Innovation and Commercialization of Emerging Technologies

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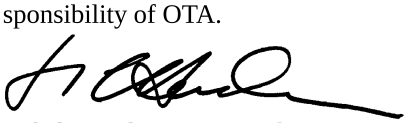
Foreword

Technological innovation is essential to the future well-being of the United States. The ability of the nation to sustain economic growth, increase its standard of living, and improve human health and the environment depends, in many ways, on its success in developing and commercializing new products, processes, and services. The growing capabilities of competitors in Europe, Asia, and elsewhere around the world increasingly challenge the ability of U.S. firms to convert the nation's science and technology base into a competitive advantage. Such concerns have prompted much debate about the proper role of government in encouraging innovation and the commercialization of new technologies. To date, however, the debate has been hampered by an incomplete understanding of the ways in which firms develop and market new products, processes, and services and the barriers they must overcome in the process.

This background paper examines the complexities of innovation and commercialization in an attempt to demonstrate the linkages between science, technology, and innovation, and to highlight the growing importance of factors other than basic research in commercial success. As shown, innovation is a complicated process in which markets often stimulate development of new technologies and product or process development stimulates scientific and technical research. Many factors influence commercial success, including the nature and composition of markets; competition from older technologies; choices of design and implementation; the availability of financing, standards, and complementary assets or infrastructure; and the ability to link with strategic partners. Government exerts significant influence on the innovation process, both intentionally and unintentionally. Research conducted for government missions can benefit commercial industry; federal procurement can jump-start nascent industries; environmental regulations can create markets for new technical approaches; government-sponsored technology demonstrations can provide useful information about new products, processes, and services to both users and developers; and laws in the areas of tax, investment, intellectual property, and antitrust shape the environment in which firms compete for resources and market share.

This background paper was prepared in response to requests from the House Science Committee (formerly the Science, Space, and Technology Committee) and the Senate Commerce, Science, and Transportation Committee. Throughout the course of this study, OTA received valuable assistance from its advisory panel, contractors, and reviewers, who both provided information for the report and ensured its accuracy and balance. The background paper is, however, solely the responsibility of OTA.



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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-

[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)

	Robotics			Genetic Engineering			Optical Fibers		
Country	1980	1985	1990	1980	1985	1990	1980	1985	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.

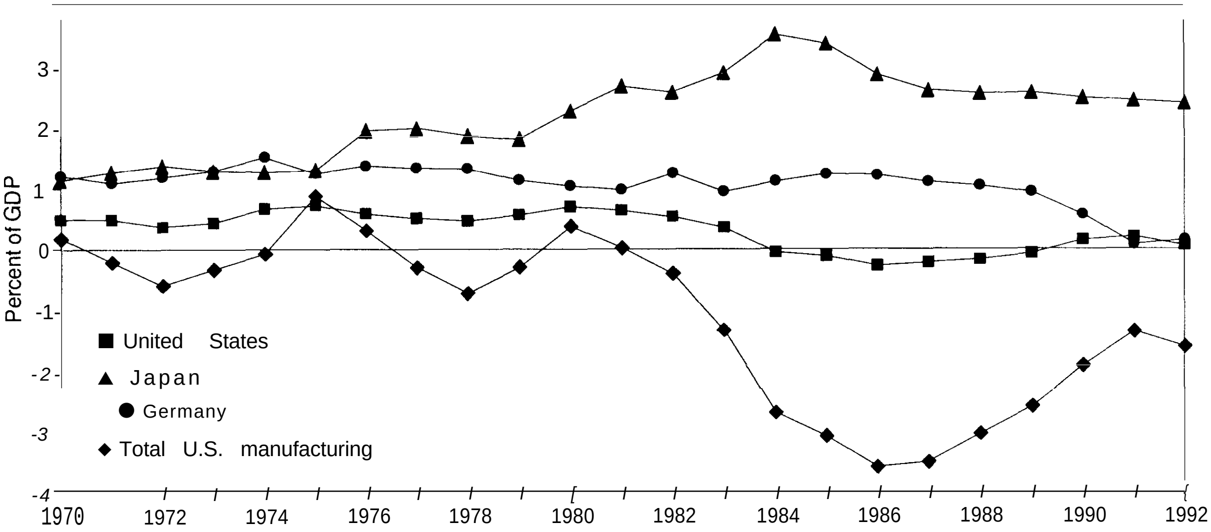
Despite these positive indicators, the United States faces increasing competition in invention and technology development. Much of the growth in U.S. patenting over the past decade resulted from an increase in patenting by foreign inventors, suggesting that foreign nations are increasing their innovative 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

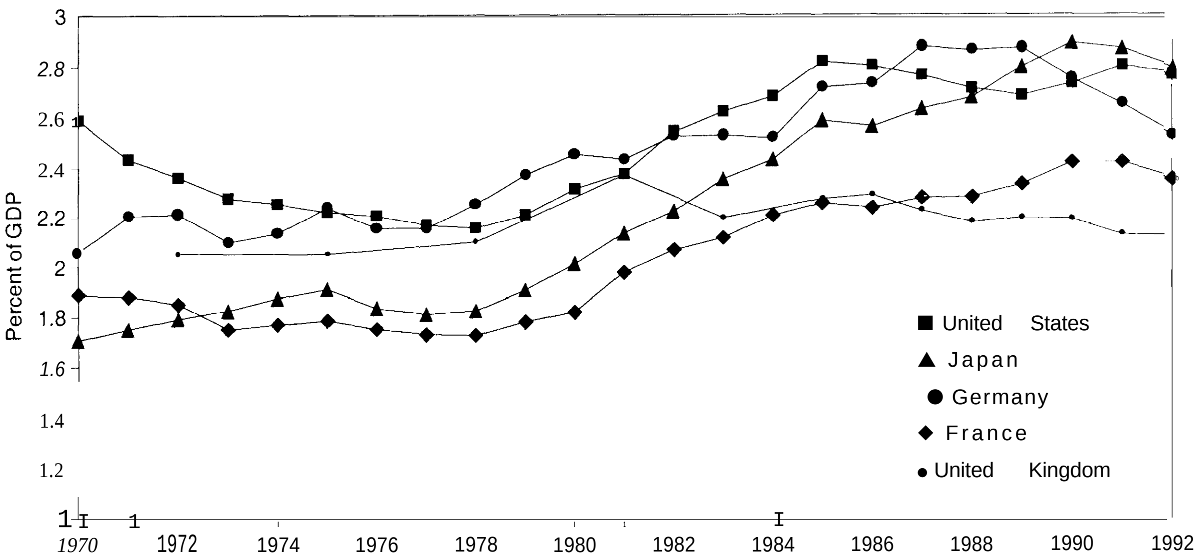
Trends in research and development spending also indicate growing competition. In absolute terms, the United States remains the world leader in R&D spending. Private and public expenditures on R&D totaled almost $173 billion in 1994. On average, between 1981 and 1992, U.S. R&D spending, measured in terms of purchasing power parity, was six times higher than that of Germany and 1.5 times higher than that of Japan.[13] In

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

[12] Trade statistics for advanced technology 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

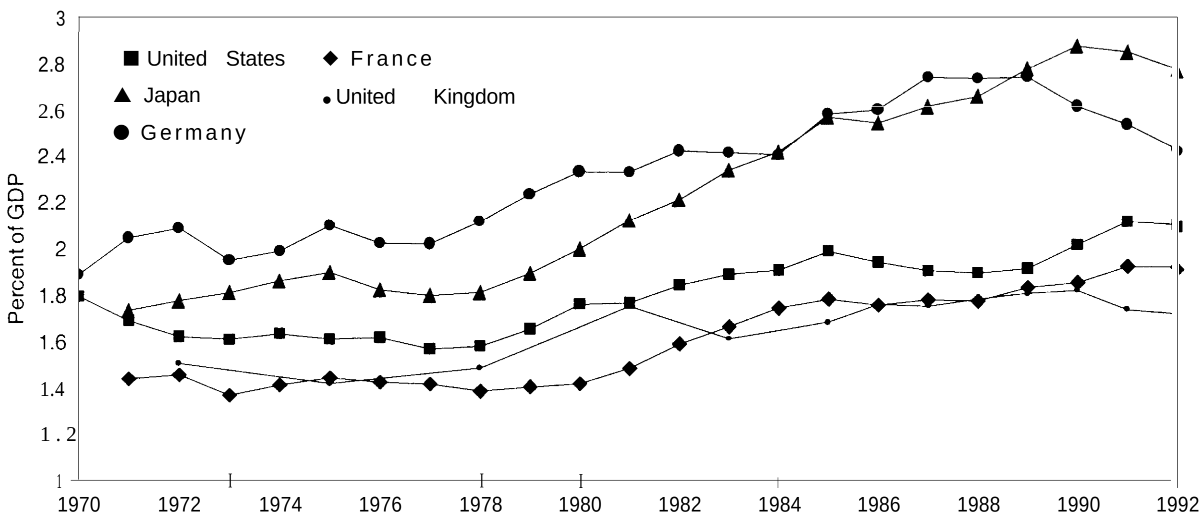
proportion to the size of the overall economy, however, U.S. expenditures on R&D are less impressive (see figure 1-2). [14] Whereas the United States and Germany had previously maintained the highest levels of R&D intensity in the industrialized world, Japan's increased dramatically after 1970 to surpass the United States in 1989 and Germany in 1990. '5 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**

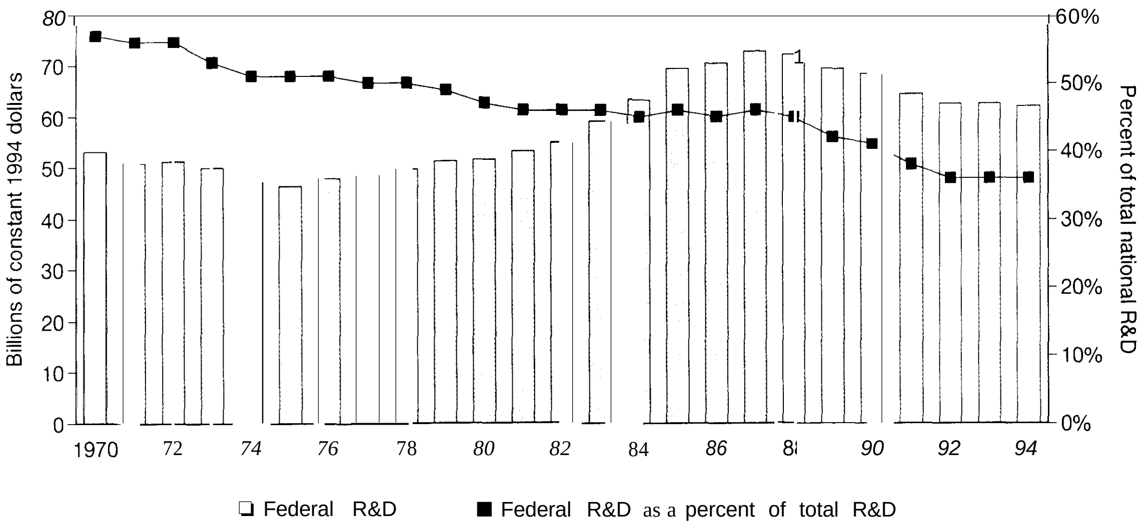
benefits for the U.S. industrial technology base.[16] Most of the U.S. defense R&D budget is devoted to military activities that have few implications for the commercial technology base. 17 Though attempts are under way to promote greater cross-fertilization in the military and civilian markets, long-standing 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)

EELEMENTS 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,

[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,

Innovation and Commercialization 2

Innovation does not necessarily proceed linearly from basic scientific research to product development; it is an iterative process of both matching market needs to technological capabilities and conducting research to fill gaps in knowledge, whether during product conception, product design, manufacturing, marketing, or other phases of the innovation process. Commercial success depends as much on the ability of firms to establish and protect a proprietary advantage in the marketplace as it does on their ability to generate new scientific and technical advances.

The process of innovation varies dramatically across industries and product lines. In some industries, like pharmaceuticals, innovation depends heavily on scientific breakthroughs; in others, like electronics, it derives more from product and process design. In addition, innovation takes on different characteristics throughout product and industry life cycles. Nascent industries exhibit high levels of product innovation as firms attempt to settle on the primary characteristics and architectures of their new offerings; later phases are characterized more by process innovation, as firms attempt to improve their means of manufacturing existing product lines. Government policies to facilitate innovation and commercialization can be more effective if they recognize the varying conditions leading to success in different industries and address the many barriers firms face in all stages of innovation, from emergence to maturity.

THE PROCESS OF INNOVATION

Technological innovation is the act of developing and putting to use new products and processes. It demands novelty in either the product/process/service, the application, or both. Innovation therefore includes not only the development of entirely new products, processes, and services that create new applications, but also the development of new products, processes, and services for use in existing applications (e.g., integrated circuits replacing vacuum tubes in electronic applications), or the use of an existing product, process, or service in a new application (e.g., manufacturers of flat panel displays adapted semiconductor manufacturing equipment to their needs). Innovation is more than just invention, which is the act of devising new products, processes, and services that are not obvious to someone skilled in the field and that represent clear departures from prior art.[1] Innovation requires that inventions be reduced to practice; that new products, processes, and services be designed, manufactured, and adopted by users. Many inventions are never put into practice—some because they cannot meet users' cost and performance requirements, others because they are technologically infeasible.

No single model accurately depicts the process of innovation; innovation occurs differently in different industries and product lines as firms attempt to develop products and processes that meet market needs. In the pharmaceutical industry, for example, innovation is closely coupled to scientific discoveries and follows a fairly linear pathway through manufacturing and marketing, although firms often begin constructing manufacturing facilities while the drug is undergoing clinical trials. Few other obstacles impede the innovation process in pharmaceuticals: new products can often be protected from imitation by strong patent protection, markets are quite easily identified and quantified, and third-party payment systems (i.e., insurance companies and Health Maintenance Organizations (HMOs)) relax some of the cost constraints on new products.[2] In contrast, innovation in the semiconductor industry derives more from new product design and improvements in manufacturing technology than from advances in basic science; product life cycles tend to be short (not longer than 3 years in most cases) and consumers are highly sensitive to cost, making commercial success more uncertain. In the commercial aircraft industry, innovation is highly centralized in a few producers who act as integrators of components from a broad range of suppliers, product cycles are several decades long, and manufacturers work closely with users to define product specifications and costs.

As these limited examples suggest, innovators face different obstacles in developing and marketing new products, processes, and services, and must proceed through a different set of steps to successfully bring a new invention to market. Not only do differences in industry structure and the nature of markets impose different constraints on the innovation process, but science, technology, and innovation are linked in different ways in different industries. These observations suggest that innovators follow many different pathways through the innovation process, and that attempts to facilitate innovation and the commercialization of emerging technologies must take different forms.

The Linear Model

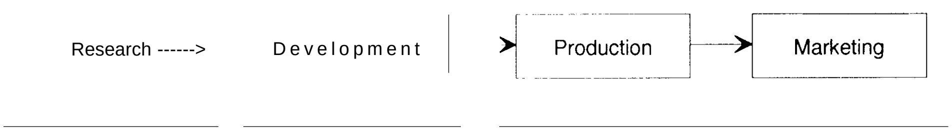
Public policymaking regarding innovation has long been based on the linear model of innovation. In its simplest form, this model postulates that innovation begins with new scientific research, proceeds sequentially through stages of product development, production, and marketing, and terminates with the successful sale of new products, processes, and services (see figure 2-1). As such, the linear model implies that the way to maintain leadership in markets for high-technology goods is to maintain leadership in basic scientific research. Though the model recognizes that development, production, and marketing activities lie between research and product sales, it views these processes more as part of the innovation pipeline than as major obstacles to commercial success.

The linear model gained considerable support after World War II, in part because it explained the

[1] In order to be considered for a patent, new products, processes, and services must be both novel and nonobvious to someone experienced in the field. Many inventions are never patented, either because of the time and effort required to acquire a patent, or because inventors do not wish to publicly disclose the operation of their new product or process.

[2] Recent changes in the health care industry, including the rapid growth of health maintenance organizations (HMOs) and the frequent mergers between hospitals and medical practices, are altering the process of innovation in medical technology by placing a greater premium on cost-effective treatments and diagnostics. See Gerald D. Laubach and Annetine C. Gelijns, "Medical Innovation at the Crossroads," *Issues in Science and Technology*, spring 1995, pp. 33-40.

FIGURE 2-1: The Linear Model of Innovation



SOURCE: Office of Technology Assessment 1995

genesis of important new military capabilities. The atomic bomb derived almost directly from fundamental research in elementary physics; radar derived from research into microwave radiation. The Department of Defense (DOD) further embedded the linear model into federal policymaking by instituting accounting categories for research and development (R&D) that corresponded to individual cells in the linear model. In its current form (revised slightly in FY 1995), the DOD model breaks the innovation process (referred to as research, development, test, and evaluation, or RDT&E) into seven stages. numbered 6.1 through 6.7 (see box 2-1). Projects move sequentially through the categories, from basic research through development and manufacturing, as the technology matures and is applied to new military systems. Because DOD funding dominated federal R&D expenditures throughout the postwar period and drove much of the U.S. research agenda, these categories permeated the thinking about innovation in the United States.

The linear model was further legitimated by Vannevar Bush, science advisor to Franklin Roosevelt, whose treatise, *Science, The Endless Frontier,* became the template for postwar technology policy in the United States. This document stated that funding of basic research would fuel development of technologies that could help advance many social goals, including national defense. health care, and industrial competitiveness. Bush saw funding of basic research as a fundamental mission of the federal government, noting that industry had several disincentives to adequately support long-term fundamental research. He believed, however, that further development and application of new technologies was the sole province of industry, which was better suited to interpreting market needs and identifying lucrative investments.

Effects on Policy

Government policy toward commercial innovation has followed the linear model to a large degree. Support provided specifically for *commercial* innovation has traditionally been limited to funding of basic scientific research. Institutions such as the National Science Foundation (NSF) and the National Institutes of Health (NIH) provide support for basic research, much of it conducted in U.S. universities. Other policies attempt to create an environment conducive to innovation through legal mechanisms such as tax codes, patent law, and antitrust regulations. Such tools tend to operate on an economy-wide level, making no distinctions between industries, though the effects often vary considerably across different industries. For example, changes in the tax code to allow faster depreciation of capital equipment would likely have a greater effect on the semiconductor industry than on pharmaceuticals because of the high cost of semiconductor manufacturing equipment and the large contribution capital expenditures make to semiconductor production costs. Changes in patent law, on the other hand, would likely affect the pharmaceutical industry more than semiconductors because patents are used more frequently in the pharmaceutical industry to protect against imitation.

[3] Vannevar Bush, *Science, The Endless Frontier: A Report to the President* (Washington, DC: U.S. Government Printing Office, 1945).

BOX 2-1: DOD's Research, Development, Test, & Evaluation (RDT&E) Budget Categories

6.1 *Research:* New concepts are developed through laboratory research.

6.2 *Exploratory development:* Promising research results are applied to preliminary laboratory devices,

6.3 *Advanced development:* Technologies are demonstrated in representative systems through Advanced Concepts Technology Demonstrations, and prototypes are developed

6.4 *Demonstration and validation:* Technologies that meet an articulated operational need are demonstrated and validated.

6.5 *Engineering and manufacturing development:* The product/system incorporating the new technology is redesigned for manufacturing.

6.6 *RDT&E management support:* Provides overhead and management funds for all RDT&E activities.

6.7 *Operational system support:* Systems in production or already fielded are improved and upgraded through the incorporation of new technology.

SOURCE: Richard M Nunno, "Defense R&D in the 1990s," IB-93096 (Washington, DC Congressional Research Service, July 18, *1994),* p. 1.

Other support for innovation has come from mission agencies of the federal government, such as DOD, the Department of Energy (DOE), and the National Aeronautics and Space Administration (NASA). Much of the $71 billion in federal R&D spending in 1994 (see table 2-1) promoted initiatives of interest to the federal government that are typically not addressed independently by the private sector. Though mission-oriented R&D does not attempt to directly influence commercial applications of technology, it can have an indirect effect by strengthening the science and technology base from which commercial firms can draw and through more explicit attempts to spin off or transfer government technologies to the commercial marketplace.[4]

Pursuit of government missions has often exerted a strong influence on commercialization of civilian technologies. Decisions by DOD to use integrated circuits (ICs) in the Minuteman missile systems and by NASA to use ICs in the Apollo program provided the first markets for the new technology, and coaxed firms to invest in manufacturing capacity. Commercial firms such as IBM had decided against using ICs in their latest products because of the uncertainty over the reliability of the new technology. Other research funded by DOD generated technologies that were quickly adopted for commercial applications. Today's Internet traces its history to the ARPANET, a computer network established by the DOD's Advanced Research Projects Agency (ARPA) around 1970. ARPA-funded research on gallium arsenide for millimeter wave communications systems and on high performance computing has found its way into wireless communications systems and parallel computers sold in the commercial marketplace.

