Summary and Introduction 1

The United States has long been considered a leader in technological innovation. Many of the most significant innovations of the past several decades, including integrated circuits, digital computers, nylon, bioengineered medicines, and xerography, trace their origins to U.S. companies and inventors. These achievements reflect the efficacy of the U.S. national system of innovation, with its strong science base, its entrepreneurial spirit, a financial system that supports a large venture capital market unparalleled elsewhere in the world, and sophisticated consumers who demand new products and processes and whose tastes signal future changes in world demand.[1] Together, these factors create the capabilities U.S. innovators need to successfully develop new products, processes, and services.

Over the last two decades, U.S. firms have faced increasing competition in developing and commercializing new inventions (see box 1-1 for a definition of terms). Other industrialized nations have developed robust research and development (R&D) systems that rival those of the United States in their ability to generate new scientific and technological discoveries and drive innovation. Many other nations with limited R&D capabilities have become proficient at adopting technologies developed elsewhere and incorporating them into new or improved products, processes, and services. As a result, U.S. firms cannot rely on scientific leadership alone to maintain their competitive advantage in the marketplace. Despite the large number of Nobel Prizes won by U.S. scientists and the large number of patents awarded to American inventors, foreign firms have been able to outperform U.S. firms in some markets and have entirely overtaken some industries by aggressively developing and commercializing new technologies, many of which were invented in U.S. laboratories by U.S. scientists.[2]

[1] For a discussion of the factors that determine a nation's competitive advantage, see Michael E. Porter, *The Competitive Advantage of Nations* (New York, NY: The Free Press, 1990), pp. 69-175.

[2] Several reports note growing competition in the commercialization of emerging technologies. See Competitiveness Policy Council, *A Competitiveness Strategy for America, Reports of the Subcouncils* (Washington, DC: Competitiveness Policy Council, March 1993); Council on Competitiveness, *Picking Up the Pace: The Commercial Challenge to American Innovation* (Washington, DC: Council on Competitiveness, 1988); Report of the President's Commission on Industrial Competitiveness, *Global Competition: The New Reality* (Washington, DC: U.S. Government Printing Office, January 1985).

BOX 1-1: Invention, Innovation, and Commercialization

The terms invention, innovation, and commercialization are commonly used in a number of overlapping ways to refer to the process of developing new technology and incorporating it into new products, processes, and services. Confusion often results from the close ties between invention, Innovation, and commercialization and from subtle differences in meaning of each term. For the purposes of this report, the three terms will be used as defined below:

Invention refers to the act of devising or fabricating a novel device, process, or service. Invention describes the initial conception of a new product, process, or service, but not the act of putting it to use Inventions can be protected by patents, though many inventions are not patented, and most patents are never exploited commercially.

Innovation encompasses both the development and application of a new product, process, or service. It assumes novelty in the device, the application, or both. Thus, innovation can Include the use of an existing type of product in a new application or the development of a new device for an existing application. Innovation encompasses many activities, including scientific, technical, and market research; product, process, or service development; and manufacturing and marketing to the extent they support dissemination and application of the invention.

Commercialization refers to the attempt to profit from innovation through the sale or use of new products, processes, and services. The term is usually used with regard to a specific technology (e g "commercializing high-temperature superconductivity") to denote the process of incorporating the technology into a particular product, process, or service to be offered in the marketplace The term commercialization therefore emphasizes such activities as product/process development, manufacturing, and marketing, as well as the research that supports them, More than invention or Innovation, commercialization is driven by firms' expectations that they can gain a competitive advantage in the marketplace for a particular product, process, or service.

SOURCE Office of Technology Assessment, 1995

In this more competitive environment, the ability of U.S. firms to innovate and commercialize new technologies depends on many factors. While basic research is still critical, it is only one element of a national system of innovation that includes systems of finance and education, facilities and know-how for manufacturing products and providing services, organizations for developing and promulgating standards, institutions for testing and approving new products, and mechanisms for creating markets. All elements of this system must act in concert to bring new innovations to the market. Although this system relies heavily on the initiative and ingenuity of private-sector actors, government actions influence the process in many ways, both directly (e.g., through funding of basic research and promulgation of product and process regulations) and indirectly (e.g., through financial and tax regulations, the fulfillment of government missions, and procurement for its own needs).

This report examines the processes of innovation and commercialization with an eye toward developing a more complete understanding of the multiple pathways linking new science and technology to new products, processes, and services. In doing so, it highlights the difficulties firms face in financing new technology ventures, settling on product architectures or standards, scaling up for manufacturing, and creating markets for innovations. Finally, the report traces government influence-both direct and indirect-on innovation and commercialization of emerging technologies. While stopping short of delineating specific policy options for improving U.S. efforts in these areas, the discussion illustrates that federal policies regarding R&D funding, environmental and other regulations, intellectual property, taxation, and procurement have a significant cumulative effect on the success of U.S. firms in the global marketplace. They help create the environment in which firms attempt to commercialize new technologies and form an integral part of the innovation systems that develop in different industries.

PRINCIPAL FINDINGS

Linkages Between Science, Technology, and Innovation

- *The linear model of innovation—which implies that innovation proceeds sequentially from new scientific discoveries to new products, processes, and services—is limited in its descriptive and predictive powers*. Innovation can assume many forms, including incremental improvements to existing products, applications of existing technology to new markets, and uses of new technology to serve an existing market. Though typically less revolutionary, these other forms of innovation are equally important to the U.S. economy and national well-being in terms of the performance improvements and cost reductions they produce.
- *Science plays a critical role in innovation, but is not necessarily the driver of new products, processes, and services*. New ideas for innovation can stem from many sources, including new manufacturing capabilities and recognition of new market needs, as well as scientific and technological discoveries. Innovation and commercialization require considerable feedback between science, engineering, product development, manufacturing, and marketing.
- *The nature of innovation changes over time as product lines and industries mature*. Whereas the early stages of an industry are characterized by radical innovations that create wholly new products, processes, or services and are often based on new science or technology, later stages are characterized by incremental innovation, which builds upon existing products, processes, and services and derives more from advances in manufacturing capability, product design, and component technologies.
- *Successful commercialization is not simply a matter of developing technology first or getting to market first*. While being first can bestow advantages on an innovating firm, firms must create and maintain a competitive advantage in the marketplace by staking out and protecting a proprietary position through patents, trade secrets, or market barriers, and by securing the complementary assets and skills needed to ensure proper manufacturing, marketing, and support.

Elements of Innovation Systems

- *Successful commercialization requires an environment conducive to innovation and requisite industrial infrastructure.* Institutional arrangements are needed to establish standards, regulations, and rules governing areas such as intellectual property and antitrust. Human, financial, and scientific resources are required as the basic inputs to the innovation process. Complementary assets—both related technologies and necessary skills in manufacturing and distribution—are often needed to ensure that companies can succeed in the marketplace. Potential customers frequently need additional assurances and warranties that new products, processes, and services will work as advertised. Policymakers cannot assume that investments in the science base alone will ensure economic success.
- *Government and industry both play a role in establishing the environment and infrastructure necessary to support innovation and commercialization*. Government influences innovation and commercialization through tax and financial policies and through the patent system. Furthermore, in fulfilling its public missions, government affects technology development and market acceptance through procurement, regulations to protect human health and the environment, development of technologies, and funding of basic research. The unintentional effects of government actions on the innovation

and commercialization process must be understood in order to maintain a healthy economy.

Increasing Competition

- *U.S. firms face an increasingly competitive environment for developing new science and technology.* The United States continues to garner a disproportionate share of Nobel Prizes and to patent a growing number of inventions. However, the proportion of foreign patenting in the United States has grown, and Japanese and European firms lead U.S. inventors in some critical technologies. The Newly Industrialized Countries (NICs) of Asia (Hong Kong, Singapore, South Korea, and Taiwan) are also increasing their technological capabilities in such areas as telecommunications and semiconductors.
- *International competition in developing and marketing new products, processes, and services has reduced U.S. market shares slightly in most high-technology industries,* demonstrating the ability of foreign-based companies to successfully convert new technology into marketable products. Competitors from Europe, Japan, and elsewhere in Asia have penetrated markets in the United States and abroad for aircraft, computers, and semiconductors, in particular. Nevertheless, the United States maintains a trade surplus in the most advanced technology products.
- *As a percentage of gross domestic product, total U.S. expenditures on nonmilitary R&D lag those of Japan and Germany by a wide margin and are more comparable with those of France and the United Kingdom.* Continued reductions in federal R&D expenditures and increasing budgetary concerns are likely to further reduce overall R&D spending and place a greater burden on the private sector for maintaining the nation's R&D investment.
- *Private-sector funding for R&D has stagnated since 1991* as U.S. firms have attempted to respond to new competitive challenges. Greater attention to short-term projects has limited support for long-term R&D, and many corporate laboratories have been scaled back or shifted to more product-oriented work. These changes have likely aided the recent resurgence of U.S. manufacturing industries, but raise questions about U.S. competitiveness in the long term.

NATIONAL INTEREST IN INNOVATION

The United States has many reasons to maintain strong capabilities in innovation and the commercialization of emerging technologies. These activities confer numerous benefits on the nation. Novel technologies spur the development of new industries and help existing industries remain competitive by enabling improvements that lower costs or enhance performance. Today's semiconductor and biotechnology industries both grew out of recent technological advances and now employ hundreds of thousands of workers in the United States alone, ranging from scientists, engineers, and managers to administrators, production line workers, and technicians. Continuous improvement in the styling, performance, and fuel economy of American cars has allowed the U.S. auto industry to repel some of the advances made by rivals in Japan, Europe, and Korea during the 1980s.

Much of the nation's growth in jobs and productivity can be traced to technological innovation. Economic studies estimate that technological change has contributed over half of the growth in economic output since the Great Depression and 17 percent or more of the growth in productivity since 1973.[3] Increased productivity, in turn, is a primary driver of rising wages and standards of living, and is one of the nation's most effective means to compete against low-wage nations such as Mexico, Taiwan, and Malaysia. High-technology industries characterized by high levels of R&D spending, such as pharmaceuticals, electronics, aircraft, and professional equipment, comprise a growing portion of the national economy. Together, these industries represented 20 percent of U.S. manufacturing output and 38 percent of U.S. manufacturing exports in 1991, up from 16 and 29 percent, respectively, a decade earlier.[4] More importantly, the output of some of these industries allows improvements in other portions of the economy, as demonstrated by the widespread use of information technologies in service sector jobs.

Innovation contributes to other national goals as well. New medical devices improve human health through better diagnostic and therapeutic procedures; cleaner-burning automobile engines and more efficient wind turbines meet transportation and energy needs, while limiting damage to the environment; advances in electronics and information technology allow new forms of entertainment and improvements in education; and new fighter aircraft and radar systems enhance national security. Ironically, technology has also contributed to many of the problems or situations that innovation must now attempt to remedy, such as environmental degradation (including threats to public safety), depletion of energy and natural resources, and the greater destructive potential of warfare.

