industries, the structure of those industries never was "perfectly competitive" in the sense articulated in standard macroeconomic theory textbooks. The second of these themes spawned a large stream of empirical research exploring the relationships between economic structure and technological advance, which I shall refer to shortly. The former theme, that technological advance must be understood as a disequilibrium process, has been ignored by most of my colleagues in economics, although it now is an understanding shared by virtually all empirical scholars of technological advance.

The strand of economic research that undoubtedly has had the greatest influence on thinking about the relationships between technological advance and economic growth, however, did not stem from Schumpeter, but rather from the work of a group of economists working in the late 1940s and early 1950s for the National Bureau of Economic Research, using the new national product data. Solomon Fabricant, Moses Abramovitz, and John Kendrick were among the most prominent of this group. These early, postwar studies led on the one hand to modern growth accounting, an artform pushed much harder by Edward Denison, and on the other hand to the empirical research based on neoclassical growth theory, stimulated by the original work of Robert Solow. While different in the details of the work, it is these kinds of studies that led, early in the game, to such propositions as "technological advance accounts for 80 percent of the productivity growth the U.S. economy has experienced," and this kind of analysis continues to provide the standard measures of technological advance.

In any case, the early work of Schumpeter, of Abramovitz and colleagues, and of Solow, set in train a significant body of research by economists focused directly on trying to understand technological advance. Prominent among the group of economists who got into the field in the 1960s were Jacob Schmookler, Edward Mansfield, Zvi Griliches, Nathan Rosenberg, and Christopher Freeman. My colleagues at this symposium—Richard Rosenbloom and David Mowery—also have done important work on technological advance. Here I want to call attention to four different features of technological advance that this body of research has highlighted.

First, the process of technological advance involves uncertainly in a fundamental way. The processes are full of surprises. There are winners and losers. And generally, it is not possible to guess in advance who and what will win. Schumpeter was right in arguing that technological advance is a disequilibrium process of creative destruction. I long have been completely persuaded of this. The fundamental uncertainty involved in technological advance seems to be the basic reason why detailed, long-range planning is doomed to frustration and often disaster, and why, to get rapid advance of technology, society generally needs a variety of different parties trying out different bets. Regrettably, this issue is repressed in much of contemporary analysis.

Second, while many economists read Schumpeter in his *Capitalism, Socialism, and Democracy* as proposing that technological advance always is associated with large firms with a considerable amount of market power, we now know that no generalizations of this sort hold up. In some cases the Schumpeterian proposition seems to hold. Consider the chemical products industry, pharmaceuticals prior to biotechnology, and mainframe computers. But we also have experienced rapid technological advance in industries marked by the absence of large dominant firms, and considerable entry of new firms. This characterizes semiconductors in the era after the invention of integrated circuits up until a few years ago, software, and biotechnology, at least in the United States. The kind of firm, and the industrial structure, that is conducive to technological advance tends to vary from industry to industry, and even within an industry to vary over time. Thus reflect on the history of computers.

Third, more generally, there are very considerable differences across the fields of technologies and industries in the way technological advance proceeds. Broad generalizations here tend to get one into trouble. Thus consider the importance of patents. Patents indeed are important in pharmaceuticals, and in certain other areas of fine chemical products, but in other high-tech industries it would appear that firms can profit handsomely from their innovations through mechanisms that do not involve patents in an essential way, like exploiting a headstart. Thus much of the history of semiconductors, and computers, has proceeded in a regime of weak intellectual property rights. And industries and technologies also differ significantly in their links with science.

Which leads me to the fourth proposition I want to highlight. It is that virtually all technologies that have experienced rapid advance are connected to various fields of science, or engineering research, that undergird them. There are a variety of different ways to measure the connection of a technology to fields of science. But using any of these measures, the correlation between technical advance and the strength of the science ties is high.

Let me turn finally to a few matters relating to technical advance, economic growth, and public policy that I personally would stress. As I reflect on these propositions, they all have an element of warning against oversimplification.

First, I am very uncomfortable with the attempts of my colleagues in economics to “divide up” credit for economic growth between capital formation, education, and other input increases, and technological advance. I think it important to understand the economic growth process as involving strong interaction among various elements. To go back to Adam Smith, it makes little sense to ask how much growth we would have experienced if capital per worker had increased as much as it has and we had had no technical advance, because it is technological advance that enabled the growth in capital intensity that we have experienced. Similarly, the rise in educational attainments that has been experienced by modern growing economies has not been a source of growth independent of technical advance, but rather has been an essential input to and complement of the technological advance we have experienced. Technological advance must be understood as part of a package of ingredients that generate economic growth.

Second, regarding the roles of public policy toward technological advance, I think it generally a mistake to think of a choice between government and markets, or of government policies being justified because of “market failure.” On the one hand, as Schumpeter argued long ago, technological advance itself is associated with and generates all kinds of deviations from the economists’ benchmark condition of “pure and perfect competition.” But that is no reason for having government try to control the process. On the other hand, virtually every economic sector that has experienced rapid technical change has been supported in one way or another by a range of government programs that, at the least, have nurtured the underlying sciences. Sometimes, as in agriculture, public programs have supported quite applied research. In other cases, such as in chemical products and pharmaceuticals, the role of government research support has primarily been focused on more fundamental work. But there is a lot of variety from sector to sector regarding the division of labor.

In my view, technological change has been the central driving force behind the economic growth we have experienced. However, the relationships and mechanisms involved are complex not simple. I hope my remarks today have brought into view both some of the key relationships and their complexity.

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Sustaining American Innovation: Where Will Technology Come From?

Richard S. Rosenbloom
Professor, Harvard Business School

We meet today in the context of an ascendant American economy. A decade ago, it seemed that key American industries such as automobiles and semiconductors faced mortal threats from Japan Inc. and the Asian Tigers. Recent developments place the so-called Asian miracles in a different light. It is fair to ask, however, just how enduring the American economic success will turn out to be. Are its underpinnings robust enough to sustain its buoyancy for a decade or more?

This era of prosperity stems from multiple sources—prominent among them are sagacious monetary policies, prudent management of the federal budget, and the strong entrepreneurial culture in American society. Also sure to be on any list of causes is the dynamic American capacity for technological innovation. Central to the concerns of today's workshop are the questions: How robust is the current blossoming of innovation? Can it be sustained throughout the next decade? And, to the extent that it is based on new technology, where will the technology of the future come from?[31]

America's innovative successes in the 1990s are concentrated in the science-based industries, and especially in two industrial sectors on the leading edges both of technological opportunity and market growth. The first, broadly speak-

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[31] A 1993 report by the National Academies' Committee on Science, Engineering and Public Policy articulated broad goals for Science and went on to advocate that the government, in partnership with industry and with an effort to be responsive to market signals, "should take a more forceful role in development and adoption of technology than it has in the past," especially those that might "create major new markets." See COSEPUP (1993).

ing, is information technology: semiconductors, computers and software, and communications equipment and services. The other is the complex of industries feeding new technology into health care, mainly biotechnology, pharmaceuticals, and medical instruments. One index of the opportunities—technological and commercial—inherent in these fields is the choices that private firms have made about where to put their R&D money (Table R-1). Among the 50 firms with the largest R&D budgets—firms spending from $300 million to several billion dollars each year on R&D (in aggregate $55.4 billion, more than half of the total for all U.S. industry)—*all 20* of the most intensive investors in R&D (i.e., those with the greatest ratio of R&D to sales) are in one of these two fields. Each of these firms spends more than 8 percent of sales on new technology ($18 billion in aggregate). In these two industrial sectors the United States has demonstrated distinctive, and superior, capabilities which have been translated into growth and competitive advantage on a global scale.

It is appropriate that discussion in this hall should focus on science and technology, but we should acknowledge, up front, that productive R&D, by itself, is not enough; new capabilities must change commercial practice before they

TABLE R-1 The most R&D-intensive large industrial firms in 1996

1. Genentech
2. Amgen
3. Upjohn
4. *Novell*
5. Eli Lilly
6. Marion Merill Dow
7. Rhone-Poulenc Rorer
8. Pfizer
9. Schering-Plough
10. *Microsoft*
11. Abbott Laboratories
12. *Digital Equipment*
13. *Sun Microsystems*
14. *Intel*
15. Bristol-Myers Squibb
16. American Home Products
17. *Motorola*
18. Merck
19. *Hewlett-Packard*
20. Johnson and Johnson

Note: Of 50 firms with greatest R&D expenditures, this lists the 20 with the highest ratio of R&D to revenues. Firms in italics are in information industries; all others are in bio-pharmaceuticals.

Source: National Science Board, *Science & Engineering Indicators—1998,* Appendix A, Table 4-23.

create economic value. As the distinguished medieval historian, Lynn White, Jr., once observed, "New technology opens a door ...it does not command one to enter" (White, 1966). What matters for the economy is *innovation*—the introduction of technology to commercial practice (Smith and Alexander, 1988). How are the results of R&D translated into economic progress?

While it is well established that there is a positive association between economic growth and a nation's abilities in science and technology (Boskin and Lau, 1992) we do not have any clear model of the connections that produce that result. Vannevar Bush shaped public policy and private practice for more than a generation with the notion of a direct relationship—the famous linear model—but we've known for some time that that is an oversimplification. The reality is complex and dominant patterns vary from field to field. The central point is that the process of innovation is at the heart of the linkages between the emergence of new technology and the realization of its economic potential.

What do we mean by innovation? A useful, plain-English definition is: "the processes by which firms master and get into practice product designs and manufacturing processes that are new to them" (Nelson, 1993). We'll take "product designs" to embrace service systems also. This definition embraces a highly diverse set of related but quite different kinds of changes introduced by businesses, ranging along a spectrum stretching from imitation of proven practice to the risky introduction of highly novel technology in radically new applications (Figure R-1).

Let's consider some illustrative examples. Most "innovations," while new to the firm in which they occur, are actually imitative of practices already proven elsewhere. Many of these individually are of small consequence, differing only incrementally from prior practice in the firm. But some imitative innovations, like Microsoft's Windows operating system, can be radically different from their predecessors and produce major economic consequences.

In those cases where the innovation is not imitative, that is, the sponsoring firm is the first to commercialize the innovative practice, the change is usually *incremental* in character, representing progress along an established technological trajectory. While they may be small individually, incremental changes may cumulate to produce major effects. For example, for the first 60 years following the commercial introduction of insulin as a therapeutic product, technical advance focused on continual improvement in the quality and cost of product made from the pancreases of pigs. Along this trajectory, impurities were reduced to one part per million (ppm) by 1980 from 50,000 ppm in 1930. Incremental change is the principal mechanism behind the phenomenon identified by "Moore's law," which has had such a huge effect on the information industries.

Sometimes, however, novel technology breaks with established trends. For example, in 1978 a new pathway for insulin technology was opened by the introduction of genetically engineered human insulin, a discontinuity that transformed the global insulin industry (Enright, 1989). In other cases, radical change

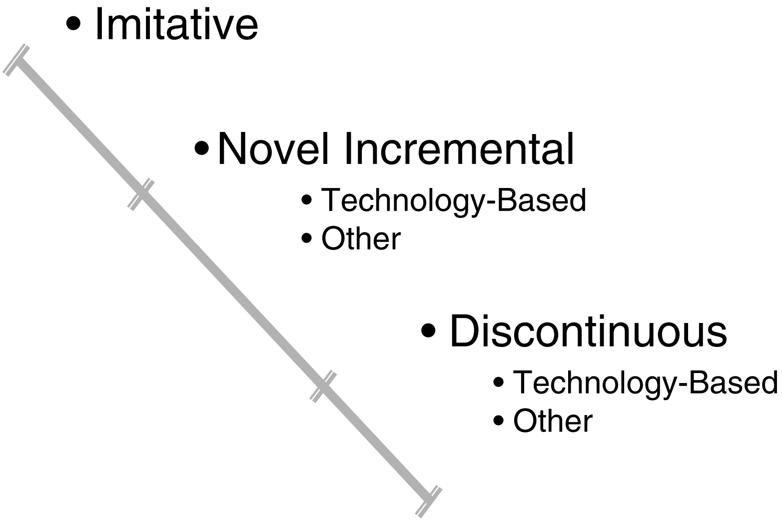

FIGURE R-1 A Spectrum of Innovation

creates new categories of products or services, as for example, resulted from Magnetic Resonance Imaging in medicine, or the inkjet desktop printer for computers. Technical change is not a necessary ingredient—important discontinuities can flow from the creative combination of available technologies—the FedEx system, or bank automated teller machines come to mind.

A key comparative strength of the U.S. National System of Innovation—to borrow a phrase from my colleague Richard Nelson—has been its ability to initiate and rapidly to exploit those innovative discontinuities that stimulate economic growth by transforming tired industries or giving birth to entirely new ones. Even when the first appearance of the core innovation is overseas, as for example the computed tomography (CT) scanner, American industry has been able to capture commercial leadership fairly rapidly in many instances.

It would be nice if we could measure the relative importance to economic growth of the different varieties. That sort of analysis is still beyond our grasp. But a few points can be made.

First, sustained economic growth probably requires balanced national capabilities to initiate innovations effectively across the spectrum described above. Imitation of new technology by firms with superior economic capability can be very productive.[32] So can radical change which effectively combines proven technologies.[33]

But because our focus today is on science and technology, I will limit my remaining remarks to those innovations in which novel technologies are first put into use. Furthermore, I will refer primarily to the two industrial sectors of greatest current salience, namely, information- and bio-technologies.

One indicator of the character of new technology can be found in the stream of patents granted. While not all innovative technology is patented, and those that are may not necessarily be representative of the whole, patents provide some interesting clues to what's happening on the frontiers of technical advance. Francis Narin's analysis of some 400,000 U.S. patents issued to inventors from all over the world in the mid-1980s and mid-1990s shows a dramatic increase in the extent to which they are based on recent science (i.e., they cite articles published within the preceding decade) (Narin et al., 1997). See Figure R-2 and Figure R-3. Furthermore, while this trend is evident in every industrial country, it is most pronounced in American inventions, and in medical and chemical fields.

The patent data also show that the scientific information originates in many different institutions—75 percent of the scientific references cited by private industry as a basis for new technology comes from universities and government agencies. This is even more pronounced in drugs and medicine, and only about 50 percent for electrical components, but still substantial there as well.

At the core of the national system of innovation is a relatively small set of institutions in government, industry, and universities that produce the scientific and technological developments in the cutting-edge fields. Basic and applied research are creating new options for industrial innovators, not only by creating wholly new opportunities, but also by strengthening the knowledge base that supports incremental progress along established trajectories. Because the nature of industry-university-government relationships is often idiosyncratic to particular fields and industries, no single model provides a useful description across the board (Powell and Owen-Smith, 1998).

It is also clear that we are seeing a reshaping of the relationships among institutions generating new technology. Gibbons and his associates have characterized a new mode of research that spans disciplines, is more commonly organized through networks than through collegial hierarchies, and is characterized by rapid, often non-linear development (Gibbons et al., 1994, p. 20). And we must remember that the working of these wellsprings of knowledge takes place in

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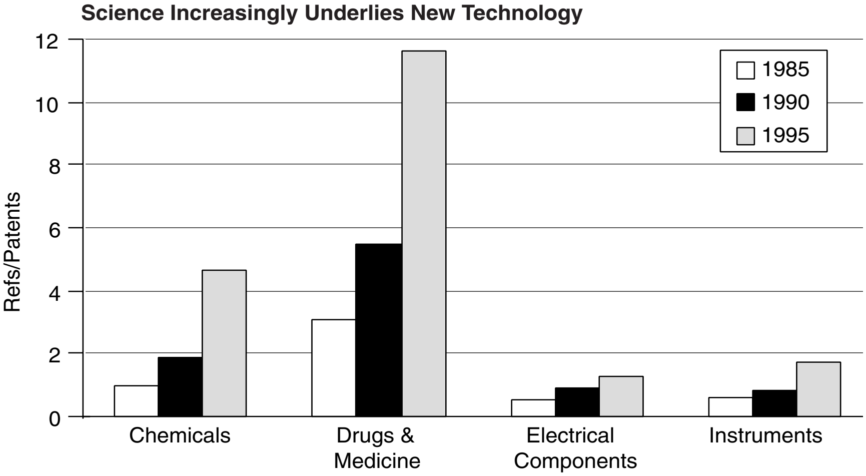
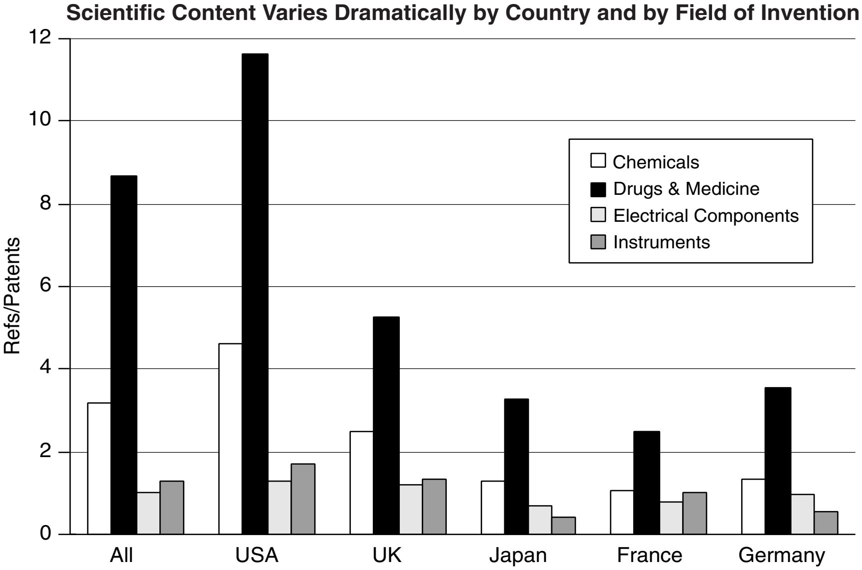
[32] Consider the economic consequences of Microsoft's major innovations, like Windows, which have characteristically been imitative, yet have been backed by highly effective commercial capabilities.

[33] Microsoft's most visible original innovation, the notion of a "suite" of related programs, was a matter primarily of novel business practice, rather than new technology.



Source: Narin et al., *Research Policy* 26:317-330 (1997).

FIGURE R-2 Scientific references per U.S. patent 1985–1995, by patent field



Source: Narin et al., Research Policy 26:317-330 (1997).

FIGURE R-3 Scientific references per U.S. patent, by nationality of the inventor and patent field the context of a number of larger social forces. What we can say, across the board, however, is that the nature of the relationships and the performance of the institutions has been changing throughout the 1990s.

Within industry, attitudes and practices toward fundamental research and pioneering investments in technology have been transformed (Rosenbloom and Spencer, 1996). The end of the Cold War is reshaping federal spending for science and technology. Universities increasingly are called upon to serve, in the words of one National Science Foundation official as “creators and retailers of intellectual property” (Chubin, 1994: quote at p. 125). Despite these changes, the institutional relationships seem well suited to sustain technical advance along established trajectories—to fuel incremental change. But in some respects current trends raise questions about the sustainability of our ability to generate and use radically different technologies. Progress in integrated circuits within the framework of the industry’s established road-maps can be achieved, but who will invest in creating the science base for whatever lies beyond that?