At times, the federal government has explicitly moved beyond a strict interpretation of the linear model in order to facilitate the development of particular innovations or industries. Since 1987, the federal government, acting through the DOD, has provided funding of $90 million to $100 million annually to support the efforts of SEMATECH, a consortium of major U.S. semiconductor

[4] John Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston, MA: Harvard Business School Press, 1992).

TABLE 2-1: Federal Obligations for R&D by Agency, 1994 (millions of dollars)

Department/Agency	R&D Funding[c]
Agriculture	$1,364
Commerce[a]	897
Defense	37,523
Energy	6,582
Health and Human Services[b]	10,723
Interior	589
Transportation	688
Environmental Protection Agency	656
National Aeronautics and Space Administration	8,637
National Science Foundation	2,217
Other	1,368
Total	71,244

[a]Includes $382 million in funding for the National Institute of Standards and Technology and $504 million for the National Oceanic and Atmospheric Administration.

[b]Includes $10.1 billion in funding for the National Institutes of Health

[c]Estimated obligations for 1994

SOURCE: National Science Foundation, *National Patterns of R&D Resources: 1994,* NSF 95-304 (Arlington, VA: 1995), pp. 79-80

manufacturers. Although the rationale for the program was based on national security grounds, federal participation in SEMATECH has strengthened the U.S. supplier base for semiconductor manufacturing equipment and contributed to the subsequent resurgence of the U.S. civilian semiconductor industry. While SEMATECH is frequently viewed as a success, government sponsorship of other technology programs, such as shale oil and the supersonic transport (SST), have been widely criticized.[5]

Limitations of the Linear Model

Despite its pervasive use, the linear model suffers from several drawbacks that limit its applicability. Many innovations derive not from advances in science, but from exploiting existing scientific knowledge and from recognizing potential new markets for certain types of products, processes, or services. Science nevertheless plays an important role throughout the innovation process by providing information with which to solve problems identified in design, manufacturing, or other stages of the innovation process. In addition, innovation does not always follow a linear pathway from research to marketing. Often, technological developments precede scientific research, and lessons learned from manufacturing and marketing operations can feed back into the product development process. Innovation is usually an iterative process in which designs must be continually tested, evaluated, and reworked before an invention achieves market success.

Science and the sources of innovation

Basic research, while an important part of the innovation process, is not the source of all technological innovation. Ideas for new products and processes derive from many sources: new science, new technological breakthroughs, new perceptions of market demand, or customers themselves. U.S. firms indicate that just 58 percent of their new R&D projects derive from ideas generated by their scientific and technical staff; the remaining 42 percent derive from marketing and production departments or from customers, although considerable variation exists across industries (see table 2-2). Japanese firms demonstrate an even greater

[5]See, for example, Linda R. Cohen and Roger G. Nell, *The Technology Porkbarrel* (Washington, DC: The Brookings Institution, 1991).

TABLE 2-2: Sources of R&D Projects for 100 Firms in the United States and Japan, 1985

Industry	R&D Us.	R&D Japan	Marketing U.S.	Marketing Japan	Production U.S.	Production Japan	Customers U.S.	Customers Japan
Chemicals	45%	49%	25%	23%	14%	15%	8%	3%
Electrical	90	47	7	21	1	5	1	27
Machinery	56	44	21	22	4	11	18	20
Autos, instruments, and metals	51	48	25	8	12	26	11	13
Average, all respondents	58%	47%	21%	18%	9%	15%	9%	15%

SOURCE: Edwin Mansfield, ' Industrial R&D in Japan and the United States: A Comparative Study, " *The American Economic Review* May 1988, p 227

reliance on ideas generated outside their R&D departments. This even applies in industries such as electronics, in which U.S. firms report that 90 percent of R&D projects are suggested by their R&D departments.

Development of new products, processes, and services is guided by a knowledge of both market needs and scientific and technological capabilities. The former helps determine the types of products likely to yield a financial return, as well as the cost and performance attributes required; the latter provides insight into viable means of serving the market need. Many attempts have been made to determine the relative contributions of these two forces-often referred to as *market pull* and *technology* push—in eliciting innovation, but such analyses suggest that innovation is strongly influenced by both (see box 2-2). Innovation is a

BOX 2-2: Technology Push v. Market Pull

New innovations are both pushed along by new scientific and technological discoveries and pulled along by market forces. Several studies have attempted to discern the relative Importance of technology push and demand pull in stimulating innovation, but the results are Inconclusive,

One set of studies traces the histories of particular innovations in particular firms in an attempt to discern whether critical events during the innovation process were motivated by new science and technology or better perceptions of market need.[1] These studies tend to conclude that market pull dominates the Innovation process. One representative study finds that market needs motivated research in 45 percent of the innovations studied; potential gains in manufacturing—which the authors consider a type of market-driven Innovation—accounted for another 30 percent. In only 21 percent of the 567 innovations examined in five Industries was technology considered the driving force [2] Such studies, however, tend to suffer from imprecise definitions of market need and view innovation from the perspective of the innovating firm, whose motivations in innovation should be market-oriented Studies such as the Department of Defense's HINDSIGHT,[3] which examined successful military development programs but considered only critical events that occurred 20 years or less before commercialization tend to ignore most of the long-term influence of basic research because of their short time horizons

(continued)

[1] R. Rothwell et al., "SAPPHO Updated Project SAPPHO Phase 11, " *Research Policy* November 1974; J. Langrish et al. , *Wealth from Knowledge: A Study of Innovation in Industry* (New York, NY: Halsted/John Wiley, 1972), S Meyers and D G Marquis, *Successful Industrial Innovation* (Washington, DC National Science Foundation, 1969), J M Utterback, "Innovation in Industry and the Diffusion of Technology, " Science, Feb. 15, 1974.

[2] S Meyers and D G Marquis, *Successful Industrial Innovation* (Washington, DC National Science Foundation, 1969)

[3] Office of the Director of Defense Research and Engineering, *Project HINDSIGHT* (Washington, DC U S Department of Defense 1969)

BOX 2-2: Technology Push v. Market Pull (Cont'd.)

Another set of studies looks more broadly across companies, industries, or economies in an attempt to link economic growth or competitive success to R&D and market demand.[4] These analyses demonstrate a much greater dependence on technology push as the dominating factor in innovation. The evidence cited in such works suggests a weak relationship between the size and sophistication of national markets and the performance in technological Innovation. Much higher correlations are found between national Innovative performance and supply side factors such as the number of large firms, levels of R&D, and capabilities in fundamental research.[5] This observation applies equally well to comparisons of the innovative performance of Industries within a national unit. Differences in rates of Innovation across Industries are more closely related to factors such as producer concentration and technological opportunity than to market factors.[6] Demand theories do not easily explain the wide variations in performance of Individual industries with respect to technological innovation and productivity growth.

Together, these studies demonstrate that both market pull and technology push play a role in initiating Innovative activities. Few Innovations can be categorized as examples of technology push or demand pull in a clear and unambiguous manner, and few can be described as a linear sequence with a clearly defined starting point.[7] Innovation is an iterative process that responds to both demand and supply side forces. Successful innovations tend to undergo extensive modification during development. This IS due to changes in perceptions of user requirements and of producers' abilities to offer the product, process, or service with the necessary features at an acceptable cost.

Technology push does appear to play a larger role than demand pull in major, revolutionary innovations. One study notes that recognition of a discovery's potential usefulness served as the impetus for Innovation in over 14 percent of the major innovations (which, themselves, represented 13 percent of their total sample), while identification of a particular market need served as the impetus in just 6 percent of the cases. [9] For minor Innovations, the study finds that technology push was important in just 5 percent of the cases, while need identification was important in more than 18 percent. The study also finds that the most Important factor delaying successful innovation—occurring in 32.5 percent of the cases—is Insufficient development of a complementary technology. In 22.5 percent of the cases, there existed at first no market or need; and management failed to recognize the need for the innovation in 76 percent of the cases. For major innovations, the lack of market and lack of complementary technology factors were of equal Importance, while for minor innovations, the lack of complementary technology was more Important than lack of market.

SOURCE Off Ice of Technology Assessment, 1995

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[4] C Freeman, *The Economics of Industrial Innovation* (Cambridge, MA MIT Press, 1982), K Pavitt, *The Conditions for Success in Technological Innovation* (Paris: Organisation for Economic Cooperation and Development, 1971)

[5] Pavitt, Ibid , p 53

[6] David Mowery and Nathan Rosenberg, "The Influence of Market Demand Upon Innovation A Critical Review of Some Recent Empirical Studies, " *Research Policy.* vol. 8, 1979, p 144

[7] J. Langrish et al., *Wealth from Knowledge: A Study of Innovation* in *Industry (New* York, NY: Halsted/John Wiley, 1972)

[8] Ibid.

process of trial and error, of finding workable solutions to known or perceived market needs. Innovators continually try to find new applications for science and technology and ways of satisfying market demands, but not until technology push and market pull are combined do innovations find market success.

Though not unique in its ability to initiate innovation, science nevertheless plays a critical role throughout the process. Scientific discoveries can pave the way for numerous innovations—and industries—as the linear model suggests. Today's semiconductor technology derives from scientific research into solid state physics; the biotechnology industry derives from recent advances in molecular biology. In these cases, long-range theoretical investigations into the nature of the physical universe provided new knowledge that, in turn, opened entirely new avenues for approaching particular problems. Such science is typically pure, long-range science, needed to test predictions of existing theory or to more fully develop that theory. Because it helps construct the theoretical framework describing natural processes, such research often takes many years—even decades—to translate into practical applications.

Science and scientific research also contribute to other stages of innovation. Product developers often conduct scientific research to solve technical problems that arise during the design of a product, process, or service. Manufacturing engineers also rely on scientific research to overcome manufacturing problems. In chemicals, better understanding of catalyst and chemical reactions can lead to improved yields or lower production costs. In semiconductors, improvements in the capability of microprocessors or the storage capacity of memory chips rely on research into manufacturing techniques that allow more devices to be packed onto an individual integrated circuit. Research performed to support development activities is often geared toward understanding the ways in which the components of a complex system interact and the properties of the overall system created by multiple interactions. Research in the production stage is often conducted to investigate ways of manufacturing particular components of a system and to find ways of reducing costs through the use of special equipment or less expensive materials. In products developed for the commercial marketplace, systems and process research are not only necessary to the proper functioning of the innovation, but are often more important than basic science in reducing costs and improving performance.

Many firms distinguish between research activities undertaken to explore and develop a new body of knowledge and those pursued to solve particular problems in the development process. In the former case, the goals of the research are often diffuse and the benefits are difficult for any one company or institution to monopolize. In the latter case, research results are more targeted and the results easier to appropriate. Researchers, therefore, tend to collaborate more widely on the former type of R&D and to share information more freely. In the latter case, researchers will usually try to solve the R&D problem with internal resources or with limited use of outside capabilities.

Science feeds into the innovation process in other ways as well. Scientific researchers often develop analytical tools that engineers later use in designing product, processes, and services. Scientists also create instrumentation, lab techniques, and analytical methods that eventually find their way into industrial process controls. Examples include electron diffraction, the scanning electron microscope, ion implantation, synchrotron radiation sources, phase-shifted lithography, and superconducting magnets. Such instrumentation is often developed in pursuit of basic research, but is later adapted for manufacturing purposes.

The pathway through innovation

Innovation rarely proceeds in a linear fashion from one well-defined stage to the next. Most innovations take a much more complicated route from invention to marketplace. Often, market perceptions generate ideas for new products that, in turn, stimulate scientific research. In addition, advances in technology can precede advances in the science base (see box 2-3). The Wright brothers, for example, knew little, if anything, about formal

BOX 2-3: Linkages Between Science and Technology

Technology is often considered the practical application of science. As such, it is commonly thought to depend on and follow behind advances in the underlying science. This progression is certainly true in some cases. The discovery of radio waves—a result of Hertz's attempt to follow up on predictions made by Maxwell several years earner-clearly paved the way for technological advances in such areas as radio, television, and communications. The discovery of superconductivity has paved the way for magnetic resonance imaging and high-strength industrial magnets.

Such an understanding of technology is limited, however. Technology is not merely the application of knowledge generated by scientific activity; it is a body of knowledge about certain classes of events and activities. It is a knowledge of techniques, methods, and designs that work, and that work in certain ways and with certain consequences, even when one cannot explain exactly why. Science and technology are best thought of as two parallel streams of cumulative knowledge that have many interdependencies and cross relations, but whose internal connections are much stronger than their cross connections. As a result, technological progress is not necessarily dependent on scientific progress.

Technology itself often dictates its own path of development along what have been referred to as technological trajectories. Just as science is often considered to operate under distinct paradigms that determine relevant problems and approaches for solving them, so, too, does technology operate under particular paradigms that consist of sets of procedures, definitions of the relevant problems, and details of the specific knowledge related to their solution. Each technological paradigm defines its own concept of progress based on its specific technological and economic tradeoffs. A technological trajectory is the direction of advance within a technological paradigm.

Technological knowledge often *precedes* scientific knowledge and signals lucrative areas for scientific research. Torricelli's demonstration of the weight of air in the atmosphere was an outgrowth of his attempt to design an improved pump. Carnot's creation of thermodynamics was an attempt to understand the efficiency of steam engines some 50 years after Watt introduced the invention itself. Joule's discovery of the law of conservation of energy derived from an interest in alternative sources of power generation in his father's brewery; and Pasteur's development of bacteriology emerged from his attempt to deal with problems of fermentation and putrefaction in the French wine industry. These limited examples show that basic science can—and often does—arise out of an attempt to understand a narrow technical problem.[1]

Technology also drives science by providing a huge repository of raw data for scientists to scrutinize in developing better scientific theories. Successful development of a new device often stimulates scientific research to better understand its operation and improve its performance. The natural trajectory of certain technological improvements identifies and defines the limits of further improvement, which in turn focuses subsequent scientific research. In some cases, the advance of knowledge occurs only by actual experience with a new technology in its operating environment, as has occurred in aviation, for example. One of the central features of high-technology industries is that technological progress identifies the directions of new scientific research offering a high potential payoff. In telecommunications, transmission over longer distances, and the introduction of new modes of transmission, have generated basic research into the interactions of electromagnetic radiation with weather and atmospheric conditions.

SOURCE: Nathan Rosenberg, *Inside the Black Box: Technology and Economics* (New York, NY: Cambridge University Press, 1982) pp. 141-159; Harvey Brooks, "The Relationship Between Science and Technology, " *Research Policy,* vol. 23,1994, p 479, Giovanni Dosi, "Technological Paradigms and Technological Trajectories, " *Research Policy,* vol. 11, 1982, pp. 147-162

[1] Giovanni Dosi, "Technological Paradigms and Technological Trajectories, " *Research Policy,* vol. 11, 1982, pp. 147-162 Examples are from R R Whyte (ed.), *Engmeermgf'regress Through Trouble* (London: The Institution of Mechanical Engineers, 1975)

aerodynamics theory; yet, through consistent refining of designs, they successfully developed the first airplane. Development of the microprocessor also derived more from advances in technology than in science, as improvements in semiconductor manufacturing techniques reduced the size of devices that could be fabricated on an integrated circuit (IC) and allowed the multiple component parts of a microprocessor to be fabricated on a single IC.

Parallel computing is a more recent example of a major innovation that derived from advances in technology that preceded the underlying scientific theory. Parallel computers use multiple processing units simultaneously to conduct data- or computation-intensive calculations. Parallel computers did not derive from basic research into the nature of algorithms for parallel computation, but from an attempt to overcome the bottleneck on processing speed imposed by reliance on a single processor. Initial activities centered around the design and construction of prototype machines with different internal architectures for linking multiple processors (which in some designs number more than 1,000) and memory. These activities fall into the category of engineering design and development, not scientific research.

Of course, the availability of parallel computers has stimulated basic research on algorithms for parallel computation, which will enable these computers to be used more efficiently. As with all electronics technology, parallel computing builds on a base of fundamental scientific knowledge about solid state physics. The components that comprise the processors and memory chips used in parallel computers could not have been made without that understanding. Several versions of parallel computers incorporate gallium arsenide processing units in an attempt to increase processing speed. But such research, in itself, did not trigger the development of parallel computers.

A further blurring of the lines between stages in the innovation process has resulted from deliberate attempts by firms to revamp their product development processes. In the past, large companies with corporate research laboratories, such as AT&T, DuPont, IBM, and Xerox, organized their product development activities as a linear progression from research lab to marketing. Corporate laboratories independently generated new science and technology and transferred their results to the product development divisions. They, in turn, designed new products, constructed prototypes, and passed the designs to the manufacturing divisions for production. This model often caused 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.[6]

This model has been replaced, to a large degree, by concurrent forms of product development in which responsibility for new product development is given to a project team consisting of representatives from the research, development, manufacturing, and marketing divisions. Such organization reflects the desire to incorporate insights from each of these areas of expertise into the original conception of the innovation, making it simpler to target corporate research toward commercial goals and eliminate downstream problems that often hampered manufacturing and marketing.

Furthermore, innovation is a highly iterative process, characterized by constant feedback from markets. The personal computer, for example, went through several iterations by SRI, Inc. and Xerox Corp., among others, before the Apple II became a success. The automobile and airplane went through similar periods of refinement. This process allows experience gained in later stages of innovation, such as manufacturing and marketing, to feed back into earlier stages, such as basic re-

[6] Council on Competitiveness, *Picking Up the Pace* (Washington, DC: Council on Competitiveness, 1988); David A. Hounshell and John Kenly Smith, Jr., *Science and Corporate Strategy: DuPont R&D, 1902-1980* (New York, NY: Cambridge University Press, 1988); and OTA interviews.

search and product design. As new products and processes are tested in the marketplace, firms learn first-hand about the performance and cost attributes demanded by consumers, and use that information to develop improved versions of the product, process, or service. In this way, the development and adoption of innovations are closely interrelated. Adoption, rather than representing the end point of the development process, constitutes the beginning of an often longer process of redesign whereby the design can be iterated, research can be conducted to identify means of improving performance or reducing cost, and manufacturing problems can be resolved.[7]

Alternative Views of Innovation

As these observations suggest, technological innovation is more that the direct translation of new scientific knowledge into marketable products; rather, it is a more complex process of developing and putting to use new products, processes, and services. This process can take many forms: 1) development and application of new products, processes, and services to satisfy previously unmet market needs, as the linear model implies; 2) development and application of new products, processes, and services—usually based on new science and technology—to existing market needs; 3) use of existing products, processes, and services in new applications; and 4) incremental improvements to existing products, processes, and services for their existing applications. Each type of innovation presents different challenges to innovators. Impediments to progress can range from a limited science and technology base, to competition from existing technologies, to unreceptive markets.

One attempt to model the complex interactions between science, technology, and innovation is the Chain-Link Model of innovation.[8] In contrast to the linear model, the chain-link model allows for feedback between stages of the development process, and separates science from the development process to highlight the multiple roles science plays in innovation. The chain-link model breaks down the process of developing new products, processes, and services into five stages: 1) recognition of a potential market; 2) invention or the production of an analytical design for a new product; 3) detailed design, test, and redesign; 4) production; and 5) distribution and marketing (see figure 2-2). The process typically proceeds linearly, but is supplemented by feedback between adjacent stages that iterates each step as necessary (arrows marked 'f' in figure 2-2). In this way, a problem identified in the design and test phase, for instance, forces innovators to attempt a new design. Additional feedback from users in the marketplace is also incorporated into each stage of the process (along the pathways marked 'F') to help ensure that the design of a new product—and the technological capabilities incorporated into it—matches the demands of the marketplace.