To capture the full benefit of innovation, the United States must actively commercialize new technologies. Only through commercialization can the nation enjoy the benefits of job and wealth creation. Invention alone is not sufficient. Some of the advantages of innovation can be acquired by purchasing new products developed by foreign firms, but neither the economic or social benefits will be as great as if commercialization occurs at home. Licensing technology to foreign producers does not generate the revenues or the jobs created by a domestic industry; nor do products, processes, and services developed by foreign countries necessarily match the requirements of the U.S. market. U.S. semiconductor manufacturers, for example, complained throughout the 1980s that they could not fully benefit from new semiconductor manufacturing equipment produced by leading Japanese suppliers because it was tailored to the needs of the Japanese industry.

THE CHANGING ENVIRONMENT FOR INNOVATION

The United States remains a strong innovator. The nation as a whole continues to spend more on research and development than any other nation, and patent statistics suggest that the rate of U.S. invention accelerated over the last decade. U.S. firms perform well at turning new technologies into successful products, processes, and services and dominate most markets for high-technology goods such as aircraft, computers, and pharmaceuticals, turning out new innovations at a staggering rate.

In the past, much of this success rested on the nation's strong science base. With little competition in the postwar period, U.S. firms could easily translate new scientific and technological break-

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[3] Jan Fagerberg, "Technology and International Differences in Growth Rates," *Journal of Economic Literature,* September 1994, pp. 1147-1175. See also Edward Mansfield, "Contribution of Research and Development to Economic Growth of the United States," *Papers and Proceedings of a Colloquium on Research and Development and Economic Growth Productivity,* National Science Foundation, Washington, DC, 1972; M. Ishaq Nadiri, "Contributions and Determinants of Research and Development Expenditures in the U.S. Manufacturing Industries," *Capital, Efficiency and Growth*, George M. von Furstenberg (ed.) (Cambridge, MA: Ballinger, 1980); Zvi Griliches, "The Search for R&D Spillovers," National Bureau of Economic Research, Working Paper #3768, 1991; and M. Ishaq Nadiri, *Innovations and Technological Spillovers*, Economic Research Report # 93-31, C.V. Starr Center for Applied Economics (New York, NY: New York University Press, August 1993).

[4] Organisation for Economic Cooperation and Development, Economic Analysis and Statistics Division, *Structural Analysis Industrial Database*, No. 1, May 1994. Hereafter referred to as OECD, *STAN (1)*, May 1994.

throughs into market successes. Increasingly, however, firms based in Japan, Europe, and elsewhere in Asia are creating a new challenge for U.S. firms. By concentrating on rapid product design and manufacturing, these nations have entered into markets long considered the sole province of U.S. firms. Japanese companies have been first to commercialize some new products—such as liquid crystal displays—based on U.S. inventions. In industries with rapid product development cycles, newly industrialized countries (NICs) such as Hong Kong, Singapore, South Korea, and Taiwan have at times been first to market new generations of existing product types, such as 16-megabyte DRAMs[5] (dynamic random access memories), or have followed closely on the heels of the original innovator. As continued globalization of manufacturing networks and advances in telecommunications technologies accelerate the diffusion of technology around the world, such competition will likely become more fierce, and U.S. firms will have more difficulty maintaining market leadership in fields they have pioneered.

Good standard indicators do not exist with which to gauge the effects of these changes on U.S. firms. It is difficult to measure the ability of a nation's firms to devise new products, processes, and services and bring them successfully to market. The three indicators most commonly used to measure innovation—patent statistics, trade statistics, and R&D spending—each capture only one small element of the innovation and commercialization processes and suffer from numerous drawbacks. Patent statistics, for example, register new inventions that meet certain criteria for novelty and utility, but provide no information about their economic value. Moreover, many innovations are not patented. In some cases, inventors decide that secrecy is better protection against imitation than a patent. Also, technological progress often emerges from incremental innovation, learning-by-doing, and the adaptation of existing technologies—activities that may not be patentable. Nevertheless, patents can be used to help gauge the comparative inventiveness of nations and identify particular technological strengths and weaknesses.

Trade statistics provide some indication of the commercial success of products, processes, and services. The degree to which consumers prefer the output of one nation's firms to that of another results in part from the ability of those firms to successfully design, develop, manufacture, and market innovations that meet market demand. In high-technology industries such as aerospace, electronics, and pharmaceuticals, customer preferences are strongly influenced by the technological sophistication of new products, processes, and services. Yet, trade performance is strongly influenced by factors other than effective innovation and commercialization. Macroeconomic factors such as interest rates and currency fluctuations influence the cost of products, processes, and services, and the ability of customers to afford them. Trade barriers, whether explicit tariffs and quotas or more subtle differences in national regulations and customs, can affect a firm's ability to penetrate export markets. Despite these limitations, trade data provide one of the few *output* measures of innovation and commercialization. When combined with patent information, trade data can help trace the linkages between the invention of a new product, process, or service and its subsequent commercialization.

R&D spending is also used to measure a nation's innovative abilities because statistics are widely available, and because R&D is one of the central activities of innovation. But R&D spending is an *input* to the innovation process, not a result of innovation. R&D statistics measure the amount of resources a firm or a nation dedicates to innovation, but not their effectiveness in converting that effort into successful products, processes, and services. While some correlation does exist between R&D spending and innovative success, the relationship between the two is not always di-

[5] IBM was the first to produce 16-Mbit DRAMs, but for internal consumption only.

TABLE 1-1: U.S. Patent Awards (thousands)

Patents	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Total	65.8	57.9	56.9	67.2	71,6	70.8	82.9	77.8	95.3	90.3	96,5	97.4
Resident	39.2	33.9	32.9	38.4	39.6	38.1	43.5	40.4	50.1	47.4	51.2	52.3
Foreign	26.5	24.0	24.0	28,8	32.1	32.7	39.4	37.4	45.3	42.9	45.3	45.1
% foreign	40.4	41,4	42.2	42.9	44.8	46.2	47.5	48.1	47.5	47.5	47.0	46.3
/10,000[a]	2.7	2.7	2,5	2.6	2.7	2,7	2.8	3.1	3.3	3.6	3.5	3.6

[a]Resident patent *applications* per 10,000 population,

SOURCE: Office of Technology Assessment, 1995; based on data from the National Science Foundation, *Science and Engineering Indicators--1993,* NSB93-1 (Washington, DC: U S. Government Printing Office 1993), appendix table 6-12, p. 456; U.S. Patent and Trademark Office *Patenting Trends in the United States,* report to the National Science Foundation, September 1994; and Organisation for Economic Cooperation and Development, *Main Science and Technology Indicators, No 2,* table 77, December 1994

rect. Nations or firms with extremely efficient innovation systems can outperform those that use greater R&D resources less wisely. Comparisons of national R&D spending are therefore better used to measure a nation's commitment to innovation and to provide clues to its future technological capabilities, rather than to measure innovative abilities directly.

Generating New Inventions—Patent Statistics

The United States continues to be a significant source of new inventions and technologies. Between 1981 and 1992, the number of U.S. patents awarded annually grew 48 percent, from 65,800 to 97,400 (see table l-l). U.S. patent intensity, expressed as patent applications per 10,000 population, climbed 33 percent from 2.7 to 3.5 during this same time period. Most other countries in the Organisation for Economic Cooperation and Development (OECD) experienced no growth or a decline in patent intensity during this period--except for Japan. Per capita patenting rates for Japan increased 67 percent between 1981 and 1992, from 16.3 per 10,000 in 1981 to 27.2 by 1992.[6] The larger rate of patenting does not imply that the Japanese population is more inventive than that of the United States. Patents granted in Japan typically have a narrow scope, which encourages multiple filings to cover permutations of an invention that in most industrialized nations would be covered by a single patent. Nevertheless, growth in Japanese patenting has outpaced that of the United States, and the United States continues to lead all industrial countries except Japan in the number of patents filed by residents in their home countries.

U.S. inventors also file more foreign patent applications than residents of any other country. Between 1981 and 1992, the number of foreign patent applications filed by U.S. inventors climbed from 127,000 to 413,000, while Japan's increased from 49,000 to 129,000, and Germany's rose from 83,000 to 163,000. Because of the additional cost and complexity involved in filing foreign patents, firms tend to reserve foreign patenting for those inventions they believe have high commercial value. Despite large growth in foreign patenting in the United States, foreign inventors still hold a smaller percentage of patents in the United States than they do in other industrialized nations except Japan and Russia.

The United States is a net exporter of technology. International sales of U.S. intellectual property (licenses and royalties) rose from $8 billion in 1986 to $20.4 billion in 1993, while U.S. purchases of foreign intellectual property grew from just $1.4 billion to $4.8 billion, pushing the technology trade surplus up from $6.6 billion to $15.6 billion (in current dollars). This large trade surplus in intellectual property is unmatched by

[6]Per capita patenting rates data from the Organisation for Economic Cooperation and Development, Economic Analysis and Statistics Division, *Main Science and Technology Indicators* database, No. 2, table 77, December 1994. Hereafter referred to as OECD, *MSTI (2),* table number. December 1994.

TABLE 1-2: International Comparison of Patent Families in Three Technologies (percent of total patent families)

Country	Robotics 1980	Robotics 1985	Robotics 1990	Genetic Engineering 1980	Genetic Engineering 1985	Genetic Engineering 1990	Optical Fibers 1980	Optical Fibers 1985	Optical Fibers 1990
United States	18%	25%	24%	72%	62%	60%	38%	24%	33%
Japan	44	35	44	12	22	18	23	37	33
Great Britain	3	7	4	16	7	8	8	11	7
France	12	14	13	0	2	5	15	5	10
Germany	22	18	14	0	7	9	16	23	17

NOTE A patent family consists of all patent applications filed in different countries to protect a single invention

SOURCE. National Science Board, *Science and Engineering Indicators--1993,* NSB-93-1 (Washington, DC: US Government Printing Office, 1993), pp. 178-184

any other OECD nation, most of which export about the same amount of technology as they import. High levels of technology exports could reflect the inability of U.S. companies to successfully commercialize their own inventions, but most of the international licensing of U.S. patents—and the bulk of the trade surplus-results from transfers of technology between affiliates of multinational enterprises (MNEs). Between 1986 and 1993, trade between affiliated firms accounted for 79 percent of all technology exports and 68 percent of all technology imports.[7] International technology trade between unaffiliated firms generates a smaller surplus for the United States, totaling $3.1 billion in 1993.