CORPORATE RESEARCH

Let’s start with the private sector. Corporate laboratories dedicated to pioneering in science and technology emerged on the scene at the start of the twentieth century. The institution blossomed most fully in the United States following World War II when numerous corporate laboratories dedicated to fundamental science and long-term development of pioneering technologies emerged in American industry. In later decades a small number of these laboratories were a fertile source of fundamental technologies sparking significant economic growth. Corporate research laboratories flourished most in organizations like AT&T, IBM, and Kodak, whose dominant market positions cushioned budgets from the pressures of narrow margins and facilitated the fullest appropriation of profits ensuing from new technologies. As deregulation and the rise of global competition have forced greater corporate attention to the bottom line, and the richest areas of technological opportunity have shifted to new fields, research budgets in those firms have come under closer scrutiny.

The changes have been most prominent among those firms most notable for their prior accomplishments in creating new technologies. For example:

- Overall employment at IBM’s research division was cut by nearly 20 percent in 1993. An atmosphere once characterized as “IBM University” vanished.
- The David Sarnoff Research Center, under RCA ownership a pioneer in electronics technology (inventor of liquid crystals, for example) has become a contract research organization dependent on government funds for its long-term research.

In aggregate, industrial *research activity* declined by 20 percent in real terms in the early 1990s (Figure R-4).

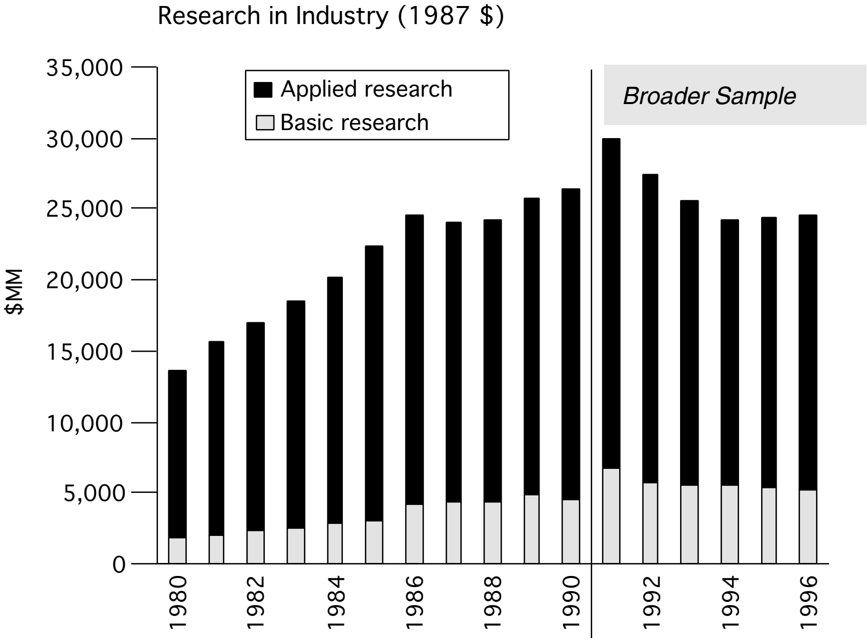
Of course, there are also counter-currents. Some seasoned companies have continued to support pioneering research. Hewlett-Packard, for example, has intensified its research commitment in the 1990s. New actors on the technology frontiers are beginning to play a role. Prominent among them is Microsoft, which recently established a substantial research organization focused on technologies likely to be significant 5 to 10 years in the future. But many of the new breed of high-technology firms in electronics and information technologies have eschewed traditional research organizations and chosen other strategies. U.S. leaders in the semiconductor industry, including Intel, Motorola, and Texas Instruments, now cooperate to fund research in universities and to develop pre-competitive manufacturing technologies, but none supports a significant central research establishment dedicated to fundamental research on the scale and of the type formerly found at IBM, RCA, and AT&T.

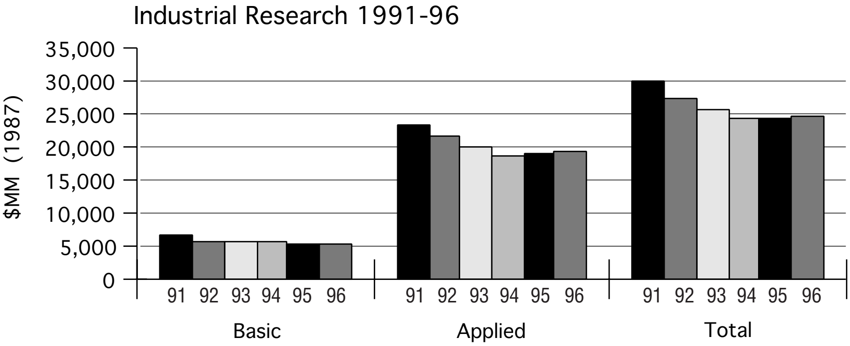
There are multiple forces at work shaping these changes. The end of the Cold War is reshaping the allocation of federal resources for science and advanced technology with undoubted consequences for the laboratories in the private sector. The new competitive environment causes some to question the benefits of private investment in fundamental research. Firms now compete in the global marketplace with rivals that do no fundamental research but are quick to exploit developments made elsewhere.

Where will the technology come from in the next decade? Continued strong progress along established pathways of incremental innovation seems highly probable across the board. Much less certain is whether the nation is investing sufficiently in pioneering research that will establish the foundations of new technologies and new markets in the future.

The direction and intensity of research efforts aimed at novel innovations are shaped by perceptions of opportunity in both the pertinent field of science or technology and in the marketplace. Breakthrough innovations are likely to involve the interplay of universities, government agencies, and firms, but these actors have quite different abilities to discern opportunity in those domains, as well as quite different incentive structures.

Important innovations increasingly have been characterized by being primarily science-based and by requiring a high degree of institutional interaction and flexibility. The full story of major contemporary innovations often displays a complex intermingling of government and university scientific strength, small firm flexibility and initiative, and large firm engineering and marketing capabilities. These phenomena are often most pronounced in the two sectors—information and biotechnology—identified as offering the greatest potential for innovation. In both sectors we have seen a high degree of individual and organizational adaptability and mobility, as evidenced by the high rates of new firm formation and growth in those fields in the United States.





Source: NSF:SRS - National Patterns of R & D Resources: 1996 - Tables C-7 & C-10.

FIGURE R-4 Industrial *research* activity declined by 20% in the 1990s.

But the pattern of institutional arrangements and the processes of innovation differ significantly between these two sectors. In biotechnology, the boundaries between universities and firms are crumbling, cutting-edge research is now performed by intellectually and institutionally heterogeneous groups, and researchers at for-profit companies play a key role in basic research (Galambos with Sewall [1995] illustrate this in the history of Merck). One thoughtful analysis concludes that "integration between biotech firms and universities is so pronounced that they constitute a common technological community" (Powell and Owen-Smith, 1998:258).

The complex partnerships in biopharmaceuticals seem well suited to sustain continued technological progress and economic growth. In information technology, the role of industry predominates—especially in the hardware underpinnings of technical advance. That works well along established trajectories (Wintel)—but is enough investment going into the search for new technological paradigms? And if so, is that happening in institutions well coupled to the innovative capabilities of the industries that must utilize the results?

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The Global Environment of U.S. Science and Technology Policies

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INTRODUCTION

No assessment of future policy priorities and instruments in U.S. science and technology can ignore the international environment. The remarkable success of economic reconstruction and growth in the 50 years following the end of World War II means that the U.S. research and development (R&D) system, which is still by far the largest (measured in terms of annual investment) in the world, accounts for a smaller share of global R&D activity than was true in the 1960s and 1970s. As such, U.S. firms and citizens can benefit from expanding their monitoring and exploitation of R&D performed offshore. In addition, like other elements of modern capitalist economies, the R&D systems of the industrial economies (and, increasingly, those of the industrializing economies) are closely intertwined with one another.

Higher levels of global technological and economic interdependence, however, do not mean that the nation-state is dead. National government policies still are important sources of support for domestic R&D infrastructures that may or may not be conducive to economic growth and competitiveness. But closer links among these economies, which differ from one another in important structural

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[34] This paper is based on remarks prepared for the National Research Council symposium on “Harnessing Science and Technology for National Goals,” February 2-3, 1998. Support for the research underpinning this paper was provided by the Alfred P. Sloan Foundation, the Andrew Mellon Foundation, the U.S. Air Force Office of Scientific Research, and the Council on Foreign Relations.

elements, have introduced a closer interdependence between trade policy and other areas of policy, such as regulation, technology policy, and competition policy. Although the innovative activities of private firms now appear to be more internationalized than at any time in the past 75 years, the "home base" of many large, multinational corporations continues to count for a disproportionate share of their inventive activities. At the same time, however, the operation of national government policies, especially those seeking to support the development of "strategic technologies," may be enhanced or frustrated by the actions of the private firms that operate global networks for innovation and the commercialization of new technologies.

The roles of national and regional governments in science and technology policy also have changed, creating another source of interdependence and conflict. With the end of the Cold War and intensified global competition, governments face greater demands to deliver tangible economic returns from their investments of public funds in R&D projects and infrastructure. Such political demands can assume a nationalistic tone and have been associated with efforts by governments in Western Europe, Japan, and the United States to restrict access to publicly funded domestic technology development projects. Resolving these conflicts, which are often heightened by other cross-national contrasts in the structure of domestic R&D systems, requires a review, and perhaps a revision, of the conceptual framework that underpins many of these publicly funded projects. In the contemporary global economy, efforts to restrict the international movement or exploitation of the results of such projects are likely to prove futile, if not counterproductive.

The U.S. policy posture toward these changing circumstances needs to proceed from the premise that the rapid and efficient adoption by U.S. firms of new technologies from foreign or domestic sources, rather than their creation, is the primary source of economic benefit (see OECD [1996b], for a recent analysis of this issue). Such a shift will confront a tension between the interests of U.S. firms seeking a nationalistic technology policy and those of U.S. citizens (and in many cases, other U.S. firms) who benefit from expanded access by foreign firms to the U.S. R&D infrastructure and from more rapid inward transfer and application of technologies developed offshore.

The issues raised by global interdependence for science and technology policy are too numerous and complex to be addressed comprehensively in this paper. Instead, I survey developments in three broad areas: (1) the "globalization" of the U.S. R&D system, (2) trends in public R&D investments among major industrial and industrializing economies, and (3) some implications and challenges created by such interdependence for the formulation and implementation of U.S. science and technology policies.

THE "GLOBALIZATION" OF R&D IN THE UNITED STATES

The terms of the domestic debate over the desirability of international R&D have undergone at least three broad shifts in the past 25 years. U.S. firms' increased investments in offshore R&D during the 1960s sparked expressions of concern over the loss of employment and other technological opportunities associated with the domestic performance of R&D. This discussion was part of a broader debate over the benefits and costs to U.S. citizens of the expanding international activities of U.S.-headquartered multinationals, in which some participants argued that the private interests of U.S. multinationals no longer coincided with those of U.S. citizens. Beginning in the early 1980s, as foreign investment into the United States grew rapidly and this economy became an important host nation for foreign-owned enterprises, critics argued that such investments created employment opportunities only in low-wage, low-skill assembly operations, and did not bring with them the "high-value-added" activities of R&D and innovation. Most recently, R&D investment within the United States has been criticized as a means of "cherry-picking" the fruits of U.S. R&D, especially publicly financed basic research in U.S. universities, and that such foreign investments are a conduit for the export of technological advances and economic opportunities from the United States to foreign economies (see OTA [1994]). The most recent debate cites differences among the "national innovation systems" of the industrial and newly industrializing economies, suggesting that asymmetries in U.S. and foreign firms' access to the technologies developed in one another's home economies creates disadvantages for U.S. firms.

To shed more light on the significance and implications of increased internationalization of R&D, some disaggregation is necessary. The pattern and trends in international R&D investment seem to differ significantly among industries and among different activities within the innovation process. Extending the work of Archibugi and Michie (1995), one can distinguish among the creation of new technologies (often identified with invention), the development of these inventions into commercially attractive products, and the production and marketing of these new products. None of these activities is well measured within industrial economies, and our measures of their international dimensions are even less reliable. R&D investment, for example, includes both the creation and the development of new technologies, and in many cases is associated as well with the exploitation of these technologies (as in the case of "localization" of new products for specific offshore markets). The available evidence on trends in each of these three activities suggests that the most significant increases in "internationalization" have taken place in the exploitation of new technologies, largely as a byproduct of increased cross-border investment in production activities. Other evidence indicates that much of the technology creation activities of large firms remains concentrated in their home economies.

TRENDS IN INTERNATIONAL INNOVATIVE ACTIVITY

Existing measures of internationalization of innovative activity are flawed for a number of reasons. They do not distinguish among the different stages of the innovation process, as was noted above. Public data on international flows of R&D investment do not cover manufacturing industries very well; their longitudinal coverage is imperfect and their coverage of R&D investment outside of manufacturing is limited. Much of the relevant activity in industrial innovation, especially in smaller firms, is not captured by conventional measures of R&D investment. Finally, some important mechanisms for internationalization of innovative activity (e.g., strategic alliances) are not captured in R&D investment data. Other indicators, discussed below, share many of these defects.

Table M-1 reproduces data from the 1996 edition of *Science and Engineering Indicators* (National Science Board, 1996) on trends during 1980-1993 in U.S. outward R&D investment, measured as a share of industry-financed R&D spending overall and in each of 11 industrial sectors. One of the most interesting points to emerge from this table is the minimal growth in the share of total industry-financed R&D in the United States that is invested in offshore R&D. Rather than a steady increase, this share declined during 1981-1985, increased from 1985 through 1992, and shrank from 1992 to 1993. Across the entire time period, the share of industry-financed R&D devoted to foreign R&D decreased by 2 percent. The table also underscores the intersectoral differences in these trends—electrical equipment, petroleum extraction and refining, pharmaceuticals, and non-electrical machinery display declines during this period in foreign R&D investment, while scientific instruments increases slightly. The chemicals industry and nonmanufacturing industry (for which the time-series coverage is especially imperfect) both display significant increases in the share of their R&D spending devoted to foreign sites. Table M-2, which reproduces other data from *Science and Engineering Indicators*, shows that Western Europe was the primary destination for outward flows of U.S. R&D investment during 1983-1993, although Japan has increased its share of U.S. firms' offshore R&D.

Although outward R&D investment by U.S. firms has scarcely grown relative to overall industry-financed R&D, R&D investment by foreign firms in the U.S. economy has grown since the early 1980s. Table M-3, drawn from *Science and Engineering Indicators*, compares the shares of industry-performed R&D in the United States and other industrial economies financed by foreign sources. Within the United States, this share more than doubled during 1980-1993 (from slightly more than 3 percent of industry-performed R&D in 1980 to 9.8 percent in 1993); but as of 1993, industrial R&D in the United States was less dependent on foreign sources of funding than that in the United Kingdom or Canada, while exceeding levels of foreign-financed R&D in Japan and Germany.

R&D investment measures inputs into the innovation process, rather than

TABLE M-1 Share of company-financed R&D performed abroad by U.S. firms and their subsidiaries, 1980-93

Industry	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Total	10.4	9.6	7.7	7.3	7.1	6.4	7.7	8.5	9.3	9.1	9.7	10.1	10.7	10.2
Food	na	9.7	8.2	7.6	6.5	6.6	5.4	3.1	2.3	3.4	3.3	5.2	6.3	8.1
Industrial Chemicals	9.8	9.1	8.6	9.4	8.7	9.2	11.6	11.7	14.4	9.5	9.9	13.5	14.6	17.2
Pharmaceuticals	20.3	20.7	14.7	12.5	12.1	11.5	13.5	15.1	14.1	16.7	21.8	20	20.6	16.4
Petroleum	10.1	10.9	6.6	5	4.5	2.1	2	2.5	3	2.2	3.3	4.3	5.2	5
Stone etc.	na	4.4	2.1	3.2	8.5	na	na	na	na	na	11	8.4	8.6	7.1
Primary Metals	1.9	1.3	1.3	1.4	1.3	na	na	2.5	3.7	3.6	3.6	2.8	3.5	1.9
Fabricated Metal	na	5.5	4.4	3.6	2.7	2.7	3.3	6.3	na	na	12.9	11.5	15.1	12.7
Machinery	11.4	10	6.8	7.3	7.9	6.4	8.9	11.7	11.1	10.7	10.7	10.8	10.4	4.2
Electrical Machinery	8.3	7	7	5.9	5.9	6.4	na	4.1	5.9	6	8.3	7.	6	5.7
Transportation Equipment	14.7	11.4	9.8	9.8	8.7	8.5	na	na	12.6	13.1	14.4	16.2	na	na
Scientific Instruments	7.6	7.7	7	na	6.2	3.7	4.5	6.4	7.6	8.3	9.7	9.6	9.4	10.1
Nonmanufacturing	0.7	0.8	0.5	0.5	0.2	0.4	0.6	1.2	2	2.5	2.5	3.4	3.6	7

Source: National Science Foundation (1996a).

TABLE M-2 Site of R&D performed by majority-owned affiliates of U.S. companies, by region, 1982, 1990, & 1993 (Millions of current dollars)

Region	1982	1990	1993
Total	3,647	10,187	10,954
Canada	545	1,159	1,030
Europe	2,591	7,952	7,550
Asia/Pacific (non Japan)	190	334	1,081
Japan	104	512	862
Latin America	179	201	384
Mideast	11	16	29
Africa	26	13	18

Source: National Science Foundation (1996a).

TABLE M-3 Percentage of industrial R&D expenditures financed from foreign sources, 1980-94

	Canada	France	Germany	Italy	Japan	United Kingdom	United States
1980	na	na	na	na	na	na	3.4
1981	7.4	7	1.2	4.3	0.1	8.7	na
1982	10.7	4.8	1.3	4.7	0.1	na	na
1983	16.6	4.6	1.4	4.3	0.1	6.8	na
1984	17.1	6.5	1.5	6.2	0.1	na	na
1985	14.3	6.9	1.4	6.1	0.1	11.1	na
1986	13.6	8	1.4	7.3	0.1	12.2	na
1987	16.8	8.7	1.5	6.9	0.1	12	4.9
1988	18	9.2	2.1	6.6	0.1	12	5.7
1989	16.8	10.9	2.7	6.5	0.1	13.4	6.6
1990	17.4	11.1	2.7	7.3	0.1	15.5	7.8
1991	18	11.4	2.6	8.6	0.1	16	7.8
1992	na	12	2.7	5.4	0.1	15	9
1993	na	na	2.9	6	0.1	15.4	9.8
1994	na	na	na	6.4	na	na	na

Source: National Science Foundation (1996a).

outputs. The only reliable data on technology creation are patenting statistics, which have important drawbacks (e.g., the widely remarked differences among industries in their propensity to patent), but nevertheless capture an important input into the innovation process that is "downstream" from R&D investment. In addition, patents contain information on the site of the invention that is assigned to a corporate entity, revealing the geographic location of the inventive activities of U.S. and other multinational corporations.