This model allows for several different types of innovation. First, new scientific discoveries can create new opportunities for novel products and processes, much as advances in physics laid the groundwork for development of the integrated circuit. New science and technology often provided new means of serving existing markets, displacing existing technologies in the process. Integrated circuits, for example, provided a new means of modifying electronic signals, and eventually replaced vacuum tubes in most applications. Second, newly recognized market needs can stimulate the development of new products and processes that are based on existing technologies, though some additional R&D may be needed. IBM's PC and Sony's first portable transistor radio, although based on existing

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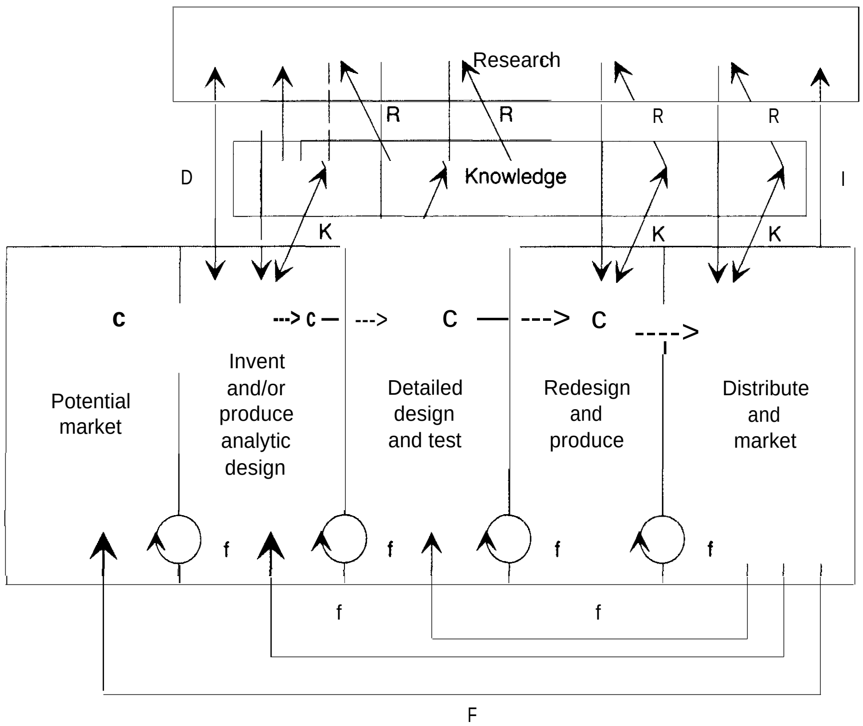
[7] Annetine Gelijns and Nathan Rosenberg, "The Dynamics of Technological Change in Medicine," *Health Affairs*, summer 1994, pp. 30-31.

[8] This description of the product/process development model is based on a model developed by Stephen Kline at Stanford University. See Stephen J. Kline and Nathan Rosenberg, "An Overview of Innovation," in Ralph Landau and Nathan Rosenberg (eds.), *The Positive Sum Strategy* (Washington, DC: National Academy Press, 1986), pp. 275-305.

FIGURE 2-2: Kline-Rosenberg Chain-Link Model of Innovation



KEY: C = central pathway of innovation; D = scientific discoveries that generate radical innovations, F = market feedback, f = iterative feedback between stages; I = innovations that contribute directly to scientific research, such as the microscope and telescope; K = contributions of existing knowledge to the renovation process, R = research used to solve problems encountered throughout different stages of innovation.

SOURCE: Stephen J Kline and Nathan Rosenberg, "An Overview of Innovation," *The Positive Sum Strategy: Harnessing Technology for Economic Growth,* Ralph Landau and Nathan Rosenberg (eds.) (Washington, DC National Academy Press, 1986), p 290

technology, opened vast new markets. Third, innovation can be incremental. Existing products can be enhanced to improve performance or lower costs, or they can be modified slightly to be used in new markets. New software development has enabled personal computers to expand into a wide variety of applications, such as word processing, database management, and electronic communications. These types of innovation differ in the ways they incorporate R&D, in the barriers they face, and in the types of innovations they generate.

Science- or Technology-Driven Innovation

Science usually plays a subservient role in innovation, providing answers to questions posed at different points in the innovation process. However, scientific or technological discoveries do, at times, act as the genesis of new innovations by creating entirely new ways of serving existing or new markets. This often occurs in industries such as pharmaceuticals, chemicals, and materials—that are characterized more by discovery of new products than by their design—but scientific and

TABLE 2-3: Time Required To Commercialize New Materials

Material	Invented	Commercialized
Vulcanized rubber	1839	late 1850s
Low-cost aluminum	1886	early 1900s
Teflon	1938	early 1960s
Titanium	mid-1940s	mid-1960s
Velcro	early 1950s	early 1970s
Polycarbonate (bullet-proof glass)	1953	1970
Gallium arsenide (semiconductor)	mid-1960s	mid-1980s
Diamond-like thin films	early 1970s	early 1990s
Amorphous soft magnetic materials (for transformers)	early 1970s	early 1990s

SOURCE: Thomas W. Eagar, "Bringing New Materials to Market" *Technology Review,* February/March 1995, pp. 42-49.

technological advances are responsible for creating major changes in other industries as well. Scientific and technological research has generated new products such as lasers, liquid crystal displays, and integrated circuits, each finding its way into myriad products, serving different markets.

Translating new science into new products is typically a slow, laborious process. New materials typically experience a 20-year lag between invention and widespread adoption (see table 2-3); lasers took decades to advance from a laboratory curiosity to an integral component of communications systems, medical devices, and consumer electronics. Much of the difficulty in commercializing scientific breakthroughs is in determining suitable applications and understanding the engineering limitations of new devices. In many cases, the science is still not sufficiently understood for scientists and engineers to select the application with the highest probability of successor the most favorable financial return.

New technology often finds its greatest success in products that were not even conceived of at the time of discovery. Low-temperature superconductors, for example, found their greatest application in medical magnetic resonance imaging (MRI) devices, which were not conceived of until six or more decades after the discovery of superconductivity. In this case, as in many others, additional pieces of information were needed before the innovation could be realized. MRI technology depended not only on the availability of high-field superconducting magnets, but of nuclear magnetic resonance spectroscopy, computer imaging, and fast signal processing technologies as well. None of these was available when superconductivity was first discovered in 1911, or when the first practical superconducting materials were found in the 1960s.[9] Similarly, the applications of lasers to communications systems had to await the development of fiber optics with low loss at laser wavelengths of light, over which optical pulses could be routed.

Considerable time and effort must be allocated to applied research in which the capabilities of the new technology in different applications are evaluated. This process often requires considerable trial and error because performance cannot be predicted with accurate models. For example, the recent discovery of buckeyballs—spherical ensembles of carbon atoms whose bonds mimic the stitching on a soccer ball—touched off a flurry of speculation regarding possible applications, including: Teflon-like ball bearings; cage-like structures for transporting atoms (especially radioactive ones) inside the human body; sieves for filtering nitrogen out of natural gas; or protecting transplanted organs by allowing sugars and amino acids, but not viruses and antibodies, to

[9] See U.S. Congress, Office of Technology Assessment, *High-Temperature Superconductivity in Perspective,* OTA-E-44 (Washington, DC: U.S. Government Printing Office, April 1990).

pass.[10] Development of any of these applications is years away as researchers attempt to further examine their feasibility and limits to their use.

High-temperature superconductors (HTS) provide another example of this phenomenon. Superconductors present no resistance to the flow of electrons below a certain critical temperature. High-temperature superconductors, typically ceramics, have critical temperatures above 35 degrees Kelvin (35° K). The more recently discovered HTS materials, based on compounds of yttrium, barium, copper, and oxygen (YBaCuO) or mercury, barium, calcium, copper, and oxygen (HgBaCaCuO), have critical temperatures well above 75° K (about 90° K and 140° K, respectively). This allows them to be cooled with liquid nitrogen, which is much cheaper and easier to handle than the liquid helium used to cool low-temperature superconductors (LTS).

Since the discovery of HTS in 1986 by researchers in IBM's Zurich research laboratory, scientists and engineers have attempted to exploit the technology in a number applications: large magnets for the Superconducting Supercollider or for separating metallic impurities from industrial powders; electric power transmission; electronic computers; filters for wireless communications systems; and sensors for detecting magnetic fields.[11] Each of these applications has presented developers with numerous engineering challenges that slowed progress in many areas. Because they are ceramics, most HTS materials are brittle, making them difficult to use in applications such as flexible wires. Engineers attempting to develop superconducting wires for use in magnets or power distribution have had to find ways of handling the material without breaking it or cracking it, which interferes with its superconducting capabilities. They have also had to design cooling systems for different applications, whether underground power transmission wires or base stations for cellular telephony. Use of HTS in computers is currently limited by the manufacturers' ability to create arrays of electronic switches called Josephson junctions with features as small as 100 angstroms—the length of about 30 atoms and 35 times smaller than the smallest features found in state-of-the-art production semiconductor circuits. While HTS could reach the marketplace as early as 1996 in the form of filters for wireless communications systems, large market growth is unlikely to occur until after the year 2000.[12]

Innovations based on new scientific or technological developments often have difficulty gaining initial market acceptance. Sometimes this happens because the new product is introduced before the market has had time to develop—or has expressed demand for the product. Innovations that follow the linear model are particularly prone to such problems because they are often pursued in response to newly derived technical capabilities, rather than newly recognized market needs. Considerable changes in the market environment may be necessary to induce sales of the new technology.

Market-Driven Innovation

Most new product and process development is not initiated by new science, but instead is an attempt to meet perceived market needs by drawing on existing technology and on the pool of scientific knowledge. This process has been described as *demand articulation*, a process whereby firms use market data to translate vague notions of market demand into a product concept and then decompose the product into a set of development

[10] Hugh Aldersey-Williams, "The Third Coming of Carbon," *Technology Review*, January 1994, pp. 54-62.

[11] This last application uses another characteristic of superconductors, the so-called Meissner effect, whereby superconductors expel magnetic fields from their interior by generating electrical currents on their surface.

[12] See Donn Forbes, "Commercialization of High-Temperature Superconductivity," unpublished contractor report prepared for the Office of Technology Assessment, June 1995.

BOX 2-4: Xerography as a Market-Driven Innovation

The initial development of xerography, the means for copying documents using a dry, photoelectric effect, highlights the market-driven model of innovation. The impetus for xerography stemmed not from the discovery of photoconductive materials—materials that change their conductive properties when exposed to light and formed the heart of early xerographic processes—but awaited the recognition of a need for a new copying process. This happened in 1935 when Chester F. Carlson, a patent attorney, realized that he needed a better way to copy paper documents. The constant need for multiple copies of patent specifications to be sent to inventors, associates in foreign countries, and others demanded a process faster than carbon copying, which required documents to be retyped or errors to be corrected on multiple copies.

Carlson examined many alternative methods for reproducing documents. He determined that chemical processes would not suffice because of the variation in inks used on originals (some were typewritten, others used India ink, pencil lead, or ink), and began looking for photographic mechanisms that made use of the only feature common to all documents: the high contrast in the light-reflecting characteristics between the paper and the markings. He began reviewing literature on the ways in which light interacted with matter—photoelectric effects and photoconductivity in particular—and found a paper describing a method for facsimile transmission in which gas ions were deposited onto a drum made of electrostatic materials to create an electronic image of the original document. The document could be made visible by dusting a fine powder onto the drum,

Carlson developed a similar process for copying paper documents. He used high-voltage ions to precharge an insulating material that would become conductive when exposed to light (a photoconductor). He then projected the image of a document onto the photoconductor to create a photostatic image and covered it with a fine powder to make it visible. The image could then be transferred to a sheet of paper. Carlson patented his invention in 1937. Though photoconductive materials had been discovered as early as 1873, their application to document reproduction had not previously been considered, Carlson's invention of xerography, in turn, stimulated considerable research into photoconductive materials and the theory of their operation, as Carlson, and later other researchers, attempted to Improve on the basic invention.

SOURCE: Battelle Columbus Laboratories, *Interactions of Science and Technology in the Innovative Process: Some Case Studies,* final report prepared under contract for the National Science Foundation, Mar 19, 1973, chapter 7, Joseph Mort, "Xerography A Study in Innovation and Economic Competitiveness," *Physics Today,* April 1994, pp. 32-38.

projects.[13] Through this process, the need 'or a specific technology or set of technologies is expressed and R&D efforts can be targeted toward developing them.

In the market-driven paradigm, innovative activity takes the form of a search for the best technology or product to meet the anticipated or expressed need. Often, the technology already exists and only needs to be acquired (if not currently existing within the organization) and modified for anew application. At other times, additional R&D is necessary to develop the technology, but the type of research performed will be much more applied than in the early stages of a science-driven innovation, searching for a technology that performs a specific function within a well-defined set of parameters (see box 2-4). In attempting to develop a VCR for home use, for example, Sony

[13] Fumio Kodama, *Emerging Patterns of Innovation: Sources of Japan's Technological Edge* (Boston, MA: Harvard Business School Press, 1 995), p. 8.

realized that it would need to find a way of recording video information onto a narrower tape than the one used by the broadcast industry, and it adopted the helical scan technology developed by a researcher at Toshiba several decades earlier. Sony also recognized that the electronic circuitry used to correct fluctuations in color in industrial VCRs was too bulky for a home device, and developed a way to eliminate the problem by reducing the carrier frequency used in the device.

Like science-based innovations, demand articulation can be a slow process as developers address the many technical problems confronting them. The VCR took 20 years to develop from an expensive, closet-sized device into a consumer product; xerography took nearly four decades. In addition, demand articulation requires that firms maintain a broad base of technological competence so they can absorb and adapt technologies from related industries. The success of Apple in commercializing the personal computer, for example, was aided in large part by its ability to identify competent producers of the key components of its device: microprocessors, displays, and storage devices. Demand articulation also thrives on brisk competition between companies that must maintain a tight focus on consumer demand and may be more willing to experiment with alternative solutions.[14]

Incremental Innovation

While science-enabled and market-driven innovation generate radically new inventions that transform markets, most innovation takes the form of incremental changes to existing products and processes. Incremental innovation improves both product features and manufacturing processes, and is an important part of a company's competitive standing. Once a new concept has been proven in the marketplace, competition quickly shifts to quality, price, and performance, with less competitive emphasis on fundamental changes in product or service characteristics.[15]

Incremental innovation differs fundamentally from both science-driven and demand-articulated innovation, in which new, fundamental knowledge is used to create new types of products. Incremental advances occur cyclically and, despite proceeding in an evolutionary fashion, can produce sizable cumulative effects. Incremental innovation has yielded continuous improvements in computer memory, the speed of microprocessors, and the thrust-to-weight ratio of jet engines. Greater increases in performance often are derived from continual improvements in existing product technologies, rather than from the introduction of radical new technologies.[16]

Incremental innovation places different requirements on science and technology than does the science-driven model of innovation. With incremental innovation, new ideas can be incorporated into the product only during a limited window of opportunity at the beginning of the product development cycle, before the design has been firmly established. New ideas introduced at a later date will often require redesign of the product and delay market introduction. In addition, new ideas need to be reasonably well developed, understood, and tested to avoid unforeseen problems that could delay the delivery schedule. To be successful, incremental innovation requires small, evolutionary advances instead of larger, more revolutionary ones, so that product performance and manufacturing techniques can be well understood. New technology-based products and the processes used to manufacture them are rapidly becoming so complex that producers do not completely understand them. Manufacturers of integrated circuits, for example, cannot completely characterize the processes used to inject or diffuse

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[14] Ibid., p. 151.

[15] Ralph E. Gomory and Roland W. Schmitt, "Step-by-Step Innovation," *Across the Board*, November 1988, pp. 52-56.

[16] Ibid., p. 53.

TABLE 2-4: Ratio of Innovation Times for U.S. and Japanese Firms, 1985[a]

Industry	Japanese Estimates	U.S. Estimates
Chemicals	096	104
Rubber	1,10	1,16
Machinery	1,23	1 17
Metals	118	0.99
Electrical	1.42	103
Instruments	138	1.00
All industries	1.18	106

[a]Based on data provided by 50 Japanese and 75 American firms U.S. firms' cycle time divided by Japanese firms' cycle time

SOURCE Edwin Mansfield. "The Speed and Cost of Industrial Innovation in Japan and the United States External vs. Internal Technology, " *Management Science,* October 1988, p 1158 '

ions or chemical dopant into a semiconductor wafer.

Time to market is critical in incremental innovation, so firms must attempt to reduce development times. Companies with shorter product development cycles can bring new technology quickly to market and benefit from more frequent feedback from consumers. During the mid 1980s, U.S. firms lagged their Japanese competitors in cycle times in a number of industries (see table 2-4), hurting their competitiveness. Fast cycle time requires close ties between development and manufacturing so products can be designed for easy manufacturing and technical problems can be identified early in the process. As a result, successful incremental innovation requires that firms become efficient at all the functions of innovation: research, design, development, manufacturing, and marketing. Having access to complementary assets, such as distribution or service networks, is often a critical element in competitive success. 17

The relative decline in U.S. industrial competitiveness during the 1980s has often been attributed to the nation's inability to master incremental innovation. As foreign nations have improved their technological capabilities, relative to the United States, they have improved their ability to rapidly adapt U.S. technologies and improve on them.[18] U.S. companies responded by devoting more of their resources to the development of new products, processes, and services, rather than improving on existing ones (see table 2-5). U.S. firms have increased their efforts in the area of product/process improvement in the last decade, and improved their competitive performance as a result.

TABLE 2-5: Composition of R&D Expenditures in the United States and Japan (by percent of total industrial R&D expenditures)

R&D expenditures devoted to	United States	Japan
Basic research	8%	10%
Applied research	23	27
Products (versus processes)	68	36
Entirely new products and processes	47	32
Projects with less than O 5 estimated chance of success	28	26
Projects expected to last more than 5 years	38	38

NOTE: Columns do not add to 100 percent because the categories are not mutually exclusive

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

[17] Alic et al., op. cit., footnote 4, p. 20.

[18] Raymond Vernon, "International Investment and International Trade in the Product Cycle," *Quarterly Journal of Economics,* May *1966, pp. 190-207.*

TABLE 2-6: Characteristics of Innovation in Different Phases of Industrial Development

	Stage of Development		
Characteristics	**Introductory**	**Growth**	**Mature**
Predominant type of Innovation	Frequent major changes in products.	Major process changes required by rising volume	Incremental for product and process, with cumulative improvement in productivity and quality
Competitive emphasis	Functional product performance.	Product variation	Cost reduction
Stimulus for innovation	Information on users' needs and users' technical inputs.	Opportunities created by expanding internal technical capability	Pressure to reduce cost and improve quality
Product line	Diverse, often including custom designs	Includes at least one product design stable enough to have significant production volume,	Mostly undifferentiated, standard parts.
Production processes	Flexible and inefficient; major changes easily accommodated	Becoming more rigid, with changes occurring in major steps.	Efficient, capital-Intenswe, and rigid, cost of change is high.
Equipment	General-purpose, requiring highly skilled labor	Some subprocesses automated, creating "islands of automation. "	Special-purpose, mostly automatic with labor tasks mainly monitoring and controlling
Materials	Inputs limited to generally available materials	Specialized materials may be demanded from some suppliers	Specialized materials will be demanded; if not available, vertical Integration will be extensive
Plant	Small-scale, located near user or source of technology.	General-purpose with specialized sections	Large-scale, highly specific to particular products

SOURCE: William J. Abernathy and James M Utterback, "Patterns of Industrial Innovation, " *Technology Review,* June/July 1978

Innovation Cycles

Radical science-enabled and market-driven innovation and incremental innovation represent different stages in the life cycle of a particular industry or product line. Most innovation tends to proceed in characteristic cycles with long periods of incremental innovation punctuated with moments of radical change. New products, processes, and industries emerge from radical innovation, then improve, diversify, and specialize until they are displaced by another radical innovation. These distinctions correspond to three distinct phases in the product life cycle: an introductory or emergent phase, a growth phase, and a period of maturity (see table 2-6).[19]

The introductory phase is characterized by considerable experimentation with fundamentally different designs for a particular product or proc - ess. In the early days of the automobile, for exampie, manufacturers experimented with cars powered by gasoline, electric, and steam engines. Today, manufacturers of electronic displays are

[19] See, for example, G. Dosi, "Technological Paradigms and Technological Trajectories, "*Research Policy,* vol. 11, *1982,* **pp.** 147- 162; M. Utterback and W. Abernathy, "A Dynamic Model of Process and Product Innovation," *Omega, vol.* 3, No. 6, 1975, pp. 639-656; W. Abernathy and K. Clark, "Innovation: Mapping the Winds of Creative Destruction," *Research Policy, vol. 14, No.* 1, February 1985. pp. *3-22:* T. Durand, "Dual Technological Trees: Assessing the Intensity and Strategic Significance of Technological Change," *Research Policy, vol. 21, No. 4,* August 1992, pp. 361-380.

working with liquid crystals, plasma cells, electroluminescent, and field emission devices. During this stage of development, competition is based largely on product characteristics rather than price, as firms attempt to provide superior functionality. New firms enter the market with new designs and functions; startup firms often play a dominant role. Production methods remain flexible to compensate for changes in design, and investment in production equipment and facilities is modest.