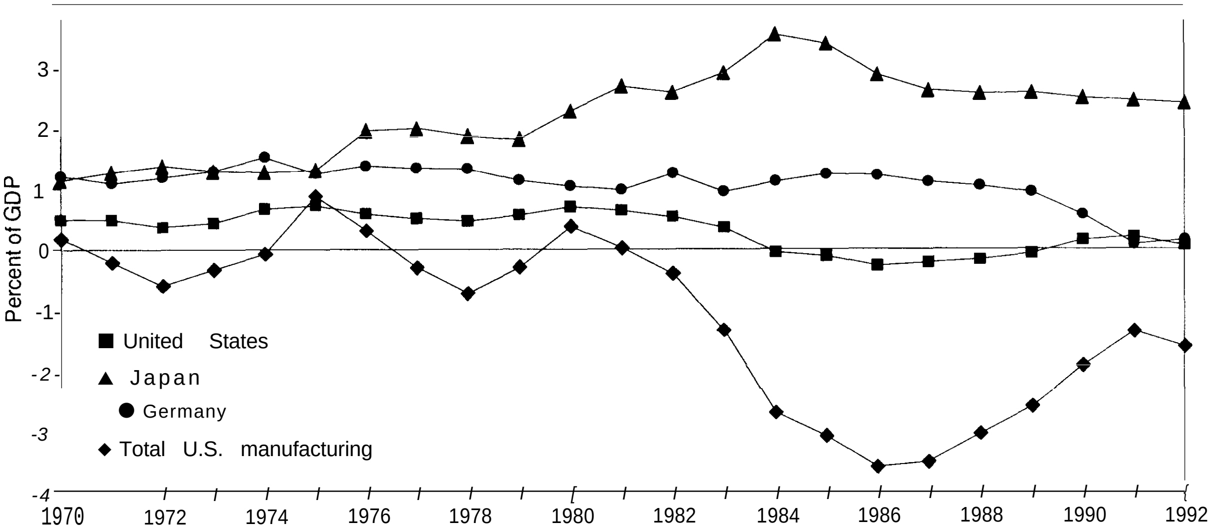
Despite these positive indicators, the United States faces increasing competition in invention and technology development. Much of the growth in U.S. patenting over the past decade resulted from an increase in patenting by foreign inventors, suggesting that foreign nations are increasing their innovative capabilities relative to the United States, or that they are increasing their access to the U.S. market. In 1992, foreign inventors accounted for over half of all U.S. patent applications and 46 percent of U.S. patent awards, up from 43 percent of applications and 40 percent of awards in 1981. In total, the number of U.S. patents granted to nonresidents increased 70 percent between 1981 and 1992. Japanese inventors account for the largest share of nonresident U.S. patents, holding 46 percent of the U.S. patents issued to foreign inventors in 1991, up from 28 percent a decade earlier. Germany is second with 17 percent, followed by France with 7 percent.

Furthermore, Japanese and European inventors lead the United States, or are strong contenders, in patenting many advanced technologies. U.S. inventors owned one-fourth of the patent families[8] in robotics technology in 1990—up from just 18 percent in 1980, but substantially below Japan's 44 percent share (table 1-2). In genetic engineering, U.S. inventors owned some 60 percent of the patent families in 1990, far outstripping Japan, but down from 1980 when they owned 72 percent of the patent families. The United States' position has also slipped in optical fibers. The United States held the lead with 38 percent of patent families in

[7] Approximately 97 percent of these exports were sold by U.S. multinational enterprises (MNEs) to their foreign affiliates, while 91 percent of MNE imports were purchased by U.S. affiliates of foreign firms. U.S. Department of Commerce, *Survey of Current Business,* September 1994, p. 101. See also U.S. Congress, Office of Technology Assessment, *Multinationals and the U.S. Technology Base,* OTA-ITE-612 (Washington, DC: U.S. Government Printing Office, September 1994).

[8] A patent family consists of all the patent documents filed in different countries that are associated with a single invention. Essentially, this statistic counts as one unit all international patents held on the same invention. The size of the family refers to the number of distinct patents held. Comparisons of patent families avoid multiple counting of a single invention that is patented in several countries. See Mary Ellen Mogee, "International Patent Analysis as a Tool for Corporate Technology Analysis and Planning," *Technology Analysis and Strategic Management,* vol. 6, No. 4, 1994, pp. 487-488.

FIGURE 1-1: High-Technology Trade Balances as a Percentage of Gross Domestic Product for Select Countries, 1970-1992



NOTE: High-technology trade balances encompass trade in six industries with the highest ratios of R&D expenditures to sales on a global basis drugs and medicines, office and computing equipment, electrical machinery, electronic components and equipment, aerospace, and scientific and professional equipment.

SOURCE: Organisation for Economic Cooperation and Development, *Scoreboard Indicators, No 2,* tables 9, 14, 25,29, December 1994

1980, but Japan achieved parity by 1990 when each nation held 33 percent of the patent families.

Newly industrialized countries of Hong Kong, Singapore, South Korea, and Taiwan have also increased their patenting activity. Between 1985 and 1990, the total number of patents awarded by these nations more than doubled from 13,100 to 32,500—more than one-third the number of patents awarded by the United States. Awards to residents and nonresidents are relatively balanced, with nonresident awards outnumbering resident awards by a factor of 1.37. Among the most active patent classes are amplifiers, telecommunications, semiconductor manufacturing processes, and dynamic magnetic information storage or retrieval.[9]

Trade Performance

The effects of this growing technological capability are becoming evident in trade statistics. U.S. firms remain competitive inmost high technology industries, but have greater difficulty maintaining market share in more mature product lines. Though the United States recovered from a six-year deficit to post a surplus in high-technology trade[10] between 1990 and 1992, the surplus—which stood at 0.05 percent of GDP in 1992—has declined since 1990 and was significantly smaller than the surpluses generated during the 1970s and early 1980s, which reached 0.72 percent of GDP (figure l-l). Over the last two decades, the U.S. high-technology trade balance has consistently

[9] National Science Foundation, *Asia's New High-Tech Competitors,* NSF 95-309 (Arlington, VA: 1995), appendix tables 3, 6-9.

[10] As defined by the OECD, high technology industries include six industries with the highest ratio of R&D expenditures to sales on a global basis: 1) drugs and medicines, 2) office and computing equipment, 3) electrical machinery, 4) electronic components and equipment, 5) aerospace, and 6) scientific and professional instruments. See Organisation for Economic Cooperation and Development, *Scoreboard Indicators '94* (Paris: Organisation for Economic Cooperation and Development, December 1994), p. 11.

TABLE 1-3: U.S. Trade in Computer and Telecommunications Equipment, 1994 (billions of dollars)

	Imports	Exports	Balance[a]
Computer Equipment			
Central processing units	$5,4	$94	$40
Peripherals	24.6	8.3	(16 .4)
Parts and accessories	16.1	11.4	(4.7)
Total	$46.2	$291	($1 71)
Telecommunications			
Network and transmission	$1,0	3.4	24
Customer premises equipment	62	1.4	(48)
Parts and other equipment	4 . 2	7 . 5	
Total	$11.3	$123	-- $0.9

[a]Parentheses denote negative balance (imports greater than exports).
NOTE: Totals may not add because of rounding.

SOURCE: C. Woods, Office of Computers and Business Equipment, U.S. Department of Commerce, Washington, DC, personal communication, Aug. 15, 1995; L. Gossack, Office of Telecommunications, U.S. Department of Commerce, Washington, DC, fax to D. Eichberg, Office of Technology Assessment, U S Congress, Aug. 16, 1995.

fared worse than those of Japan and Germany (though Germany’s balance plummeted shortly after reunification and sank below the U.S. balance in 1991), but it has outperformed the U.S. trade balance for all manufactured products.

U.S. trade performance has deteriorated across many segments of high-technology industry. While aerospace trade has posted a slight gain as a percentage of GDP since 1970 and pharmaceuticals has remained essentially flat, trade in computers and office equipment has dropped from a surplus of 0.20 percent of GDP in 1980 to a deficit of 0.14 percent of GDP in 1992. The remainder of the electronics industry, while having improved since the late 1980s, is still below its performance in the 1970s, relative to GDP, and the surplus in professional instruments was less than half as large in 1992 as in 1970.

This decline reflects both a drop in U.S. export performance and a much larger increase in import consumption. Between 1972 and 1992, imports grew from just 6 percent to 22 percent of the U.S. market for high technology goods, while U.S. exports declined moderately from 25 percent to 23 percent of total OECD exports of high-technology goods. Import penetration has occurred across nearly all high-technology industries, though most notably in computers and electronics. Imports now account for some 45 percent of the U.S. market for computing and office equipment, 34 percent of electronic equipment and components, and 24 percent of electrical equipment. Exports have declined most notably in computing and aerospace, which declined from peaks of 39 percent and 65 percent of total OECD exports, respectively, to just 26 percent and 44 percent by 1992. Much of this decline is due to the rapid growth of foreign production capacity in these industries. U.S. production of computers and office equipment accounted for over half of total OECD production in 1980, but for only one-third of total production in 1992. Similarly, Europe’s Airbus Industry, a relative newcomer to the aerospace industry, now holds nearly 30 percent of the global market for aircraft.

Most competition in high-technology industries comes from less sophisticated products such as telephone handsets and computer peripherals. In computing equipment, for example, the U.S. deficit results almost wholly from imports of peripheral devices such as disk drives, monitors, and keyboards; trade in central processing units posted a surplus of $4 billion in 1994 (see table 1-3). Similarly, in telecommunications, the United States runs a deficit in customer premises equipment such as telephones, fax machines, and answering machines, but posted a surplus of $2.4 billion in network and transmission equipment and $3.3 billion in parts and other equipment in 1994. The semiconductor industry follows a

TABLE 1-4: U.S. Trade in Advanced Technology Products by Field, 1994 (billic

Field	Exports	Imports	Balance [a]
Advanced materials	$0.9	$06	$02
Aerospace	35.0	11,4	236
Biotechnology	1,0	01	10
Electronics	25.8	259	(o 1)
Flexible manufacturing	5.2	29	23
Information and communications	42,9	49,9	(7 o)
Life science	6.8	4.8	20
Nuclear technology	1.6	0	1,5
Optoelectronics	0.9	2,5	(1 6)
Weapons	0.7	0.1	06
Total	$120.8	$98.4	$224

[a]Parentheses denote negative balance (Imports greater than exports)
NOTE: Totals may not add because of rounding

SOURCE: Nick Orsini, Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce, Washington, DC, fax to J Sheehan, Off Ice of Technology Assessment, U S Congress, Washington, DC, Mar 8, 1995

similar pattern. While U.S. semiconductor manufacturers lagged far beyond Japan in 1992 with an 18.2-percent share of the world market for dynamic random access memories, a commodity memory chip for computers, they dominated the market for microprocessors with a 69-percent market share. [11]

U.S. firms perform better in products that incorporate leading-edge technology. Trade in advanced technology products, as defined by the U.S. Bureau of the Census,[12] posted a surplus of $22.4 billion in 1994; however, the surplus has declined 46 percent in real terms since its peak in 1991. Advanced technology products comprise a growing portion of U.S. trade. The total volume of trade (imports plus exports) accounted for by advanced technology products grew from 12 percent of total U.S. merchandise trade in 1982 to 18.7 percent in 1994. At the same time, advanced technology trade grew from 1.7 percent to 3.3 percent of U.S. GDP, demonstrating the growing importance of these products to the U.S. economy. Most of the current surplus is generated by trade in aerospace, which includes exports of U.S. military—as well as civilian—aircraft; in other areas of great importance to the economy, such as information and communications technology and optoelectronics, the United States runs a deficit (see table 1-4).