The patent data compiled by Patel (1995) suggest that the technology creation activities of large firms, measured by the site of the inventions underlying the U.S. patent applications of U.S. and foreign corporations, are less internationalized than their manufacturing operations, sales, or (in many cases) their R&D investment. Patel analyzed the patents obtained by 569 of the world's largest firms during 1985-1990 (Patel's 1995 work extends work by Patel and Pavitt [1991]). Table M-4, from Patel's study, shows that the U.S. patenting activity of large firms from the United States, Japan, France, Italy, and Germany is dominated by domestic inventive activity, based on the reported site of the patented invention—more than 85 percent of these firms' U.S. patents are based on "home-country" inventive activity. For U.S. and Japanese firms, these shares exceed 90 percent. Large firms from Great Britain, Canada, Sweden, the Netherlands, Switzerland, and Belgium are less domestically focused in their inventive activity but, with the exception of Dutch and Belgian firms, all of these firms report that more than 50 percent of their patents are based on inventions from their home

TABLE M-4 Geographic location of large firms' U.S. patenting activities, according to nationality, 1985-1990 (percentage share)

			Of which			
Firms' nationality	Home	Abroad	United States	Europe	Japan	Other
Japan (139)	99.0	1.0	0.8	0.2	—-	0.0
United States (243)	92.2	7.8	—-	6.0	0.5	1.3
Italy (7)	88.2	11.8	5.3	6.2	0.0	0.3
France (25)	85.7	14.3	4.8	8.7	0.3	0.6
Germany (42)	85.1	14.9	10.4	3.9	0.2	0.4
Finland (7)	82.0	18.0	1.6	11.5	0.0	4.9
Norway (3)	67.9	32.1	12.7	19.4	0.0	0.0
Canada (16)	67.0	33.0	24.9	7.3	0.3	0.5
Sweden (13)	60.8	39.2	12.6	25.6	0.2	0.8
United Kingdom (54)	57.9	42.1	31.9	7.1	0.2	3.0
Switzerland (8)	53.3	46.7	19.6	26.0	0.6	0.5
Netherlands (8)	42.2	57.8	26.1	30.6	0.5	0.6
Belgium (4)	37.2	62.8	22.2	39.9	0.0	0.6
All firms (569)	89.1	10.9	4.1	5.6	0.3	0.8

Note: The parenthesis contains the number of firms based in each country.

Source: Pari Patel.

countries. Equally interesting is the geographic distribution of inventions made outside of their home countries by these firms. Their foreign inventive activities are sited primarily in Europe and the United States.

If this measure suggests that technology creation remains "localized," other evidence suggests that the activities further downstream in the innovation process, such as development and exploitation of technology, are more international in scope. Foreign firms seek U.S. patents in order to exploit their technologies in this market. The size and importance of the U.S. economy are such that most foreign firms are likely to apply for U.S. patents on only their most important inventions—in other words, foreign patents are likely to be somewhat higher in quality than patents assigned to U.S. firms and domestic inventors. Figure M-1 plots trends in the share of all U.S. patents granted during 1973-1993 that were obtained by foreign inventors. Foreign inventors' share of U.S. patents grew from less than 38 percent in 1978 to roughly 45 percent by 1993. Interestingly, increases in the share of non-U.S. inventors receiving patents did not result from growth in the share of patents granted to inventors from Japan, Germany, or other members of the G-7**.** Instead, this growth appears to reflect increased U.S. patenting by individuals and firms from a more diverse array of foreign nations. Although the share of U.S. patents received by foreign inventors has declined from its 1988 peak, it remains well above the 1973 level.

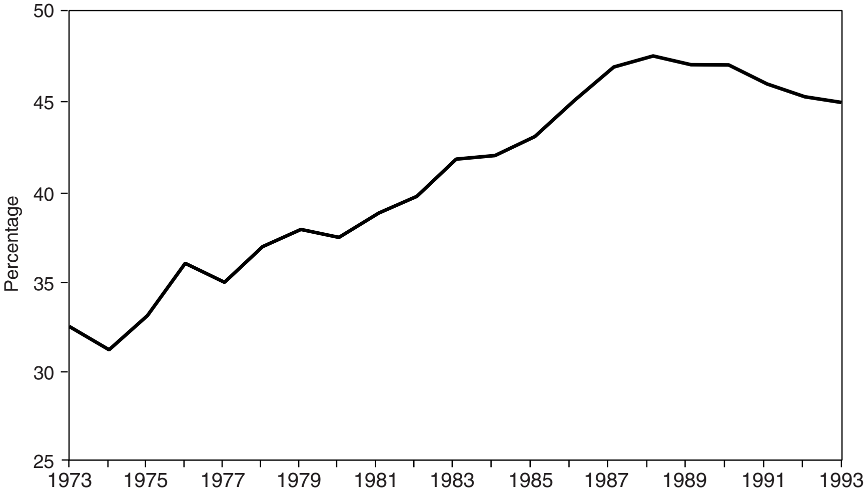

FIGURE M-1 Share of US. patents granted to foreign inventors (1973–1993)
Source: U.S. Patent and Trademark Office, Fiscal 1993 Annual Report.

Another indicator of the international reach of technology development and exploitation activities is the formation of international strategic alliances, which typically focus on the development, manufacture, and marketing of new products, rather than invention or basic research. The number of such alliances has grown since 1980, and they now appear in industries (e.g., commercial aircraft) that historically have not been major sources of direct foreign investment. During the 1980-1989 period, nearly 600 such alliances were formed between U.S. and Japanese firms, and more than 900 between U.S. and European firms (National Science Board, 1993). Thus far, very few of these alliances link U.S. firms with those from newly industrializing economies such as Taiwan or South Korea (Mowery et al., 1996), although such links are likely to increase in the future.

These alliances focus on the commercialization and exploitation of new technologies rather than the basic research underpinning their creation. Growth in alliance activity is attributable in part to the increased importance of foreign sources of technology for U.S. high-technology firms, but this trend also reflects the economic importance of foreign markets for these U.S. firms. Foreign markets for such high-technology industries as commercial aircraft are projected to grow more rapidly than the U.S. domestic market during the next 20 years. Faster growth in these large foreign markets combined with the need to recover the escalating costs of new product development have increased the economic importance to U.S. high-technology firms of penetration of foreign markets. The growth in alliances in at least some high-technology industries also reflects the response of U.S. and foreign firms to nontariff barriers to trade and investment, as well as government policies that seek to restrict access to domestic strategic technology programs, such as SEMATECH in the United States and JESSI in Western Europe (Mowery, 1997). These and other government efforts to restrict the international mobility of technology-based "created assets" paradoxically contribute to the formation of interfirm alliances that support such mobility.

Still another measure of the global scope of technology exploitation concerns the licensing of technologies. Here too, the balance between outflows from and inflows into the U.S. economy appears to have shifted somewhat in the 1990s. U.S. receipts of royalty and licensing income grew at an average annual rate of 20 percent during 1986-1990, but slowed to 7 percent per year during 1990-1993, and grew by only 2 percent during 1992-1993 (Figure M-2). The data in Figure M-2 portray trends in U.S. imports and exports of technology, as measured by licensing and royalty income and payments. These data reflect receipts and payments covered by all extant agreements; a far more revealing measure, for which the U.S. government does not collect data, concerns the "balance of trade" on only the contracts and agreements signed during the previous year. Japanese data on new contracts and agreements reveal a dramatic improvement in that nation's importance as an exporter of industrial technology (Mowery and Teece, 1993). The 1992-1993 slowdown in nominal growth may reflect the cyclical downturns in Western Europe and Japan (receipts from Western Europe declined

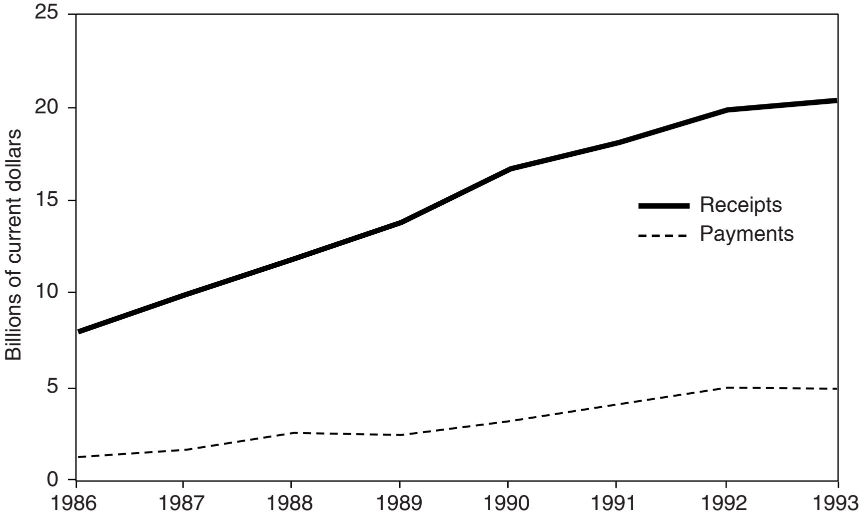

FIGURE M-2 U.S. royalty and licensing receipts and payments (1986–1993)
Source: Survey of Current Business, September 1994.

during 1992-1993). But these measured trends are dominated by intrafirm flows of technology—in 1992, 80 percent of U.S. receipts were accounted for by technology exports to foreign affiliates, a modest increase from 75 percent in 1986, and the average annual growth rate of intrafirm receipts during 1986-1992 exceeded that for exports to nonaffiliates.

U.S. payments of royalties and licensing fees grew even more rapidly than U.S. receipts during 1986-1993, registering an average annual growth rate of 23 percent during 1986-1990, and 16 percent per year during 1990-1993, although these payments declined by 3 percent during 1992-1993. These payments also are dominated by intrafirm transactions, although the share of affiliates is lower. In both 1986 and 1992, intrafirm technology flows accounted for approximately 65 percent of total U.S. technology imports. The importance of intrafirm transactions within both technology exports and imports makes it difficult to infer much about the technological competitiveness of the U.S. economy from these trends. The apparent increase in the role of foreign affiliates of U.S. multinationals as sources of licensing fees and royalties, for example, could reflect a tendency for these offshore affiliates to receive more advanced technologies from their U.S. parents, as offshore sites have become more attractive locations for advanced production operations than the United States. These trends might also result from stronger international intellectual property rights, which facilitate the arms-length transfer of technology between parent and affiliate.

In summary, these indicators reveal increases in foreign-financed R&D within the U.S. economy to levels that approach those observed for some time in several European nations. By contrast, the outward flow of U.S. R&D investment has remained nearly constant (as a share of total U.S. industry-financed R&D spending) since the early 1980s, although this flat overall trend conceals significant interindustry variation. Still other evidence suggests that the earliest stages of the innovation process are the least internationalized, by comparison with the exploitation or commercialization of technologies. The data on foreign firms' patenting activity in the United States, licensing and royalty income, and international strategic alliances also suggest that the channels through which R&D "internationalization" takes place are expanding in number and changing in structure. Finally, as was noted above, it is important to keep in mind the imperfections in these measures. They focus on inputs to the process of industrial innovation, their coverage of nonmanufacturing industry is poor, and they do not cover important phases of the overall process of industrial innovation.

EXPLAINING THE TRENDS

The most straightforward explanation for the trends in international innovation is based on work by Cantwell (1991, 1995), who emphasizes the use by multinational firms of international R&D strategies to create interfirm and intrafirm networks for the creation and strengthening of firm-specific knowledge and technological capabilities. This view contrasts with the previous view (articulated in Vernon's [1966] celebrated product-cycle model) of multinational firms' R&D strategies as motivated primarily by efforts to exploit products developed to serve the market of their high-income home economies in foreign markets. Both motives influence international R&D strategies, but there is some basis to suspect that the first will become more important in the future.

Cantwell and others argue that the acquisition or maintenance of firm-specific technological capabilities relies on extensive contacts with external sources of expertise in both the home and foreign economies. These contacts require either a physical presence or some other complex organizational form, because of the difficulties of transferring technologies through conventional contracts or market channels. The local infrastructure supporting the creation of these competencies may be very concentrated in a specific region, such as the Silicon Valley in California or the biotechnology complex around Boston. As a result, specific sites become centers for specific technological competences and attract considerable investments by multinational firms in R&D and often production (because of the need for close links between this activity and R&D):

> [F]irms may wish to directly establish production in a foreign centre of innovation in order to gain access to a potential source of technological development which is distinctive to firms operating in that location but complementary to their own. Certain aspects of innovation which are specific to the foreign loca-

> tion can then be incorporated by the firm into a broadening of its own path of technological development. In such cases intra-industry production will tend to replace intra-industry trade, as the most innovative firms ensure that they expand their research and production in all the most important locations for technological activity in their sector. (Cantwell, 1991, pp. 135-136).

Such motives for offshore R&D investment also tend to direct such outward flows to other industrial economies, consistent with the data in Table M-2.

These influences on cross-national R&D investment and other forms of international interaction in the innovation process resemble the factors that have given rise to high levels of intraindustry trade—the growing returns to specialization in specific technological activities or competences, some apparent decline in "scope economies" among specific competences (reflected as well in the recent efforts of U.S. firms to restructure, divest unrelated lines of business, and focus on "core competences"), and the increased international dispersion of these competences. As a result, we find firms in industries such as pharmaceuticals seeking to establish R&D centers in "centers of excellence" around the world, even as these R&D centers specialize in certain products or drug therapies. Strategic alliances among firms for the development or manufacture of new products often are based on the effort of participants to combine their complementary technological and other skills. Indeed, recent work by Mowery et al. (1996) suggests that a substantial fraction of recent strategic alliances tends to enhance the dissimilarity of participants' technological capabilities. Other strategic alliances, however, result in high levels of interfirm learning and transfer of such capabilities, producing greater similarity among participants' technological capabilities. This observation underscores the broader point that both technology transfer and knowledge accumulation are aided by cross-national R&D investments and other international linkages in the innovation process.

International flows of R&D investment thus are attracted to national or regional economies that can nurture specific technology-based capabilities, just as other types of international investment flows tend to reward policies favoring economic stability, property rights, and human capital. This argument has two implications. Even as the nationality of investors in R&D activity within a given locality may become more and more blurred, the importance of "national innovation systems" in supporting the infrastructure and other local capabilities to attract these investments remains important. Increased cross-national R&D investment thus may not reduce international or even intranational differences in such localized capabilities and infrastructure. (Within the United States, for example, California's Silicon Valley remains a dominant center for R&D in the electronics industry, although it now has scarcely any semiconductor manufacturing capacity.) Cantwell (1995) asserts that "The globalisation of technological innovation in MNCs, in the sense here of an international integration of geographically dispersed and locally specialised activities, tends to reinforce and not to dismantle nationally distinctive patterns of development or national systems of innovation…. Contrary to what is sometimes alleged, globalisation and national specialisation are complementary parts of a common process, and not conflicting trends" (p. 171). Secondly, these localized capabilities are developed through path-dependent processes in which both supply and demand factors, as well as history, matter a great deal.

R&D INVESTMENT TRENDS IN INDUSTRIAL AND INDUSTRIALIZING ECONOMIES, 1980-1995

This section discusses recent trends in R&D investment, primarily government-funded R&D, in the United States and other industrial and industrializing economies since 1980. Especially among the member states of the Organization for Economic Cooperation and Development (OECD), restructuring of domestic R&D systems has followed broadly similar lines since the early 1980s, largely as a result of the end of the Cold War. But many of the features that distinguished the U.S. federal R&D budget from those of other industrial economies, including its size and emphasis on defense-related and health-related objectives, remain salient. This cross-national comparison of industrial-economy public R&D spending also includes the European Commission, whose civil R&D spending priorities contrast with those of both Western European member states and other industrial economies. What is lacking in this comparison, however, are measures of effectiveness, be these defined in terms of "R&D productivity" or some other measure of economic or social returns from public R&D expenditures. The only reliable data for cross-national comparisons involve input measures, but the real concern for policy is the relationship between inputs and outputs. Nonetheless, although measures of performance are lacking, there is abundant anecdotal and descriptive evidence that suggests that performance is affected at least as much by the structure of government R&D programs and supporting policies as by the scale of these budgets.

The United States

The most dramatic shift in spending trends within the U.S. R&D system during the past 15 years is the decline in R&D spending by the federal government. Having grown at an average rate of 6 percent per year in real terms during 1980-1985, inflation-adjusted federal R&D spending declined at an average rate of roughly 1 percent per year during 1985-1995. R&D spending from "Other nonfederal sources" (R&D funded by state and local governments, as well as universities and colleges) grew by 2 percent in real terms during 1994-1995. The National Science Foundation (NSF) data currently available from the updated version of *National Patterns of R&D Resources: 1996* provide only estimated levels of R&D spending for 1996 and 1997 (NSF, 1996), and these are less reliable, particularly for industry-funded R&D investment, than the actual spending levels reported (with a lag) by the NSF. In addition, revisions in NSF data collection procedures mean that the data on industry-funded R&D before and after 1991 are not strictly comparable with one another, especially for the disaggregated components of R&D spending and for individual industries (see NSF [1996]). Accordingly, our discussion of spending trends covers only the period through 1995, and we confine the analysis of trends in the components of industry-funded R&D investment to the 1991-1995 period. The other major source of R&D spending within the U.S. system is industry, which accounted for 59 percent of total R&D spending in 1995. Industry-financed R&D scarcely grew at all in real terms during the early 1990s, but this trend was reversed in 1993, and the NSF data for 1993-1995 reveal that real industry-funded R&D spending grew at an average annual rate of nearly 10 percent during that period (NSF, 1998).

These shifting growth trends in industry- and government-funded R&D have produced wide swings in the rate of growth in overall U.S. R&D spending since 1980. Total national R&D spending grew by nearly 7 percent annually in constant-dollar terms during 1980-1985, but during 1985-1993, the average annual rate of growth in total constant-dollar R&D spending declined to 1 percent. More recently, however, total U.S. R&D spending has grown in real terms at an average annual rate of almost 3 percent between 1993 and 1995.

Declines in federal R&D spending are largely due to reductions in defense-related R&D spending, which increased from 50 percent of federal R&D spending in 1980 to almost 70 percent by 1986, a level from which it has declined once again to approximately 52 percent of total federal R&D spending. NSF measures of the share of defense-related spending in the U.S. federal R&D budget are somewhat lower than those from the OECD, which estimates the 1996 defense-related share of U.S. R&D spending to be closer to 55 percent. Both sets of data, however, highlight a decline in this share since 1980. The economic consequences of this reduction in defense-related R&D spending are difficult to project. Technological “spillovers” from defense to civilian applications of this spending now are less significant than was true of the 1950s and early 1960s, as the requirements for military and civilian applications in such technologies as aerospace and electronics have diverged. In addition, a considerable portion of federal defense-related R&D spending was directed to applied research, such as weapons testing, that generated few civilian economic benefits. Nevertheless, the enormous defense-related R&D budget contained a substantial basic research component, and defense-related R&D accounted for a considerable share of federally funded research in U.S. universities in such areas as electronics (see below). Reductions in spending in these areas could have negative consequences for civilian innovative performance. Further reductions below this share of the overall federal R&D budget appear to be unlikely, although pressure for increased procurement spending may increase the share of development activities within the defense-related R&D budget.

The outlook for growth in federal civilian R&D spending is uncertain. Legislative actions by the Senate and the House of Representatives in 1997 increased the fiscal 1998 federal R&D budget by more than 4 percent above its prior-year levels, and more recent forecasts of budgetary surpluses may result in further increases in federal R&D spending, especially in biomedical research. Longer-term trends, however, are less favorable for civilian R&D spending. In the absence of political agreement on reductions in entitlement spending for the elderly and health care, growth in these items will constrain growth in federal R&D spending. Even in the context of a balanced overall federal budget, a state of grace that is likely to be temporary at best, it is unlikely that future federal R&D spending will increase significantly above its 34 percent share of total U.S. R&D spending for 1995.