During the growth phase, markets expand rapidly as industry settles on a set of offerings that is more or less standard, and product variation decreases. Competition begins to shift from product differentiation to cost reduction, and profit margins often decline. Innovation shifts toward cyclical improvement of existing products through the incorporation of new features and components, and toward process improvements to drive manufacturing costs down. Production processes become more stable, stimulating development of improved manufacturing equipment and capital investments. Product stability can encourage the innovating firm or others to develop complementary assets needed to further expand markets.

As the product matures, product and process innovations slow, and further improvements in performance or costs become evasive. Additional expenditures on R&D are unlikely to yield significant improvements in performance or cost. Firms must decide whether to proceed with existing product lines or develop new ones. Because of the large investments in production capability and complementary assets, mature products and processes can often resist challenges from alternative technologies—even those that offer significant technical, financial, or societal advantages. The nation's existing investment in volume production plants, refueling infrastructure, and repair facilities, for example, make it difficult for alternative-fuel vehicles to challenge gasoline-powered automobiles. Yet, continued improvement of alternative technologies often results in development of new products and processes that replace mature ones.

A critical element in the transition from an emergent industry to a growth industry is the determination of a dominant design. This design—or set of designs—is the one that emerges as most promising in the marketplace. It does not necessarily outperform all others on any particular functional attribute, but overall it meets the desires of the market. Examples of such dominant designs include: the IBM PC, which set the standard for most personal computers over the past decade, but incorporated no leading-edge technologies; and the DC-3, which became the standard for commercial aircraft, but lagged behind several competing designs in terms of range and payload.

Designs that prove successful early in the development cycle can gain momentum quickly and become established dominant designs. Once a successful design is demonstrated, others will likely copy it rather than risk a new approach. Economies of scale in production and learning-curve effects also tend to instantiate a dominant design by making it more cost competitive. Development of complementary assets can further tip the scales by making the design more compatible with existing infrastructure. An example is sequential software for single-processor computers, which makes the transition to multiple-processor machines less attractive to users. Similarly, in the home VCR market, the greater availability of VHS-format prerecorded tapes in the early 1980s accelerated the triumph of VHS players over the alternative Beta format machines.

COMMERCIALIZATION

Commercialization is an attempt to profit from innovation by incorporating new technologies into products, processes, and services and selling them in the marketplace. For many new technologies, commercialization implies scaling up from prototype to volume manufacturing and committing greater resources to marketing and sales activities. In industries such as pharmaceuticals and aircraft, commercialization is also contingent on receiving product approval from relevant organizations. Typically, the cost of commercialization activities

TABLE 2-7: Distribution of Costs for Developing and Introducing New Products[a] (Percentage of Total Project Cost)

Phase of Development	United States	Japan
Applied research	18%	4%
Preparation of product specifications	8	7
Prototype or pilot plant	17	16
Tooling and equipment	23	44
Manufacturing startup	17	10
Marketing startup	17	8

[a]Survey figures for new products introduced in 1985 by 100 U S and Japanese firms in the chemicals, machinery, electrical and electronics, and rubber and metals industries.

NOTE: Totals may not add up to 100 percent because of rounding

SOURCE: Edwin Mansfield, "Industrial Innovation in Japan and the United States, " Science, Sept. 30, 1988, p 1770

far exceeds that of R&D (see table 2-7). R&D and product design comprise approximately one-quarter of the cost to introduce a new product to market.[20] Invention—defined as the conception of a new product, including some basic and applied research—represents only 5 to 10 percent of the total effort.[21] Thus, scale-up activities act as a filter for selecting inventions to commercialize. Many innovations are developed to the prototype stage or are produced in small volumes, but are not fully commercialized because the financial and managerial resources required are too great. Such innovations are often licensed to another firm, sold off in the form of a divestiture, or simply passed over.

Decisions to commercialize new technology are made by individual firms, but are closely linked to characteristics of the innovation system in which the firm operates. Manufacturers must assess the likelihood of securing funding from internal and external sources, their ability to develop or gain access to manufacturing equipment and supplies, and the size of potential markets. Without the proper infrastructure to support their efforts, firms cannot be assured of winning returns from their investment, and competitors with abetter support infrastructure may be able to capture the market. Pioneers in a new market often lose out to imitators with better financing, infrastructure, and strategy. Examples include EMI, Ltd. 's loss of the market for computer axial tomography (CAT) scanners to General Electric Co.; MITS's loss of the personal computer market to Apple and IBM; and U.S. firms' loss of much of the flat panel display industry to Japanese firms such as Sharp and Toshiba.

Many factors enter into a firm's decision to commercialize an innovation. Companies must try to assess the profitability of a new venture, taking into account its ability to protect intellectual property, the degree of existing or anticipated competition, the size and profitability of possible markets, and the cost of manufacturing and marketing activities. They must also assess their ability to harness necessary complementary assets—such as other technologies needed to make their innovation more useful, or capabilities in manufacturing, marketing, and distribution need-

[20]This figure has remained remarkably constant over the past few decades, despite the apparent changes in industry structure, globalization, and product mix. One report released in 1967 and relying on 10-year-old data found that product conception and design accounted for 15 to 30 percent of the cost of new product introduction; manufacturing preparation, manufacturing startup, and marketing startup comprised the balance. See U.S. Department of Commerce, *Teckdogica/innovation: Its Environment and Management,* report of the Panel on Invention and Innovation (Washington, DC: U.S. Government Printing Office, January 1967), p. 8.

[21]R&D is actually a greater percentage of total innovative activity than these figures indicate because many projects never make it out of R&D and because there is a certain amount of background research that is carried out without any specific project in mind. Furthermore, all of the activities listed in table 2-7 involve some technical work that is not classified as formal R&D.

ed for business success—and the degree to which the technology fits in with the company's general business plans.

Potential Markets

The overall profitability of an innovation is largely determined by the size and nature of potential markets. Market segments differ considerably along both these dimensions. At the one extreme lie large markets for undifferentiated commodity goods that maintain small profit margins. Many product lines in high-technology industries match this description: computer memory chips, consumer electronics, and low-end telecommunications equipment such as telephones and answering machines—even low-end personal computers. In order to generate suitable profits in industries with low profit margins, firms must attempt to sell large volumes of goods. Competition in these markets is therefore driven by steep learning curves (in which the cost of production drops precipitously as workers gain experience with the manufacturing process) and economies of scale that tend to concentrate market power in the hands of a limited number of firms.

At the other extreme are markets in which product differentiation and customization are the most important aspect of the product. These markets are typically small, and competition is often based on performance rather than price. Hence, they can be lucrative areas for innovative firms that have well-developed design skills. Customers in such markets are often discriminating purchasers. Examples include government programs in military or space applications, and industrial, medical, or other customers that demand high performance and are less cost sensitive than customers in consumer product markets. While these market segments are often smaller than high volume markets in consumer or commodity products, the profit margins can be higher. In semiconductor devices, market segments such as application-specific integrated circuits and static random access memories allow for product diversification at lower volumes. These areas can have lower entry barriers to manufacturing than high volume, standardized devices.

Between these two extremes lies a wide variety of markets that offer different combinations of size and profitability. The market for microprocessors for personal computers, for example, is large and boasts high profit margins—but only for leading-edge processors. Older generation processors have smaller markets and lower profit margins. In pharmaceuticals, too, new drugs can both offer high profit margins and serve large markets. The primary driver of the high profit margins in both leading-edge microprocessors and pharmaceuticals is the ability of firms to control and protect their intellectual property.

Firms must assess potential markets in relation to their proprietary advantages and capabilities. Firms tend to succeed in markets that best match their strengths, whether in developing leading-edge technology, providing high quality at low cost, or meeting rapid product development cycles. Small startup firms typically lack the marketing and manufacturing capabilities to compete in large, commodity markets, but perform admirably in many smaller niche markets. They also play an important role in commercializing emerging technologies that compete against entrenched technologies produced by existing competitors. Larger firms often lack the flexibility and desire to pursue smaller niche markets, but can dominate large markets. They also have more resources to expend on R&D to develop immature technologies.

Competition from Other Technologies

Competition from existing or alternative new technologies can shrink markets for a given innovation. Emerging technologies in their nascent stages rarely offer sufficient advantages over existing technologies in all aspects of performance, including compatibility with existing ways of doing things. As a result, their emergence often stimulates improvements in the existing technology, touching off a period of intense competition before a winner emerges. Such competition is seen

BOX 2-5: Competition Between New and Existing Technology in Lith

Advances in the capabilities of integrated circuits (ICs), such as those used in personal computers, are determined in large part by reductions in the size of the electronic components that can be patterned onto a silicon wafer. By reducing the size or minimum linewidth of these devices, circuit designers can fit more components onto a given IC, thereby increasing the capacity of a memory chip or adding additional power to a microprocessor.

The size of the smallest feature that can be created on an IC is determined by the resolution of the lithography system used to project patterns onto the substrate. Traditionally, IC manufacturers have produced devices by using lithography systems based on optical and ultraviolet wavelengths of light. Such systems shine light through glass masks containing an image of the desired circuit and pass the light through a series of optical lenses that reduce the size of the pattern on the mask by a factor of five and focus it onto a silicon wafer. The resolution of such systems is limited by the wavelength of light used, with shorter wavelengths yielding smaller resolution. Since 1970, advances in light sources, optics, and machine design have reduced the minimum resolution of optical lithography systems from about 70 microns to around 0,35 microns (a micron is one thousandth of a millimeter, or approximately one fiftieth the width of a human hair).

Semiconductor manufacturers and their equipment suppliers have long been predicting that optical lithography will soon reach its theoretical limit of resolution. As the wavelength of light is reduced, building suitable light sources becomes more difficult, and the optics become less effective at creating a tight focus. Hence, developers have investigated numerous alternates to optical lithography systems, incorporating x-rays, electron beams, and ion beams into their designs. Each of these techniques offers Improved theoretical resolution over optical systems; yet each possesses significant drawbacks as well in order to generate x-rays of the intensity needed for lithography, the system needs a large synchrotrons costing approximately $35 million, masks for such systems cannot be made of glass; and the pattern on the mask must be made as small as the desired feature size because optical lenses cannot be used to reduce the size of the pattern. Laser-generated x-rays have also been explored as an

(continued)

in many areas of emerging technology examined by OTA: 1) in high-performance computing, massively parallel computers compete against traditional supercomputers; 2) in computer displays, flat panel technologies—whether liquid crystal, plasma, electroluminescent, or field emission—compete against an existing base of cathode ray tubes (CRTs); and 3) in lithography—a critical step in the manufacture of integrated circuits—x-ray, ion beam, and electron beam technologies compete against entrenched optical steppers (see box 2-5). Continued improvement of the existing technology often slows adoption of the new technology until one or other exhibits a distinct advantage.

New technologies often have difficulty dislodging an entrenched technology because of resistance from potential users of the new product. Customers must be convinced that the new technology offers superior performance in their particular application and is reliable-characteristics a new technology cannot always achieve at first. IBM, for example, opted against using integrated circuits in its System 360 series computer. The company chose hybrid transistors instead because it was not sure the new technology would

BOX 2-5: Competition Between New and Existing Technology in Lithography (Cont'd.)

alternative to expensive synchrotrons, but such systems require a series of mirrors to focus the radiation onto the wafer. The mirrors must be polished smooth to a tolerance well beyond current Industrial practices.

Ion beam and electron beam systems overcome most of these problems; in their simplest configurations, they use narrow beams of particles to produce images rather than a broad beam of light. In this form, they cannot be used with masks and, instead, must physically draw each circuit element onto the IC—a procedure far too slow for industrial processes. Considerable work is under way to develop ion and electron beam techniques that employ either multiple beams or a broad beam of particles, but such projects are still in their infancy.

None of these alternatives has yet found use in Industrial practice, despite the fact that some systems—those based on x-rays—have been under development for 20 years. While part of the reason IS the immature state of alternate technologies, the principal reason IS that designers have continued to Improve the installed base of optical steppers. Advances in light sources and adoption of techniques, such as phase shift masks and off-axis illumination, have enabled continued improvements in the resolution of optical systems. New techniques for scanning the optical beam across the wafer (such as "step and scan") have simultaneously boosted resolution and maintained high operating speeds, or throughput, Whereas practical limitations were once expected to preclude the use of optical lithography below linewidths of 0.5 microns, current estimates indicate that optical lithography will probably remain the technology of choice for another decade, until resolutions drop below 0,1 microns,

Eventually, optical lithography will reach its theoretical, if not practical, limit and alternative technologies will need to be Introduced into semiconductor manufacturing, At that point, semiconductor manufacturers may have to sacrifice cost or throughput in order to achieve better resolution, unless Improvements in alternative technologies can compensate for their current deficiencies, In the meantime, competition between the old and new technology will continue.

SOURCE Off Ice of Technology Assessment, 1995

perform reliably over the computer's lifetime.[22] IBM could not afford to field a general purpose business computer that might have a high rate of failure and require constant servicing. Instead, the first large-scale use of integrated circuitry was in DOD's Minuteman missile system and NASA's Apollo program, both of which placed a high premium on small size and low power consumption.

Many new technologies are not compatible with existing ways of doing things and require some changes in the ways customers perform certain tasks. Users of integrated circuits had to learn new design rules for creating electronic devices: users of electric vehicles have to learn to plan their trips to compensate for the shorter range of their cars. Such considerations can slow diffusion of new technologies to a crawl, and typically require that developers target their marketing efforts toward users who highly value a critical dimension of the new technology (such as small size in the case of integrated circuits) or can easily tolerate its disadvantages. Local delivery services (such as the postal service), for example, might be able to tolerate the short driving range of an electric ve-

[22] Charles H. Ferguson and Charles R. Morris, *Computer Wars: How the West Can Win in a Post-IBM World* (New York, NY: Times Books, 1993), pp. 8-9; and Arthur J. Alexander, *The Problem of Declining Defense R&D Expenditures,* JEI-14A (Washington, DC: Japan Economic Institute. Apr. 16, 1993), p. 11.

hicle and be able to recharge the batteries overnight at a central facility. As users and developers gain experience with the new technology and performance increases, markets can begin to expand.

Similarly, manufacturers of the existing technology often have a strong disincentive to invest in new technologies. By their very nature, new technologies tend to destroy the competencies that firms have developed in certain technical areas; they often require capabilities and skills different from those used in manufacturing the entrenched technology. For example, manufacturing computer displays using traditional cathode ray tube (CRT) technology is highly dependent on skills in forming picture tubes out of glass, aligning shadow masks, depositing phosphors on glass, and controlling the scanning of an electron gun using magnetic fields. In contrast, the manufacture of flat panel displays requires expertise in depositing thin film transistors on a glass substrate and minimizing contamination across an area the size of the display. Because flat panel displays require knowledge of new technologies and new manufacturing skills, manufacturers of CRTs have not, by and large, shifted into production of flat panels. They have responded to the challenge instead by improving their existing technology. Zenith has developed its flat tension mask technology, which eliminates the curvature of the CRT screen, making it more readable, and several companies have introduced CRTs that are not as deep as conventional models. For the most part, flat panel technology has been developed by entrants new to the field of displays.

Cost

The profitability of innovation depends on the costs of commercialization. In some industries or technologies, the sheer size of the investment required is the largest single hurdle to commercialization. This is particularly true in segments of the electronics industry, such as semiconductors, in which efficient-sized plants frequently cost over $1 billion to build and equip. Smaller plants cannot compete in the volume segments of such markets because they cannot spread their fixed costs over a large enough production run. Only in niche markets, with less competition and consideration of costs, can small plants compete successfully in these industries. In other industries, however, capital costs do not present as great a barrier to commercialization. Efficient consumer electronics or chemical plants can often be set up for $100 million, or can be expanded slowly over time to meet growing demand.

Uncertainties regarding cost also enter the decisionmaking process. Especially in new industries that are expected to demonstrate strong learning-curve effects, decisionmakers often cannot determine how quickly production costs will drop to a desired level. For first movers, rapid cost reduction is important to building barriers to entry and to expanding markets. For imitators trying to catch up with a market leader, uncertainties over cost make it difficult to determine the period of time required to become a competitive player in a market. U.S. manufacturers of flat panel displays, for example, are currently stymied by this second type of uncertainty. They cannot predict how long it will take them to match the manufacturing costs Japanese firms are currently achieving. As a result, they are experiencing difficulty securing financing for scaling up their manufacturing efforts.

Ability To Capture Market Share

Innovating firms must assess the degree to which competitors may capture, or *appropriate*, some of the returns from their innovation. Often, the company that is first to introduce a new product loses the market to followers who either improve on the original innovation in a timely manner or market the innovation better. Only rarely is a company the lone pioneer in a new technical area or does it possess truly unique capabilities that would preclude competition. In emerging areas of technology, such as high-temperature superconductivity (HTS) and scalable parallel computing, competition abounds and the industry is fluid. Over 20 American companies, large and small, have active research programs in HTS;[23] a similar number compete in the market for scalable parallel computers. Research suggests that firms that run in packs, rather than going it alone, are more successful in the long run because competitors can collectively contribute the research base and develop markets.[24]

In addition to direct competitors, suppliers of critical components or capabilities may also be able to extract profits from an innovation. In the market for personal computers, for example, Intel Corp., the supplier of microprocessors to most IBM-compatible machines, has benefited more than the innovator, IBM, or most other manufacturers of compatible machines. Microsoft Corp., too, by providing the operating system for IBM-compatible computers, has reaped benefits far in excess of many computer manufacturers.

Innovators have several mechanisms for protecting their innovations from competitors. They can use patents and software copyrights to legally bar other firms from copying their invention without an explicit license; they can keep their innovation secret from potential imitators; or they can take advantage of other barriers to market entry. The choice of method is, in many ways, determined by the nature of the technology itself.

Patents arguably offer the strongest form of protection, but are highly effective for only a limited number of product types, in a limited number of industries. Patents allow innovators the rights to their inventions for 20 years after the patent application is filed, allowing them a period of exclusivity during which they can attempt to earn monopolistic returns on their innovation. Patenting requires innovators to publicly disclose the details of their innovation; in some fields, competitors can then invent around the patent by devising a somewhat different way to provide the same functionality. Surveys have found that patents generally raise imitation costs 30 to 40 percent for drugs and 20 to 25 percent for chemicals, but only 7 to 15 percent in electronics (including semiconductors, computers, and communications equipment).[25] In chemicals, for instance, competitors cannot easily find an alternative compound with characteristics similar or identical to the patented substance, making imitation difficult. But in electronics and other areas, it is easier to invent around patents. The elements of a product's design and manufacture can be gleaned through careful analysis, and similar products can be manufactured that perform almost identically. This capability makes it more difficult for innovators to capture or *appropriate* the returns from a new innovation because they cannot maintain their monopoly positions for long.

In cases in which patent protection is not effective, innovators may instead opt to keep the workings of their inventions secret, to the extent possible. The law provides only partial protection for trade secrets. Firms can attempt to restrain former employees from competing with them by using knowledge gained during their employment. Similarly, they can sue firms that illegally gain access to trade secrets. But the law normally permits competitors to analyze products, figure out how they work, and find ways to produce similar products. AMD Corp., for example, has been highly successful in reverse-engineering microprocessors manufactured by Intel Corp. and selling a nearly identical product. As a result, trade secret protection is most useful for innovations whose workings can be hidden from the eyes of skilled analysts. Process innovations can often be kept secret because they can be hidden behind factory

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[23] Forbes, op. cit., footnote 12, pp. 70-104.

[24] Andrew Van de Ven, "A Community Perspective on the Emergence of Innovation," *Journal of Engineering and Technology Management*, vol. 10, 1993, pp. 41-42.

[25] Richard Levin et al., "Appropriating the Returns from Industrial Research and Development," *Brookings Papers on Economic Activity,* No. 3, 1987, pp. 783-831; Edwin Mansfield et al., "Imitation Costs and Patents: An Empirical Study," *Economic Journal*, vol. 91, December 1981, pp. 907-918.

TABLE 2-8: Effectiveness of Different Means of Protecting New Product and Process Innovations

Means of Protection	Overall Mean Process	Overall Mean Product	Range of Industry Means[a] Process	Range of Industry Means[a] Product
Patents to prevent duplication	3.52	4,33	2,6- 4,0	3 0 - 5 0
Patents to secure royalty income	3.31	3.75	2.3 -4.0	2 7 - 4 8
Secrecy	4,31	3.57	3.3- 5.0	2 7 - 4 1
Lead time	5.11	5.41	4,3 -5.9	4 . 8 - 6 0
Learning curves	5.02	5.09	4,5 -5,7	4 4 - 5 8
Sales or service	4,55	5.59	3.7 -5.5	5 0 - 6 1

[a]Measured from the 20th to 80th percentiles of 130 separate Industry means

NOTE: Rankings based on a survey of 650 Industry executives in 130 lines of business using a 7-point scale with 1 as least effective and 7 as most effective.