Research and Development Spending

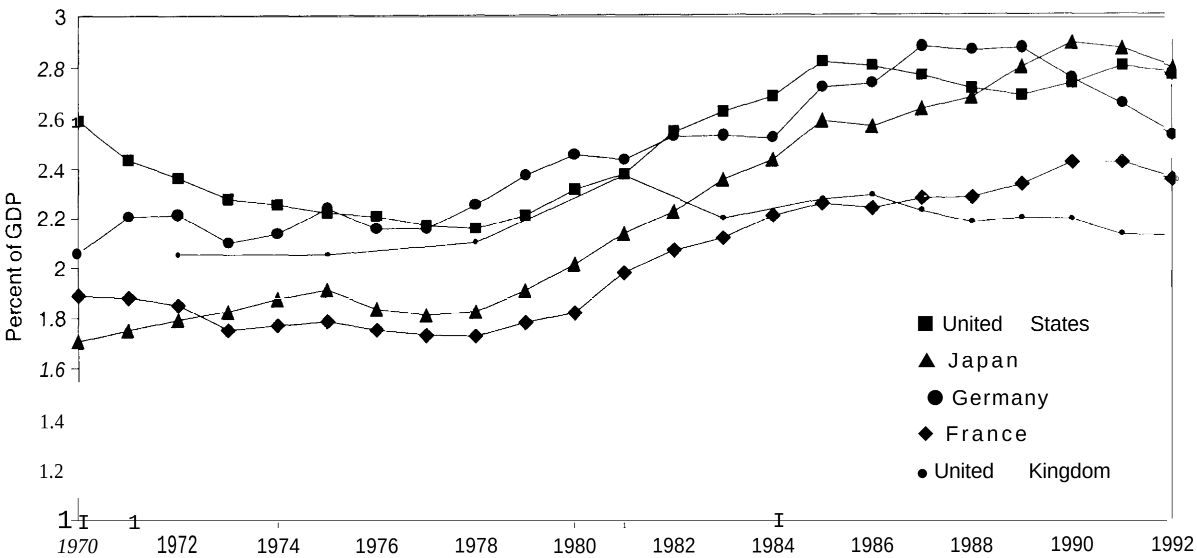
Trends in research and development spending also indicate growing competition. In absolute terms, the United States remains the world leader in R&D spending. Private and public expenditures on R&D totaled almost $173 billion in 1994. On average, between 1981 and 1992, U.S. R&D spending, measured in terms of purchasing power parity, was six times higher than that of Germany and 1.5 times higher than that of Japan.][3] In

[11] *Daraquest,* "Final 1992 Worldwide Market Share," 1993.

[12]Trade statistics for advanced technolog, products are collected and published by the U.S. Bureau of the Census. The measure attempts to account for the mix of high- and low-technology products contained within industrial trade data by including only those products that incorporate significant amounts of one or more leading-edge technologies, as determined by bureau analysts. The product mix changes annually, reflecting new technological developments. While it excludes some products manufactured by high-technology industries (such as telephone answering machines), it includes products such as advanced materials and nuclear technology that are not reflected in the OECD trade data.

[13] Data from OECD, *MSTI (2),* table 2, December 1994.

FIGURE 1-2: National Expenditures on R&D as a Percentage of Gross Domestic Product in Select Countries, 1970-1992



NOTE: Data for Germany Include the former East Germany after 1990

SOURCE: National Science Foundation, *National Patterns of R&D Resources 1994* (Arlington, VA 1995), table B-20, p 77

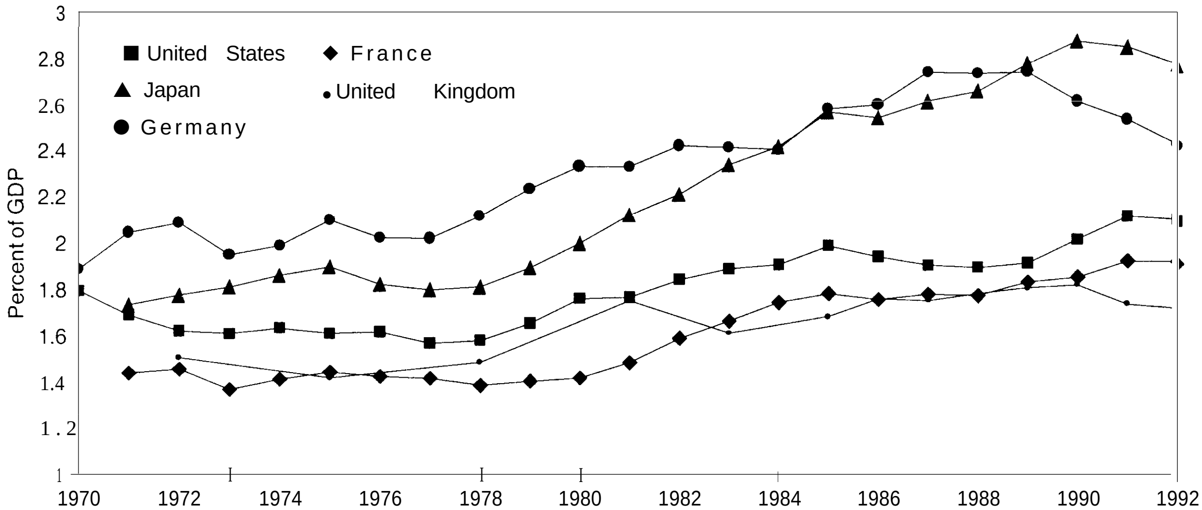
proportion to the size of the overall economy, however, U.S. expenditures on R&D are less impressive (see figure 1-2).[14] Whereas the United States and Germany had previously maintained the highest levels of R&D intensity in the industrialized world, Japan's increased dramatically after 1970 to surpass the United States in 1989 and Germany in 1990.[15] As of 1992, U.S. expenditures on R&D stood at 2.77 percent of GDP, compared to 2.80 percent of GDP for Japan. Germany's expenditures, largely as a result of reunification, had fallen to 2.53 percent of GDP.

Furthermore, the United States directs far more of its R&D spending toward defense technologies than does Germany or Japan, limiting its potential effect on economic competitiveness. When defense-related expenditures are removed from R&D figures, U.S. R&D spending drops to 2.1 percent of GDP, considerably below that of Germany or Japan (see figure 1-3). Although past defense R&D and procurement enriched the technological growth and capacity of some U.S. industrial sectors—particularly aerospace and electronics--eurrent defense R&D has less direct

[14] R&D as a percentage of GDP (also referred to as R&D intensity) is widely considered superior to absolute spending on R&D as a means of making cross-national comparisons of innovative capacity because it is scaled to the size of the national economy.

[15] U.S. Congress, Office of Technology Assessment, *Multinationals and the U.S. Technology Base*, OTA-ITE-612 (Washington, DC: U.S. Government Printing Office. September 1994), pp. 65-66.

FIGURE 1-3: National Expenditures on Nondefense R&D as a Percentage of Gross Domestic Product in Select Countries, 1970-1992



NOTE: Data for Germany includes the former East Germany after 1990

SOURCE: National Science Foundation, *National Patterns of R&D Resources 1994* (Arlington, VA 1995), table B-20, p **77**

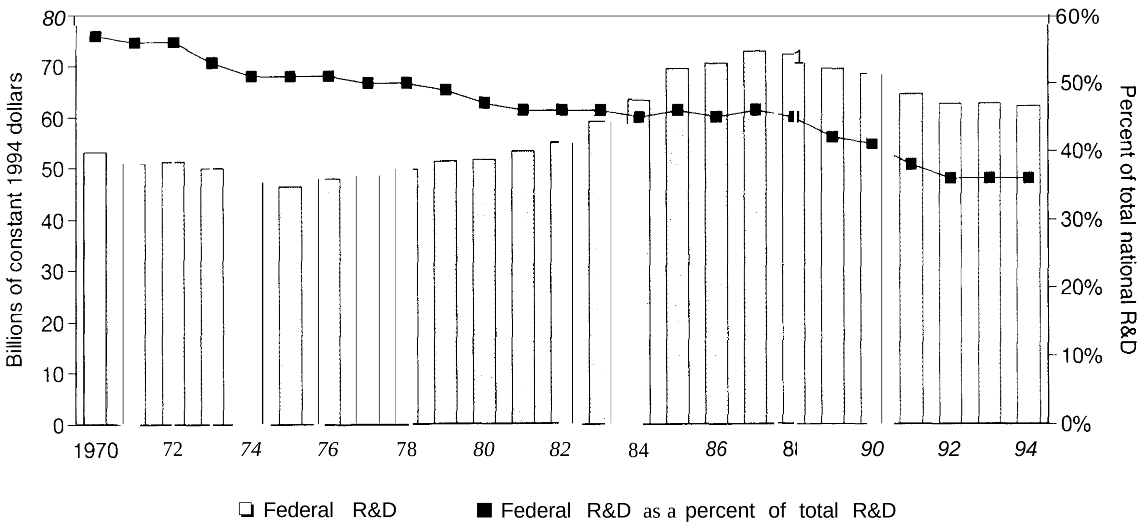
benefits for the U.S. industrial technology base.[16] Most of the U.S. defense R&D budget is devoted to military activities that have few implications for the commercial technology base. 17 Though attempts are under way to promote greater cross-fertilization in the military and civilian markets, long-standing legal, institutional, and administrative barriers restrict technology transfer between the defense and civil sectors.[18] Spin-off from military R&D to commercial projects that in the past contributed to civilian technology development (such as in semiconductors, computers, jet engines,

[16] Numerous studies have analyzed the impact of the U.S. innovation system's orientation toward defense technologies on the nation's relative technological position and international competitiveness. See U.S. Congress, Office of Technology Assessment, *Defense Conversion.. Redirecting* R&D, OTA-ITE-552 (Washington, DC: U.S. Government Printing Office, May 1993); National Science Board, *The Competitive Strength of U.S. Industrial Science and Technology: Strategic Issues* (Washington, DC: National Science Foundation, 1992); David C. Mowery and Nathan Rosenberg, "The U.S. National Innovation System," *National Innovation Systems: A Comparative Analysis,* Richard R. Nelson (cd.) (New York, NY: Oxford University Press. 1993).

[17] Of the pentagon's research, development, test, and evaluation (RDT&E) budget, the science and technology portion—arguably the area with the greatest potential for spinoff effects-totaled less than 50 percent throughout the 1980s. In recent years, the science and technology portion of the RDT&E budget has varied from 20 to 25 percent. U.S. Congress, Office of Technology Assessment, *Multinationals and the U.S. Technology Base* (Washington, DC: U.S. Government Printing Office, September 1994), pp. 67-69. See also U.S. Congress, Office of Technology Assessment, *Defense Technology Base: Introduction and Overview),* ISC-309 (Washington, DC: U.S. Government Printing Office, June 1987), p. 34.

[18] U.S. Congress, Office of Technology Assessment, *Holding the Edge: Maintaining the Defense Technology Base,* OTA-ISC-420 (Washington, DC: U.S. Government Printing Office, 1989), p. 176.

FIGURE 1-4: Federal Expenditures on R&D in the United States, 1970-1994



NOTE Data for Germany include the former East Germany after 1990

SOURCE National Science Foundation, *National Patterns of R&D Resources' 1994* (Arlington, VA: 1995), tables B-1, B-3, pp. 53, 57

and airframes) has declined substantially in recent years, and in some technologies the flow has reversed.[19]

Current trends point toward a further erosion of U.S. standing in R&D funding. Real U.S. expenditures on R&D stagnated between 1991 and 1994, averaging annual growth of just 0.15 percent. Part of the reason is a reduction in federal R&D spending resulting from the end of the Cold War and growing concern over the federal deficit. Between 1987 and 1994, federal funding for R&D declined from a peak of $73 billion to $62 billion in constant 1994 dollars (see figure 1-4). The percentage of national R&D funding provided by the government declined accordingly from 46 percent to 36 percent of the total; this trend has reinforced the role of business as the dominant source of R&D funds in the United States. Industry spent $102 billion on R&Din 1994, contributing nearly 60 percent of all such funding for that year.[20]

Industry expenditures on R&D have also stagnated in recent years. In real terms, total U.S. business expenditures on R&D slowed to an average annual growth rate of less than one percent between 1991 and 1994, after averaging real growth rates of approximately 7.5 percent during the late 1970s and early 1980s. Moreover, this small rise is attributable entirely to growth in nonmanufac-

[19] J. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston, MA: Harvard Business School Press, 1992). See also D.C. Mowery, "The Challenges of International Trade to U.S. Technology Policy," *Linking Trade and Technology Policies: An International Comparison of the Policies of Industrialized Nations,* M.C. Harris and G.E. Moore (eds.) (Washington, DC: National Academy Press, 1992), p. 125.