Another important shift in the profile of U.S. R&D spending growth during the 1990s is the reduction in the share of “research” within overall “R&D.” During 1991-1995, total U.S. spending on basic research (measured in 1992 dollars) declined at an average rate of almost 1 percent per year. Industry-funded basic research dropped from $7.4 billion in 1991 to $6.2 billion in 1995 (in 1992 dollars)—real federal spending on basic research increased slightly during this period, from $15.5 to almost $15.7 billion. Industry-funded investments in applied research scarcely grew during this period, while federal spending on applied research declined at an annual rate of nearly 4 percent. In other words, the upturn in real R&D spending that has resulted from more rapid growth in industry-funded R&D investment is almost entirely attributable to increased spending by U.S. industry on development, rather than research. Indeed, the NSF reports that industry-funded real spending on “development” grew by more than 14 percent during 1991-1995, from $65 billion to $74.2 billion (federal development spending declined during this period, reflecting the cutbacks in defense-related R&D spending).

Extrapolation of future trends from recent data that cover only four years is hazardous. Nevertheless, if the trends of the early 1990s continue unabated, U.S. R&D spending could change its profile and pattern of growth significantly. The reduction in the federal government’s share of overall R&D means that increased federal R&D spending will do less to offset the effects of any future reductions in the rate of growth in industry-financed R&D spending on overall U.S. R&D spending levels. Since industry-funded R&D investment tends to move procyclically, future trends in total U.S. R&D spending are likely to be more sensitive to the domestic business cycle. In addition, the reduction in the federal government share of total R&D spending and the apparent shift in the profile of industry-funded R&D spending to favor development more heavily than “upstream” research activities (basic and applied research) could shorten the time horizon of overall U.S. R&D investment, with important consequences for both national and international scientific and technological advance.

Comparing the U.S. and Other Industrial Economies

How do U.S. R&D spending trends compare with those of other major industrial economies? One of the most important and dramatic trends is the declining share of global R&D spending accounted for by the United States. Figure M-3 displays trends during 1960-1994 in the U.S. share of total G-7 R&D spending, along with trends in the U.S. share of total R&D spending within the OECD economies since 1990. Within the G-7, U.S. R&D spending has declined from almost 70 percent of the total in 1960 to slightly more than 48 percent in 1994. The bulk of this decline occurred during 1960-1980, and the U.S. share of G-7 R&D spending has been nearly constant since 1990. Interestingly, the U.S. share of OECD R&D spending has increased slightly since 1990, from 42.8 percent in 1990 to 43 percent in 1994.

The overall decline in the U.S. share of G-7 R&D is by no means undesirable. First, it reflects the successful reconstruction and growth of the European and Japanese economies since 1945, developments that have contributed to international political and economic stability. Second, the growth of non-U.S. R&D spending creates opportunities for U.S. taxpayers to benefit from the public expenditures of foreign governments, just as foreign citizens have benefited from U.S. public financing of R&D. But it is critically important that U.S. firms and nationals have access to these foreign R&D programs, an issue that has sparked controversy in the past.

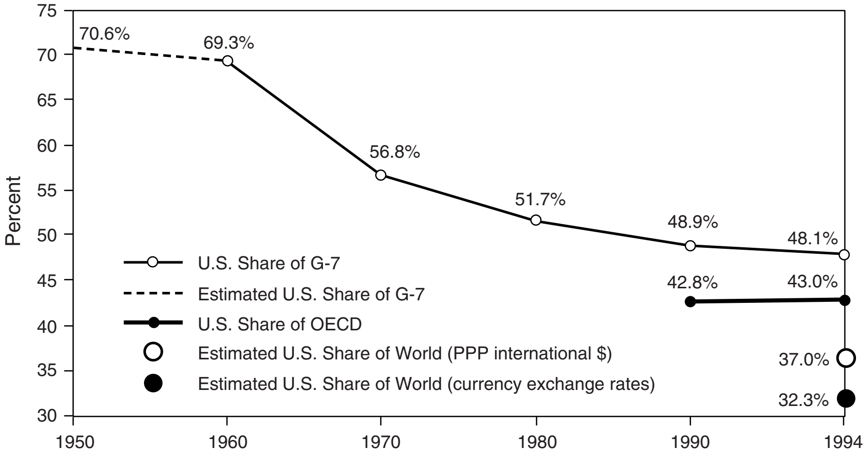

FIGURE M-3 U.S. share of G-7, OECD, and World R&D
Source: U.S. Department of Commerce.

Beyond its declining relative size, how do recent changes in the structure of the U.S. R&D system compare with those in other OECD economies? The most recent comparative data suggest that structural change in the pattern of U.S. R&D spending and performance since 1980 parallel trends in other OECD economies. Table M-5 contains data on trends during 1971-1993 in the distribution of R&D performance and funding among government, academia, and industry in the five OECD member states with the largest R&D budgets. These indicators suggest that the post-1981 restructuring of the sources of funding in the U.S. R&D system resembles similar processes in the United Kingdom, France, Germany, and Japan—the share of public funding of R&D is declining and industry R&D funding is growing (although the Japanese government made a public commitment in 1996 to significantly increase public R&D spending, slow economic growth may constrain growth in public R&D spending). The sharpest decline in public-sector R&D funding among these five nations during 1981-1993 occurred in the United Kingdom, where the share of national R&D spending funded by public sources dropped by roughly one-third. In both the United States and France, public funding declined by approximately 10 percent of R&D spending, a decline in the public share of roughly one-fifth. The data for Germany and Japan reveal smaller declines in the public share through 1993.

The shifts during 1981-1993 among universities, industry, and government in the performance of R&D within these five economies are less significant (again, with the exception of the United Kingdom, where a number of public research laboratories have been privatized). The data for the United States reveal very small increases (a shift of less than 1 percent in the share of each) in the share of R&D performed by industry and universities, and a slightly larger decline (of nearly 2 percent) in the share of R&D performed in government laboratories. The share of publicly performed R&D in both Japan and France declined by comparable or slightly larger amounts, while the German data (which include the effects of unification) rise modestly. The United Kingdom data, however, reveal a sharp decline of nearly 7 percent in the share of R&D performed in government facilities.

If there is an "outlier" in these measures of structural change since the early 1980s in national R&D systems, it is the United Kingdom, rather than the United States. In general, the shifts in funding sources in the United States and these other economies are slightly larger than the shifts in performance. Indeed, the contrasting magnitude of the shifts in funding sources, as opposed to R&D performance, reflects the difficulties of undertaking radical structural changes in national R&D systems of the sort observed in the United Kingdom. The political costs of closing or privatizing large public research establishments often outweigh those associated with the gradual shrinkage of such facilities through incremental shifts in the shares of public and private R&D spending.

TABLE M-5 Structural change in the five largest OECD national R&D systems, 1971-1993

Sources of R&D Finance (percentage)

	Industry				Government				Other national sources			
	1971	1981	1991	1993	1971	1981	1991	1993	1971	1981	1991	1993
United States	39.3	48.8	57.5	58.7	58.5	49.3	40.5	39.2	2.1	1.9	2.0	2.1
Japan	64.8	67.7	77.4	73.4	26.5	24.9	16.4	19.6	8.5	7.3	6.1	7.0
France	36.7	40.9	42.5	46.2	58.7	53.4	48.8	44.3	0.9	0.6	0.7	1.3
Germany	52.0	57.9	61.7	60.2	46.5	40.7	35.8	37.0	0.6	0.4	0.5	0.5
United Kingdom	43.5	42.0	50.4	52.1	48.8	48.1	34.2	32.3	2.3	3.0	3.6	3.9

Shares of Total R&D Performance (percentage)

	Industry				Government				Other national sources			
	1971	1981	1991	1993	1971	1981	1991	1993	1971	1981	1991	1993
United States	65.9	70.3	72.8	71.2	15.5	12.1	9.9	10.2	15.3	14.5	14.1	15.2
Japan	64.7	66.0	75.4	71.1	13.8	12.0	8.1	10.0	19.8	17.6	12.1	14.0
France	56.2	58.9	61.5	61.7	26.9	23.6	22.7	21.2	15.6	16.4	15.1	15.7
Germany	63.7	70.2	69.3	66.9	14.2	13.7	13.9	14.8	21.6	15.6	16.3	18.1
United Kingdom	62.8	63.0	65.6	65.9	25.8	20.6	14.2	13.8	8.7	13.6	16.3	16.5

Source: OECD (1996b).

Comparing the Objectives of Public R&D Spending

Although the patterns of structural change in these large industrial-economy R&D systems display considerable similarity, substantial differences remain in the objectives of their public R&D spending. These contrasts are heightened when the R&D budget of the European Commission, which accounts for roughly 4 percent of total government R&D spending in Western Europe, is added to a comparison of civil and defense-related R&D spending in 1991 and 1996 (Tables M-6 and M-7).

Despite the sharp cutbacks in defense spending and defense-related R&D, for example, the United States continues to spend substantially more on defense as a share of its central government R&D budget than any of these other indus-

TABLE M-6 Defense-related R&D as a share of total government R&D spending, 1991 and 1996 (% of total government R&D budget)

	Defense		Civil	
	1991	1996	1991	1996
United States	59.7	54.7	40.3	45.3
Japan	5.7	5.9	94.3	94.1
Germany	11.0	9.8	89.0	90.2
France	36.1	29.0	63.9	71.0
United Kingdom	43.9	37.0	56.1	63.0
European Commission	0.0	0.0	100.0	100.0

Source: OECD (1998).

TABLE M-7 Composition of government-funded civil R&D by program goal (% of civilian R&D budget), 1991 and 1996

	Economic Development		Environment/ Health		Space		Basic research n.e.c.	
	1991	1996	1991	1996	1991	1996	1991	1996
United States	22.1	20.5	43.5	45.1	24.5	25.2	9.9	9.2
Japan	33.5	34.4	5.7	6.9	7.2	7.0	8.5	10.2
Germany	25.5	23.1	13.0	12.7	6.0	5.5	17.0	16.5
France	32.8	19.1	9.8	12.5	13.5	15.3	23.9	27.0
United Kingdom	28.8	16.6	22.3	31.7	4.8	4.3	9.1	18.3
European Commission	82.1	63.6	10.7	18.1	0.7	1.7	3.0	6.7

Source: OECD (1998).

trial economies. Reflecting its lack of responsibility for national security matters, the entirety of the European Commission's R&D budget is devoted to civil R&D. In 1995, the United States spent a smaller fraction of gross domestic product on nondefense R&D than any nation besides the United Kingdom among the five nation-states in this comparison (NSB, 1998).

There are also significant differences in priorities within the civilian R&D budgets of these five nations and the European Commission (Table M-7), contrasts that are stable across the 1991-1996 time period. The United States devotes a larger share of its civilian R&D budget to environmental and health objectives than any other entity in Table M-6—more than 6 times the environmental and health R&D share of the Japanese civil R&D budget in 1995, and more than 3 times this share in the German or French civil R&D budgets. The vast majority of the U.S. "environment and health" civil R&D budget is devoted to biomedical research. Interestingly, the share of the U.S. civil R&D budget devoted to "economic development" objectives (the OECD survey from which these data are taken defines "economic development" to include "promotion of agriculture, fisheries, and forestry; promotion of industry; infrastructure; energy" [OECD, 1997, p. 27]) does not differ greatly from those of the four other nation-states in Table M-7, as the United States ranks ahead of France and the United Kingdom, but behind Japan and Germany, in this share. The European Commission, however, allocated more than 60 percent of its R&D budget (more than $2.5 billion) to economic development, almost twice as high a share as that in Japan's civil R&D budget. The United States also devoted a much higher share of its civil R&D budget than any of these other nations to space exploration in both 1991 and 1996. Reflecting the longstanding dominance of the U.S. R&D budget by mission-oriented agency spending, the share of U.S. civil R&D allocated to undirected basic research was lower in 1996 than that of any other nation-state in Table M-7.

Both the European Commission and Japan also devote significant resources to electronics-related R&D within their civil R&D budgets. More than $370 million ECU (approximately $450 million to $500 million) were allocated by the European Commission in 1995 to support R&D in electronics. The Japanese government announced a new initiative in semiconductor-related R&D in 1996, involving public contributions of roughly $100 million to $110 million to a set of public-private collaborations whose total annual budget is nearly $200 million (Flamm, 1996). In contrast to many previous government-sponsored collaborative R&D projects, Japanese universities are involved in this initiative.

Nevertheless, these programs in electronics and information technology R&D are dwarfed by recent U.S. government-funded initiatives. The federal High-Performance Computing and Communications (HPCC) program spent more than $700 million in fiscal 1993 alone, and more than $1 billion annually in fiscal 1997 and 1998 (AAAS, 1997). The HPCC program includes the bulk of NSF spending on information technology R&D, but the Department of Defense (DoD) contributes additional funds to support R&D in both academia and industry in this area. In fiscal 1995, the federal government spent $766 million on R&D in electrical engineering, $793 million on R&D in metallurgy and materials science, and $982 million on R&D in computer science. This total includes funds allocated to the HPCC. DoD funds accounted for more than 62 percent of this total budget of more than $2.5 billion (NSF, 1997). U.S. federal R&D spending in fields supporting advances in electronics and computer technology thus appears to be substantial.

Governments in the industrializing Asian economies, including South Korea, Indonesia, Taiwan, and Singapore, also laid plans for higher public spending on R&D in the 1980s and 1990s. By the late 1980s, industrial technology projects accounted for almost 20 percent of Taiwan's government R&D budget (Schive, 1995). In both Taiwan and South Korea, the Asian economies with the strongest electronics and semiconductor industries, the role of government shifted by the mid-1990s. In the 1970s and 1980s, governments encouraged inward technology transfer and supported applied R&D in industrial and government laboratories. As domestic firms developed their capabilities, government-performed R&D lost much of its importance and effectiveness. Beginning in the 1990s, both South Korea and Taiwan sought to develop domestic R&D infrastructures capable of supporting R&D at the frontiers of technology, rather than the sorts of "catch-up" activities involving the inward transfer, adoption, and improvement of technologies developed elsewhere. Among other mechanisms, increased funding of academic R&D, the reform of higher education, and the development of "science parks" have played important roles in these recent efforts.

Despite increased public R&D spending, however, the even more rapid growth of privately funded R&D spending in both economies reduced the publicly financed share of total R&D investment during the 1980s (Dahlman and Kim, 1992; Schive, 1995). In South Korea, as well as Malaysia and Indonesia, two other Asian economies seeking to strengthen their domestic R&D capabilities, the financial crisis now roiling the region is likely to further reduce the government share of total R&D investment. A few others, however, such as Taiwan, are maintaining programs of public-private collaboration in industrial and academic R&D.

Public R&D spending priorities in the United States contrast with those of other major industrial economies, contrasts that are heightened when the significant R&D programs of the European Commission are added to the comparison. The United States continues to devote a larger share of total public R&D spending to defense (a significant portion of which goes to support R&D in information technology and electronics, some of which in turn yields civilian technological "spin-offs"). In addition, within its civilian R&D budget, the U.S. government spends a much larger fraction of total resources on health-related and space R&D.

Any assessment of the likely effects of these contrasting priorities must recognize that the scale of the overall U.S. federal R&D budget exceeds those of other nations and the EU by such a wide margin that even R&D priorities (such as information technology) that account for relatively small shares of the total federal R&D budget still receive a level of investment that compares favorably with those of other governments. Moreover, the economic effects of public R&D programs are heavily affected by the structure of these programs and the R&D systems within which they operate. Previous large-scale regional European programs of "strategic-technology" R&D in information technology (e.g., ESPRIT, JESSI) have failed to prevent the decline of large segments of the European information technology industry. Recent Japanese initiatives, such as the Fifth Generation computer technology program that sparked a hysterical reaction in the United States, as well as other collaborative efforts in software technology (see Baba et al. [1996]), have had little effect on the competitive fortunes of Japanese electronics and computer firms. Many European programs have been hampered by cumbersome and inflexible administrative structures, as well as continuing pressure to distribute R&D funds among EU member states in some equitable fashion. In addition, regulatory, trade, and competition policies within EU member states often have insulated domestic firms from competition, reducing pressure to adopt and implement the results of these R&D programs more rapidly. Japanese collaborative programs have suffered from the inability of program designers to develop a sufficiently robust and reliable "vision" of future technology developments to coordinate the R&D efforts of firms and universities effectively in "frontier" areas of science and technology that are subject to severe uncertainties.

The pluralistic institutional and programmatic environment of the United States as well as the large-scale and highly competitive nature of the U.S. domestic market have in recent years produced high rates of product innovation that have yielded high economic returns. But U.S. firms arguably remain weaker in the "cyclical innovation" highlighted by Gomory (1989) as critical to long-term competition in more mature markets. In addition, Japanese and European policy makers are aware of the structural weaknesses of their innovation systems, and future programs may prove to be more effective. Although the recent performance of the U.S. R&D system seems to compare favorably with those of many nations, U.S. managers and policy makers cannot be complacent. As international competition is based more and more on knowledge, the assets and capabilities that produce national competitive advantage become more and more mobile across international boundaries. Competitive and technological challenges are likely to appear from unexpected quarters and will emerge more rapidly.

IMPLICATIONS

Although overall U.S. foreign R&D investment has been growing slowly during the past 15 years, cross-national R&D investment, especially inward R&D investment in the U.S. economy, and other forms of interaction between U.S. and foreign firms in the technological innovation process are virtually certain to grow in the future. The forces giving rise to these trends are both pervasive and deeply rooted in the economic reconstruction and global growth that have characterized the post-1945 era. What does this imply for the future evolution of "systems frictions" in the areas of technology and trade policy that have previously been discussed by Ostry (1990)? In this section, I briefly consider possibilities for conflict flowing from the unusual structure of the U.S. "national innovation system" within the global economy, and then discuss some implications for U.S. technology policy.

National Innovation Systems in Technologically Interdependent Economies

The concept of a "national innovation system" emerged from earlier work by Freeman (1987) and Nelson (1993), among others. A "national innovation system" refers to the collection of institutions and policies that affect the creation, development, commercialization, and adoption of new technologies within an economy. As such, the U.S. national innovation system includes not just the institutions performing R&D and the level and sources of funding for such R&D, but policies—such as antitrust policy, intellectual property rights, and regulatory policy—that affect investments in technology development, training, and technology adoption. But government policies by no means determine all elements of the structure of national innovation systems, which are themselves the result of complex historical processes of institutional development. Moreover, the performance of these systems within most industrial economies depends on the actions and decisions of private enterprises, and these decisions can reinforce or offset the effects of public policies.

Much of the current controversy over foreign firms' exploitation of U.S. technological assets through their R&D investments in this economy (OTA, 1994) rests on a set of assertions about the contrasting structures of the U.S. and other national innovation systems, such as those of Japan and Germany. Access by foreign enterprises to locally developed inventions or technologies within an economy is heavily influenced by the structure of that economy's national innovation system. The U.S. system probably is "leakier" than other systems, because of (1) the prominent role of relatively open institutions, especially universities, as performers of world-class R&D; (2) the highly developed market for corporate control, which facilitates acquisitions of U.S. firms by other U.S. or foreign firms; and (3) relatively liberal U.S. government policy toward direct foreign investment. But the "openness" of the U.S. national innovation system is only partly a function of government policy—this condition also reflects historical evolution and other factors. The prominent postwar role of high-technology start-up firms in the U.S. national innovation system, for example, is partly a result of government defense procurement and antitrust policies. But, this unusual structure was also influenced by the development of financial institutions and a financial system that are regulated, but hardly controlled, by government, as well as a university research infrastructure that mixes public and private funding and institutions.

The national innovation systems of other industrial economies are the outcome of similar combinations of government policy, historical evolution, and private decision making. As such, the possibilities for intergovernmental negotiations over access to industrial technologies to produce meaningful results may be limited. How, for example, should one measure the extent of openness of one nation's "innovation system," relative to that of another? What does reciprocity imply? Since a far greater proportion of Japan's R&D is carried out in industry (see Table M-5), does an agreement on reciprocal access imply that both U.S. and Japanese firms must open their sensitive technology development activities to visitors from firms in each nation? Such an agreement would not be welcomed by U.S. firms. In addition, as this example suggests, government policies may have little near-term effect on access—the differences between the U.S. and Japanese systems of corporate governance will not be eliminated by government initiatives alone. Concerns over the access by one nation's firms to another's industrial technology base may be well founded, but their resolution is likely to be slow.