SOURCE: Richard Levin et al., "Appropriating the Returns from Industrial Research and Development, "*Brookings Papers on Econornic Activity,* vol. 3, 1987, p 794.

walls, but even they can eventually leak out. Secrets involving products are harder to maintain.

Many firms must, therefore, rely on other barriers to entry to protect their innovations. In industries characterized by significant economies of scale or steep learning curves, innovators can often gain protection by being first to market and rapidly expanding production. Although this strategy may often require large up-front investments in plant and equipment, it can enable companies to rapidly reduce their production costs by spreading the capital investment over a larger number of products and by allowing them to rapidly gain experience with the manufacturing process. Such experience frequently translates into lower manufacturing costs over time, as workers and managers begin to understand the subtle interactions between components of a system or the effects of changes in manufacturing conditions on product performance. Experiential knowledge of this sort, often referred to as tacit knowledge, is not easily codified and conveyed; therefore, it cannot easily be acquired by a competitor who does not make a similar investment in production.

Firms can also erect barriers to entry through superior strategies for product development, sales, or service. Rapid product development, for example, can allow an innovator to put new, improved products on the market more quickly than its competitors, thereby incorporating newer technology and responding to more recent changes in market demand. Such a strategy was particularly helpful in enabling Japanese auto and consumer electronics manufacturers to enter the U.S. market. Alternatively, innovators can attempt to dominate marketing channels or bundle new products with goods in high demand to increase their rate of penetration into the marketplace. Software companies, such as Microsoft Corp., have been particularly successful in bundling together new products and linking them closely to specific changes in hardware to increase their hold on particular market segments.[26]

In general, neither patents nor trade secrets are as effective as lead time, learning curves, or attention to sales and service in protecting innovations (see table 2-8). Hence, appropriability by the innovator is difficult to ensure through formal means in most industries. Industries that rate patenting most highly include portions of the chemicals industry (inorganic, organics, drugs, and plastics) and petroleum refining; but only the pharmaceuticals industry considers patents more effective than other means of protecting new products and processes. Industries such as food products and metal-working rate no mechanisms

[26] Some bundling strategies run afoul of antitrust considerations. Some of Microsoft's strategies have been investigated by the Justice Department for possible antitrust violations.

highly effective (greater than five on a seven-point scale) for protecting product innovations, and about one-third of the 130 industries represented in the sample—including food products, metal-working, fabricated metals, and machinery—rated no mechanisms highly effective for protecting process innovations. The remaining industries, including electronics, motor vehicles, aircraft, and instruments, rated nonpatent mechanisms as most effective.[27]

Complementary Assets

The ability to capture market share and profit from innovation is also dependent on the ability of firms to develop or acquire complementary assets—other technologies needed to make the innovation useful, and the capabilities necessary to manufacture and market the innovation. An innovation cannot be successfully commercialized without adequate manufacturing capacity and skill, suitable marketing and distribution channels, and after-sales support. Nor can innovations succeed without other technologies that interact with the new innovation. Users of new computer hardware often need specialized operating systems and applications software. Drivers of electric vehicles need a network of convenient recharging stations.

The lack of such complementary assets can retard the diffusion of new technologies—especially the more radical ones. Radical technologies almost always require new infrastructure, new suppliers, and often new distribution channels. During the early stages of an innovation, firms will often integrate these capabilities into their own corporate structure because they often do not exist elsewhere in the economy. As the industry grows, specialized firms tend to develop to fill these roles and companies will purchase goods from specialized suppliers.

Firms that are better able to harness these capabilities and orchestrate the contributions of the various actors responsible for creating the industry infrastructure have the best chance of succeeding in commercialization (see box 2-6).[28] Japan's success in the global marketplace has often been attributed to its ability to harness or develop complementary assets, such as manufacturing capability, that allowed it to develop 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 served only to perpetuate this advantage, as U.S. firms continued to pour greater resources into product innovation.[29]

The need for complementary assets often puts small U.S. firms at a disadvantage in competing with large, vertically integrated firms, whether in Japan or the United States, that have access to complementary assets in-house. 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 also can take longer to complete than if conducted in-house, thereby slowing the commercialization process in the United States.

[27] Levin et al., op. cit., footnote 25, pp. 795-798.

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

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

BOX 2-6: Commercialization of Videocassette Recorders

Early competition in the videocassette recorder(VCR) industry demonstrates the importance of design, manufacturing, marketing, and experience in the successful development and commercialization of new technologies, Ampex Corp., located in Redwood City, California, gave the first public demonstration of a video tape recorder (VTR) in 1956. Ampex sold its machines to television broadcasters for $50,000. Ampex had a patent for its "transverse scanner, " in which four recording heads on a rapidly rotating drum scanned across a two-inch-wide tape. Ampex licensed RCA in exchange for licenses under RCA's color television patents, in order to be able to produce color VTRs. Ampex also entered a joint venture with Toshiba to produce VTRs. Ampex remained dominant, but all three firms made money selling VTRs for commercial use. However, none of these firms pursued a long-term strategy to create a smaller, much cheaper product for home use, with easy-to-use cassettes—a videocassette recorder, or VCR.

Sony, Matsushita, and the Victor Co. of Japan (JVC, 50 percent owned by Matsushita) all pursued such a strategy, and gained a substantial share of the household market in the late 1970s and early 1980s. Many factors contributed to this success, In 1958, Japan's National Broadcasting Corp. (NHK) imported an Ampex VTR and invited Japanese firms to examine it. The three firms built on prior technical achievements, such as magnetic audio recording television receivers and semiconductors, Perhaps most Importantly, the firms consistently followed the vision of a VCR, guided by stable management with sound technical knowledge, They built several generations of machines that did not succeed as consumer products, and learned by this what was needed, All three firms developed a two-headed helical scanner, which they believed necessary to build a household product; that scanner also got around Ampex's patent,

Two leading machines emerged the Beta format, designed by Sony, first sold in 1975, and JVC's VHS format, first sold in 1976. Though second to market, the VHS format overtook Beta in 1978 and pulled farther ahead each year until the end of the 1980s, when the Beta format machines were no longer produced. JVC achieved this reversal by superior strategy in winning other firms over to its format. Sony committed to its format and then asked other companies to adopt it; JVC courted other firms before finalizing its format, and showed a willingness to listen to their ideas. Matsushita, in particular, provided valuable technical feedback. Sony was not willing to manufacture VCRs for other firms; JVC was. JVC provided considerable assistance in manufacturing and marketing. JVC pursued the European market much more aggressively,

(continued)

Fit with Corporate Goals

Firms must also decide whether a new technology fits in with their broader corporate goals. While it may seem that any innovation developed by a corporation would, by definition, be connected to the markets and technologies that the company wants to pursue, this is not always the case. Often researchers will—by following their own interests or instincts, or through pure serendipity-develop a new product or process at the level of a prototype. Once the researcher has an understanding of the innovation, he or she can then try to convince corporate management of its potential, and present a case for manufacturing. At this point, the company must decide if the innovation fits in with its corporate goals.

Companies often define their business and technology goals along three dimensions (though most strategies are a combination of all three): technology focus, product focus, and market focus.[30] New products must fit in with this strategy or vision. A technology-focused company uses

[30] Lewis M. Branscomb and Fumio Kodama, *Japanese Innovation Strategy: Technical Support for Business Visions,* Harvard University, Center for Science and International Affairs, Occasional Paper No. 10 (Lanham, MD: University Press of America, Inc., 1993), chapter 3.

BOX 2-6: Commercialization of Videocassette Recorders (Cont'd.)

and worked with its Japanese partners to define technical standards for a VCR suited to Europe's color television standard. JVC was also helped a great deal by Matsushita, which supplied the market with VHS machines faster than Sony could supply it with Beta machines. Matsushita also approached RCA to be a VCR supplier and worked quickly to satisfy (in October 1977) RCA's request for a machine that "could record a football game" (at least 3 hours). U.S. distributors believed that the format that RCA supported would probably become dominant in the U.S. market; that belief, plus the longer playing time that Matsushita offered, led U.S. distributors to favor VHS.

The VCR Installed base increased dramatically in the first half of the 1980s, triggering a dramatic increase in production, sale, and rental of prerecorded tapes. The VCR and prerecorded tape markets took off in Europe before the United States, apparently because Europe's relative scarcity of broadcast channels made watching prerecorded tapes on VCRs more attractive. European producers and distributors of prerecorded tape tended to favor VHS over Beta because VHS already had a much larger installed base of machines there, In the U.S. market, VHS did not overtake Beta decisively until the mid-1980s. However, RCA set out early on to make VHS dominate the prerecorded tape market. Starting in 1978, RCA encouraged Magnetic Video Corp. of America (MV) to produce prerecorded VHS tapes by developing equipment for high-speed fast duplication and providing cheap blank tapes, Sony similarly tried to induce Video Corp. of America to produce prerecorded Beta tapes, but was less successful. By 1980, according to one estimate, VHS made up 70 to 90 percent of U.S. cassette dealers' revenues. In both Europe and the United States, the greater availability of VHS over Beta prerecorded tapes accelerated the decline in the Beta format's percentage of VCRs produced.

SOURCE: R. Rosenbloom and M. Cusumano, "Technological Pioneering and Competitive Advantage: The Birth of the VCR Industry, " *California Management Review,* vol. 29, No 4, summer 1987, pp. 51-76; M. Cusumano, Y. Mylonadis, and R. Rosenbloom, "Strategic Maneuvering and Mass-Market Dynamics The Triumph of VHS over Beta, " *Business History Review,* spring 1992, pp. 51-94.

technology to achieve a competitive edge in the marketplace, and will enter markets that draw from a limited set of core technologies. Many small firms in the high-temperature superconductivity field fit this description, since they plan to serve a variety of markets with an array of products that incorporate HTS technology. They would likely opt against developing products or processes that do not contain HTS. Other firms, such as Chrysler, Ford, and GM, have a product focus. Their goal is to design and sell automobiles, developing or adopting whatever technologies are necessary to the success of this venture. They would likely opt against commercializing innovations that do not contribute to automotive technology. Finally, firms with a market focus attempt to serve a broadly defined set of customers, such as the military. Large firms, such as Northrop/Grumman and Lockheed/Martin, sell a number of products—tanks, aircraft, and missiles—incorporating a wide variety of underlying technologies, to a specific set of customers. At times, they have attempted to diversify into new (i.e., commercial) markets, but such attempts have often met with failure.[31]

Firms sometimes decide against commercializing innovations that could cannibalize existing product lines that have not yet reached maturity. For example, although IBM pioneered the field of reduced instruction set computing (RISC) in the

[31] See U.S. Congress, Office of Technology Assessment, *After the Cold War: Living with Lower Defense Spending,* OTA-ITE-524 (Washington, DC: U.S. Government Printing Office, February 1992), chapter 7.

late 1970s and early 1980s, the company failed to commercialize the technology because it feared it would steal market share from its own line of Series 370 computers.[32] Instead, RISC was commercialized by a startup firm, Sun Microsystems, with no existing sales to cannibalize.

Concluding Remarks

The concepts developed in this chapter help explain the complex dynamics of innovation and commercialization. As shown, successful R&D alone cannot assure commercial success in areas of advanced technology. Firms must also develop or acquire the capabilities to design, manufacture, and market new products, processes, and services. They must develop complementary technologies needed to make their innovation more useful, and find financing to support their efforts. Numerous barriers can impede the progress of even the most capable firms as they try to introduce new inventions to the marketplace, and numerous firms fail in their attempts.

From a national perspective, these lessons are equally valid. While construction of a strong science and technology base is essential to innovation and commercialization, it is not sufficient. Firms must be able to find—within their national innovation systems or abroad—the resources needed to convert new science and technology into a proprietary advantage they can defend in the marketplace. While firms can develop many of the requisite tools themselves, others often lie beyond their control. These needs can often be met through cooperative actions between firms, or between industry and government.

[32] Ferguson and Morris, op. cit., footnote 22, pp. 37-45.

Elements of Innovation Systems 3

Innovation rarely results from the actions of a single individual or firm; rather, it is the result of numerous interactions by a community of actors that is often widely dispersed both geographically and temporally. Scientists discover new facts and develop new theories about the workings of nature; engineers design and develop new technologies and products; financiers—both public and private—fund research, development, and manufacturing; skilled laborers manufacture new products and implement new processes; and public and private institutions educate and train these different types of workers. This community often extends beyond the boundaries of any particular firm or nation. For example, continued development of high-temperature superconductivity, though discovered by IBM researchers in Switzerland, will depend on scientific and technological advances in the United States, Japan, and Europe. It will also depend on the availability of financing—whether public or private—in each of these nations and regions.

Although influenced by the strength of the international community as a whole, the ability of any particular nation to capitalize on new technological developments depends heavily on its system of innovation. Nations vary considerably in the ways innovation occurs within their borders and in the relationships among industry, government, and academia.[1] In Japan and Europe, industry and government are more closely linked than in the United States, and universities play a smaller role in industrial research. Japanese corporations also have a stronger history of collaboration than U.S. firms, due in part to encouragement by their government. Differences in the structure of national innovation systems are partially responsible for differences in competitive performance.

Because of the myriad factors influencing innovation, policymakers interested in facilitating the commercialization of emerging technologies must consider not only the means by which firms develop particular products, processes, or services, but also the need for creating and supporting the necessary institutions and institutional relationships. While many innovations are largely compatible with existing infrastructure, radical innovations often require an entirely new set of relationships and institutions. The required infrastructure consists of nine basic elements that can

[1] For an international comparison of innovation systems, see Richard R. Nelson (ed.), *National Innovation Systems: A Comparative Analysis* (New York, NY: Oxford University Press, 1993).

TABLE 3-1: Generic Components of Industry Infrastructure for Innovation

Institutional arrangements

- Governance (norms, rules, regulations, laws)
- Legitimation (creation of trust)
- Technology standards

Resource endowments

- Scientific/technological research
- Financing and insurance arrangements
- Human resources

Proprietary functions

- Technology/product development
- Networking and development of vendor/distributor channels
- Market creation and consumer demand

SOURCE Andrew H Van de Ven, "A Community Perspective on the Emergence of Innovations, " *Journal of Engineering and Technology Management,* vol. 10, No 1, June 1993, p 26

be grouped into three general categories (see table 3-1).[2] The lack of any one of these elements can cripple attempts to innovate and launch new industries. While creation of these elements is the task primarily of the private sector in the United States, government either directly or indirectly influences aspects of nearly all of them.

This chapter analyzes the nine elements of innovation systems to demonstrate their significance in the innovation process and to highlight the contribution of government to each. As shown through both historical and contemporary examples, industry and government have forged a complex set of relationships in different industries to support the tasks of innovation and commercialization. Government influences both the development of new technology and the creation of markets by funding research and development (R&D); procuring goods and services for public missions; providing regulatory approvals; helping set technical standards; issuing regulations on human health and the environment; sponsoring technology demonstrations; and enforcing tax, antitrust, and patent laws. Government contributes to innovation and commercialization by: being an early or important user; providing information that informs the decisions of the private sector; and supporting private-sector efforts, rather than dictating how they should proceed.

As industries develop, firms determine which parts of the infrastructure they will develop: 1) individually, 2) in collaboration with other firms, and 3) with the support of government. The resulting linkages are often numerous and overlapping, and change over time as the industry evolves.

GOVERNANCE

Government rules, regulations, and laws affect the ability of firms to innovate, and can either facilitate or inhibit the emergence of new industries. Particular aspects of governance affecting innovation include patent policy, antitrust provisions, and regulations in areas such as environmental protection and human health. Patent policy, for example, gives firms an incentive to innovate by granting them exclusive rights to their inventions and by protecting these rights against infringe-

[2] This framework derives from the work of Andrew H. Van de Ven, "A Community Perspective on the Emergence of Innovations," *Journal of Engineering and Technology Management,* vol. 10, 1993, pp. 23-51; and Andrew H. Van de Ven and Raghu Garud, "A Framework for Understanding the Emergence of New Industries,"in *Research on Technological Innovation, Management, and Policy,* vol. 4, Richard S. Rosenbloom (cd.) (Greenwich, CT: JAI Press Inc., 1989), pp. 195-225.

ment. By requiring public disclosure of new inventions, the patent process also encourages dissemination of new technical information. Changes in enforcement of patent law also influence the ability of firms to innovate. Commercialization of microelectronics and biotechnology was aided, in part, by a permissive patenting regime that reduced the threat of litigation against newer firms that adapted innovations originally developed within established firms or research institutions.[3]

Similarly, antitrust law governs the types of activities, such as research or production, that firms may jointly undertake in developing new technologies. U.S. antitrust provisions are generally more stringent than those of the nation's primary industrial competitors. Strict enforcement of antitrust provisions in the postwar era has been cited as one of the factors that led to the creation of large integrated research firms in the United States.[4] Conversely, investigations of alleged antitrust activities by two of the largest electronics corporations, AT&T and IBM, ended in consent decrees (both issued in 1956) that required widespread licensing of inventions in microelectronics and computers, respectively, fostering competition and aiding entry by new firms. Clarifications of antitrust law have also served to encourage innovation. The National Cooperative Research and Development Act of 1984 allows companies to collaborate on R&D—through the prototype stage—without being presumed to violate antitrust laws, and, in some cases, removes the treble damages penalty against firms found in violation of the law. The 1984 act had a liberating effect on consortia, encouraging several hundred to form within the first few years. As amended in 1993, the act now extends such protections to firms collaborating in production as well as R&D.

LEGITIMATION

Legitimation is the attempt to reduce customer uncertainty about new products, processes, and services in order to promote development of new markets. Lack of trust can be a significant barrier to the successful commercialization of innovations that are costly, technologically sophisticated, or potentially harmful to human health and the environment. With emerging technologies, in particular, performance often is difficult to guarantee because the properties of the technology are not fully understood, the underlying science is not yet fully developed, and the functioning has not been fully tested during years of use and modification. Risks and costs are difficult to quantify, and the objectivity of information provided by the producer is suspect.

Both the private and public sectors play a role in legitimizing new technologies. Private organizations such as the Consumers' Union provide independent evaluations of consumer products, engineering consultants help evaluate and approve larger scale projects, and private standards organizations may certify performance of equipment. In the public realm, policies governing product liability suits and the size of possible awards (compensatory and punitive) affect the incentives for companies to thoroughly test their products and seek approvals. The threat of medical malpractice suits, for instance, is an incentive for practitioners to adopt medical services and devices that they might not otherwise use if only price and performance were considered.[5] Government approval of new technologies can help reduce customer uncertainty. Many regulatory approval programs in the Food and Drug Administration (FDA) and the Federal Aviation Administration (FAA) play this role by enforcing

[3] David Mowery and Nathan Rosenberg, "The U.S. National Innovation System," in *National Innovation Systems*, Richard Nelson (ed.) (New York, NY: Oxford University Press, 1993), p. 49.

[4] Ibid.

[5] Annetine Gelijns and Nathan Rosenberg, "The Dynamics of Technological Change in Medicine," *Health Affairs*, summer 1994, p. 29.

standards for safety. Government-sponsored demonstrations of new technology also can provide potential customers with valuable information on which to base purchasing decisions.

Regulatory Approvals

Regulatory approvals are an inherent part of the commercialization process for many innovations in pharmaceuticals, aerospace, and other industries. Approvals help ensure the safety of innovations that, through their manufacture or use, could adversely affect human health and the environment. Failures can be costly for customers; damages can far exceed the cost of the product itself. Unsafe drugs can have health effects far more severe than the conditions they are supposed to ameliorate, and failed aircraft engines can result in the loss of the aircraft, passengers, and cargo.[6]

The lack of an effective regulatory approval process can be debilitating to sales of such products because consumers often have limited alternatives for independently evaluating safety and efficacy on their own. Moreover, lack of an appropriate regulatory structure can prevent emerging technologies from being evaluated on their own merits. Commercialization of cochlear implants for the hearing impaired, for example, was aided by the formation of a separate panel within the FDA to evaluate cochlear devices on terms and standards more appropriate to the technology than those developed for existing alternatives, such as vibrotactile and hearing aid devices. The establishment of a special committee within the American Speech and Hearing Association to evaluate safety and efficacy of cochlear implants helped further distance the new technology from the old.[7]

Clearly, regulatory approvals can burden innovators by adding time and uncertainty to the commercialization process. Biotechnology companies view the FDA requirement that companies simultaneously submit applications for both drugs[8] (Product License Applications) and their manufacturing facility (Establishment License Applications) as particularly burdensome because they require the firm to invest in full-scale production facilities before knowing whether the drug will be approved. Biotechnology industry executives also complain about unclear FDA review requirements and inadequate communications between the agency and industry.[9] Tensions exist between the desire to rapidly bring new products to market, and the need to protect the public from potentially deleterious effects of new technologies. While weaker approval standards for medical products and pesticides could speed commercialization, they could also come at the cost of human health and undermine consumer confidence, thereby slowing adoption and diffusion. Looser permitting requirements could allow industry to install new process technologies more quickly, but might create loopholes that allow firms to pollute the environment more and endanger the safety of workers and nearby communities.