[20] Academia and other sources account for only 3 and 2 percent, respectively, of all R&D funding in the United States. National Science Foundation, *National Patterns of R&D Resources: 1994* (Arlington, VA: 1995).

turing industries, which posted real annual growth rates of 26 percent from 1987 to 1992.[21] Real rates of R&D spending in manufacturing industries *declined* an average of 2 percent per year throughout most of this period, due primarily to cutbacks in transportation equipment, electronic and other electric equipment, petroleum refining and extraction, and industrial machinery and equipment. Despite the current economic expansion, real R&D spending declined 0.2 percent in 1994, and recent surveys predict only a modest increase in 1995.[22]

As a result of such cutbacks, the U.S. share of OECD expenditures on R&D in high technology industries declined from 63 percent in 1973 to 50 percent in 1992, driven by substantial declines in all high-technology sectors except pharmaceuticals and instruments. Similarly, in medium technology industries[23] the U.S. share decreased from 48 to 37 percent, with long-term declines in all sectors except industrial chemicals and transportation equipment (excluding motor vehicles). In many high-technology industries, such as aerospace, electronic equipment and components, and to a lesser extent pharmaceuticals, U.S. R&D spending has not kept pace with value added. Average U.S. R&D intensity levels in high technology industries were substantially above most other major industrial nations for most of the 1970s and 1980s, but they declined from 0.28 in 1985 to 0.22 in 1992, to approximately the level of France and the United Kingdom, though they still exceed those of Japan and Germany.[24]

Changing R&D Priorities

In response to increasing competitive pressures, U.S. firms have begun to alter their R&D patterns. Firms have shifted a greater portion of their R&D resources away from long-term investments and toward shorter term projects. Recent evidence indicates that U.S. companies now allocate only 22 percent of their R&D spending to long-term projects, compared with their Japanese counterparts who devote 50 percent.[25] Increasingly, firms are emphasizing short-term R&D for immediate problem-solving or near-term development over basic research; and basic research is being directed toward the needs of product development and manufacturing teams.[26] Many central research laboratories at large companies—such as AT&T, IBM, General Electric, Kodak, and Xerox—have been downsized and work more closely with prod-

[21] There is considerable uncertainty associated with R&D figures for the nonmanufacturing sector. Such data have only recently been collected and as a result may overestimate growth rates. Nevertheless, nonmanufacturing R&D comprises about one-fourth of total U.S. R&D expenditures. These figures include R&D expenditures in communications, utility, engineering, architectural, research, development, testing, computer programming, and data processing service industries, as well as hospitals and medical labs. National Science Foundation, *National Patterns of R&D Resources: 1994* (Arlington, VA: 1995).

[22] See Industrial Research Institute, *Annual R&D Trends Forecast* (Washington, DC: Industrial Research Institute, November 1994); Jules Duga, Steve Millett, and Tim Studt, "Battelle-*R&D Magazine* 1995 R&D Forecast," *Battelle Today*, April 1995, pp. 4-7.

[23] OECD defines medium technology industries to include nonpharmaceutical chemicals, rubber and plastics, nonferrous metals, nonelectrical machinery, motor vehicles and other transportation equipment, and other manufacturing.

[24] OECD, *MSTI (2)*, December 1994, op. cit., footnote 6; sectoral R&D intensities expressed as R&D divided by value added.

[25] Erich Bloch and Mark S. Mahaney, "U.S. Research Effort Steers New Course," *Forum for Applied Research and Public Policy*, spring 1995, p. 124.

[26] Duga et al., op. cit., footnote 22, p. 7. A recent survey by the Industrial Research Institute also demonstrates cutbacks in basic research amid overall increases in R&D. See Industrial Research Institute, *Annual R&D Trends Forecast* (Washington, DC: IRI, November 1994); see also M.F. Wolff, "U.S. Industry Spent $124B on R&D Last Year, as Real-Dollar Decline Appears to Level Off," *Research-Technology Management*, vol. 38, number 3, May-June 1995, pp. 2-3.

uct development divisions.[27] They now receive a larger share of their operating funds from individual business units rather than general corporate funds.[28] Even in strongly science-based industries, such as chemicals and pharmaceuticals, basic research declined from 1988 to 1993.[29]

Collaboration between firms—through joint ventures, consortia, and outsourcing—is on the rise as firms attempt to distribute risk, pool resources, and tap into necessary sources of expertise required to design and manufacture increasingly complex products.[30] Alliance strategies have become particularly common in biotechnology, as large pharmaceutical firms with diverse product portfolios and powerful testing and marketing resources combine with smaller biotechnology firms with leading-edge, niche technologies. Alliance strategies are also being used heavily in information, communication, and advanced electronics industries, in which firms need to maintain access to a rapidly changing and expanding set of product and process technologies. The magnitude of alliance formation is difficult to gauge, as are the implications for innovation and commercialization of new technologies in the United States; however, these alliances are likely to quicken the rate of technology diffusion across firms, industries, and nations.[31]

Firms have also increased their reliance on basic research performed at universities and federal laboratories. Both the percentage of university funding provided by industry and the number of cooperative research and development agreements (CRADAs) signed between industry and federal laboratories have climbed in recent years.[32] Such restructuring seems to have paid off for firms in terms of increased competitiveness and shortened production cycles (see table 1-5). Yet reductions in basic and long-term research could threaten the ability of U.S. firms to generate future high-payoff products and processes. As pressures mount to reduce the federal budget deficit, and government expenditures for R&D continue to decline, funding for basic research at universities and federal laboratories is likely to drop. This change could potentially reduce the amount of basic research results available to U.S. firms.

THE POLICY DEBATE

These changes in the competitive environment have triggered renewed debate over the proper role of the federal government in innovation and

[27] See, for instance, Malcolm W. Browne, “Prized Lab Shifts to More Mundane Tasks,” *New York Times*, June 20, 1995, p. C12; Gautam Naik, “Top Labs Shift Research Goals to Fast Payoffs,” *Wall Street Journal*, May 22, 1995, p. B1; Vanessa Houlder, “R&D Placed Under the Microscope,” *Financial Times*, May 22, 1995; Vanessa Houlder, “Revolution in Outsourcing,” *Financial Times*, Jan. 6, 1995, p. 10; “Could America Afford the Transistor Today?” *Business Week*, Mar. 7, 1994, p. 80.

[28] For example, corporate support for R&D at General Electric has declined from about 75 percent of its total R&D budget to about 25 percent since 1985. At Kodak, corporate support for R&D has dropped from 85 percent to just 5 percent of the R&D budget. See Charles F. Larson, “Research/Development in the Private Sector,” *Forum for Applied Research and Public Policy,* spring 1995, p. 130.

[29] ISI/CSIM preliminary survey results. By this estimate, chemical firms now spend about 3 percent of their R&D on basic research.

[30] A recent survey by the Industrial Research Institute indicates that the percentage of corporate R&D managers expecting an increase in alliances and joint ventures rose from 33 percent to 49 percent between 1989 and 1993. The number of respondents expecting to license technology from or to other firms also increased from 14 percent to 22 percent and from 19 percent to 34 percent, respectively, during the same time period. Industrial Research Institute, *Annual R&D Trends Forecast* (Washington, DC: Industrial Research Institute, November 1994).

[31] The extent of international R&D spillovers has been a matter of debate. Some studies indicate that R&D spillovers remain relatively localized; see Adam B. Jaffe, Manuel Trajtenberg, and Rebecca Henderson, “Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations,” *Quarterly Journal of Economics*, August 1993, p. 577. Others indicate that international spillovers are much more significant for small countries than for large ones; see David T. Coe and Elhanan Helpman, “International R&D Spillovers,” National Bureau of Economic Research Working Paper No. 4444 (Cambridge, MA: National Bureau of Economic Research, 1993).

[32] CRADAs do not typically support basic research, but they do allow companies to access basic research results derived from previous laboratory work.

TABLE 1-5: Examples of Reduced Product Development Time

Industry	Company	Announcement
Aircraft	Boeing	Established goal to cut time to complete new plane from 12 months to 6
Apparel	Berghaus	Cut delivery time from 6 to 12 weeks in 1980 to 1 week by early 1990s
Autos	Chrysler/Ford	Reduced time for new model introduction from 5 years to 3
Computers	Compaq	Introduced notebook computers in 8 months
Construction Equipment	Caterpillar	Since late 1980s, reduced time to build new tractor from 25 days to 6
Electric Equipment	ABB	Reduced time-to-market for high voltage transmitters/switching gears by 21 percent
Off Ice Products	Rubbermaid	Shortened time to enter new market from 18 to 24 months to 12 to 18.
Pharmaceuticals	Zeneca	Reduced time from drug synthesis to first testing on human volunteers from 30 months to 14
Semiconductor	Texas Instruments	Cut time to market from 24 to 36 months to 12 to 18
Telecommunications	AT&T	Reduced design-to-delwery time for custom power supplies from 53 days to 5.

SOURCE Institute for the Future, *The Future of America's Research Intensive Industries,* Report R-97 (Menlo Park, CA Institute for the Future, May 1995), p 50

commercialization (state and local governments also play a role in technology development—see box 1-2). Traditionally, the government has played a limited role in innovation. It has funded basic research to advance scientific knowledge and has implemented policies regarding finance, taxation, science education, antitrust, and intellectual property to create an environment conducive to innovation and commercialization. Otherwise, government usually has left to the private sector the act of translating new scientific knowledge into new products, processes, and services. This division of labor reflected broad consensus that while private industry has a strong disincentive to invest sufficiently in basic research, which tends to produce more benefits than any individual firm can hope to capture, it is better equipped than government to interpret market signals and allocate innovative resources efficiently. Government policy, therefore, concentrated on factors that address the economy as a whole, rather than focusing on individual industries.

Nevertheless, government has also influenced commercial innovation by developing and procuring technology for public missions, such as defense, space, energy, and agriculture. Development of the Minuteman missile system and procurement for the National Aeronautics and Space Administration's (NASA's) Apollo program generated most of the early demand for integrated circuits and jump-started the nation's semiconductor industry. Defense R&D also laid the groundwork for today's telecommunications and computing industries, though such spin-offs have declined in recent years as commercial industries have matured.[33] Concerns over energy costs and availability in the 1970s led to expanded energy research, technology development, and demonstration projects, which produced more efficient lighting technologies and renewable energy sources. Support for agriculture has taken on many forms, from basic and applied research to extension activities. Such activities have led to the development and use of new strains of crops, as

[33] See John Alice et al., op. cit., footnote 19.