The influence of government policies on the "openness" of national innovation systems also is a result of both public policies and private firms' reaction to these policies. Indeed, as was suggested earlier, a portion of the recent growth in international strategic alliances reflects the actions of individual firms, often in reaction to state policies. For example, the "technonationalist" R&D policies of the European Union and the United States in semiconductors have provided a motive for the formation of strategic alliances among firms from these economies; so have managed trade policies in industries such as automobiles. Both the static characteristics and the dynamic evolution of these national innovation systems thus depend critically on the behavior of private firms.

U.S. TECHNOLOGY POLICY

The Clinton administration, which came to power in a flurry of commitments to a "new approach" in U.S. technology policy, has in fact displayed considerable consistency with many of the programmatic precedents established by its immediate predecessors, reflecting the fact that many of the technology policies of the Reagan and Bush presidencies were the result of pressure from Democratic Congresses. These similarities extend to two dilemmas that also confronted the Reagan and Bush administrations: (1) the problems imposed by political requirements to capture the bulk of the economic returns from technology policies whose results may benefit foreign firms; and (2) the enduring tension between programs that support technology development and those supporting technology adoption. Portions of the following paragraphs draw on Ham and Mowery (1995).

The political justification for many U.S. technology development programs (including those supported with DoD funds) now rests on the ability of U.S. firms and citizens to capture the economic benefits of these programs. Such justifications also apply to more and more federal science programs and funding. Unfortunately, given the characteristics of the outputs of many of these programs, the structure of the U.S. firms participating in them, and the structure of the markets for the goods into which the results of these programs are incorporated, capturing the entirety or perhaps even a majority of the economic benefits from some of these programs is infeasible. The constraints imposed on program design by these political realities exacerbate tensions between U.S. trade and technology policies and, paradoxically, may reduce the economic returns to U.S. firms and taxpayers from these programs.

Reconciling the political requirements for such a distribution of benefits with the economic and technological realities of the late twentieth century has proven difficult. Many of the technology policies of the Reagan, Bush, and Clinton administrations have attempted to restrict foreign firms' access to domestic programs or have attempted to limit the international diffusion of the results of such programs. The White House restricted foreign access to public discussions of research in high-temperature superconductivity in 1987, and foreign firms' access to the results of federally funded research in the national laboratories has been restricted in several cases.

The National Center for Manufacturing Sciences (NCMS) and the U.S. Consortium for Automotive Research (USCAR), announced by the Clinton administration in 1993, exclude foreign firms from formal membership. SEMATECH also excluded foreign firms from participation while it was receiving federal funds. This consortium now has enlisted electronics manufacturers from Taiwan, South Korea, and Western Europe in a new, parallel collaborative R&D organization (see Appleyard et al. [1998]). Foreign participation in the Commerce Department's Advanced Technology Program (ATP) is subject to various restrictions, which include determinations by U.S. policy makers that the home-country governments of these firms provide nondiscriminatory access to similar technology development programs, that they provide significant protection for intellectual property, and other conditions that have little bearing on the benefits to the U.S. economy of foreign participation (these conditions have resulted in the denial of funding thus far for only one ATP project, which included a Japanese firm among its participants). Transfer of NCMS-developed technologies by member firms to their foreign subsidiaries is selectively restricted. Cooperative research and development agreements between federal agencies (including the National Institutes of Health or the Department of Energy laboratories) must include provisions to ensure "substantial domestic manufacture" of the resulting technologies or products. Many of the current restrictions on foreign participation, which differ among U.S. technology programs, base the determination of foreign-firm eligibility on assessments of home-country government policies, on the assumption that denial of access to foreign firms will increase pressure for change in the policies of their governments. The bases for such assessments of home-government policies are relatively subjective, and are surprisingly "nontransparent" (i.e., they are not based on any single or comprehensive published assessment, and there is no well-developed process for review of these determinations). These statutory requirements for the fulfillment of a lengthy, inconsistent, and complex set of conditions across programs also mean that foreign-firm participation that is deemed by policy makers to be economically beneficial for U.S. firms and taxpayers may be prohibited for one or another reason that has little to do with the specific merits of an individual proposal.

Many of these U.S. government restrictions on foreign access to U.S. technology programs are a response to similar restrictions on U.S. firms' access to the strategic "technology" programs supported by other industrial economies. Japan's cooperative R&D programs long excluded foreign firms, although many of these restrictions have been relaxed in recent years. In addition, many of the programs of the European Union and its member states have restricted participation by non-European firms, although partial exceptions have been made in the case of such firms as IBM.

U.S. restrictions on foreign participation or international dissemination of results are not likely to affect the distribution of the economic returns to these programs. For example, the automobile firms participating in USCAR maintain extensive manufacturing and product development links with foreign firms, as did the U.S. semiconductor firms participating in SEMATECH when the consortium prohibited foreign participation. The "U.S. discovery" of high-temperature superconductivity that led to the 1987 White House symposium was in fact accomplished by two German scientists working in a Swiss industrial R&D laboratory owned by a large U.S. multinational firm, IBM. Establishing the "national ownership" of this scientific accomplishment is futile and counterproductive. Such restrictions also create some risk that U.S. firms will continue to be excluded from foreign nations' current and future technology programs.

The focus of many Clinton administration policy makers, as well as those of previous administrations, on technology creation and development as the key source of economic benefits overlooks the benefits from technology adoption in a U.S. economy that now is "first among equals," rather than technologically preeminent, and that is open to international trade and technology flows. Like its immediate predecessors, technology policy in the Clinton administration supports the creation of knowledge-based competitive assets that are internationally mobile, while placing less weight on improvements in the ability of U.S. firms and workers to absorb and apply technological advances from external or foreign sources.

Government actions continue to matter a great deal in the modern global economy of mobile capital, goods, and technology. But the mobility of the technological assets created with federal funds means that the consequences of many government policies may differ from their intended goals. Moreover, the economic interests of U.S. citizens may not always coincide with those of U.S. firms that seek restrictions on foreign firms' access to U.S. technology development programs. As foreign firms play a larger role in this economy in production, technology development, and, potentially, in the support of research in small firms and universities, the economic benefits from any restrictions on foreign-firm access are likely to flow primarily to the shareholders and managers of U.S. firms competing with these foreign entities, rather than benefiting the larger public. Similarly, U.S. government programs to support the development of "strategic technologies" such as flat-panel displays create considerable risk that imports of cheaper versions of these important intermediate goods may be restricted, imposing severe costs on U.S. firms seeking to compete in the production of systems incorporating such components.

CONCLUSION

The global environment within which future science and technology policies will be formulated and implemented will be characterized by a broader distribution of scientific and technological "centers of excellence," and by greater cross-border flows of R&D investment and technology. The U.S. R&D system and the federal R&D budget will remain by far the largest in the world, but the share of global R&D accounted for by R&D activity within the United States has declined significantly from its level of the 1960s and is unlikely to increase. Policies for the future thus must recognize the greater mobility of intellectual property, technological capabilities, and R&D investment. The United States must remain an attractive "platform" for R&D and related investments by U.S. and foreign corporations. Because much of the infrastructure that has contributed to the excellence of the U.S. R&D system and its attractiveness for U.S. and foreign corporations is public, federal investments in R&D remain essential to the future well-being of the U.S. economy.

But federal policies for science and technology also must be predicated on a more realistic view of the relationship among the U.S. and foreign nations' R&D systems and on a more realistic conceptualization of the sources of the economic benefits associated with innovation. Rather than restricting foreign access to the results of publicly funded R&D in the United States, results that themselves are internationally mobile, policy makers should focus on strategies to improve the domestic adoption and implementation of new technologies from domestic and international sources. Among other things, such an approach will require that both policy makers and U.S. industrial managers redouble their efforts to improve access to the growing R&D systems of other industrial and industrializing nations. The current environment is a legacy of enlightened U.S. and foreign policies of support for liberalized trade and economic development throughout the global economy. Future science and technology policies should be designed to exploit these legacies of past policy successes.

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The U.S. Environment for Venture Capital and Technology-Based Start-Ups

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As often happens in these conferences, as I listen to the magnitude of the issues being discussed and the incredible insight that so many people have, both on the panels and in the questions they are asking, I begin to wonder whether there is much I can add. Today, I would like to give you a very brief perspective from someone who is in an industry and company supported by venture capital, and living in one of the "sticky" environments that were talked about before. Silicon Valley is probably the biggest "sticky environment" in the world, certainly the biggest in the United States.

My perspective is very specific to the information technology sector. I am not an expert in biotechnology or in venture capital. But I do work in that environment and can at least give you an idea of our strategy and our attitudes toward what is happening in research and development (R&D) and the successful competitive positioning of U.S. companies and technologies.

Adobe Systems, of which I am the cofounder with my partner John Warnock, turned 15 years old in December 1997. We are a venture-capital-based company. Both John and I were veterans of Xerox PARC. Many of you have heard stories of companies started by folks who found it difficult to get their ideas into products within Xerox, and who spun out and started their own companies. We are one of those stories; a company that started out with two guys and the equivalent of a garage.

Our business is not based on natural resources, but on artificial resources and capital. In the software industry, successful companies typically generate a lot of cash. A prudent board of directors has to be very careful in what it does with that asset. It is typically invested fairly conservatively because we want to demonstrate that we are taking good care of the asset. The difficulty is that the return on equity for the business begins to precipitously drop as it earns more and more cash, because conservative investments naturally produce conservative results.

We decided about three or four years ago to try and deal with two problems more or less simultaneously. The first problem being the conservative use of cash and not earning a fair return to our investors. The second problem, and the primary motivator in many ways, was the observation that several other presenters have made that we live in an environment that is captive to the 90-day performance report card. Every 90 days, we as a management team are responsible for generating revenue growth and profitability. The analysts do not want to know what my long-range view is until after I report this quarter's results.

This environment is not conducive to long-term investment, nor often to high-risk investment. So what we did is set aside a venture fund and became, in effect, venture capitalists. Within the software industry we were among the first to do this in a deliberate and disciplined way. Today, we manage about $80 million in the fund. We see dozens of business plans come through on a weekly basis. We try to target the investment of that asset, our cash, in ways that allow us to develop new markets, and in some cases acquire more direct access to new technology and integrate it with our product line. We find it an innovative way to do slightly more advanced research than we are likely to do on our own operating budget because of the 90-day phenomenon that I talked about. We have been fortunate so far to have invested in the prepublic stage of Netscape and a few other successes. While I do not want to predict that as future performance of the fund, it has given us an entry point into developing markets and a way to expand our business.

If you look at the technology business that we are in, basic research in very sophisticated areas of physics and chemistry and biotechnology does not usually drive our industry. More often, the important advances have been applications of relatively sophisticated but well-understood concepts underlying mathematics and systems design, and the integration of various pieces of research that have been developed independently into systems that provide solutions.

With that as background, there are a few issues I would like to raise to help you understand where we are positioned as a U.S. industry based in Northern California. First, as others have mentioned, it is not atypical for high-growth, high-technology industries to find themselves in a very constrained geographic environment. Certainly, Silicon Valley is a very constrained environment. Why does this happen? Well, it happens for a lot of reasons. One is the insight and investments made very early on, in this case by Stanford University, to look at what was needed to take technology being researched at Stanford and turn it into practical applications and corporate relationships. This is somewhat different, incidentally, than some other regions because in the formative stage there was almost no direct investment by government.

More important is the infrastructure that provides an incubation environment for new businesses. This environment consists of more than the products and the key individuals who start the companies. It consists of mundane things that allow venture capital to be readily available, including the know-how that allows people to sign leases for equipment and facilities, to set up banking relationships and human resource support systems, and all the other things necessary to start a business. You can literally go to the Yellow Pages in Palo Alto or San Jose and get a sampling of a dozen or more vendors in each of those categories who are completely comfortable dealing with this. By contrast, in most places in America it is difficult to find the infrastructure to put together a high-technology business.

The other key ingredient, of course, is that as these "sticky environments" grow, more people want to attach themselves. They know this is where the germination of ideas is. You cannot go to the grocery store, or clothes shopping, or to a cocktail party or restaurant without running into people and absorbing knowledge about what is going on in Silicon Valley. We are beginning to see this environment duplicated in other places, such as Research Triangle Park and Austin. Route 128 for a long time has provided a lot of pieces of this infrastructure.

The growth of high-technology business brings problems as well. For example, we have a less than 1 percent housing vacancy rate at the moment in Silicon Valley. Our freeways, if you know anything about queuing theory, have passed the critical point. It is difficult to get in an accident because you cannot move on the freeway. Employee retention is a problem. We are an old company in Silicon Valley, so we are not growing as quickly as a start-up company. We have to make special efforts to retain employees.

What are companies in Silicon Valley doing to respond? We are beginning to diversify geographically. We are fighting the "sticky" phenomenon, at least internally, and setting up engineering groups in remote locations, both in the United States and in the rest of the world. This is what is causing R&D money to move out of the United States. We have opened a development lab in Norwich, England, and are moving into India. We have already set up a development group in Japan. You will see more of this happening simply because of the constraints in Silicon Valley that I described.

The next issue, which is very important in our component of the high-technology industry, is the scarcity of domestic talent. We see this everywhere. When I talk to groups of fresh bachelor's degree holders that we bring out for interview trips to attract them to our company, I typically ask how many were born outside of the United States. The answer now is typically in the 30 percent range. I suspect that this percentage of foreign-born employees applies across our entire company. Because our business is based on intellectual capital, the educational process that produces candidates to work in the company are critical. They are critical for us to be successful, so we have to go anywhere in the world to find talent that will fuel our growth. U.S.-born talent is not only scarce in engineering, so is management talent to run the business. I know that venture capitalists must from time to time struggle with young companies that cannot grow talent fast enough inside. How do you acquire that talent and bring it into the company? Because we all compete in the global marketplace, international marketing expertise is also necessary to be truly successful. Today more than 50 percent of our revenue is outside the United States, and will probably grow to two-thirds or three-quarters in the long term.

In terms of what we look for in national policy and support from the government, Dick Thornburgh mentioned the national standards for securities litigation, which is important for us to reduce the legal costs associated with running our business and working with our shareholders. More important in our business, frankly, is intellectual property, including the application of copyright and piracy issues. Our revenue at Adobe would easily more than double today if piracy were eliminated on a worldwide basis and my suspicion is that it would go up by a factor of three. That would turn us from a $1 billion company into a $3 billion company. It is a big issue, even in the U.S. government because they have not yet adopted the policy to eliminate piracy there. It is difficult for me to sit across from a minister in China and tell them I am upset with the fact that we only sell, in effect, one copy of our major software programs in that market and he will ask me what the U.S. government policy is. Unfortunately, I cannot give a good answer today.

As for investing in R&D, my personal belief is that the government should focus on longer-term basic research and the production of intellectual capital rather than try to pick the technological winners. Frankly, I think that our industry does that pretty well. We would prefer to see the government produce the raw materials we use, which are talented, educated people. It is also important for the government to understand what is necessary to foster competition in this new economy. I have talked with regulatory agencies and have seen them apply economic models that work well in natural resource industries and smokestack industries but make no sense in intellectual-property-driven businesses.

Finally, I would like to talk about foreign competition and what we see in the future. We have had a great run in our industry. Today, the United States is by far the dominant supplier of products and software for PCs. Thanks to Bill Spencer and others who have worked so hard at it, we are also strong in the sophisticated silicon processing businesses. You always worry when you are at the front because everyone paints a target on you.

What we have seen in Europe, for example, is not a lack of intellectual capital, which is fairly uniform across the world within a certain range. Their difficulty is that they have never really embraced the notion of letting the people who are the pioneers actually own the assets of the company. They could learn to change that, but it will be a long-term process. In Japan, similarly, it has not been possible to allow venture capital and ownership in the hands of entrepreneurs to the extent that we see in this country. In addition, the risk-taking culture, which is almost a badge of honor in Silicon Valley, is not present in Japan.

In terms of emerging cultures, I personally believe that in the software industry China will be very competitive in the future. The culture is very entrepreneurial. Their universities are improving rapidly. For example, one company I know of was essentially venture-capital-funded by Beijing University and run by professors and students. The university transferred partial ownership to the management, which has taken the company public. The next step is to move into the global market. They understand almost all the issues that the other geographic economies seem not to have quite put together in a complete package. So I think, going forward, that China will be a formidable competitor.

Finally, the last thought I will leave you with is this. When you look at our experience of the past several decades, we all point to Xerox PARC as the incubator for the personal computer (PC). Frankly, it was the Advanced Research Projects Agency research investments of the last half of the 1960s and the early 1970s that created the intellectual capital that has allowed the current PC industry to flourish. The question I have, almost a rhetorical question, is where is the comparable investment coming from today to create the industry that will be the anchor of growth for the first half of the twenty-first century? If I knew the answer, I would share it with you, but I don't.

The U.S. Environment for Venture Capital and Technology-Based Start-Ups

John Shoch
General Partner, Asset Management Associates

In response to Bill Spencer's original suggestion, I will talk a little bit about the venture capital business in the aggregate. At the end I will offer some observations and a perspective on current trends.

The broad statistics give us an idea of the magnitude of venture capital investing, but some of the data are pretty ragged. For example, how do we define venture capital? Do we count early stage, later stage, corporate investments, and angel investors? Taking the data available from the National Venture Capital Association (NVCA), the most interesting thing to me is the growth rate. The broad inflow of money into traditional venture capital funds has grown from $1.3 billion in 1991 to $6.6 billion in 1996. The outflows have gone from $1.4 billion to $10 billion. You might wonder how we manage to operate with an inflow of $6.6 billion and an outflow of $10 billion.

There are several kinds of venture investment entities beyond the traditional, professionally managed venture capital firms which are measured by NVCA. Investments into target companies by larger companies such as Adobe and other corporate investors would not show on the inflow but would probably show on the outflow. The statistics are compiled by calling venture capital firms and finding out what companies they invested in. So there are specific corporate entities and others that are investing to make the outflow higher than the inflow. In addition, so-called "angel investing" by individuals does not show up in the statistics. I do not think anyone has particularly reliable numbers for this. Some of the analysis indicates that funding from angels, relatives, friends, mortgaging your house, and small business loans may be 10 times as much as the investment from professional venture capital sources.

These numbers are growing at a ferocious rate. To give you some perspective, in the 1970s inflows into professionally managed venture capital firms on a yearly basis were as low as $50 million in some years. We call these “the good years” because there was not as much competition for good investments, and the prospects for high returns were better. We have seen several cycles over the years: in the 1980s we reached a $3 billion to $4 billion annual inflow, and then it dropped. Now we are back up to a $6.6 billion rate. This is probably bad news in terms of the returns that anyone can accomplish. The capital market is working. When we produce extraordinary returns, the capital flows in, and then the returns go down. This is exactly as it should be.