Increased cooperation among federal, state, and local regulatory agencies may make regulatory approvals more conducive to innovation without compromising health, safety, and the environment. Such actions could broaden markets by lowering the expenses and uncertainties innovators and their potential customers face when implementing new technologies in different jurisdictions. Unlike national regulatory approvals granted in the pharmaceutical and aerospace industries, regulators in environmental and other areas usually have separate procedures and requirements for permitting new facilities in differ-

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[6] Such high costs are one of the reasons the aircraft industry, in particular, is often slow to adopt radically new technologies that have not been rigorously analyzed and tested.

[7] See Van de Ven and Garud, op. cit., footnote 2, p. 204.

[8] Actually biologics in this case. Biologics, which include vaccines, blood products, and other products derived from living tissues, are regulated somewhat differently from drugs made through chemical synthesis.

[9] Kenneth B. Lee, Jr. and G. Steven Burrill, *Biotech 95: Reform, Restructure, Renewal* (Palo Alto, CA: Ernst & Young LLP, 1994), p. 25.

ent states. The Western Governors Association has an initiative under way to encourage states to recognize data submitted to other states for permitting,[10] and California initiated an environmental technology certification program that might give potential customers and regulators confidence in innovative compliance technologies. In the health care industry, too, differing state requirements hamper streamlining of health administration records.[11]

In addition, approval processes can often be streamlined. In 1988, in response to the AIDS epidemic, FDA issued "Subpart E" regulations to expedite approvals for drugs to treat life-threatening and severely debilitating conditions.[12] However, expediting approval for particular types of products may both delay and raise the cost of approvals for other products. In the late 1980's, FDA reviewed some of its drug approval regulations and implemented a number of changes. These changes simplify or reduce some regulatory requirements, increase and improve communications between the agency and applicants, and alter contents and formats on applications to facilitate review, among other actions.[13] Such activities may be continued as other regulations are due to be rewritten. FDA has also proposed streamlining approvals for certain drugs and devices. This proposal includes a pilot program to allow manufacturers to hire private reviewers for certain devices, although final approval would still be given by the FDA.[14,15] Computerization of applications, data submittal, and regulatory review—as well as better training of regulatory agency reviewers—may also help speed the approval process for FDA, the Environmental Protection Agency (EPA), and other agencies.

Technology Demonstration and Performance Verification

Testing, evaluation, and demonstration outside of the regulatory context provide an alternative means of building consumer confidence in new products, processes, and services. Developers commonly build prototypes, bench-scale models, and pilot plant facilities before adopting new technologies or offering them in the marketplace. Firms also test-market new offerings before committing to full-scale production, or seek certification from private standards organizations. For pharmaceuticals, demonstration of efficacy and safety is a condition for regulatory approval. Collective industry action—coordinated through industry councils, technical committees, and trade associations—can assist in the promulgation of industry regulations and safety standards, and can help overcome concerns about the viability of new technology. For instance, SEMATECH—a consortium of 11 large semiconductor manufacturers—tests and qualifies new and improved semiconductor manufacturing equipment.[16] The results are shared with member firms who can use the results in their purchasing decisions; equipment suppliers also use the test results to gain feedback on their products.

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[10] U.S. Environmental Protection Agency, "Technology Innovation Strategy of the U.S. EPA," external discussion draft, Washington, DC, January 1994.

[11] See U.S. Congress, Office of Technology Assessment, *Bringing Health Care Online: The Role of Information Technologies,* OTA-ITC-624 (Washington, DC: U.S. Government Printing Office, September 1995), ch. 3.

[12] U.S. Congress, Office of Technology Assessment, *Pharmaceutical R&D: Costs, Risks and Rewards*, OTA-H-522 (Washington, DC: U.S. Government Printing Office, February 1993), p. 155.

[13] Ibid., pp. 151-158.

[14] Philip J. Hilts, "F.D.A. Moves To Hasten Marketing of New Devices," *New York Times*, Apr. 7, 1995, p. A22.

[15] "FDA Plans To Speed Approvals," *Financial Times*, Mar. 17, 1995, p. 6.

[16] Peter Grindley, David C. Mowery, and Brian Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia," *Journal of Policy Analysis*, vol. 13, No. 4, 1994, pp. 723-758.

While demonstrations occur largely in the private sector, government, too, has a useful role to play, especially in providing unbiased information to developers and users (see box 3-1 for a description of government demonstration programs for scalable parallel computers). Government demonstrations and evaluations are often most effective when the government, federal laboratories, and government-supported entities (such as universities) possess specialized or unique facilities or expertise useful for testing and evaluation. For instance, the National Aeronautics and Space Administration's (NASA's) wind tunnels, computational models, and flight-testing capabilities are useful for demonstrating and validating new civil aviation technologies.[17]

Government capabilities are also useful in evaluating technologies developed to meet regulatory requirements. For example, the Superfund Innovative Technology Evaluation (SITE) program, sponsored by EPA, helps speed the development and diffusion of new environmental remediation technologies by allowing vendors to test new technologies at contaminated sites.[18] A number of federal, state, and university-associated facilities also provide some testing and evaluation services for environmental technologies, although difficulties and uncertainties in permitting fixed test facilities and onsite demonstrations limit their effectiveness.[19] The largest federally supported demonstration program is the Clean Coal Technology Demonstration Program (CCT), which received $2.4 billion from the Department of Energy (DOE) and $4.6 billion in nonfederal contributions.[20] Because many CCT projects are still under way, it is too early to ascertain the final results of the program. However, a number of commercial sales of clean coal technologies have followed the demonstration.

Federal support of technology demonstrations appears to yield poor commercial dividends if: 1) demonstrations are conducted before major research uncertainties are resolved, 2) government technology push overwhelms market pull, or 3) there is low industry commitment to demonstration through cost-sharing. Government-supported development and demonstration of ceramic engine components, the supersonic transport (SST), the space shuttle, synthetic fuels, the Clinch River breeder reactor, and a variety of renewable energy projects have failed largely for these reasons.[21] In a number of these cases, the federal government continued to fund projects even as technical and economic milestones were not achieved, cost overruns accrued, and industry support weakened. To ensure greater success, government must win strong industry interest and financial commitment, avoid hasty leaps toward demonstration when important research problems remain unresolved, and maintain managerial and political dis-

[17] National Research Council, *The Competitive Status of the U.S. Civil Aviation Manufacturing Industry: A Study of the Influences of Technology in Determining Competitive Advantage* (Washington, DC: National Academy Press, 1985), cited in John A. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston, MA: Harvard Business School Press, 1992), p. 403, fn. 20.

[18] U.S. Environmental Protection Agency, "Innovative Hazardous Waste Treatment Technologies: A Developer's Guide to Support Services," 2nd edition, EPA 540/2-91/012, June 1992. SITE's 1995 budget was $16 million; EPA evaluation programs for waste reduction and municipal waste technology evaluation were much smaller; see U.S. Congress, Office of Technology Assessment, *Industry, Technology, and the Environment: Competitive Challenges and Business Opportunities*, OTA-ISC-586 (Washington, DC: U.S. Government Printing Office, January 1994).

[19] U.S. Environmental Protection Agency, National Advisory Council for Environmental Policy and Technology, *Report and Recommendations of the Technology Innovation and Economics Committee: Permitting and Compliance Policy: Barriers to U.S. Environmental Technology Innovation*, EPA 101/N-91/001, January 1991; U.S. Congress, Office of Technology Assessment, ibid.

[20] U.S. Department of Energy, *Clean Coal Technology Demonstration Program: Program Update 1993*, DOE/FE-0299P, March 1994.

[21] U.S. Congress, Office of Technology Assessment, *Commercializing High-Temperature Superconductivity*, OTA-ITE-388 (Washington, DC: U.S. Government Printing Office, June 1988), pp. 44-45; Linda R. Cohen and Roger G. Noll, *The Technology Pork Barrel* (Washington, DC: The Brookings Institution, 1991); Alic et al., op. cit., footnote 17, pp. 369-370.

BOX 3-1: Evaluation and Demonstration of Scalable Parallel Computers

Scalable parallel computers (defined in box 1-3) can sometimes provide the performance of a conventional supercomputer at a much lower price. Many designs of scalable parallel computers compete in the market, and potential users often have difficulty determining which design best suits their particular needs, Because the machines are still quite expensive and writing software for them is difficult, users incur substantial costs if they buy machines just to try them out or make an incorrect choice in their purchase. The limited penetration of scalable parallel computers into the marketplace limits the ability of potential buyers to learn from other users about the strengths and weaknesses of particular designs in different applications.

As a large user of high performance computing, the federal government has long been interested in evaluating supercomputer performance and learning to use supercomputers efficiently. Through its own efforts, the government has been in a good position to help inform other potential users.

One example is benchmarking, which is measuring the speed with which computers perform certain standard calculations. These benchmark calculations are not whole applications programs, rather, they are one or more isolated calculations (such as matrix inversion) chosen to represent the types of computation the user expects to encounter. Different benchmark tests involve calculations typical of different types of applications. Researchers at the Department of Energy's Oak Ridge National Laboratory (ORNL) first conducted benchmark evaluations m 1979. Since then, researchers at ORNL and at the National Aeronautics and Space Administration's (NASA's) Ames Laboratory have run a variety of benchmark tests on a range of different supercomputers and made the results available to industry. The benchmark reports have helped potential users, many of whom have difficulty evaluating manufacturers' performance claims. [1] Government benchmark results do not usually provide enough information to make a purchasing decision, but they help in choosing machines for further evaluation, The results also provide valuable feedback to manufacturers.

The Joint National Science Foundation (NSF) -NASA Initiative on Evaluation (JNNIE) is studying the performance of numerous scalable parallel computers on a wide variety of computations. As well as measuring performance, the project seeks to understand why the machines perform as they do, including the effect of different computer design features. The project will also evaluate the ease of use of different machines. This project could provide valuable information to users as well as to manufacturers designing next-generation computers.

The federal government has also made it easier for firms to try out these computers for themselves. NSF funds a high performance computing Metacenter, which includes five national computation laboratories the Cornell Theory Center, the National Center for Atmospheric Research, the University of Illinois' National Center for Supercomputing Applications, the Pittsburgh Supercomputing Center, and the San Diego Supercomputer Center. While these labs primarily serve government and academic missions, in some cases, firms have used the labs' computers, software packages, and consulting services for their own purposes. Private firms must pay the centers for work that is kept proprietary, for results that become publicly available, grants are available on a competitive basis to defray costs. In 1994, to increase access to industry and academia, NSF expanded its Metacenter to include six Regional Alliances,[2]

SOURCE: Office of Technology Assessment, 1995.

[1] D. Bailey "Twelve Ways To Fool the Masses When Giving Performance Results on Parallel Computers," *Supercomputing Revlew,* August 1991, pp. 54-55

[2] "NSF Establishes Six Supercomputing Subcenters with $6 Million in Awards, " *High Performance Computing and Communications Week,* vol. 3, No 44, Nov. 10, 1994, p. 3.

cipline to terminate programs when project failure is apparent.

TECHNOLOGY STANDARDS

Standards are defined as acknowledged measures of comparison for quantitative or qualitative values, or norms.[22] Thus, standards can be virtually any characteristic by which a class of objects is compared. For example, pistols can be compared by the size of bullet they use; and automobiles can be compared by how many miles they can travel per gallon of fuel. The term *standard* can refer to both the characteristic being measured (bullet size or miles per gallon) and to a specific required value for that characteristic (0.22 caliber, 30 miles per gallon).

Technical standards are particularly important in the development of new technologies because they help channel resources toward a limited number of designs. Standards also provide a basis for products to interact compatibly. For example, two fax machines that use the same standard for encoding transmitted data can communicate with each other, even if they work very differently internally. Similarly, a touch typist trained on one typewriter can readily switch to another one because virtually all English-language typewriters in use today arrange the letters in a standard pattern, starting with QWERTY at the left side of the upper row.

Standards can be established in several ways. Industry may agree on standards; government may impose them; or the market may determine them. Often a standard is established by the dominant producer of a new technology, but such de facto standards can take considerable time to emerge if several competitors offer different designs. Major consumers can also create de facto standards, as in the case of military standards and specifications on certain electronic assemblies. Numerous committees have been established, with and without the help of government, to facilitate standards-setting. While technical considerations are important in standards-setting, social and political considerations often overwhelm them as companies attempt to impose the standards that best suit their own interests.

The governments of Japan and many European countries provide a great deal of support to the private sector's standards activities and view standards as a strategic tool to enhance markets for domestic industries. The U.S. government provides much more modest support and a less strategic view.[23] It has taken an active role in cases in which the government is a large user of a technology, as with software (see box 3-2), or has an accepted regulatory role, as with broadcasting. In high definition television (HDTV), for example, the Federal Communications Commission (FCC) encouraged firms to develop digital—as opposed to analog—systems for transmission and display of HDTV broadcasts. After evaluating four proposed systems—none of which was clearly superior—the federal government encouraged competing teams to arrive at a consensus on a digital standard.[24] The shift to a digital standard may have put U.S. firms back in the running against Japanese firms, which had staked out an early lead in HDTV with its analog MUSE standard. Digital systems offer many performance advantages over analog systems, most notably in signal processing and compression capabilities, and allow greater synergy with U.S. strengths in computer technology. Though Japanese manufacturers will likely be strong competitors in producing devices that meet the U.S. standard, their competitive position will be much weaker than if the United States had adopted the MUSE standard.

Federal procurement policies also influence standards-setting. After several years of debate

[22] *The American Heritage Dictionary of the English Language,* New College Edition (Boston, MA: Houghton-Mifflin, 1980).

[23] U.S. Congress, Office of Technology Assessment, *Global Standards: Building Blocks for the Future*, TCT-512 (Washington, DC: U.S. Government Printing Office, March 1992), ch. 1, esp. pp. 17-18.

[24] See J. Hart, "The Politics of HDTV in the United States," *Policy Studies Journal*, vol. 22, No. 2, summer 1994, pp. 213-238.

BOX 3-2: Industry/Government Interaction To Develop Standards for Software Portability

Widespread diffusion of computer technology—from desktop PCs to high-performance computers—hinges on the development of standards to promote software portability; that is, the ability of software written for one type of computer to run correctly and efficiently on another type of computer without modification, Portability encourages development of applications software because it expands potential markets to Include owners of different types of computers. Increased software development, in turn, makes the computer hardware more valuable because it can perform more functions.

Government has been involved in several industry efforts to develop standards to promote software portability, including development of the COBOL programming language in the 1960s. Some recent examples include scalable parallel computing, whose commercialization has been hampered by a proliferation of differing computer architectures that run incompatible software. No single architecture has yet become an Industry standard, which has stymied the development of applications software and made the machines less attractive to prospective users.

To help overcome this deficiency, the federal government supported the development of the Message Passing Interface (M PI) standard, which helps to make applications portable across different types of scalable parallel computers. ' The standard defines a set of system software routines that applications programs may call to pass messages between processors. Each participating computer manufacturer provides system software routines written to run efficiently on its machine, taking into account factors such as the number of processors and the number, speed, and arrangement of communications channels between them. When a program is ported (i.e., moved) from one machine to another, the second machine's system software routines perform the required interprocessor communication efficiently, just as the first machine's system software routines had done. This approach, while not perfectly efficient and not always applicable, has substantially contributed to software portability.

The effort to create the MPI standard, lasting from summer of 1991 until March 1994, was led by the University of Tennessee and the Department of Energy's Oak Ridge National Laboratory, and was supported by modest grants from the Advanced Research Projects Agency (Department of Defense) and the National Science Foundation (NSF). Several European participants were supported by ESPRIT, a technology program of the European Union. The process involved two-day working group meetings every six weeks for nine months and extensive discussions by electronic mail, both open to all in the high-performance computing field. Most major vendors of scalable parallel computers participated, and the MPI standard was strongly influenced by existing industry message-passing approaches.[2]

Government is also supporting the High Performance Fortran Forum (HPFF), an ongoing effort led by Rice University and the NSF-supported Center for Research on Parallel Computation. HPFF is trying to extend the standard Fortran computer language to computers having more than one processor. Fortran, commonly used in scientific and engineering computing, was developed to run efficiently on various single processor computers and is not well suited for use on multiprocessor machines. Various extensions of Fortran were developed for particular multiprocessor machines, but a standard, widely accepted extension of Fortran was needed to achieve software portability. HPFF is trying to achieve this. A first version of a standard Fortran extension was completed in the fall of 1994; an improved version is under development. As with the MPI standard, the HPFF's approach is not perfectly efficient, and IS not always applicable; but the HPFF's effort is expected to contribute substantially to software portability.

SOURCE: Office of Technology Assessment, 1995

[1] MPI is intended primarily for distributed memory computers and for networks of workstations, but can also be used for shared memory computers *The Internationai Journal of Supercomputer Applications and High Performance Computing,* voI. 8, Nos. 3/4, fall/winter 1994, pp. 159-416 (Special Issue: MPI: A Message-Passing Interface Standard), p 171

[2] Ibid., pp. 165-168

between IBM and other computer manufacturers (including RCA and Univac) regarding a standard for COBOL, a high-level computer language for business applications, the American National Standards Institute (ANSI) adopted a single standard COBOL version. DOD quickly adopted that standard as a federal data processing standard, guaranteeing that major manufacturers would supply compilers for the ANSI version of COBOL, and enabling programs written in ANSI COBOL to be used on various types of computers.[25]

Federal procurement standards can sometimes impede the commercialization of new technology by being overly prescriptive. Military standards and specifications have been cited as factors that limit innovation in developing systems for the military and that segregate the military and commercial domestic production bases.[26] Military standards and specifications often specify in detail the inputs and processes required in the production of goods and services. As practices have changed in the commercial sector, military standards have presented increasingly insurmountable barriers to commercial firms that might otherwise participate in defense markets. For many advanced technologies, the military's reliance on outdated standards has left it behind commercial systems in performance; this practice has resulted in segregated manufacturing facilities for military systems, driving up the costs of production. Recognizing these problems, DOD has begun to move toward performance-based standards that emphasize characteristics of the end product or system, rather than the method of production. This approach allows military procurement officials to take advantage of the commercial sector in many areas. It also enables the use of military procurement policies in fostering the development of new technologies and products, such as those that are less harmful to the environment (see box 3-3).

Government attempts to dictate standards for commercial or dual-use technologies (i.e., those with both military and commercial applications) have also run into difficulty. DOD's efforts to establish Ada as a standard language for object-oriented computer software, for example, have generally fallen short of their initial objectives and failed to promote synergy between defense and commercial computer markets. Similarly, government adoption of the Escrowed Encryption Standard (EES) in 1994 as a voluntary, federal information-processing standard has not enticed commercial organizations to follow. This standard includes a decrypting key that can be reconstructed by combining information escrowed with two different federal agencies. Only with a court order—and for law enforcement purposes only—would the information from the two agencies be combined to decrypt a particular communication. Because of its interest in law enforcement, the government hoped that EES would be accepted by industry. However, the private sector has shown little interest in EES since it can be cracked by the government.[27]

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[25] IBM apparently opposed the standard proposed by RCA and Univac because easy transfer of software from one machine to another would help RCA and Univac to compete against IBM, which dominated the market. Such behavior by IBM is consistent with economic theory; see S. Besen and J. Farrell, "Choosing How To Compete: Strategies and Tactics in Standardization," *Journal of Economic Perspectives,* vol. 8, No. 2, spring 1994, pp. 126-129.

[26] For an examination of factors in the integration of defense and commercial sectors, see U.S. Congress, Office of Technology Assessment, *Assessing the Potential for Civil-Military Integration: Technologies, Processes, and Practices*, OTA-ISS-611 (Washington, DC: U.S. Government Printing Office, September 1994).

[27] U.S. Congress, Office of Technology Assessment, *Information Security and Privacy in Network Environments*, OTA-TCT-606 (Washington, DC: U.S. Government Printing Office, September 1994), pp. 127-132; see also U.S. Congress, Office of Technology Assessment, *Issue Update on Information Security and Privacy in Network Environments*, OTA-BP-ITC-147 (Washington, DC: U.S. Government Printing Office, June 1995).