BOX 1-2: State Technology Programs

Over the past 15 years, the number of states funding and operating programs to promote technological innovation and commercialization has grown from nine to 50. These programs complement the states' longstanding interest in recruiting and retaining business and in funding higher education and infrastructure development. Like these other policies, state-supported technology programs aim to leverage existing industry, universities, human resources, and services to promote economic growth. In fiscal year 1994, states spent nearly $385 million on some 390 distinct technology programs. Although programs vary considerably in structure, focus, and services offered, they generally fall into five categories: technology development, technology financing, industrial problem-solving, startup assistance, and teaming.

Technology development programs received $131 million in 1994 to support research and application of technology for new and enhanced products and processes. These programs assume several forms. University-industry technology centers (UITCs) are the most common. They exist in nearly half the states and received $105 million in 1994. UITCs concentrate on interdisciplinary and applied research in specific technologies and industries, typically those most important to the regional economy. Organized so that several companies work with one university, these centers seek to develop ongoing relationships between the university and local businesses. An alternative type of arrangement, the university-industry research partnership (UIRP), exists in 12 states and received $12 million in funding in 1994. UIRPs usually involve just two partners and are organized around a specific project with a timetable for developing a technology and bringing a new product to market. States also supported 10 equipment and facility access programs, which provide small businesses with low-cost access to expensive equipment and facilities, such as supercomputers and clean rooms. These programs received about $6 million in funding in 1994.

Technology *financing* programs received over $100 million in state funding in 1994 to help small technology firms raise capital Two-thirds of this total supported specific R&D projects and local, nonprofit economic development programs, such as incubators. The remainder took the form of grants, low-interest loans, or equity investments directly financed by state governments or accredited financial institutions. Most states also assist companies applying for funding from federal technology programs, such as the Small Business Innovative Research (SBIR) program and the Technology Reinvestment Project (TRP).

Industrial problem-solving programs help firms improve production, management, and technical capabilities. Such programs received over $55 million in 1994. The most prominent form of industry problem-solving program is technology extension and development (TED), currently under way in 40 states. TED programs teach firms about new manufacturing technologies and best-practice manufacturing techniques to enhance their efficiency and productivity. Several states enjoy federal support from, and play host to, federal manufacturing extension programs such as the Manufacturing Extension Partnership (MEP).[1]

Startup assistance programs encourage entrepreneurship, commercialization of new technologies, and the expansion of regional businesses. With $8 million in funding in 1994, these programs supported business incubators, small-business development centers, and research parks that, in turn, provide business, technical, and often financial assistance to new technology-based firms

(continued)

[1] The National Institute for Standards and Technology's (NIST's) Manufacturing Extension Partnerships are made up of Manufacturing Technology Centers (seven have been established, 28 are planned) and the State Technology Extension Program, which awards competitive grants to state-government or state-affiliated manufacturing extension programs

BOX 1-2: State Technology Programs (Cont'd.)

Teaming programs encourage collaboration among companies as a means of sharing technical information and facilitating business development, These programs develop industrial networks and interactive databases to match up business interests and develop communication within and across industries. Teaming programs received just under $8 million in 1994,

By bringing together a diverse set of players—venture capitalists and bankers, entrepreneurs and established businesses, and university scientists and engineers—state technology programs encourage synergy between traditional state-sponsored activities and local and regional economies. Although many states support only local firms or require project work to be carried out within the state, membership and participation in state initiatives, especially UITCs, is not always limited to local or regional companies,

State programs are not substitutes for federal programs. Rather, state and federal technology initiatives complement each another, though, to date, there has been little coordination or cooperation between state and federal efforts. State programs operate closer to immediate local needs and show preference for state enterprises and interests, Federal programs, in contrast, address industrywide and regional problems, advancing innovation and commercialization through federal missions, regulatory bodies, and economic policies, Federal programs are also far larger than state-led efforts, Total federal funding for technology programs, excluding basic research, was seven times larger than state funding in 1994,

SOURCES: Robert D Atkinson, "New Partnerships in Technology Policy, " *Forum for Applied Research and Public Policy,* fall 1992, pp. 21-26, Christopher Coburn (ed.) and Dan Bergland, *Partnerships: A Compendium of State and Federal Cooperative Technology Programs* (Columbus, OH: Battelle Press, 1995)

well as new methods of planting, growing, and harvesting them.

Starting in the 1980s, Congress and the executive branch began to supplement this approach with a series of programmatic efforts aimed at helping specific industries or correcting perceived market failures in the innovation process. In SEMATECH (the Semiconductor Manufacturing Technology consortium), the government and industry share the costs of strengthening the supplier base for the U.S. semiconductor industry.[34] In the Advanced Technology Program (ATP), government shares with industry the cost of *precompetitive* research projects—projects with an applied focus, but in which the research results may be useful to many companies developing similar products.[35] Manufacturing Technology Centers (MTCs) help disseminate best-practice manufacturing methods to the nation's small manufacturing firms, many of which are unfamiliar with the most advanced manufacturing technologies and practices. Legislation was also enacted to encourage greater transfer of technology from federal laboratories to the private sector.[36]

[34] The industrial members of SEMATECH have decided not to request federal funding after FY 1996.

[35] Technological uncertainties often go unresolved and hinder the commercialization of such research results because (as with basic research) individual firms cannot easily appropriate the benefits of their efforts.

[36] The Stevenson-Wydler Technology Innovation Act of 1980 (P.L. 96-480) established Offices of Research and Technology Applications at federal labs and requires laboratory directors to allocate 0.5 percent of the R&D budget for their funding; the Federal Technology Transfer Act of 1986 gave directors of government-owned and -operated laboratories the authority to enter into cooperative research and development agreements (CRADAs) with industry and established the Federal Laboratory Consortium for Technology Transfer (FLC) to match inquiries from firms to appropriate lab researchers; the National Competitiveness Technology Transfer Act of 1989 (P.L. 101- 189) granted directors of government-owned, contractor-operated laboratories authority to sign CRADAs with industry.

This more programmatic approach to innovation expanded the government's role into *downstream* elements of the innovation process, including product development and manufacturing, in which Japanese competitors, in particular, were believed to hold an edge over U.S. firms. It did not, however, replace policies aimed at maintaining an economic environment conducive to innovation. Continued revisions and extensions to the research and experimentation (R&E) tax credit, for example, allowed firms to write off part of their R&D investments against tax liabilities. The National Cooperative Research Act of 1984 clarified antitrust laws related to cooperative R&D ventures and removed the threat of treble damages in some cases, thereby encouraging the creation of several hundred consortia in its first few years. Amendments in 1993 extended these provisions to joint manufacturing efforts. Similarly, the consolidation of patent-related appeals into the U.S. Court of Appeals for the Federal Circuit in 1982 strengthened and clarified patent law, tilting the law in favor of patent owners.[37]

Many in the 104th Congress have begun to question the programmatic efforts of the past decade and, more generally, the optimal scope and character of the government's role in the national innovation system. Though proponents of cost-shared partnerships have assembled a mass of data to demonstrate the success of their programs, critics contend that the programs interfere with market forces for allocating R&D resources (i.e., they pick winners and losers) and crowd out private-sector investment. The new congressional leadership has proposed a reversion to more traditional forms of stimulating innovation through continued support for basic research, revision and extension of the R&E tax credit, and removal of regulatory barriers to innovation. The first of these proposals is seen as a way of creating the knowledge base necessary for innovation; the second, as a means of stimulating industry investment in R&D to bring new technologies to market; and the third, as a means of removing government interference from the marketplace. Evaluation of these alternative approaches to stimulating innovation should take into account the complexity of innovation and commercialization and the inadequacy of the much-used linear model of innovation.

UNDERSTANDING INNOVATION AND COMMERCIALIZATION

Debate over the government's role in innovation hinges implicitly on the conceptual models used to describe innovation and commercialization. Traditional views of innovation have been strongly influenced by the linear model of innovation, which, in its simplest form, posits that innovation proceeds sequentially through stages of basic research, applied research, development, manufacturing, and marketing. This model assumes that basic research serves as the source of innovation, and that new scientific knowledge initiates a chain of events culminating in the development and sale of a new product, process or service. In this view, basic research is the major source of uncertainty; once basic research is conducted, innovation and commercialization can proceed apace. Firms with the best technology, or that are first to market, win the lion's share of profits. Combined with arguments about the difficulties firms face in capturing the returns from investments in basic research, the linear model reinforces the view that government should restrict its role to support of basic research, letting market forces control the rest of the innovation process.

Models of Innovation

The linear model is an inadequate description of the innovation process because it describes only one pathway to innovation, that of reducing new scientific discoveries to practice. Innovation is a much broader process of developing and putting

[37] See U.S. Congress, Office of Technology Assessment, *Making Things Better: Competing in Manufacturing,* OTA-ITE-443 (Washington, DC: U.S. Government Printing Office, February 1990), pp. 211-229.

into use new and improved products, processes, and services. As such, it takes on many forms, including: 1) incremental extensions of existing product lines to provide new or enhanced features; 2) development of entirely new products that combine existing technologies in novel ways to serve new market needs; 3) applications of existing products and processes to new market needs—much as manufacturers of flat panel displays have adapted semiconductor manufacturing equipment to their needs; and 4) use of new technology to serve an existing market need, much as transistors, and later integrated circuits, replaced vacuum tubes in electronic devices. Though incremental innovation and adaptations of exiting technology to new markets may seem mundane, they account for most innovative activity and, in aggregate, generate returns equal to those created by less frequent radical innovations.

In many cases, science is not the genesis of innovation. Ideas for new inventions more often arise from recognition of new market opportunities, advancing manufacturing capabilities, or advances in technology that proceed apart from advances in the underlying science. The Wright brothers, for example, developed the first airplane without an understanding of aerodynamic theory; Chester Carlson developed the first xerographic copier without a thorough understanding of photoconductive materials; and many drugs have been developed with little or no understanding of the molecular basis for their effects. These inventions, in turn, have triggered considerable research into aerodynamics theory, materials science, and molecular biology, respectively, as scientists and engineers attempted to improve upon the basic invention.

Nevertheless, science plays a vital role throughout the innovation process. Many of the most radical innovations stem from scientific breakthroughs, whether in solid state physics (the basis of today's semiconductor industry) or molecular biology (the source of many biotechnologies). More frequently, knowledge gained from scientific research (basic or applied) provides valuable information for solving problems encountered throughout the innovation process. During the product development phase, research is often needed to understand and analyze the ways in which components of the product interact or operate under different circumstances. In the production stage, research is often needed to improve yields, raise product quality, or lower manufacturing costs. Much of the progress in integrated circuits, for example, derives from research into ways of making electronic devices smaller, which involves investigations into fields such as optics, materials science, and quantum physics.

As this discussion suggests, innovation rarely proceeds sequentially from one stage to the next. It is more often an iterative process in which scientists, design engineers, production engineers, and marketing experts share information as they design and test new products, processes, and services. Many firms have attempted to institutionalize this type of process by reorganizing their operations into project teams with multidisciplinary membership, rather than maintaining a linear progression from research lab, to product development teams, to production, to marketing. This older model often produced mismatches between the output of the research labs, the needs of the product designers, and the capabilities of the manufacturing process, resulting in wasted effort, high costs, and low quality. Insight from marketing divisions and customers often failed to adequately influence decisionmakers in R&D, design, and manufacturing, resulting in products ill-suited to the marketplace.