To put this into perspective, let’s take the $10 billion outflow figure as the aggregate number for all venture capital. We are finding more and more people coming under the umbrella of venture capital for later stage investments in retail chains, commercial shopping centers, and other private equity investments outside high technology. The best estimate I have is that about 60 percent of this money goes into high technology, broadly including information technology and life sciences or medical technology. So if you take 60 percent of the $10 billion, that says perhaps $6 billion is going into high technology. However, this also includes later-stage deals and buyouts. There are people raising billion-dollar venture capital funds to do $250 million buyouts of existing companies. I do not consider those sorts of investments as traditional venture capital funding for start-ups or growth-phase companies. For the sake of argument, let’s say half of the $6 billion is really early to middle-stage venture capital, or $3 billion. Then if we deduct another third of it that goes into the life sciences, we probably have $1.5 billion or $2 billion going into information technology. People think that this is a massive number, that this is the panacea that will solve all the development problems for our country going forward. I certainly do not believe that.

This $1.5 billion or $2 billion, much of which goes into support of marketing, sales, and manufacturing, comes to less than half the $4.8 billion annual R&D expenditure by IBM, just one company. It is fair to say that, although there is a tremendous amount of innovation and imagination, the scale of venture capital in information technology is relatively small when compared to the rest of the industry. To take another example, the aggregate market capitalization of all the venture-capital-backed biotechnology companies is less than the market capitalization of one large pharmaceutical company. As much as those of us in the venture capital world think that we are creating a lot of value and new products, the scale of the activity is still fairly small compared with the rest of industry.

Moving from this macro view of the economics at a high level, I want to offer several observations about the state of the venture capital business, what is driving it, and how it operates. First, as most of you know, it is an unusual process that is generally unstructured, certainly unregulated, and somewhat unplanned. We have the fortuitous combination of entrepreneurs who are willing to take risks, capital that is willing to take risks, and a culture that is willing to at least tolerate failure, even if we don't particularly like it. People know how to bounce back and we know how to look with an open mind at individuals who have been part of a start-up that did not work. Perhaps we hope, sometimes wistfully, that they have all of the mistakes out of their systems, but this is often not the case.

In addition, we have a very unusual situation in Silicon Valley, in Austin, in Cambridge and several others places, where there is a community that has grown over a very long period of time. We are frequently asked by other regions in this country and abroad, "How do we build the next Silicon Valley?" We can describe the historical process in a rough way; but it is very hard to manage or organize. If you look at the history of Silicon Valley, probably the most important single force is the core semiconductor industry. If you look at the fourth-generation companies that we are funding now, they were all spawned by the third-generation companies, such as Intel and National Semiconductor and others. These were produced by the second-generation company, Fairchild, where the "traitorous eight" went when they left Shockley Semiconductor, which, in effect, begat the entire industry. This was triggered by William Shockley coming to California. Why did all of this happen? You might think that it is similar to chaos theory, where the outcome is determined by whether the last drop of rain went on the west side or the east side of the continental divide. I believe the story is that William Shockley's mother happened to live in Palo Alto, so when he left AT&T it was the first place he wanted to go. He attracted Gordon Moore, Robert Noyce, and others who came West to join Shockley Semiconductor. Shockley was a fairly aggressive manager and Gordon Moore recently thanked him profusely for having propelled Moore out of Shockley Semiconductor with his management style.

So when people ask "How do we build the next Silicon Valley?" I usually suggest to them facetiously that they find the next Nobel Prize winner, get his mother to move, and wait about 50 years. It does take that much time to develop the infrastructure and feedback loop of venture capitalists, banks, landlords, and others who understand the culture and the dynamic. To reiterate what Chuck Geschke said, I think it is literally true that I can stand in our local grocery store for an hour or two on Saturday and find an entrepreneur, other venture capitalists, a banker that will loan them money just because I say it is a good company, and an investment bank that is ready to take them public as soon as they might have some revenue. If I wait an extra day I could probably fill out the whole management team.

We like to think that this is unique to Silicon Valley, but I do not believe it is unique. We have had fortuitous circumstances and more time to mature. For those of you who are familiar with Palo Alto, there is a trendy restaurant called Il Fornaio. It is a frequent breakfast spot, where you do not want to go to have a "secret" meeting. In the morning, if I go there for breakfast, it takes me about 10 minutes to sit down because I have to say "hello" to all the other venture capitalists, entrepreneurs, managers, and headhunters. You have to wonder when you see this headhunter with that CEO. Is the CEO hiring the headhunter to replace one of his vice presidents? Or is the headhunter trying to recruit the CEO to go to another company? You might be terrified if he is the CEO of one of your companies, so you have an interesting dynamic.

However, if you go to the branch of the same restaurant located in Beverly Hills, there is a very similar dynamic—except the activity revolves around the film industry. I go down there with some friends occasionally and we have brunch at Il Fornaio in Beverly Hills, and I am completely at sea as I watch the exact same process going on. But it is directors and agents and other people in the industry that dominates southern California (which, by the way, traces its history to having good weather and being a better place to make movies than New York). I think there are some very unique characteristics that operate to our advantage in places such as Silicon Valley, probably the most developed, followed by Route 128 and a couple other areas in the United States, and growing here in the Washington area. There are signs of this growth abroad as well. It is not nearly as well developed, but it is starting to emerge in Cambridge, England, which possesses a major research university with a strong program in computer science, a history of entrepreneurship, and a growing group of venture capitalists.

My second observation is that it is important to recognize that while there are many great successes that have come from venture capital, there are also many failures. It is important that we can bounce back from failure, move quickly, exploit innovations, and identify markets. However, start-up companies are probably not great places to do fundamental knowledge-driven research that will have value for a broad array of potential businesses. Such a start-up is pretty hard for us to invest in. The truth is, I have invested in some projects like that. Those are what we call “mistakes” in which we thought the technology was ready for the marketplace but it turned out that not all the fundamental issues were solved. We needed to go back to the drawing board and either do some fundamental work or see if we could develop a new application of the technology. One example of this is the laser industry. If you go back and look at the evolution of Coherent Radiation and Spectra-Physics, the two primary independent laser companies, they had some very ragged early years as people tried to figure out what to do with this unusual technology. We look to universities and the corporate industrial labs as a far more appropriate place to do this sort of research than small start-ups.

The third observation I will make is about shortages. There are various kinds of shortages in this process. Entrepreneurs always complain that there is a shortage of risk capital, but this usually means that there is a shortage of capital willing to invest in their specific deal. Those of us who are investors competing for the good deals think that there is too much capital around and we complain that there is a shortage of good ideas. I think we all complain that there is a shortage of good managers and good technologists. To repeat another point of Chuck Geschke’s, we welcome anybody from anywhere with the right skills who can contribute to the growth of these companies. Many of these start-ups are classic “rainbow coalitions" of people with very diverse backgrounds working hard to build the company.

The fourth observation is one I hinted at earlier, and is directed to those who are tempted to think that this is an easy business. It is actually highly cyclical. I believe the data indicate that the capital markets are working. The extraordinary returns of the past decade have attracted a massive amount of new capital into the venture capital field. This will cause us to do bad deals, pay prices that are too high, and lose money. Then the cycle will start up again, eventually. I hope we get through it pretty quickly.

The fifth observation I would like to make is on the broad question of "picking winners" in industrial policy. These are loaded phrases and it again depends on where you are sitting. As a venture capitalist, I am completely opposed to picking winners when you have picked a winner that is not one of my companies. But when you have picked a winner that is one of my companies, I appreciate the profoundly wise investment in the core scientific base of the country. In a similar way, Congress's problem with picking winners and setting industrial policy is that if you invest in a plant in someone else's district it is very bad industrial policy, whereas if you invest in a company in my district, it is a valuable investment in the infrastructure. We have seen many of these programs and there are some gray zones. The Advanced Technology Program of the Department of Commerce or the Small Business Innovation and Research grants are selected competitively, based on the merits of the idea. We are frustrated when a targeted grant goes to some university that everyone in industry knows does not have any competence in this area other than that its Congressman is on the appropriate committee. When I complain about them, I am told to shut up or they will kill the whole program, so let that one go by. We have seen many of these programs where there is fair competition on the technical merit for precompetitive technology, for infrastructure development, or for the development of tools. It can be an extremely effective way to lever public dollars along with our equity dollars.

My final observation reinforces some things that Chuck Geschke and Dick Thornburgh said earlier on the issue of tort reform and securities litigation. I know that, for many people here who primarily focus on broader policy issues, this must seem like an incredibly irrelevant, narrow point. We have had the adoption of the federal laws that have helped to reduce the number of what I consider extortionary lawsuits.

This is how they typically work. The lawyers file a class-action lawsuit against a company because it has a highly volatile stock that bounces up and down. They say that either management knew the stock was going down and was negligent for not doing anything, or was negligent because they were too stupid to know it was going down. These suits are usually settled in the $5 million to $15 million range with the vast majority of that going to the lawyers and a small fraction to shareholders. The federal legislation, that we are very appreciative of, has provisions that allow class-action lawsuits for genuine fraud but helps to reduce frivolous lawsuits. The problem now is that the battle has moved into the state venues and therefore you will hear continued interest in the so-called National Uniform Standards for securities class action law suits. I regret that we have to spend time on it, but it is an important reality in our business environment.

The Education Challenge

Wm. A. Wulf
President, National Academy of Engineering

When I was first beginning to think about what remarks I would make at this meeting, a message came from Bill Spencer saying that he wanted presentations with "bite." It just so happened that at the moment that the message arrived, I was re-reading the report of the subcommittee of the President's Council of Advisors on Science and Technology (PCAST), on the use of technology to strengthen K-12 education. I have to admit that that report set my teeth on edge a little bit. So, what I will do is talk about *why* my teeth were on edge. In doing so I am speaking not as an educator but as a technologist; a computer scientist who has had the good fortune to participate in the development of information technology for many years.

At the surface level, the report says a lot of good things. It says that we should focus on learning with technology, not about technology. It says that we should emphasize content and pedagogy and not just hardware. It says that we should give special attention to professional development of teachers, engage in realistic budgeting, and so on. But as a bottom line, it recommends a massive program of deploying computers to elementary and secondary schools. I am not sure that current personal computer (PC) technology is the right technology to do that. I am not sure that the style in which computers have been used for education is appropriate. I am not sure that the business model of shrink-wrapped software is appropriate for education. I have deep concerns about whether once again we are spending before thinking. Moreover, we are spending as a "patch" to a broken system. Let me try to justify some of those remarks.

First of all, I deeply believe that there is enormous opportunity to improve education through the use of information technology, and that information technology will profoundly change our concepts of how to educate. I will try to give you an example of what I mean by that later. However, in nearly 40 years of observing the evolution of the use of computers in all fields of human endeavor, one of the things that jumps out at me is that the first use of computers is always to automate what we already do in the way that we already do it. The *profound* use of computers is always to do something differently—to do something that achieves the original goal, but does it in a different way.

I was a graduate student at the University of Illinois in 1961 when there was a project in computer-aided instruction called Plato. Its underlying model was automated drill. Alas, that is still the model of most of the uses of computers in education. It has gotten fancier. We have been able to put some graphics in, and so forth, but automated drill is still, as acknowledged in the PCAST report, the predominant use. I do not mean to say that it does not help; it does. Test scores are improved through the use of automated drill, but we are not anywhere close to exploiting the opportunity that we have. So I worry that the deep thinking about the use of information technology in education has not yet been done. It seems to me that the base question is: "Should we be using information technology to do what we already do, better? Or is there a better thing to do?" And again I would claim that the history of the use of computers in every other arena suggests the latter—there *is* a better thing to do!

I would also observe that the PC is a fairly expensive device. I do not think that we need anything like the power or storage capacity of a contemporary PC to do automated drill. Nor do we need the power of a PC to do perhaps what we could and should do. By the way, I am not going to claim that I have answers for what we should do. I simply have questions prompted by my looking at this as a technologist and seeing that the approach does not match my experience.

Let me give you an example. It is taken from higher education, but is suggestive. By way of introduction, about eight years ago, the president of my university asked me to chair a committee to develop a strategic plan for information technology and the university for the next 20 years. This is an absurd idea; no one has that much foresight about a technology that is moving so rapidly. It turns out, however, that the experience had a profound effect on me because on the committee there were a number of folks from the humanities departments who were moderately savvy users of information technology.

Frankly, going into that committee, my assumption was that the only things that humanists would be interested in is using computers as word processors. But I was wrong. In fact, I have come to believe that information technology will have a more profound impact on scholarship in the humanities over the next two decades than it will on science and engineering. What resulted from the chance encounter of savvy humanists and several of us computer scientists was the creation of the Institute for Advanced Technology in the Humanities, which explores the use of information technology in humanistic scholarship.

Now for the promised example. It is an example from historical scholarship, and information technology is having a profound impact on education in a way that none of us would have anticipated. One of the humanists on that original committee was Edward Ayers. Ed is a historian and, in particular, a historian of the U.S. Civil War period. Historiography, the methodology of historical research, has been transforming itself over the past several decades away from a focus on the kings and the generals to a focus on individuals, or ordinary people, who lived during interesting historical times. Ed is assembling detailed records on about 10,000 such individuals. It so happens that about half of them lived in Staunton, Virginia, and the other half lived in Chambersburg, Pennsylvania. Those towns happen to be at the north and south ends of the Shenandoah Valley. In almost every respect, the two communities are identical. They came from the same European roots, the agriculture is virtually identical, there is no difference in industrialization between the two, and so on. However, they did happen to be on opposite sides of the Mason-Dixon line. They both happened to field a regiment and the regiments fought each other.

When I said we have detailed records on 10,000 individuals, it is surprising how detailed they are. It turns out that right about the time of the Civil War, there is an explosion in the written record and so there is a huge amount of information. We have newspapers from both communities for about 30 years surrounding the war. We have birth and death records, tax records, which include maps of where each individual lived, military records, letters, and diaries. In fact, we have letters and diaries that we could not have had access to before information technology. Ed took our scanners over to Staunton, put a notice in the paper and asked people to go up in the attic and bring down letters from ancestors who were living at that time and bring them in to be scanned. People were surprisingly willing to do that. They would not give those records away to a library, they were too important to the family, but they were delighted to have them scanned in and become part of this record.

What results from this is an archive of information accessible to historical scholars, to be sure. But it also becomes available as a potent educational tool that is entirely different from the traditional textbook. It turns out that it demands an entirely different pedagogy. It is not linear. The author cannot control the order in which the student progresses through it. The author/teacher cannot control what detours the student wants to follow. What the teacher *can do* is engage the students in scholarship rather than merely rote learning. What Ed now does, in his course that used to be a lecture course, is guide the students in scholarship. He assigns them, or they pick, admittedly small but scholarly hypotheses, which they can then explore. He has become a mentor and a guide rather than a lecturer. Pedagogy has completely turned on its head. It is no longer linear, and is a lot more fun.

As someone has observed, in the past we have always demanded that students rediscover what is already known. And the audience for what the student rediscovers that is already known is an audience of one, namely the teacher. How dull! Now, all of a sudden, every one of the students in Ed's class is an original scholar and publisher. She or he publishes, at a minimum, to the rest of class. At a maximum, the audience is anyone in the world who is interested in the Civil War period. I think that is pretty profound, and it is certainly not automated drill!

It does not require a PC to do what most students do now. It is difficult to overstate the rapid pace of this technology. The questions we ought to be asking are:

- "What's the minimum cost that we could get away with to do what students are currently doing?" My guess is probably $50 or $100 of hardware, not $1,000 or $2,000.
- "If you are going to spend $1,000 on a student, then what could you do with $1,000 in 10 years?" By the time they deploy all of these PCs they are talking about, it will be 10 years and the first ones will be obsolete. By that time a $1,000 computer will be 10 to 100 times more capable than those of today and we will be able to use them in fundamentally different ways.

My second observation is that the Internet and World Wide Web are much more important than the computer for education. The material from Ed Ayers' project is all available on the Web, for example. Although it is popular in some circles to decry the amount of junk on the Web, and there is a lot, we need to keep in mind that the Web is only a bit over five years old. In that very short time, a tremendous amount of good educational material has been developed on it, and the rate is accelerating. And, by the way, it doesn't take a $1,000 computer to access everything on the Internet!

Observation number three is this: There are many unstated assumptions about the way we currently educate that are challenged by information technology. The current way that we organize courses is designed to optimize faculty and buildings, not learning, for example. The whole notion of lecture formats is there to optimize the teacher. As I understand it, the data suggest that students only capture one-tenth of what is said in a lecture, so clearly the format was not designed to optimize learning! We make little or no use of student-student interactions as an integral part of the pedagogy, yet one of the things that information technology facilitates is student-to-student interactions. We meet in classes in a fixed time and place. Why? Because it was, in the old world, more efficient to move students to the teacher. That is not true anymore. Why are all courses a semester long? Because that was a way to optimize the scheduling of space. Why is a course the same length of time for every student? In order to optimize faculty time and the scheduling of space. Bruce Alberts will speak about asynchronous learning networks. They make sense to me. We are hanging on to a compartmentalized institutional model of education when the unstated assumptions behind that model are rapidly becoming obsolete.

I saw an interesting statistic the other day. According to a poll, 82 percent of those questioned would be interested in "residential learning," receiving education in their homes. Only 84 percent said they would like movies on demand. I thought that was fascinating. It would seem that the public is as interested in education as entertainment *if* it could be delivered conveniently. But the old model is not convenient; to optimize teachers and space, we choose to inconvenience the student—to make them assemble at specified times and places, for example.

It seems to me that if we are serious about education, and we *have* to be, we need to step back and take a long view. We need to be willing to make fundamental changes, not just use technology to do what we are already doing a little bit better. I hear Bruce Alberts talk all the time about the fact that we know how to educate better but we do not do it. We need to stop spending now on incremental patches to a broken system and be willing to say that maybe we cannot improve things so much this instant, but could make an enormous change out into the future.

Meeting the Education Challenge

Bruce M. Alberts
President, National Academy of Sciences

Improving K-12 education in order to advance science, technology, and our economy over the long term is a crucial challenge. Suppose we try to look out 100 years, and ask whether America is going to be a leading country of the world at that time? No one knows, of course, but I believe that it is going to depend more heavily on our ability to support and sustain a high quality of education for most Americans than on anything else we can do.

It is very clear that on the education front we are not doing well. In fact, many of us are convinced that we urgently need a revolution in our schools. Let me give you a few indicators.

1. The problem is not that the schools have gotten worse. It's that the bar has been raised enormously, as we all know. The kind of education that used to be adequate for adults to function in society—for work on an assembly line, for instance—is no longer adequate for the workplace of today. We are told over and over that only 10 percent of the high school graduates who apply are qualified to be hired by companies like Motorola, even for an entry-level job. This is because they do not have the kind of thinking skills, problem-solving skills, or quantitative skills needed in today's factory. The assembly line, in fact, is a very sophisticated, highly complex place to work these days. Our school systems are not educating people in a way that meets today's societal needs.

2. Secondly, let's look at the attitude that kids have about school. Lawrence Steinberg and a group of other researchers have carried out a 10-year study of middle-class kids from sixth to tenth grade, examining their feelings about school. If you want to be depressed, read the book *Beyond the Classroom*, which Steinberg published in 1996 to summarize their study of 20,000 students in

Wisconsin and California. These were youngsters in middle-class America. The study found that 40 percent of them were simply going through the motions at school, and were completely disengaged from the learning experience. They were in school for social reasons, or because they had to be there, but they were not paying any attention to the lessons being taught. The book goes on to describe many other unfavorable attitudes that the students had toward learning. This is a very disturbing book to read.

3. Last but not least, we have seen the discouraging results of the Third International Math and Science Study, the TIMSS report. This is an international comparison of our kids' performance relative to those in other countries. U.S. twelfth graders outperformed only 2 of the 21 participating countries in math and science. The eighth-grade results showed that we were average in science and below average in math among the 41 countries that were tested.