BOX 3-3: Military Standards and the Development of CFC Alternatives

Military standards and specifications are important factors that govern the cleaning of electronic assemblies. Because the military IS such a large customer for electronic products, its standards have served as de facto Industry standards. One example is CFC-113, a solvent used for cleaning electronic assemblies, fine optical and mechanical parts (e. g., disk drives and gyroscopes), and dry cleaning of delicate materials. CFC-113's superior cleaning characteristics, noncorrosiveness, low cost, low toxicity, slight odor, and nonpolluting qualities made the compound ideal for many cleaning applications. The chemical's characteristics also meant that users did not have to install and operate expensive ventilation or air pollution control equipment. A 1989 estimate suggested that 50 percent of global CFC-113 use in electronic circuit board manufacturing was determined by U.S. military specifications.

However, CFC-113 has been identified as an ozone-depleting substance (ODS). In September 1987, the United States joined 23 other countries in signing the Montreal Protocol on Substances that Deplete the Ozone Layer. The June 1990 London Amendments to the Protocol require the total phaseout of various CFCs by the year 2000, including CFC-113. In 1987, the Environmental Protection Agency and the Department of Defense (DOD) created an Ad Hoc Solvents Working Group to develop a benchmark program to test CFC alternatives. Manufacturers, academics, and government officials initiated a strategy to switch military specifications from prescribing particular production processes, Including CFC use, to procurement standards based on product performance. One estimate concluded that at one time nearly 2,000 military specifications or standards required CFC cleaning.

One result of the Working Group's efforts was creation of MIL-STD-2000 Rev. A, a military standard on soldered electronic assemblies that allows contractors—with adequate documented testing and evaluation—to use alternatives to CFC solvents. Most other DOD procurement documents referencing ODSs have also been revised.[1] DOD also cooperates with NATO and other foreign militaries on military standards and ODS alternatives. These performance-based revisions have removed impediments to the adoption of CFC-113 alternatives by manufacturers. More generally, they remove the impediments to innovation created by procurement standards that constrain manufacturers' ability and incentives to try new processes and materials.

SOURCE: Alan Miller, Pamela Wexler, and Susan Conbere, "Commercializing Alternatives for CFC-113 Solvent Applications, " unpublished contractor report prepared for the Off Ice of Technology Assessment, U S Congress, Washington, DC, May 16, 1995

[1] U.S. Air Force Materiel Command, *Specifications and Standards Revision Tracking System DOD Revision Summary Report,* Mar 271995, cited in Alan Miller, Pamela Wexler, and Susan Conbere, "Commercializing Alternates For CFC-113 Solvent Applications, " unpublished contractor report prepared for the Off Ice of Technology Assessment, U S Congress, Washington, DC, May 16, 1995

In sum, government does, at times, influence the standards-setting process. Cases in which government has attempted to facilitate industry's own attempts to set standards, or in which it has used its procurement policies to tip the balance in favor of a proposed standard, appear to have met with success. Attempts to unilaterally impose standards on commercial industry have met resistance from private industry whose interests differ from those of the government.

SCIENTIFIC RESEARCH

Basic scientific research is a key resource for successful innovation, providing scientific knowledge to support the development of new products,

TABLE 3-2: U.S. R&D Performance by Sector, 1994 (in billions of dollars and percent of total)

Performer	Basic research		Applied research		Development		Total R&D	
Industry	$9 7	31 %	$2 8 3	69%	$8 5 8	85%	$123.8	72%
Government	2 7	9	4,9	12	9 6	10	17.2	10
University	137	54	5 2	13	1 6	2	20.5	12
Other[a]	5 1	16	2 7	7	3 3	3	11.1	6
Total	$312	10070	$410	10070	$100,4	10070	$1726	1 00%

[a] Includes nonprofit institutions and federally funded research and development centers run by colleges and universities.
NOTE Totals may not add because of rounding

SOURCE National Science Foundation, *National Patterns of R&D Resources 7994,* NSF *95-304* (Arlington, VA 1995) pp. 57-69.

processes and services. For example, advances in the nascent biotechnology industry rely heavily on advances in genetics and biochemistry; and early advances in electronics were based on new insight into solid state physics. Yet, firms invest less in research than economic theory suggests would be optimal for society as a whole.[28] This underinvestment is due largely to problems of *appropriability,* the ability of firms to capture the benefits of their research efforts. Basic research is often far more costly to produce than to diffuse or imitate, so companies cannot easily prevent their competitors from benefiting from their research activities. Nor can they hope to fully exploit all the knowledge they could gain from basic research. Several studies confirm that companies rely on outside sources of knowledge and technical inventions for the vast majority of their commercially significant new products.[29]

Firms conduct basic research for a number of reasons—to gain first-mover advantages; to help them better plan and interpret the results of applied research programs; and, more importantly, to enable them to better evaluate and exploit knowledge produced elsewhere[30]—but the conduct of basic research in the United States has fallen mostly to universities. University-performed research accounted for only 12 percent of the nation's total R&D spending in 1994, but amounted to 54 percent of all basic research (table 3-2). Universities allocated two-thirds of their R&D to basic research, compared with only 8 percent for development activities. Industry, in contrast, skews its R&D heavily toward development. In 1994, almost 70 percent of industry-performed R&D was in development, versus only 8 percent in basic research. Government laboratories performed less than 10 percent of the nation R&Din 1994, with over half of the effort in development. Most of this work supports government missions that are of limited commercial interest.

University research plays several roles in the development of industrial technology. In immature industries such as biotechnology, university research is often the source of new inventions. University researchers accounted for over 18 percent of the patents in genetic engineering in 1990 and had high shares in some related patent classes (table 3-3). Other chemical and biological research, though rarely the source of new drugs, identifies the types of reactions pharmaceutical companies should look for in their quest for new

[28] Kenneth Arrow, "Economic Welfare and the Allocation of Resources for Invention," in *The Rate and Direction of Inventive Activity* (Princeton, NJ: Princeton University Press, 1962); and Richard Nelson, "The Simple Economics of Basic Research." *Journal of Political Economy,* June 1959.

[29] R.S. Rosenbloom, '"Product Innovation in a Scientific Age," ch. 23 in *New Ideas for Successful Marketing,* Proceedings of the 1966 World Congress, American Marketing Association, Chicago, IL, 1966; J. M. Utterback, "Innovation in Industry and the Diffusion of Technology," *Science,* Feb. 15.1974, pp. 620-626; C. Freeman, *The Economics of Industrial Innovation* (Cambridge, MA: MIT Press, 1982).

[30] Nathan Rosenberg, "Why Do Firms Do Basic Research (With Their Own Money)?" *Research Policy, vol. 19, 1990,* pp. 165-174

TABLE 3-3: University Share of Patents in Technologies Relevant to Industry, 1990

Patent class	Total patents	University patents	University share
Genetic engineering/recombinant DNA	321	58	18.1%
Molecular biology and microbiology	1,417	171	121
Superconductor technology	233	25	107
Drugs: bio-affecting and body-treating	1,490	147	99
Robots	251	12	48
Semiconductor device manufacturing	755	23	30
Active solid state devices (e g , transistors)	1,535	34	22
Optics: systems and elements	2,280	41	18
Electrical computers and data processing	6,474	53	08
Communications	2,026	14	07

SOURCE: Nathan Rosenberg and Richard R Nelson, "American Universities and Technical Advance in Industry" *Research Policy,* vol. 23, No. 3 May 1994, p 339, from unpublished data gathered by Jonathan Putnam and Richard Nelson

drugs, and enables companies to better assess the possible uses for a drug they are testing. In more mature industries, such as electronics, that are characterized by greater emphasis on incremental innovation and improvement in existing product lines, innovation is less dependent on academic research. Universities held less than 3 percent of the patents in fields such as semiconductors, computers, and communications in 1990. Nevertheless, academic research serves as the source of revolutionary new technologies that provide the impetus for entirely new types of products in these fields.[31]

The linkages between university research and industrial technology vary considerably across academic disciplines and industries (see table 3-4). Survey data indicate that in the pharmaceuticals industry, 27 percent of new products and 29 percent of new processes introduced between 1975 and 1985 could not have been developed without substantial delay without university research. Another 17 percent of products and 8 percent of processes relied substantially on recent academic findings. In other fields, the linkages are not as strong. In the information processing, scientific instruments, and electronics industries, only 11, 16, and 6 percent, respectively, of new products were highly dependent on academic research.[32]

As companies redirect their own R&D funding toward shorter term projects, they are increasing their reliance on university research. Between 1974 and 1994, the percentage of university R&D funded by industry increased from 3.1 percent to 7.1 percent, while total university R&D more than doubled from $8.75 billion to $20.5 billion.[33] Recent estimates indicate that 19 percent of all university research is conducted in programs that have significant industrial participation.[34] Except in rare cases in which university R&D substitutes for industrial R&D (typically in industries that do not support much in-house R&D), the vast majority of this work involves basic and applied research.

[31] Government-University -Industry Research Roundtable, *New Alliances and Partnerships in American Science and Engineering,* (Washington, DC: National Academy Press, 1986), as reported in Nathan Rosenberg and Richard Nelson, "American Universities and Technical Advance in Industry," *Research Policy,* vol. *23,* 1994, p. 343.

[32] Edwin Mansfieid, "Academic Research and Industrial Innovation," *Research Policy,* vol. 20, No. 1, February 1991. pp. 1-12.

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

[34] Wes Cohen et al., *University-Industry Research Centers in the United States,* report to the Ford Foundation, 1993.

TABLE 3-4: Percentage of New Innovations Based on Recent Academic Research, 1975-1985

Industry	Percentage that could not have been developed (without substantial delay) without recent academic research		Additional Percentage developed with substantial aid from recent academic research	
	Products	*Processes*	*Products*	*Processes*
Information processing	11%	11%	17%	16%
Electronics	6	3	3	4
Chemicals	4	2	4	4
Instruments	16	2	5	1
Pharmaceuticals	27	29	17	8
Metals	13	12	9	9
Petroleum	1	1	1	1
Average	1170	8%	8%	6%

SOURCE: Edwin Mansfield, "Academic Research and Industrial Innovation," *Research Policy,* vol. 20, No *1,* February 1991, table 1, p 2

FINANCING

New technologies often require decades to move from the laboratory to the marketplace, and costs tend to increase exponentially with each step forward. Availability of capital can, therefore, become a bottleneck for large and small companies alike as they attempt to move promising technologies closer to the marketplace and select among multiple projects that compete for limited resources. Firms differ in the types of financing they seek and attract. Large, established firms tend to finance innovation from revenues generated by sales of existing products, but corporate decisions regarding resource allocation are influenced by the structure of external capital markets and the expectations of investors. Large, established firms can also issue a new stock series to raise additional capital. Small startup firms, in contrast, tend to finance innovation with their own savings, venture capital, and wealthy investors referred to as *angels.* Each of these sources has its own strengths and weaknesses that reflect the differing relationships between investors and innovators.

■ Sources of Financing

Government and industry share responsibility for funding innovation and commercialization in the United States. Public institutions tend to play a major role in financing basic scientific or technical research, whereas primarily private capital supports company efforts to transform basic knowledge into proprietary commercial applications. Government expenditures for R&D totaled $62.2 billion in 1994, representing just over one-third of total R&D (table 3-5). Some$18 billion of this funding went to basic research, making the government the largest supporter of basic research in the country, accounting for more than half of all such funding. Industry funded 59 percent of total R&D, but spent about 69 percent of its resources on development activities and another 23 percent on applied research. Only 8 percent of industry funding went toward basic research.

Federal R&D funding has declined in both real and relative terms since 1987. Between 1987 and 1994, federal expenditures declined from $73 billion to $62 billion (in constant 1994 dollars), falling from 46 percent to 36 percent of total U.S.

TABLE 3-5: U.S. R&D Expenditures by Source of Funding, 1994 (billions of dollars and percent of total)

Source	Basic research		Applied research		Development		Total R&D	
Industry	$8,2	26%	$23.9	58%	$70.0	70.0%	$1021	59%
Government	18,2	58	14,5	35	29.6	29.0	622	36
University	3.3	11	1.7	4	0.4	0.4	5.3	3
Other[a]	1,5	5	1 0	2	0 5	0 5	3 0	2
Total	-- $31.2	100'%0	$41.0	100?40	$1004	100%	$172.6	10070

[a] Includes nonprofit institutions and federally funded research and development centers run by colleges and universities.

NOTE: Totals may not add because of rounding

SOURCE: National Science Foundation, *National Patterns of R&D Resources, 7994,* NSF 95-304 (Arlington, VA: 1995), pp. 54-68.

R&D.[35] This trend places greater demand on private sources of funding. Private financiers typically provide equity rather than debt financing for new technology development. One reason is that technology development typically offers little collateral for a loan. Failed R&D projects generally do not generate any salable property, physical or intellectual. Specialized facilities and equipment purchased for technology development often have low resale value, and can be difficult to resell at all.[36] Also, technology development tends to be riskier than other sorts of investment. Not only do new technology ventures need sound business plans, appropriate marketing strategies, and requisite management and business skills in order to succeed; they must also develop the technology sufficiently to turn it into a product. Potential investors often lack the ability to evaluate a project technical merits.

Private funding for innovation ultimately derives from national savings.[37] U.S. savings rates, however, lag those of its major economic competitors. Between 1990 and 1992, the U.S. national savings rate averaged 2 percent of GDP, compared with 20 percent for Japan, 11 percent for Germany, 8 percent for France, and 3 percent for the United Kingdom.[38] This lower rate results in part from the need to pay interest on the national debt, which amounted to roughly 4 percent of GDP. U.S. investments in nonresidential fixed capital have also lagged those of its primary competitors since at least 1970. Between 1990 and 1992, nonresidential fixed investment (including government capital expenditures) in the United States averaged 12 percent of GDP, compared with 26 percent for Japan, 15 percent for France and Germany, 14 percent for Canada, and 13 percent for the United Kingdom.[39] This may result, in part, from the U.S. tax system, which taxes corporate investments twice: once as corporate profits and once as distributed dividends.

■ External Capital Markets

Differences in the structure of capital markets tend to make U.S. providers of equity capital less patient and less knowledgeable about the internal operations of particular firms than capital providers in Japan and Germany. In Japan, most large

[35] National Science Foundation, op. cit., footnote 33.

[36] Stephen J. Kline and Nathan Rosenberg, "An Overview of Innovation," in *The Positive Sum Strategy,* Ralph Landau and Nathan Rosenberg (eds.) (Washington, DC: National Academy Press, 1986), p. 300.

[37] Foreign investment in the U.S. economy during 1990-92 averaged less than 1 percent of GDP. National Research Council, Board on Science, Technology, and Economic Policy, *Investing for Productivity and Prosperity* (Washington, DC: National Academy Press, 1994), p. 15, table 2.

[38] Ibid., p. 16, table 3. Earlier years show a similar pattern.

[39] Ibid.,p. 4, table 4, citing Organisation for Economic Cooperation and Development, Annual and Quarterly National Accounts.

company stock is held by *keiretsu*, or groups of related industrial firms that give preference to other group members in procuring supplies and services.[40] Each group member has a vested interest in other group members' long-term success and tends to hold the stock for long periods of time, rather than trading it to win short-term profits. In addition, both Japanese and German banks may hold equity in borrowing firms, giving them a further interest in the firms' long-term success. Bankers also tend to understand in detail the business of firms they lend to, which can give them confidence in a firm's long-term viability in the face of short-term setbacks. Both banks and stable shareholders often have close relationships with the firm's management and offer them advice. Of course, such arrangements can have negative consequences if the bank within the *keiretsu* or closely affiliated with a particular company fails.

In the United States, company stock is less closely held; most is readily traded by investors looking for short-term gain. In fact, most publicly traded stock is owned by managed funds, such as pension funds and mutual funds, whose managers are evaluated on the fund's quarterly performance. U.S. tax laws provide no incentive to hold stocks for sustained periods, as capital gains tax rates no longer distinguish between stocks held for shorter or longer periods of time. The average period a stock is held has declined from over seven years in 1960 to just two years in 1990.[41] U.S. banks are prohibited from owning equity in their clients, and typically know little about their clients' business; therefore they add little stability to the market. While the effects of rapid turnover are hard to deduce, the frequent revaluing of stock prices, combined with an obligation to protect shareholder interests, provides an incentive for company managers to favor short-term returns over long-term investments such as R&D.

On the other hand, the openness of the U.S. capital system allows mobilization of large amounts of capital, and enables small firms better opportunities to raise money on the stock market through an initial public offering. This ability motivates a vital venture capital industry—unparalleled abroad—to invest in risky startup companies. New firms rely on venture capital and angels—wealthy individuals who invest in small companies—for much of their startup funding because they have no product, track record, or earnings. They must sell investors on the viability of their idea and the competence of their people. Both the venture capital and angel markets share some attributes with the overall financial systems of Japan and Germany in that investors are patient, they are well informed about the firms they invest in, and they have a say in management decisions.[42] However, both are limited in their ability to help startup firms.

Venture Capital and Angel Financing

Small startup companies in the United States often look to the venture capital markets and wealthy *angels* for their capital needs. These markets bear some resemblance to external capital markets in Japan and Germany. Investors tend to be patient, are knowledgeable about the firms in which they invest, and provide management expertise. Yet, these markets are much smaller than other capital sources for innovation.

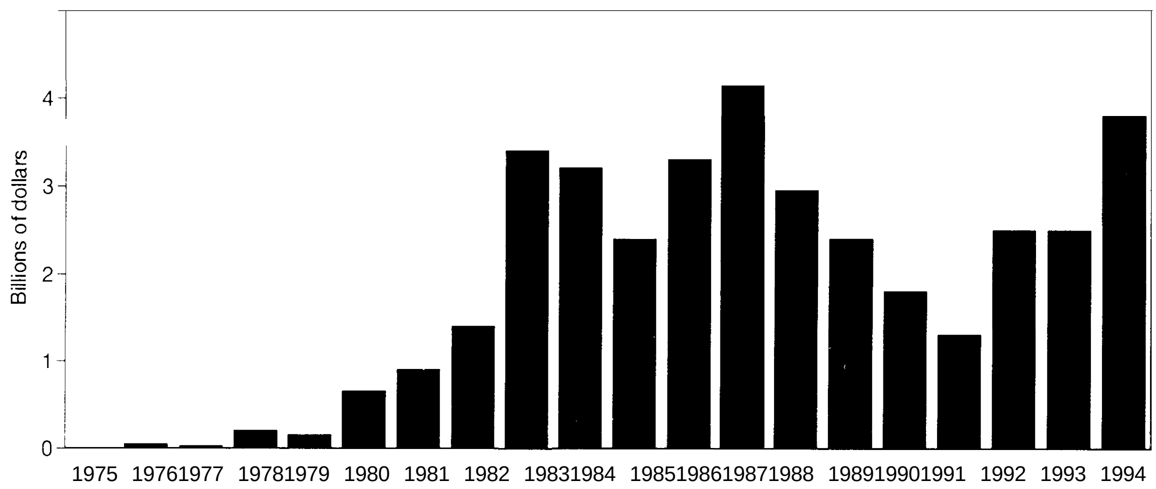
Venture capital is widely viewed as a strength of the U.S. system of innovation. The total value of existing venture capital investments in U.S.

[40] Typically, a minority portion of the target firm's stock is sold on the open market. While that portion is frequently traded and can experience large price swings, it tends to have little effect on the firm's behavior. Japan is moving somewhat in the direction of the United States. Long-term investors are reconsidering their strategies and, in some cases, selling stock, partly to gain needed liquidity during Japan's current recession. R. Steiner and J. Sapsford, "Japanese Investors Get Choosy About Stocks, Depressing the Market," *Wall Street Journal*. June 28, 1995, p. A1.

[41] Michael Porter, *Capital Choices: Changing the Way America Invests in Industry*, report presented to the Council on Competitiveness and cosponsored by the Harvard Business School (Washington, DC: Council on Competitiveness, June 1992), p. 5.

[42] Although neither Japan nor Germany has a robust venture capital market for financing startup companies.

FIGURE 3-1: New Commitments to Private Venture Capital Funds, 1975-1994



SOURCE: Venture Economics, Inc., as cited in William D. Bygrave and Jeffry A. Timmons, *Venture Capital at the Crossroads* (Boston, MA Harvard Business School Press, 1992), p 26, and in Lisa Vincenti, "Fund Raising Renaissance, " *Venture Capital Journal,* Feb. 1995, p *40*

firms was $35 billion in 1992, more than 10 times that of Japan or Germany.[43] Venture capital firms raise money from institutions and individuals to invest in relatively high-risk, but potentially high-reward, new firms. In return, firms receiving funding from venture capitalists transfer an average of 69 percent of their equity to venture capital firms.[44] Within a fixed period of time, typically seven to 10 years for successful investments, venture capitalists liquidate their holdings, often through private buyouts or initial public offerings in the stock market. Because their compensation depends on the performance of their investments, venture capitalists not only have strong stakes in the success of firms in their portfolio, but they have strong incentives to cut losses on firms that do not perform satisfactorily. Venture capital helped spawn many startup companies such as Apple, Digital Equipment Corp., Genentech, and Intel by providing not only early-stage financing, but managerial assistance to help firms develop business plans, manage technology and product development, and deal with regulations in areas such as taxes, working conditions, and environment.