The nature of innovation changes as industries and product lines mature. In most industries, innovation proceeds in an evolutionary fashion through long periods of cumulative incremental innovation punctuated by moments of radical innovation.[38] An industry's early stages typically show a high degree of product innovation as firms develop new means of satisfying a previously unmet demand. Designs are fluid as firms search for the combination of features and performance that meets market demand and gains market acceptance; competition is based primarily on product differentiation. Over time, a dominant design often emerges that encapsulates a set of performance features that best matches market demand, and competition shifts away from performance toward cost. The rate of product innovation tends to slow and become more incremental, but the rate of process innovation tends to rise. In many high-technology industries, innovation may shift toward improved cost/performance combinations as firms develop new product generations with noticeable improvements in performance (as with the shift from 386 to 486 processors).

Such changes have strong implications for the nature of competition in an industry and the position of entrenched competitors. While incremental innovation tends to reinforce the capabilities of entrenched market leaders, radical innovation often demands competencies that incumbent firms lack. In this way, radical innovations can undermine the strengths of established competitors and allow new firms to gain a foothold in the industry.[39] Sometimes entrenched firms lack the technical capability to develop or manufacture the new technology: manufacturers of television screens based on cathode ray tubes, for example, generally lack the skills required to develop flat panel displays based on liquid crystal technology. At other times, competitors have a disincentive to abandon their existing product lines and markets. Despite inventing reduced instruction set computing (RISC), IBM was slow to introduce computers based on the new technology, in part because it feared the new machines would detract from sales of its existing product lines. Commercialization of RISC awaited new entrants, such as SUN Microsystems and Apollo Computer Systems, who had no stake in the existing complex instruction set computing (CISC) technology. There are also cases in which entrenched firms fail to see the market applications of a new technology. In the disk drive industry, market leadership has passed to a new group of firms with each major generational change, not because entrenched firms lacked the technical skills to adopt the new technology, but because the technology did not seem to serve the needs of their established customers, and manufacturers failed to perceive the value of the technology to a new group of customers.[40]

Commercialization

Commercialization is an attempt by a firm to profit from innovation by incorporating new technology into products, processes, and services used or sold in the marketplace. Successful commercialization hinges on many factors. Firms must be able to: 1) finance new technology ventures; 2) hire and train skilled scientists, engineers, managers, and production workers; 3) protect their innovation from imitators; 4) acquire or access complementary skills and technologies required to make an innovation useful; and 5) gain market acceptance. The availability of standards, existence of regulatory approval bodies, and the relative ease of new business formation and interfirm collaboration influence the ability of firms to commercialize new technologies.

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[38] James M. Utterback, *Mastering the Dynamics of Innovation* (Boston, MA: Harvard Business School Press, 1994), p. xix. See also Michael Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly,* vol. 31, 1986, pp. 439-465.

[39] For a more detailed discussion of this phenomenon, see Utterback, op. cit., footnote 38.

[40] Richard S. Rosenbloom and Clayton M. Christensen, "Technological Discontinuities, Organizational Capabilities, and Strategic Commitments," forthcoming.

Firms must anticipate future profits in order to commit to commercializing a new technology. They must therefore be convinced that markets exist for their innovation; that they will be able to appropriate an acceptable share of the total available profits; and that they will be able to develop or acquire the skills and assets needed to bring the innovation to market. Estimates of overall profitability hinge on the size of the potential market, production costs, and the price consumers are willing to pay for the innovation. These factors are, in turn, influenced by the availability of complementary assets that make them useful. New computers, for example, have little utility unless accompanied by software to run on them; electric cars are of little interest without recharging stations. Unless these assets are developed and deployed, a new product or service is unlikely to be profitable. Competition from alternative technologies can also limit markets for innovations, as consumers have several means of satisfying a particular need (see box 1-3).

In order to capture a share of the profits generated by innovation, firms must be able to protect their proprietary position from imitators. In the pharmaceuticals industry, firms tend to protect their innovations through patents, which grant the owners exclusive rights to their invention for 20 years from the date on which an application is filed. In most other industries, including electronics, autos, and aircraft, patents do not offer sufficient protection because imitators can more easily find alternative ways of providing the same capability without violating the patent. Therefore, firms in these industries attempt to keep the workings of their innovations secret (a difficult task for product innovations) or erect strong barriers to entry by investing in production capacity to reduce production costs or by rapidly introducing improved products.

Before they can do so, firms must develop or acquire the skills to design, manufacture, and market the innovation. Firms that can better harness these capabilities and orchestrate the contributions of the various actors responsible for bringing a new technology to market have the best chance of succeeding in commercialization.[41] Japan's success in the global marketplace has often been attributed to its ability to harness or develop complementary assets, such as the manufacturing capabilities that allowed it to introduce new products faster than U.S. firms. Japanese firms boasted faster product development cycle times than U.S. firms and often achieved higher quality in the process. As a result, they were able to bring new and improved products to market faster than U.S. firms and win large portions of the market. Large investments in process technology rather than product technology increased this advantage, as U.S. firms continued to pour greater resources into product innovation.[42]

Small U.S. firms are often at a disadvantage in competition against large, vertically integrated firms, whether in Japan or the United States, that have access to necessary complementary assets and skills internally. Without their own manufacturing facilities or marketing and distribution channels, small firms are often forced to align with larger firms or to license their technology to the owners of such assets. This process not only can result in the transfer of technology to rival companies and nations, but can take longer to complete than if conducted internally, thereby slowing the commercialization process in the United States. Conversely, the flexibility afforded small firms by their limited capital investments contributes to the dynamism of U.S. industry. They are less bound to existing investments and technological pursuits than large firms like DuPont and IBM.

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[41] For a more complete discussion of this topic, see David J. Teece, "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy," *The Competitive Challenge: Strategies for Industrial Innovation and Renewal*, David J. Teece (ed.) (New York, NY: Ballinger Publishing Company, 1987).

[42] Edwin Mansfield, "Industrial R&D in Japan and the United States: A Comparative Study," *American Economic Review,* vol. 78, No. 2, May 1988.

BOX 1-3: Commercialization of Scalable Parallel Computing

Since 1950, almost all computers—including desktop personal computers—have followed the so-called von Neumann design, in which a single processor performs calculations and a single memory stores both the program and the data. Increasing numbers of computers are being built with multiple processors—from a few to thousands—that for some applications can work together on the same problem, The term "scalable parallel computer" denotes a computer in which the number of installed processors can be scaled up—for example, from one to 32, from eight to several hundred, or from 16 to a few thousand. The United States is the clear leader in the development and commercialization of scalable parallel computing technology.

For some important applications, scalable parallel computers provide the fastest computing available. They can often provide the most cost-effective computing in terms of hardware cost, although high software development costs often more than outweigh the hardware savings Worldwide sales of supercomputers in 1993 totaled $1 7 billion. Of that total, about $300 million was for scalable parallel computers,[1] and the proportion is expected to grow. Today, every major supercomputer manufacturer sells scalable parallel computers as part of its product line. High performance computing is revolutionizing the way R&D is performed and businesses are run by enabling calculations and analysis that were not possible before. Leading-edge computers have fundamentally changed the way that quantum physicists test theories, scientists investigate the risk of global climate change, pharmaceutical companies discover new drugs, and engineers design automobiles and airplanes. They have also changed how Wal-Mart manages inventory, American Express uses customer data, and Amtrak manages its fleet of trains.

Scalable parallel computing has not followed the linear model of innovation. Its commercial development in the 1980s was triggered not by new science, but by the demand for increased computing power and the widespread availability of microprocessors. Commercial development preceded a good theoretical understanding of how multiple processors can work efficiently together, and spurred advances in that theory. Several factors other than scientific understanding have determined the pace of commercialization: complementary assets, market development, design and standards issues, and finance.

Complementary Assets—The lack of adequate, affordable software is the main impediment to commercialization. Writing software that lets many processors work efficiently together is inherently more difficult than writing efficient software for just one processor, and also requires the retraining of programmers. Until more software is available, scalable parallel computers remain relatively unattractive for most users, compared with more traditional machines with huge software libraries As long as the number of scalable parallel computers in use remains low, software vendors have limited incentive to develop software for these computers.

Government software development has facilitated commercialization of scalable parallel computing, just as it helped Cray commercialize the first supercomputers in the late 1970s. Government laboratories have written software for scalable parallel computers in order to perform government missions. Some of this software has been used by others; some has also been further developed into commercial products by firms. Some private sector software development has received direct government funding

(continued)

[1]U.S. Department of Commerce, *U.S. Industrial Outlook 1994,* pp. 26-8 through 26-9. This estimate excludes approximately $300 million in specialized computers for database processing manufactured by Teradata (now part of AT&T), as reported by International Data Corp. (Some do not consider those machines to be scalable parallel computers.)

BOX 1-3: Commercialization of Scalable Parallel Computing (Cont'd.)

Market Development— Expansion of markets for scalable parallel computers has been paced by the ability of firms to better understand user needs and to establish proper distribution channels Early users of scalable parallel computers needed the fastest possible computing and were willing, for example, to write application software and endure frequent system crashes, Early use included scientific applications (e.g., nuclear weapons design and weather forecasting), and businesses analyzing very large amounts of data, Teradata (now part of AT&T) held half of the 1992 world market for scalable parallel computers with specialized machines to analyze data from IBM mainframes.[2] In 1992, Federal Express bought a Thinking Machines computer to analyze customer data—for example, to determine which customer-recruiting methods yielded the best types of customers and to target mailings to consumers interested in particular products and services. Federal Express viewed such analyses as an important business management tool, but could not perform them effectively on its IBM mainframes.

Some manufacturers have formed alliances to gain access to, and credibility with, customers, and to better understand their needs. Intel has teamed up with Unisys to sell to banks and with Honeywell to serve the military market, Hewlett-Packard (HP) is marketing Convex's machines to HP's more extensive customer base (and is also providing Convex with equity capital, microprocessors, and software), IBM IS using its established mainframe marketing channels to sell scalable parallel computers, just as decades ago it used its established business machine marketing channels to sell mainframe computers

Design and Standards Issues— Lack of a dominant design has also slowed commercialization Scalable parallel computers have many different designs, representing different approaches to sharing data. When one processor is working with a particular data item, other processors that need that item must often wait until the first IS done, Some designs include expensive hardware to reduce these delays; others do not, and can run efficiently only if the processors rarely need to share data For some applications, this condition is easy to achieve; for others, it is achievable, if at all, only through great programming efforts, Physically, designs differ in how the processors are connected to memory. Variations include: 1) using a shared central memory *(shared memory);* 2) giving each processor its own local memory, but letting other processors access that memory through a multistage switching network *(shared virtual memory* or *logically shared memory);* and 3) giving each processor a purely private memory, but letting processors send each other messages through an Internal communications network *(distributed memory).* An extreme version of distributed memory, made more attractive by advances in digital communications, involves the use of software that enables desktop computers connected by a local or wide area network to work together on the same problem, This approach can take advantage of the time that desktop machines would otherwise be idle.[3]

The proliferation of designs and vendors exacerbates the software shortage because different types of computers normally require different software. Some industry standards efforts, facilitated by government, are making it possible in some cases to write software that will run efficiently on different types of machines (see chapter 3), In addition, the many choices probably have made customers cautious in terms of which firms will survive to provide support and upgrades

(continued)

[2] Debra Goldfarb, Director, High-performance Research, International Data Corp., presentation to Office of Technology Assessment, Aug. 26, 1993.