Your first reaction may be that we do poorly because of all of those kids in urban school systems. What about our suburban schools? Don't we have good school systems there? Let's look at the results for the top 10 percent of the kids in the world. For the 300,000 students tested, what fraction of them from various countries were in the top 30,000 in the eighth-grade TIMSS? What you see is that Asian countries, as well as others, are doing much better than we are, even at the top 10 percent level. In math, only 5 percent of our kids were in the world's top 10 percent and in science only 13 percent. So even if we continue our attention to the students whom we think are getting the best education, we are not doing at all well.

All of this is a very poor omen for our future. In fact, I view it as a wakeup call for America. But if we are going to do something serious about education, we must start by recognizing that improving it is a very complex problem. Figure A-1 shows a grid of some of the interacting systems in education. The textbooks support the tests and the tests support the textbooks, while the teachers rely on the textbooks for their curricula. As a chemist, I would say that this is a system in a stable equilibrium, with many components that are self-reinforcing. So we will need a very large input of energy to change it.

I was a working biologist for 30 years, and so, I am used to dealing with very messy problems. What scientists try to do with a messy problem is to find a few focus areas. Likewise, we need to concentrate on several ways to attack the education problem; pursue those consistently over 10 years or so; and show that we can make a difference. Only in this way can we give people the confidence that education is something that intelligent effort can improve.

Let me present, briefly, the five focus areas that I would choose for emphasis. The first focus area is something the Academies are just beginning to try to do something about: the nation's school systems. If you look around America for good schools, you can find lots of them. But if you look around America for good school systems, you will find very few. School systems must become learning organizations that empower teachers, otherwise we will never increase the number

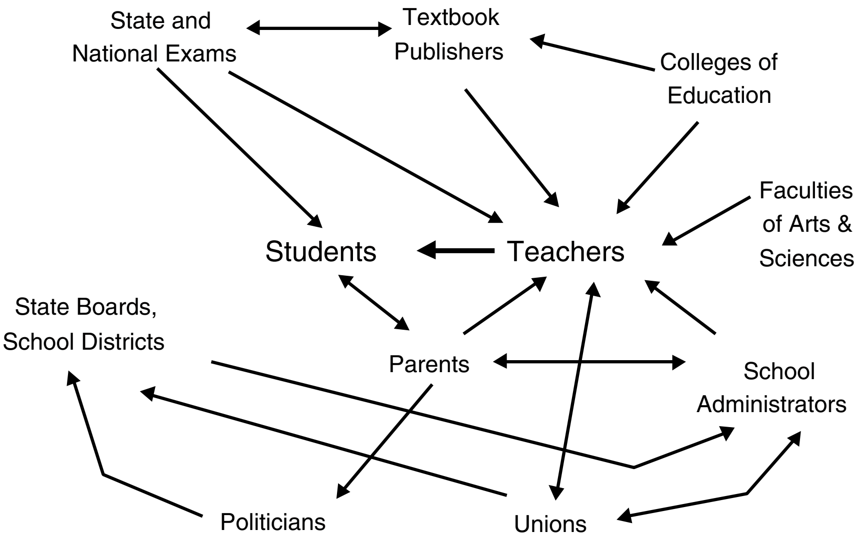


FIGURE A-1 Interacting systems in education

of good schools. We will only have a smattering of truly outstanding schools scattered here and there that are likely to be performing well in spite of the school system in which they function.

The second focus area is the teacher. Teachers must be given continuous professional development throughout their careers. And the professional development that they receive, of course, must constantly improve their teaching. This must become a central, if not *the* central, focus of school systems. We are very far from achieving such a goal today.

The third focus area is student assessment; the tests that we give to measure performance. Many of them are completely inappropriate. High-stakes exams, by which schools and students are measured and compared, directly drive the kind of teaching that teachers engage in. The kinds of tests that we have today, by and large, drive the wrong kind of teaching, and they do not measure the kind of performance or the thinking skills that society at large wants or needs. Instead, today’s tests tend to emphasize rote learning and the regurgitation of facts and vocabulary, which will not drive the economy of tomorrow.

The fourth focus area addresses the central issue of curriculum. Most teachers cannot teach well unless they have excellent teaching tools to work with. The idea that teachers should invent their own curriculum is as nonsensical as the idea that a scientist should invent his or her own science. Instead, we need to take the best tools and continuously improve them, and then make them available to all teachers.

Finally, who are the people in our school systems? Our nation requires a new generation of talented teachers and administrators. We need to make this possible by creating new pathways for people to break into education careers. In addition, all of us, wherever we are, must support excellent teachers through local partnerships—so that they prosper and stick with it.

I think the connectivity we have through the Internet is wonderful. But we have yet to exploit it adequately as a new tool to make major differences in our schools. The situation that we face in education, with all the gridlock, requires something really new in order to shake up the stable equilibrium we are in.

So let me talk about one use that the Academy is making of the Internet to encourage scientists to be effective in their local schools. Last year, our RISE program, Resources for Involving Scientists in Education, launched a Web site that contains a huge amount of advice from scientists who have been effective in their local schools. It tells other scientists and engineers who want to help how to engage a school district and teachers effectively and, equally importantly, what not to do in the schools. It also offers them resources so that they can become effective partners. The Internet has many more potential functions in education, so many, in fact, that we don’t yet know all of the ways that we can use this marvelous communication and information device.

We need to define what we want students to know and do in each subject area before we can think about what the curricula should look like. In science, this is a particularly serious problem. Anybody who has ever looked at the textbooks for middle school or high school will see how tough it is. The scientific community has let the textbook industry and the market drive textbooks to the point where they offer little more than lists of science words. The books are quite uninteresting. So you don’t need to wonder why kids don’t like science. In fact, most elementary school students love science. But as students move on to middle school, “science” becomes a memorization chore. This system turns most young people off of science, and it completely misrepresents science to them.

This issue is addressed in the *National Science Education Standards* that the National Research Council (NRC) produced in 1996. In 1989 the state governors met in Charlottesville, Virginia, and called for the first-ever national standards in major academic subjects. In 1991, NRC was assigned the task of producing the science standards. It took us four years; its writing involved hundreds of people, including more than 40 Academy members; and the last draft was sent out for review to 40,000 people. It then took us another year to revise and produce the final document. So this almost certainly is by far the hardest report that we ever prepared. It is 240 pages in length, all available for free on-line at our Web site, which is www.nas.edu.

The *Standards* are not curricula; they are guidelines for what we want kids to know and understand at the end of fourth grade, eighth grade, and twelfth grade.

Whatever the curriculum, it should have the following features according to the Standards:

- Science should become a core subject in every year of school starting at kindergarten.
- Science should be for all students, not just for those who might seek to be engineers or scientists.
- Most important, science should not be treated as the memorization of science words. It should focus instead on inquiry-based learning—and on the concepts that excite kids about science and allow them to understand the scientific process and use it in their everyday lives.

These are very ambitious, revolutionary goals. I am not sure that most people recognize how revolutionary the *Standards* are. It will take time to enact this grassroots vision from all across America—from teachers, teacher educators, and scientists. Classrooms should look different. Instead of a teacher sitting in front of the class lecturing or having kids memorize words, the students should be actively involved. Classrooms should be noisy places, where students are involved in problem solving, struggling with a problem before they are told the answer. That is the basic nature of inquiry.

This kind of learning builds both cooperation skills and communication skills, which are both badly needed in the modern world of work. If you want to see what it really looks like, take a look at some curricula that have been developed in accord with the Standards. The best that I know of so far have been developed for elementary school. One set has been produced in a joint project between the National Academy of Sciences and the Smithsonian Institution through the National Science Resources Center. They have produced 24 modules for elementary school—each an eight-week set of materials, not a textbook. Each module is grade appropriate, has been field tested in the schools, and then revised based on teacher input.

Other organizations, such as the Lawrence Hall of Science, have produced similar kinds of teaching materials. The students don’t get a textbook; instead, the teacher receives a box of materials for 30 kids. The materials do not cost more than textbooks. I worked in San Francisco for many years before I came to Washington. One of my major successes was helping San Francisco to adopt this kind of curriculum material for all of their elementary schools rather than the typical textbooks. A compilation describing all of the best elementary school science curricula has been put together by the National Science Resources Center. Again, it is available on our World Wide Web site.

When we turn from elementary school to middle school and high school, the textbooks only get worse. A few years ago, the state of California wrote new specifications for textbooks. Despite an elaborate adoption process, San Francisco’s sixth graders now have to endure textbooks on the human body that are incredibly dull, confusing, and probably not even scientifically accurate. We have millions of students across America being subjected to this kind of junk. Something is badly broken.

What can we do about it? We need to give teachers many more options through a thorough exploitation of the Internet. First, we must get all teachers connected—both at school and at home. Then we must provide the necessary resources so that they can use the Internet as their major source of teaching materials. The NRC has had a great deal of experience in providing our reports on-line. As many of you know, our 200 reports a year are uploaded to the Web and can be printed out, or read on-line for free. In our experience, this increases the sale of books rather than decreases it. I would like to see textbook publishers upload their books on the Web, so that we would have a resource that children and teachers could get access to no matter where they are across the world.

Putting materials on-line also allows teachers to choose the best things from many different places and combine the best units on the subject that they want to teach, rather than being confined to the one-size-fits-all textbook, which cannot be the best at everything and doesn't have the space to treat any one topic in depth. The Academy is trying to contribute to this by producing some teaching materials for teachers. Our first experiment was produced by our Center for Science, Mathematics, and Engineering Education, and is called *Teaching Evolution and the Nature of Science*. This is a 150-page book that has been written specifically for teachers to help them teach evolution. It has been mailed out for free as well as posted on the Web, so that anybody in the world can use it. If this is successful, we will produce others in this series. We really need to let a thousand flowers bloom. I'm very excited to see many other contributions to education on the Web along these lines. It is a wonderful experience to watch.

For example, there is a group that I discovered called Optimizing National Education (ONE). In California, several expert teachers got together in 1991 and started developing curricula for kindergarten through sixth grade. They have placed thousands of pages on the Web, beautifully drawn and illustrated, and all of it can be printed out for free. Similar efforts are emerging all over the country. There are also experiments in developing asynchronous learning networks, through which high school teachers are teaching courses on the Internet to students all around the country. There is an organization called the Concord Consortium, led by Bob Tinker in Concord, Massachusetts, that is teaching the teachers how to use the Web in this way. As a nation, we are struggling to break out of the old mold—like a butterfly coming out of a cocoon—and we are starting to see the liberation of curriculum from the tyranny of the single textbook.

The role of the Academy is to try to encourage these efforts as much as we can, to convene networks, and to get people to work together. As a nation, too often those working on important education activities compete with each other. Our job is to do what we can to enable them to work together much more effectively.

We also need a strong focus on improving our universities, most which are pretty hopeless with regard to the science education they provide. If you go to a first-year science course, you generally find lectures. And in my field, you generally find all of biology covered in one year—with little teaching for understanding, and no inquiry-based learning in the lab. Universities must change because they set the example for all of us. Their Biology I courses are supposed to teach teachers what science is all about, but they ignore the scientific process. This is an area where the Academies can play a major role and where we have been working actively. Many universities also require that students take the SAT II exams for science achievement in assessing them for admission. The SAT II exam in biology has been an enormous embarrassment. It has covered the vocabulary of all of biology, and it drives high school teachers to teach not according to our Science Education Standards, but in the very way that we don't want them to teach. The universities must wake up and change the way that they look at performance—they are suffocating the whole system! This is a major part of the educational gridlock that I talked about earlier.

Finally, the Academies must use their position to support and advertise the teaching profession. We need an enormous number of new teachers. We need new pathways to get them in. We need to get large numbers of scientifically trained and talented people prepared to teach in our schools. Right now, we have incredible inertia in this respect. Our schools of education and our credentialing systems prevent gifted and enthusiastic people from going into the teaching field.

Today we have a great opportunity. We have an excess of scientifically trained energetic young people who can't do research—there aren't enough research careers for them. Many are willing to do new things. What the Academies have been doing is distributing career booklets through the Web and by mail. Our *Careers in Science and Engineering* emphasizes all of the different careers that are possible with a background in science, including precollege teaching. We have a career site on the Web for beginning scientists and engineers that connects them to real people in case they want to exchange information with someone who is a teacher, for example, or an engineer working on solar energy—whatever career they might be interested in.

We discovered from talking to students that the real problem is not the students but their advisors. Professors in science departments strongly discourage students from anything but becoming a researcher or, in many cases, a professor. We can't continue to have a system where students are made to feel that they are failing if they don't become professors. It is counterproductive to the students and counterproductive to science, and it doesn't meet our urgent national needs. One of our latest booklets is *Advisor, Teacher, Role Model, Friend*, which is aimed at advisors, providing them with resources to help them to think differently.

We need new pathways into teaching, and I am very pleased that Eric Ryan is here, because he has participated in a bold experiment to prove that we can do better. Eric is a 1990 graduate of Berkeley. He taught for six years at Teach for America and is going to be, I hope and expect, a future leader in education in our country. The program that he is involved with is called Teach for America. It was developed out of a senior thesis written by a Princeton University student named Wendy Kopp. She shopped her ideas for a new teacher training program around and was unable to get government support for it. So, with private funding, she started Teach for America. Each year the young teachers participating in the program reach 100,000 American children.

This program has been met with strong opposition from many in the education establishment. They say it demeans teaching because these teacher trainees get only five weeks of boot camp in the summer to prepare them to go into some of the most difficult schools in America. Admittedly, five weeks is not enough preparation, but it's better to have these people in our schools than to not have them. In fact, 80 percent of principals say that Teach for America teachers are better than their average new teacher despite their abbreviated preparation. Two-thirds of students said that they learned more from their Teach for America teacher than they did from their average teachers. Although the program as originally set up assumed that participants would teach for two years, 50 percent stay in teaching for a longer period. Many of them have become dynamic leaders in school systems and elsewhere. We need to think about the implications of this experience for getting new kinds of people in our schools and infusing our education system with new energy and inventiveness.

With that I'll introduce Eric Ryan, who is a 1990 graduate of Berkeley. He taught for six years at Teach for America and is going to be, I hope and expect, a future leader in education in our country.

The Northeast Ohio Experience

Dorothy Baunach
Cleveland Tomorrow

TODAY'S PRESENTATION

- Give an overview of Northeast Ohio.
- Describe our technology infrastructure and model.
- Share lessons learned.

NORTHEAST OHIO OVERVIEW

- Eight-county region with two major urban areas, Cleveland and Akron
- Almost 3 million people (fourteenth largest consumer area in the United States)
- Twenty-three percent of jobs are in manufacturing
- About half as high-tech as San Francisco or Boston
- High-school educated region
- High-poverty region, 11.8 percent

NORTHEAST OHIO'S TECHNOLOGY INFRASTRUCTURE

- Years of experience (making it up as we go along)
- But the key has been a comprehensive partnership with industry; academic and research organizations; state, federal and local governments; and foundations.
- All partners are organized and managed to harness technology for economic benefit.

TARGETED R&D/INDUSTRY CLUSTERS

- Automotive—large employment base, losing inventive edge.
- Aerospace—anchored by NASA Lewis Research Center.
- Biomedical—eighteenth largest city for receipt of National Institutes of Health (NIH) funding.
- Polymers/advanced materials—ranks in top five U.S. regions for industry and research and development (R&D).
- Information/telecommunications—impacts all other segments.

OUR STRATEGY

- Increase the competitiveness of businesses in key sectors of the economy.
- Form, incubate, and retain new businesses.
- Support research collaborations and tech transfer.
- Develop the workforce—general, highly skilled, entrepreneurial.
- Figure B-1.

OUR VEHICLE ENHANCED: A COMPLEMENTARY SET OF FINANCIAL TOOLS

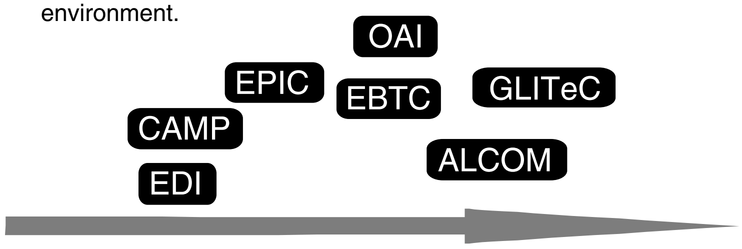
- Primus Venture Partners ($350 million venture capital fund)
- Cleveland Development Partnership ($60 million real estate development fund)
- Ohio Innovation Fund ($11 million in seed capital)
- Figure B-2.

ECONOMIC IMPACT

This has been difficult to track and measure. Anecdotes abound and a few accomplishments are worthy of note:

- Manufacturing employment has stabilized and CAMP's (Cleveland Advanced Manufacturing Program) GLMTC (Great Lakes Manufacturing Technology Center) has reached annual fees of $5 million from industrial projects.
- Industrial research consortia and networks have formed around several key technologies.
- Incubator tenants have returned state investment in payroll taxes.
- Biomedical research base has tripled and company formation is improving.
- Companies started during the past 15 years are making real contributions to the economy (STERIS Corp. is an example).

Our Vehicle: A system of technology intermediary organizations with superior staff and board leadership that merits sustained support from public and private partners and dynamically responds to the technology environment.



1980	1985	1990	1995	1997
State	58%	51%	30%	22%
Industry/Foundations	41%	37%	23%	18%
Federal		12%	47%	60%
Total Support	$0.9	$13.2	$44.8	$57.0
				$ million

KEY: **EPIC** Edison Polymer Innovation Corp.
EDI Enterprise Development, Inc.
ALCOM Advanced Liquid Crystalline Optical Materials Center
GLITeC Great Lakes Industrial Technology Center
EBTC Edison BioTechnology Center
OAI Ohio Aerospace Institute

FIGURE B-1 Northeast Ohio technology intermediaries and funding trends

TECHNOLOGY LEADERSHIP COUNCIL LESSONS LEARNED

- Leadership matters.
- Public/private partnerships work.
- It’s really hard to maintain long-term commitments.
- Partners and programs need to innovate as region learns/changes over time.
- Federal funds are critical to regional science and technology strategies.
- Toughest support to find is for early stage, technology-based business formation.

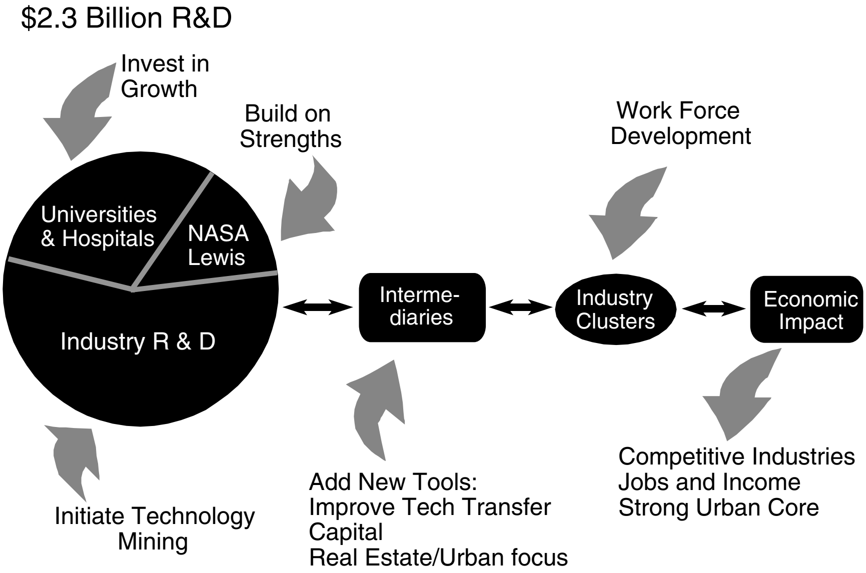


FIGURE B-2 Technology Leadership Council Model

EXAMPLES OF FEDERAL GOVERNMENT ROLE IN TECHNOLOGY-BASED ECONOMIC DEVELOPMENT, NORTHEAST OHIO

- Research grants—National Science Foundation (NSF), NIH, National Aeronautics and Space Administration (NASA), Department of Defense (DoD), etc.
- Small Business Innovation Research grants
- National Institute of Standards and Technology—Manufacturing Technology Center funding; Advanced Technology Program
- NSF Science and Technology Center
- EDA (Economic Development Administration) grant for urban Bio-Enterprise incubator
- NASA–RTTC (Regional Technology Transfer Center), incubator, education grants
- DoD ECRC (Electronic Commerce Resource Centers) funding

TECHNOLOGY LEADERSHIP COUNCIL, AN EXECUTIVE NETWORK

- Enhance the model by identifying and implementing select initiatives.
- Facilitate activities among intermediaries to remove barriers, build linkages, and garner support.
- Communicate and advocate the importance of technology to regional economic growth.
- Target technology investments to build on regional strengths and focus on economic development returns.

APPENDIXES

APPENDIX A:

Forum Agenda

HARNESSING SCIENCE AND TECHNOLOGY FOR AMERICA'S ECONOMIC FUTURE: A FORUM ON NATIONAL AND REGIONAL PRIORITIES

National Academy of Sciences
2101 Constitution Ave., Washington, D.C.
NAS Auditorium
February 2-3, 1998

Day One: Monday, February 2, 1998

Opening Plenary Session

9:00 A.M. Welcoming Remarks: Wm. A. Wulf, National Academy of Engineering

9:15 A.M. Opening Remarks by Forum Co-Chairs
Dick Thornburgh, Kirkpatrick & Lockhart LLP
Bill Spencer, SEMATECH

9:45 A.M. Video Presentations

10:00 A.M. Congressional Perspectives
    Senator Jeff Bingaman
    Representative George Brown
    Kevin Sabo, Senate Commerce Committee

Noon Lunch

Plenary Session on Context and Key Trends

1:15 P.M. Technology and Long-Term Economic Growth
    Richard Nelson, Columbia University
  Transformation of U.S. Innovation: Where Will Technology Come From?
    Richard Rosenbloom, Harvard Business School
  The Global Context
    David Mowery, University of California at Berkeley

3:15 P.M. The U.S. Environment for Venture Capital and Technology-Based Start-Ups
    Charles Geschke, Adobe Systems
    John Shoch, Asset Management Associates
  What's Gone Wrong in Asia?
    C. Fred Bergsten, Institute for International Economics

4:15 P.M. Lessons Learned from State, Local, and Regional Partnerships
    Dorothy Baunach, Cleveland Tomorrow
    Christopher Coburn, Battelle

5:30 P.M. Adjourn

Day Two: Tuesday, February 3, 1998

Plenary Session on Challenges and Issues

8:30 A.M. Science, Mathematics, and Technology Education to Support U.S. Prosperity in the Next Century
    Wm. A. Wulf, National Academy of Engineering
    Bruce Alberts, National Academy of Sciences
    Eric Ryan, Tufts University

10:00 A.M. Defining the Federal Role
  Mary Good, Venture Capital Inc., moderator
  Duncan Moore, Office of Science and Technology Policy
  Peter Lyons, Office of Senator Pete Domenici
  Lewis Branscomb, Harvard University

11:15 A.M. Science, Technology, and the Economy: Other Perspectives
  Stephen S. Roach, Morgan Stanley
  Randy Barber, Center for Economic Organizing
  Kevin P. Stiroh, The Conference Board

12:45 P.M. Breakout groups meet over lunch

2:15 P.M. Breakout groups report

3:00 P.M. Closing discussion

4:00 P.M. Adjourn

APPENDIX B:

Forum Roster

John Ahlen
Office of Science and Technology Policy

Eman Ahmed
Saudi Cultural Mission

Diane Albert
National Academy of Engineering

Bruce Alberts
National Academy of Sciences

Richard Alkire
University of Illinois

Don Alstadt
Lord Corporation

Ray Altevogt

Thomas Althuis
Pfizer Inc.

James Anderson
Ford Motor Company

Alex Annett
The Heritage Foundation

Tom Arrison
National Research Council

Win Aung
National Science Foundation

Gary Bachula
U.S. Department of Commerce

Lee Bailey
U.S. Department of Commerce

Anita Balachandra
U.S. Department of Commerce

Elizabeth Baldwin
Optical Society of America

Randy Barber
Center for Economic Organizing

Douglas Bauer
National Research Council

Dorothy Baunach
Cleveland Tomorrow

Edward Behrens
Procter & Gamble

C. Fred Bergsten
Institute for International Economics

Bill Berry
Air Force Research Laboratory

Jeff Bingaman
U.S. Senate

C. Diane Bishop
Arizona Department of Commerce

Attilio Bisio
The Chemical Engineer

Erich Bloch
Council on Competitiveness

Jacques Bodelle
Elf Aquitaine, Inc.

Karl Boer
University of Delaware

Renate Boer
International Council of Delaware

John Boright
National Research Council

David Boron, National Science Foundation

Richard Bradshaw
Energy Efficiency & Renewable Energy

Jeffrey Brancato
National Science Foundation

Jay Brandinger
New Jersey Commission on Science & Technology

Lewis Branscomb
John F. Kennedy School of Government

Andy Briney
Society of Research Administrators

Jennifer Brower
RAND Corporation

Eric Brown
National Research Council

Duncan Brown
Duncan Brown Associates

Fred Brown
U.S. Department of Energy

George Brown, Jr.
U.S. House of Representatives

William Butcher
National Science Foundation

Frank Calzonettie
Governor's Office of Technology, West Virginia

Robert Carr
SRI International

Marta Cehelsky
National Science Board

David Challoner
University of Florida

Connie Chang
National Institute of Standards and Technology

Rita Chow

Denis Cioffi
George Mason University

Alan Claflin
U.S. Department of Energy

Julia Clark
Office of Representative Bob Etheridge

Marianne Clarke
Battelle Tech. Partnership Practice

Christopher Coburn
Battelle Memorial Institute

Gary Conley
Institute of Advanced Manufacturing Sciences

Mark Crawford
New Technology Week

Marc Cummings
U.S. Department of Commerce

William Danvers
OECD Washington Center

Ruth Davis
The Pymatuning Group

Piero Di Porto
Embassy of Italy

Michael Dingerson
University of Mississippi

Richard Donnelly
George Washington University School of Business

Paul Eckert
Office of Senator Breaux

Maryann Feldman
Johns Hopkins University, Institute for Policy Studies

Irwin Feller
Pennsylvania State University

Robert Feuerstein
Office of Senator D'Amato

Maki Fife
National Research Council

Kevin Finneran
Issues in Science and Technology

Alexander Flax

Rick Focht
National Institute of Standards and Technology MEP

Ray Fornes
National Research Council

Sybil Francis
Office of Science and Technology Policy

Sue Fratkin
Coalition of Academic Supercomputing Centers

Njema Frazier
House Committee on Science

Laura Garwin
Nature

C. William Gear
NEC Research Institute

Steve Gehl
Electric Power Research Institute

Charles Geschke
Adobe Systems

Robert Gillespie
Governor's Office of Technology, West Virginia

Gary Gilliland
National Institute of Standards and Technology

Randy Goldsmith
Oklahoma Alliance for Manufacturing Excellence, Inc.

David Goldston
Office of Representative Sherwood Boehlert

Mary Good
Venture Capital Inc.

Dan Greenberg
Science & Government Report

Michael Greene
National Research Council

Jamie Grivich
Office of Representative Amo Houghton

Jerome Grossman
Health Quality Inc.

Margaret Grucza
Industrial Research Institute

Arthur Guenther
Center for High Technology Materials/UNM

Bruce Guile
Washington Advisory Group, LLC

Phil Hamilton
ASME International

Paul Harris
Technology Business Magazine

Robert Hebner
National Institute of Standards and Technology

Maria Hedzqvist
Embassy of Sweden

Karen Hein
Institute of Medicine

Bill Hendrickson
Issues in Science and Technology

George Hennigan
OCAST Board

Eileen Heveron
Virginia's Center for Innovative Technology

Louis Higgs
Center for the New West

Daniel Hill
Small Business Administration

Ron Hira
George Mason University

John Holmfeld
Washington Fax Newsletter

B. Dundee Holt
National Action Council for Minorities in Engineering

Amo Houghton
U.S. House of Representatives

Gary Isom
Purdue University/ Purdue Research Foundation

Arthur Jaffe
Department of Physics, Harvard University

John Jennings
Office of Senator Jeff Bingaman

Nathaniel Jezzi
American Institute for Contemporary German Studies

Brian Kahin
Office of Science and Technology Policy

Ray Kammer
National Institute of Standards and Technology

Melinda Kelley
Spinal Cord Research Foundation, Paralyzed Veterans of America

William Kelly
Catholic University of America

Ehsan Khan
Office of Energy Research

David King
National Institute of Standards and Technology

Russell Kitchner
University of Notre Dame

Genevieve Knezo
Congressional Research Service

Gus Koehler
California Research Bureau

Lester Koransky
U.S. Department of Labor

Richard Kouzes
West Virginia University

George Kozmetsky
IC2 Institute, University of Texas at Austin

David Kramer
Science and Government Report

Norman Kreisman
U.S. Department of Energy

Charles Kruger
Stanford University

Takao Kuramochi
Embassy of Japan

Alan Ladwig
NASA Headquarters

Patrice Laget
Delegation of the European Commission

Carrie Langner
National Research Council

Carl Lankowski
American Institute for Contemporary German Studies

Charles Larson
Industrial Research Institute

Kathleen Latta
National Science Foundation

Andrew Lawler
Science

Rolf Lehming
National Science Foundation

Wil Lepkowski
Chemical & Engineering News

Flint Lewis
American Chemical Society

Margot Leydic-Boyd
Economic Development Administration

Marshall Lih
National Science Foundation

Maxine Lunn
Virginia's Center for Innovative Technology

Peter Lyons
Office of Senator Pete Domenici

Jill MacNeice
Technology Access Report

Mike Magner
Newhouse Newspapers

Joseph Magno
SUNY Research Foundation

Tom Mahoney
QB Analysis

Thomas Malone
Connecticut Academy of Science and Engineering

Mark Marin
Lewis-Burke Associates

Genny Matthews
Kirkpatrick & Lockhart LLP

Hideaki Matusada
JiJi Press

Peter McDavitt
Center for Technology Commercialization

Mike McGeary
National Academy of Sciences

Lawrence McGeehan
Ben Franklin Technology Center of Western Pennsylvania

Merle McKenzie
Jet Propulsion Laboratory

John McNamee
Economic Development Administration

Reese Meisinger
ASME International

Dean Menke
AAAS Fellow

Steve Merrill
National Research Council

James Merz
University of Notre Dame

Fred Metrailer
Amoco Corporation

A. Duff Mitchell
U.S. Department of Commerce

Anne Money
National Research Council

Duncan Moore
Office of Science and Technology Policy

Robert Morgan
National Academy of Engineering

Tom Moss
National Academy of Sciences

David Mowery
University of California

Jeremiah Murphy
Siemens Corporation

Anthony Myers
Maryland Department of Business & Economic Development

Albert Narath
Lockheed Martin Corporation

Shanna Narath
Sandia National Laboratories

Patrick Neary
Wyoming Science, Technology, and Energy Authority

Richard Nelson
Columbia University

Patricia Nettleship
The Nettleship Group, Inc.

Jeff Newman
California Trade & Commerce Agency

Robert Norwood
NASA

Cary Nourie
State of North Carolina Washington Office

Patricia O'Neill-Brown
U.S. Department of Commerce

William Owczarski
McDermott Technology Inc.

Robert Palmer
House Committee on Science

David Parkhurst
National League of Cities

Norman Paulhus, Jr.
U.S. Department of Transportation

Ronald Paulson
Lockheed Martin Corporation

Roy Pea
SRI International

Dan Pearson
House Science Committee

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Ed Perez
Texas Department of Economic Development

Jack Pevenstein
National Institute of Standards and Technology

Kees Planque
Netherlands Embassy

Gary Poehlein
National Science Foundation

Elizabeth Price
Bridge News

Jim Quinn
U.S. Department of Energy, Office of Industrial Technologies

Herbert Rabin
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National Research Council

Samuel Rankin III
American Mathematical Society

Alan Rapoport
National Science Foundation

Tom Ratchford
George Mason University

Steve Rattien
RAND Corporation

Lawrence Rausch
National Science Foundation

Melvin Ray
Mississippi State University

Proctor Reid
National Academy of Engineering

Barton Reppert
CBR Information Services

Robert Rich
AAAS Research Competitiveness Program

Kristen Rivas
Fujitsu Limited

Stephen Roach
Morgan Stanley

David Robinson
Carnegie Corporation of New York

Sally Rood
National Technology Transfer Center—Washington

Peter Rooney
Office of Senator Lieberman

Allison Rosenberg
National Academy of Sciences

Richard Rosenbloom
Harvard University

Deborah Rudolph
IEEE-USA

Fraser Russell
University of Delaware

Eric Ryan
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Ann Rydalch
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Kevin Sabo
Senate Commerce Committee

Wendy Schacht
Congressional Research Service

Ann-Marie Scheidt
SUNY Stony Brook

Mikhail Schenev
Russian Embassy

Wolfrom Schoett
German Embassy

Tom Sciance
Sciance Consulting Services

John Shoch
Asset Management Associates

Joel Shulman
The Procter & Gamble Company

Bob Simon
U.S. Senate, Office of Jeff Bingaman

Lana Skirboll
Office of Science Policy, National Institutes of Health

Philip Smith
Geary and Smith

Durand Smith
Science & Technology Division/ EDD, New Mexico

Rebecca Speiler
The Blue Sheet

William Spencer
SEMATECH

Richard Spivack
National Institute of Standards and Technology, Advanced Technology Program

Marc Stanley
Advanced Technology Program

H. Guyford Stever
Policy Division, National Research Council

Skip Stiles
U.S. House of Representatives, Office of George Brown

Debbie Stine
National Research Council

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Dick Thornburgh
Kirkpatrick & Lockhart LLP

Jay Tieber
Ohio Department of Development, Technology Division

Kathryn Tollerton
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Christopher Tucker
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John Yost
University of Idaho

Joel Yudken
AFL-CIO

Sharon Yun
U.S. Department of Commerce

Jean Zettler
National Technology Transfer Center

APPENDIX C:

Steering Committee Member Biographical Sketches

Dick Thornburgh (*Co-chair*) is of counsel to Kirkpatrick & Lockhart LLP, a former United Nations official, and served as U.S. attorney general, and governor of Pennsylvania. Mr. Thornburgh holds a Bachelors of Engineering from Yale University, an LL.B. from the University of Pittsburgh, and honorary degrees from 30 colleges and universities. He is Chairman of the State Science and Technology Institute, and a trustee of the National Academy of Public Administration.

William J. Spencer (*Co-chair*) is Chairman of SEMATECH and a professor at the University of New Mexico Medical School. Dr. Spencer holds an A.B. from William Jewell College, and an M.S. and Ph.D. in physics from Kansas State University. He specializes in the biomedical applications of integrated circuits design and processing.

Dennis W. Archer has been the Mayor of the City of Detroit since 1994. Mayor Archer is on the board of the National Conference of Black Mayors. He holds a B.S. from Western Michigan University and a J.D. from Detroit College of Law. He has served on the Detroit Board of Education, as an associate justice on the Michigan Supreme Court, and as an associate professor at Detroit College of Law.

Richard T. Atkinson is the seventeenth president of the University of California, taking office on October 1, 1995. Before becoming president of the UC System, he served as chancellor of UC San Diego; prior to that he served as director of the

National Science Foundation and was a long-term member of the faculty at Stanford University. Atkinson's research deals with problems of memory and cognition. His theory of human memory has been influential in shaping research in the field. His scientific contributions have resulted in election to the National Academy of Sciences, the Institute of Medicine, the National Academy of Education, and the American Philosophical Society. He is past president of the American Association for the Advancement of Science, former chair of the Association of American Universities, the recipient of numerous honorary degrees, and a mountain in Antarctica has been named in his honor.

Dorothy Baunach is Deputy Director of Cleveland Tomorrow, an organization that focuses on building public-private partnerships that enhance the region's economic competitiveness. She has served as President of the Edison BioTechnology Center and as Vice President of Enterprise Development, Inc., and has helped the start-up and development of numerous technology-based businesses throughout Ohio. She hold a B.S. in biology and education from Wittenberg University, an M.S. in biology from the University of Dayton, and an M.B.A. from Case Western Reserve University's Weatherhead School of Management.

Charles M. Geschke is the President of Adobe Systems and a member of the National Academy of Engineering. He holds an A.B. and an M.S. from Xavier University and a Ph.D. in computer science from Carnegie-Mellon University. He has taught at John Carroll University, was a research scientist at the Palo Alto Research Center and manager of the Imaging Science Lab for Xerox Corporation.

Mary L. Good is a Managing Member of Venture Capital and a member of the National Academy of Engineering. Dr. Good has served as the Under Secretary for Technology in the Department of Commerce, as a professor in the Louisiana State University system, and Senior Vice President of Technology at Allied Signal Research & Technology Laboratory. Dr. Good was appointed to the National Science Board in 1980 and served as chairman from 1988 to 1991 when she was appointed to the President's Council of Advisors on Science and Technology. She holds a B.S. in chemistry from the University of Central Arkansas, an M.S. and a Ph.D. in inorganic chemistry and radiochemistry from the University of Arkansas.

Phillip A. Griffiths has been Director of the Institute for Advanced Study since 1991. He was the Provost and James B. Duke Professor of Mathematics of Duke University from 1983 to 1991. Dr. Griffiths, a member of the National Science Board, became a member of the National Academy of Sciences in 1979. He chaired the Board on Mathematical Sciences from 1986 to 1991, and the Commission on Physical Sciences, Mathematics, and Applications in 1992. Dr. Griffiths holds a B.S. from Wake Forest University and a Ph.D. in mathematics from Princeton University.

Harold Shapiro is the President of Princeton University and a member of the Institute of Medicine. He holds a B.A. from McGill University and Ph.D. in economics from Princeton University. Dr. Shapiro has served as a professor of economics at Princeton, on the board of directors for Dow Chemical, and as a member of the President's Council of Advisors on Science and Technology.

John F. Shoch is a General Partner of Asset Management Associates, a venture capital firm in Palo Alto, California. He holds a B.A. in political science, and an M.S. and a Ph.D. in computer science, from Stanford University. He joined the Research Staff at the Xerox-Palo Alto Research Center in 1971, and served as Assistant to the President of Xerox Corporation and Director of the Corporate Policy Committee. From 1982 to 1985, he served as President of the Office Systems Division of Xerox.

H. Guyford Stever has had a career as a scientist, engineer, educator, and administrator. He served as the director of the White House Office of Science and Technology Policy for President Ford, President of the Carnegie-Mellon University from 1965 to 1972, and Chief Scientist of the U.S. Air Force in 1955 and 1956. He is a member of both the National Academy of Sciences and the National Academy of Engineering. He holds an A.B. from Colgate University, a Ph.D. in physics from the California Institute of Technology, and numerous honorary degrees.