[3] Another variant of the distributed memory approach is to have stripped-down processors that all execute the same instruction at once (but on different data).

BOX 1-3: Commercialization of Scalable Parallel Computing (Cont'd.)

Finance-- In the 1980s, most firms trying to commercialize scalable parallel computing had no other business, and financing was often difficult to obtain. In the 1990s, many established computer manufacturers—such as IBM, Silicon Graphics, Convex, DEC, Cray Research, and the Japanese supercomputer manufacturers—have entered the market. These firms can finance the development of scalable parallel computing from other corporate profits. Similarly, some Important independent vendors of software for traditional supercomputers have used revenues from that business to adapt their software for scalable parallel computers.

Government has been an important source of funds, for both R&D and machine purchases Under the umbrella High Performance Computing and Communications (HPCC) program, government has spent roughly $1 billion per year since 1992, of which a substantial portion has been for scalable parallel computing. HPCC has emphasized the development of hardware to perform scientific calculations very quickly for applications such as weather forecasting and airplane design. This orientation has recently lessened somewhat, however, with increased emphasis on software to make the computers easier to use and on handling very large amounts of data for applications such as electronic libraries and telemedicine.[4]

Some government R&D support has found direct commercial application. The Defense Department's Advanced Research Projects Agency (ARPA) funded Cal-Tech in the early 1980s to build the Cosmic Cube prototype, which inspired the distributed memory machines marketed by Intel and Thinking Machines. After ARPA funded two professors in the late 1980s to write software to handle large databases on scalable parallel computers, their students took jobs commercializing that approach in several firms. ARPA has purchased many scalable parallel machines for use in universities and government laboratories, In the early 1990s, ARPA's procurement heavily favored Intel and Thinking Machines, and thus favored the distributed memory design. This procurement pattern may have contributed to the failure of some other firms such as Kendall Square Research that built machines based on other designs.[5]

SOURCE Office of Technology Assessment, 1995

[4]See Executive Office of the President, Office of Science and Technology Policy, National Coordination Office for HPCC, *High Performance Computing and Communications FY 1996 Implementation Plan* (May 1995), and prior annual reports.

[5]U.S. Congress, General Accounting Office, *High Performance Computing: Advanced Research Projects Agency Should Do More To foster Program Goals,* GAO/IMTEC-93-24 (Washington, DC May 17, 1993)

ELEMENTS OF INNOVATION SYSTEMS

Though decisions to pursue particular areas of innovation or to commercialize particular technologies are made by individual firms, these decisions are influenced by factors external to the company that are often beyond their control. Innovation is rarely the result of individual genius or the actions of individual firms. Successful innovation requires the coordinated action of numerous actors who play vastly different roles, from creating new science, to financing startup firms, to developing standards and regulatory regimes. Taken together, these actors constitute an innovation system, each component of which is essential to the overarching act of bringing new products, processes, and services to the market. Though innovation systems span the borders of individual nations, the ability of a nation to capitalize on new technology development is largely dependent on its particular system of innovation.

The Framework

Innovation systems generally comprise three main elements:[43]

1. *institutional arrangements* that establish the general environment for innovation;
2. *resource endowments* that provide the basic feedstock of innovation; and
3. *proprietary functions*, typically performed by private industry, that harness resources and combine them into new products, processes, and services.

Responsibility for building and maintaining these elements falls to both private- and public-sector actors. While, on the surface, creation of institutional arrangements and resource endowments might appear to be public responsibilities and proprietary functions may seem like private-sector functions, all three major elements are influenced by both industry and government. Hence, both government and industry have roles to play in launching new technologies and new industries.

Institutional arrangements are mostly the responsibility of government. Federal agencies promulgate and enforce rules that establish norms for corporate behavior. These include antitrust policies to limit collusion, and patenting policies to protect inventors' rights and promote disclosure of inventions. Federal agencies also build consumer trust in new products, processes, and services by verifying or warranting their safety and efficacy; and they participate in standards-setting activities. Industry also plays a role by individually or collectively attempting to influence the legal framework to support its needs. Firms conduct legitimation activities by testing and providing warranties for their products. Many standards-setting bodies are industry-led; and firms often establish *de facto* standards by winning broad consumer acceptance of their designs.

Resource endowments such as financial, scientific, and human resources also have both public and private components. The federal government has been the major supporter of basic research in the United States since World War II, providing nearly half of the nation's basic research funding in 1994.[44] It also funds applied research and technology development, both in support of its own missions and through initiatives like the Small Business Innovative Research program and the Advanced Technology Program. Along with state and local governments, the federal government provides support for public education from kindergarten through graduate school. Private firms also have a role in resource creation. Though the returns are difficult to appropriate, companies do fund basic research to promote their own business agendas and to maintain their ability to evaluate and acquire outside research. Private investors put money into the stock market, venture capital funds, or directly into startup companies. In addition, private-sector actors contribute to the development of human resources. On-the-job training, conferences, and employee turnover tend to create and disseminate human resources throughout an industry.

Even the functions normally considered proprietary—technology and product development, creation of interfirm linkages and supply chains, and market creation—are influenced by government activities. As government attempts to develop technology for its own missions, whether defense, health, or energy, spin-offs to the commercial sector are inevitable. Jet aircraft engines and supercomputers are just two examples. Similarly, government purchases have provided early markets for many new technologies, encouraging producers to invest in manufacturing capacity and giving them an opportunity to demonstrate their products in an operational environment. Aircraft,

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[43] This framework derives from Andrew Van de Ven and Raghu Garud, "A Framework for Understanding the Emergence of New Industries," *Research on Technological Innovation, Management, and Policy,* Volume 4, R. S. Rosenbloom and R. A. Burgelman (eds.) (Greenwich, CT: JAI Press, 1989), pp. 195-225.

[44] National Science Foundation, *National Patterns of R&D Resources: 1994,* NSF 95-304 (Arlington, VA, 1995), table B-2, pp. 54-55.

integrated circuits, satellites, some energy technologies, and biotechnology products all received significant early boosts from government procurement. Recent efforts to stimulate cooperative research between federal laboratories and private industry intend to more fully exploit the compatibility between government and commercial markets.

Implications

These observations suggest that government may have a valuable role to play in helping firms overcome the barriers they face in bringing new technologies to market. To many, barriers to innovation simply represent the market at work, producing efficient outcomes. If a firm cannot find financing, it is because financiers have determined that the technology is not worth developing or that the firm does not have an acceptable business plan. If customers will not purchase a new product, it is because they have decided the product is too difficult to use, does not meet their requirements, or may have undesirable side-effects. Not all inventions merit being put to actual use; not all innovations merit being sold. The market provides an essential discipline as investors and, ultimately, customers decide which new products and processes are worth paying for. In this view, government has little or no role to play in assisting innovation and commercialization of particular technologies.

This view, while correctly stressing the central role that market discipline plays in channeling innovation and commercialization in profitable directions, appears too simple. As shown in the body of this paper, many factors can impede commercialization of a technology that producers can supply and potential customers want. Often economic actors do not have enough information: investors are not aware of investment opportunities, banks do not understand a firm's business, producers have a hard time assessing potential customers' needs, and potential customers cannot easily determine whether a product will work as claimed. Without such information, markets cannot operate efficiently, and commercialization prospects for new technologies can be greatly diminished.

Government already participates in and shapes markets for new technologies in many ways. It supports R&D related to government missions; buys a great deal of goods and services; regulates financial markets; provides a multitude of incentives and disincentives through its tax laws; has various programs to help small business; controls exports of many high-technology goods; and enforces extensive regulations to protect health, safety, and the environment. Thus, the issue is often not *whether* the government has a role in the commercialization process, but rather *how* the interaction between government and industry can best be structured to accommodate technological innovation and commercialization. Often both industry and government can help firms overcome the barriers to commercialization, in whatever forms they may appear (see box 1-4).

The proper role for government can often be determined only on a sector-by-sector basis. Economy-wide measures, while often helpful in changing general incentives for innovation and commercialization, cannot always address the barriers identified in this report. As the innovation process itself differs across industries, so do the barriers to successful innovation and commercialization, and so, too, does the proper role of government. In many cases, government has already found its niche in the commercialization process. In pharmaceuticals, government funding of basic research has enabled commercial enterprises to develop new diagnostic and therapeutic products and treatments. In electronics, government support for basic research and the development of technologies for its own (typically defense) missions has accelerated commercial development of computers, telecommunications, and semiconductors. Changes in the competitive environment affect these industries differently, requiring different responses from government. New forms of cooperation will need to be developed and tested.

BOX 1-4: Overcoming Barriers to Commercialization: Industry and Government Roles

Firms can encounter difficulties bringing new technology to market at any of several points in the commercialization process. Often the most difficult stage is that of converting a prototype into a salable product. In pharmaceuticals, for example, new drugs must undergo clinical trials, which can be both costly and time-consuming, with no guarantee of a successful outcome, In electronics, scaling up production is often the bottleneck, as state-of-the-art manufacturing facilities can cost several hundred million dollars or more (a semiconductor facility can easily cost over a billion dollars) and there IS great uncertainty over the amount of time required to bring the plant up to full-scale production with acceptable yields. Small firms, in particular, face significant financial constraints in these stages of commercialization, Venture capital and contributions from wealthy individuals (often called angels) are rarely sufficient to meet such costs,

To overcome these barriers, firms frequently ally with partners that provide the necessary working capital in exchange for patent licenses, equity or some other form of compensation. Such arrangements appear to work best in cases in which both the capital providers and the recipients are in the same line of business, Several large pharmaceutical companies, for instance, have provided support to small biotechnology firms in return for a license to the new drug. The large company can manufacture and market the product through existing distribution channels. In other cases, however, firms cannot attract funding from other organizations. U.S. flat panel display companies, for example, have been unable to win much support from large electronics firms, many of whom decided against investing in the technology a decade ago or more. Part of the reason for this difficulty is that large firms view themselves not as potential manufacturers of flat panel displays, but as users of the displays Gwen the availability of displays from Japanese producers, these large users have little incentive to support small U.S. firms.[1]

Government can sometimes assist companies facing such difficulties, In the case of flat panel displays, it is trying several different approaches. First, government IS providing some funding for the U S Display Consortium (USDC), a group of display manufacturers, suppliers, and users attempting to develop the infrastructure required for a domestic display industry, USDC has helped to interest large potential users in investing in display manufacturing firms, though no such transactions have yet occurred In addition, through the National Flat Panel Display Initiative (NFPDI), the federal government IS attempting to use its purchasing power to provide market assurances to firms willing to scale up to volume manufacture. By tying some portion of federal R&D funding to commitments from firms to invest in production capacity, the government is also trying to reduce the financial risks associated with scale-up It is unclear whether such measures will be effective, but they demonstrate the variety of roles government can play in helping industry overcome obstacles to commercialization,

SOURCE: Office of Technology Assessment, 1995,

[1] For a more thorough discussion of the difficulties facing the U.S. flat panel display industry, see U S Congress, Office of Technology Assessment, *Flat Panel Displays In Perspective,* forthcoming,