Venture capital can support only a limited number of technology-based firms at any given time. While new venture capital commitments have nearly tripled since 1991, reaching $3.8 billion in 1994, they are still only slightly larger than the R&D budget of IBM Corp. (figure 3-1). Only 10 to 20 percent of the new technology ventures started in the United States each year receive venture capital. Far greater resources are invested by entrepreneurs themselves, larger companies, and angels. In addition, venture capitalists appear to be backing away from capital-intensive industries like electronics and shifting their attention toward

[43] Richard Florida and Donald F. Smith, Jr., "Keep the Government Out Of Venture Capital," *Issues in Science and Technology,* summer 1993. p. 62.

[44] Coopers & Lybrand, *Fifth Annual Economic Impact of Venture Capital Study,* 1995, as cited in Gene Koprowski, "Venture Capitalists Taking Big Chunks Of Startups," *HPCC Week,* Apr. 20, 1995, p. 7.

industries like biotechnology and software that have lower startup costs.[45] Despite growth in seed capital investments in 1994, venture capitalists also appear to be moving toward funding at later stages, reducing their emphasis on seed capital.[46]

Angels—affluent individual investors—play an important role in seeding startup firms, infusing an estimated $10 billion to 30 billion per year into firms at the earliest stages of development.[47] In contrast to the market for venture capital, the market for angel funding is informal and fragmented, limiting its potential ability to help startup firms. Angel investors typically learn about investment opportunities through accidents of geography and personal acquaintances. More formal mechanisms for matching angels to needy companies, or for pooling the resources of several angels for a single investment, do not exist on a large scale. Some researchers estimate that up to $300 billion in angel funding could be tapped if information about investments could be targeted to potential investors.[48]

Several initial efforts have been made to help entrepreneurs and angels find each other. In 1984, the Venture Capital Network, Inc. (VCN) was established as a not-for-profit affiliate of the Center for Venture Research at the University of New Hampshire. VCN began to build databases of entrepreneurs and angels and to provide selective introductions. VCN moved to the Massachusetts Institute of Technology in 1990, and was renamed the Technology Capital Network, Inc. in 1992. Between 1984 and 1990, the program served 1,200 entrepreneurs and 800 investors. It made 3,500 introductions that led to at least 31 ventures (of which 80 percent were technology-based), raising a total of $12 million from 50 investors. VCN helped initiate six similar networks in the United States and Canada.[49] Another effort to facilitate angel financial markets is The Capital Network (TCN), established by the IC^2 Institute at the University of Texas and located at the Austin Technology Incubator. TCN provides a computerized information clearinghouse and introduction service that matched up nearly $25 million in investments over the past five years.

Small Business Assistance Programs

Small firms also receive assistance from technology incubators (see box 3-4) and from federal programs that address entrepreneurial needs. Many of these latter programs, however, are not targeted to the specific needs of high-technology firms. Programs operated by the Small Business Administration (SBA) serve small firms, whether or not the firms focus on high-technology work, and they serve small, high-technology firms without specifically targeting startups. For example, the SBA operates a number of small business development centers (SBDCs) that provide small firms with an array of services—from expert referrals to export assistance—but they often lack the exper-

[45] Of new venture capital commitments in 1994, 28 percent went to biotechnology, 14 percent to software, 14 percent to media and communications, and 12 percent to semiconductors and electronics. Coopers & Lybrand, ibid.

[46] OTA interviews with venture capitalists and managers of high-technology startups.

[47] J. Freear, J. Sohl, and W. Wetzel, "The Private Investor Market for Venture Capital," *The Financier: ACMT*, vol. 1, No. 2, May 1994, pp. 7-15.

[48] J. Freear, J. Sohl, and W. Wetzel, "Angels and Non-Angels: Are There Differences?" *Journal of Business Venturing*, vol. 9, pp. 109-123.

[49] J. Freear, J. Sohl, and W. Wetzel, "The Private Investor Market for Venture Capital," *The Financier: ACMT*, vol. 1, No. 2, May 1994, pp. 7-15.

BOX 3-4: Business In

Often endowed with both public and private support, a business incubator helps entrepreneurs by providing: 1) low-cost office space; 2) shared support services; 3) assistance in developing business strategy and in coping with practical concerns such as government regulations; and 4) access to capital sources, technical expertise, and business partners. Incubators form a hub for entrepreneurial interaction and business development by connecting investors, business groups, universities, and public agencies with new firms.[1] About 20 to 25 percent of the more than 700 existing incubators specifically assist new high-technology firms. Many are located at or near universities or research parks, bringing entrepreneurs close to valuable technical resources and making them a natural home for commercialization efforts arising from Innovations at academic laboratories.

Data on the success rates of technology incubator clients are sparse, partly because two-thirds of incubators are less than five years old and have few, if any, graduates, However, evidence suggests that they contribute to the creation and development of technology-based firms. One study showed that graduates of the selected incubators experienced an average annual growth rate of 166 percent in sales and 49 percent in employment between 1986 and 1990.2

Although incubators are intended to breed successful companies, critics charge that they offer Iife support to firms that would and should ordinarily fail. While some incubators have graduated dozens of firms, others have experienced only failures. Moreover, despite their expressed preference for high-technology firms, few Incubators can provide technology-based firms with the expertise and resources they need to flourish,[3] To succeed, incubators must provide the resources and services that clients need, Some say that an incubator, by example, can show how to run an efficient, customer-oriented firm. To succeed, an incubator also needs clients committed to business success, rather than entrepreneurs content to remain small [4]

The federal government currently assists incubators. Regional offices of the Department of Commerce's Economic Development Administration support feasibility studies, technical assistance, and construction costs for Incubators sponsored by both public and nonprofit organizations.[5] Incentives and assistance have been offered to help link disparate public and private resource providers into incubators and other small business assistance programs. Small Business Development Centers perform some of these services, and other entitles, such as the federal/state-supported TEXAS-ONE initiative and the private Coopers & Lybrand Batorlink, provide electronic links among small businesses, research organizations, incubators, and other resources. A possible future federal role would be to work with the National Business Incubators Association to develop criteria and certification procedures to assure quality services to clients.

SOURCE Office of Technology Assessment, 1995

[1] S. Birley, "The Role of Networks in the Entrepreneurial Process, " *Journal of Business Venturing,* vol. 1, No. 1, winter 1985, pp. 107-117, R. Smilor and M.D. GiII. *The New Business Incubator* (Lexington, MA: Lexington Books, 1986); M.P. Rice, *Linking the Performance of the Rensselaer Incubator Program and the Performance of its Participating Companies,* paper presented at the 1994 Babson Entrepreneurship Research Conference, University of Houston, Houston, TX, June 11, 1994.

[2] S.A. Mian, "U.S. University-Sponsored Technology Incubators: An Overview of Management, Policies, and Performance. " *Technovation,* voI. 14, *No 8,* 1994, pp. 515-528.

[3] Johanna Ambrosio, "Incubators Nurture Start-up Firms, " *Computerworld,* Sept 16, 1991, pp 105, 112; G.G. Udell, "Strategies for Stimulating Home-Grown Technology-Based Economic Development, " *Business Horizons,* November-December 1988, pp 60-64, see also, *The State of the Business Incubation Industry 7997* (Athens, OH National Business Incubation Association). In a mid-1980's study, 86 percent of responding incubators indicated a preference for high technology. Cited in R. Smilor, "Commercializing Technology Through New Business Incubators, " *Research Management* September-October 1987, pp 36-41

[4] M.P. Rice and J B Matthews, *Growing New Ventures—Creating New Jobs Principles and Practices of Successful Business Incubation,* (Kansas City, KS CEL Kauffman Foundation, forthcoming 1995), Smilor, ibid., Rice, op. cit., footnote 1.

[5] About 10 percent of the Economic Development Administration's work is related to assisting incubators, Rick Sebenoler, Technical Assistance Program, Economic Development Administration, U.S. Department of Commerce, Austin, TX, personal communication, Aug 22, 1995.

tise and contacts needed in many high-technology sectors.[50]

The SBA also authorizes and supports Small Business Investment Companies (SBICs) that invest in small business through long-term loans and equity stakes. Although data are limited, available evidence indicates that SBICs help channel investment to new high-technology firms. It is estimated that of the $11 billion invested in over 57,000 small businesses between 1958 and 1992, 60 percent went to firms less than three years old.[51] Over the same period, approximately $1.6 billion of SBIC investments went into high-technology enterprises.[52] SBICs often finance low-collateral business activities—including R&D, marketing, and self-acquisition—that are crucial to such firms.[53]

Small, high-technology businesses are the target of the federal Small Business Innovative Research (SBIR) program. The program requires large federal agencies to reserve a percentage of their extramural research budget for competitive grants to small firms (see box 3-5). The SBIR program provides critical funding, as well as the opportunity to further R&D and product development, to many firms in the early stages of their development. Many small businesses also participate in other federally sponsored cooperative technology programs, such as the Advanced Technology Program (ATP), which funds *precompetitive* research programs. Approximately half of the ATP awards to date have gone to small businesses or joint ventures led by small businesses.[54]

HUMAN RESOURCES

Human resources are important to innovation because new technologies imply new ways of performing tasks related to research, manufacturing, or marketing.[55] Successful innovation requires that entrepreneurs assemble a team of well-trained scientists, engineers, technicians, managers, and marketers who develop new technologies; incorporate them into products; manufacture them in a way that is timely, cost-effective, and responsive to the market; and sell them. Training workers with these diverse skills is the responsibility of different institutions, both public and private.

The formal education system, from kindergarten through graduate school, provides the basic

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[50] G. G. Udell, "Strategies for Stimulating Home-Grown Technology-Based Economic Development," *Business Horizons*, November-December 1988, p. 63; in interviews with OTA, administrators of technology incubators and state technology programs stated that high-tech firms typically sought assistance from SBDCs only after pursuing the support of a technology incubator or state-sponsored technology program. In recent partnerships with other federal agencies, however, the SBDC program combines small business assistance with other agencies' technical resources. For example, SBDC subcenters have been established at 10 National Institute for Standards and Technology (NIST) Manufacturing Technology Centers to bring a greater range of financial and business expertise to the centers' primary manufacturing extension services for small and medium-sized manufacturers; "NIST Manufacturing Centers to Host SBA Experts in Coop Program," *Industrial Engineering*, December 1993, pp. 7-8.

[51] U.S. Congress, Senate, Committee on Small Business, "Hearing on Investment in Critical Technologies Through the Small Business Administration's Existing Financing Programs," 103d Congress, 1st session, June 9, 1993.

[52] This amount is said to have leveraged an additional $7.1 billion from other private sources; ibid. Apple Computer, Cray Research, and Intel received SBIC financing in their early years.

[53] E. Brewer, III, and H. Genay. "Funding Small Business Through the SBIC Program," *Economic Perspectives*. May-June 1994, pp. 22-34. On average, bank-related SBICs raise more private capital and rely less on SBA funding and guarantees than other SBICs.

[54] Of the 24 ATP awards announced in July 1995, 18 of the total 47 participants were small businesses and 13 of the 24 joint ventures were led by small businesses; U.S. Department of Commerce, "NIST Announces 24 New Advanced Technology Program Awards," *Commerce News* press release, Washington, DC, July 13, 1995, p. 30.

[55] For a more in-depth discussion of this subject, see U.S. Congress, Office of Technology Assessment, *Worker Training: Competing in the New International Economy*, OTA-ITE-457 (Washington, DC: U.S. Government Printing Office, September 1990); U.S. Congress, Office of Technology Assessment, *Higher Education for Science and Engineering—A Background Paper*, OTA-BP-SET-52 (Washington, DC: U.S. Government Printing Office, March 1989); and U.S. Congress, Office of Technology Assessment, *Educating Scientists and Engineers: Grade School to Grad School*, OTA-SET-377 (Washington, DC: U.S. Government Printing Office, June 1988).

BOX 3-5: Small Business Innovative Research Program

The Small Business Innovative Research program (SBIR) seeks to increase the level of small firm participation in federal R&D activities and to improve private sector commercialization of federally developed Innovations. All federal agencies with external R&D budgets greater than $100 million must set aside a specified percentage of this budget for small businesses. [1] Although the SBA is the overseeing agency, each participating agency selects areas of research, solicits and chooses proposals, and administers funding. This keeps the SBIR work closely related to each agency's mission. After two phases of SBIR funding, a firm may move its renovation toward commercial markets by seeking private investment and support; although no SBIR funding is available for the third phase, these firms may win production contracts or non-SBIR funding from federal agencies.

Between 1983 and 1993, 11 agencies gave nearly 25,000 Phase I and II awards worth over $3.2 billion to more than 50,000 small firms. Awards enable small firms to expand research, hire new personnel, develop new products, and find new markets and customers. Eighty-four percent of one study's respondents Indicated that their technology would not have been pursued without SBIR assistance. Many SBIR participants are young firms; over 20 percent of Phase I awardees are less than two years old, For most participants established after 1983, SBIR was their first experience with federal R&D programs. In 1989, project administrators judged about half of SBIR projects to be at least equal in quality to other agency R&D, nearly 30 percent were considered better. There was a strong sense at all agencies that SBIR work was more Iikely to be commercialized than other agency-supported R&D.

Evidence suggests that SBIR maybe helping to increase the participation of small firms in federal R&D activities In 1982, the National Science Foundation estimated that small firms' share of federal R&D was 2.8 percent. By 1991, that share had reached 3.7 percent. Commercialization, too, may be facilitated. By 1992, SBIR firms had received $471 million in sales and $646 million in additional development funding for Phase Ill (commercialization) work. While the sales figure is modest compared to the $3.2 billion in federal Phase I and Phase II investments, many investments are still maturing. A total of 27 percent of the firms responding to one study had commercialized or expected to commercialize SBIR related work in the near future.

There are some downsides, however. A large percentage of sales realized through SBIR work is derived from the public rather than the private sector. In 1991, the majority of SBIR participants earned 65 percent or more of their sales from government markets. In addition, because SBIR is based on agencies' R&D needs, award selection is driven by technology, not by markets; market concerns are left for Phase Ill. By this point, however, the deck may be stacked against a number of innovations with little or no identifiable commercial appeal. Also, while some grant recipients may seek commercialization, a large portion may be Interested primarily in further research. Some recent agency efforts have taken modest steps to increase the priority on commercialization. The Department of Energy has provided commercialization training sessions, and in 1994 the Navy required firms to submit a commercialization plan before receiving the last 20 percent of a phase II award. Another concern is that some firms have received several duplicative grants from different agencies

SOURCES: U.S. Congress, General Accounting Office, *Federal Research: Interim Report on the Small Business Innovation Research Program,* GAO/T-RCED-95-154 (Gaithersburg, MD: Apr. 6, 1995), U.S. Small Business Administration, *Small Business. Building America's Future, Results of a Three-Year Commercialization Study of the SBIR Program* (Washington, DC 1991), p 5, U S Congress, General Accounting Office, *Federal Research' Small Business Innovation Research Participants Give Program High Marks,* GAO-RCED-87-161-BR (Washington, DC July 1987), pp. 13-30,35-38, U S Congress, General Accounting Office, *Federal Research: Assessment of Small Business Innovation Research Programs,* GAO/RCED-89-39 (Washington, DC January 1989), and Thomas Enterprises, Inc., *Small Business Innovation Research (SBIR) Program Analysis,* report prepared for the Office of Technology Commercialization, U.S. Department of Commerce, Washington, DC, Jan. 17, 1995, pp. 8-9

[1] Public Laws 97-219, 99-443, and 102-564 The percentage rose annually from O 2 percent m 1983 to 1 25 percent in 1986, increased to 1 5 percent in 1993 and 20 percent in 1995, and is scheduled to increase to 25 percent in 1997.

[2] U.S. Congress, General Accounting Office, *Federal Research: Interim Report on the Small Business Innovation Research program,* GAO/T-RCED-95-154 (Gaithersburg, MD: Apr. 6, 1995), pp. 4-5

[3] Ibid., pp. 5-6.

skills that workers can apply to innovation. While U.S. universities are generally considered the best in the world, especially in technical fields, they have also been criticized for training graduates too narrowly, especially engineering graduates who often receive little training in manufacturing processes, product design (including design-for-manufacture and design-to-cost), and teamwork. Moreover, in international comparisons of achievement in mathematics and science, U.S. schools from kindergarten through high school perform poorly compared with other industrialized and industrializing countries, and often fail to impart the basic reading and math skills required in the workplace.

Workplace education supplements formal education, as workers learn through experience and formal training programs. For emerging technologies in particular, many of the skills needed for commercial success are not available in the formal education system, but are developed instead by firms engaged in proprietary R&D programs. Few engineering graduates could develop a new device using high-temperature superconductors without the guidance of a more experienced engineer; similarly, the skills of managers tend to improve with experience. Universities, research institutes, and corporations recruit and train people in skills related to innovation, whether in research techniques, project management, or production. Job transfers and workforce mobility tend to disseminate these skills throughout the industry, but, at the same time, reduce the ability of organizations to capture the benefits of their investments in training and education.

Labor force skills are expanded through industry conferences, technical committees, trade publications, and technical journals, which provide an opportunity for industry participants to exchange ideas and share knowledge. Information is also exchanged through "invisible colleges" or informal networks of engineers within particular industries who exchange know-how. Studies of steel-making minimills reveal that engineers frequently trade information that is not critical to their companies' competitive advantage.[56] This is especially useful when the particular piece of information is too small to justify a negotiated license or exchange because it effectively distributes technical information among participants in an industry. Recent evidence indicates that differences in the degree to which researchers share information can influence a region's ability to successfully innovate and commercialize new technologies. The greater success of California's Silicon Valley compared with Boston's Route 128 during the late 1980s and early 1990s has been attributed, in part, to the more open culture of Silicon Valley, which facilitated information sharing.[57]

TECHNOLOGY DEVELOPMENT

Development of new technology—as well as new products, processes, and services based on new technology—is the central activity of technological innovation. Private corporations must appropriate basic knowledge of science, technology, and markets and convert it into proprietary knowledge through applied research and development. This process is best characterized as a trial-and-error search for a viable set of product attributes that meets market demand, and for technologies capable of providing those attributes at a cost the market will support.

While the private sector bears primary responsibility for developing commercial technologies in the United States, government activities influence those efforts. Products and technologies developed by or for the government often find commercial application. Most U.S. jet engines

[56] Eric von Hippel, "Cooperation Between Rivals: Informal Know-How Trading," *Research Policy*, vol.16, 1987, pp. 291-302.

[57] AnnaLee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge, MA: Harvard University Press, 1994).

used on commercial aircraft today derive from military antecedents,[58] as do other aircraft technologies such as fly-by-wire control systems and swept-back wings. The Internet derives largely from ARPANET, a national computer network developed in the early 1970s by DOD's Advanced Research Projects Agency (ARPA). Numerous other examples of such "spin-off" exist in industries such as aircraft, electronics, and materials that serve important government missions. Though spin-off has declined over time as military and commercial requirements have diverged and commercial markets have developed,[59] military technology—and government technology more generally—contributes substantially to the nation's stock of technical knowledge and to its current competitive position.

Federal laboratories also contribute to commercial technology development. Several hundred federally funded research and development centers (FFRDCs)[60] and government-owned laboratories conducted $22.3 billion in R&D in 1994.[61] Since 1980, numerous attempts have been made to facilitate the transfer of technologies from these labs to the commercial sector. The Stevenson-Wydler Technology Innovation Act of 1980 requires most federal laboratories to establish Offices of Research and Technology Applications to promote technology transfer and to allocate 0.5 percent of their R&D budgets to technology transfer activities. The Federal Technology Transfer Act of 1986 amended Stevenson-Wydler to allow government-owned and -operated laboratories to enter into cooperative research and development agreements (CRADAs) with private industry. Under this authority, which was extended to government-owned, contractor-operated labs in 1989, government laboratories were allowed to contribute personnel, equipment, and other nonfinancial resources to projects undertaken jointly with industry. Such legislation has resulted in thousands of CRADAs to date with firms working in the automotive, biotechnology, computer, and semiconductor industries, to name a few.

NETWORKS AND LINKAGES

In developing new products and processes, firms must create linkages to sources of new knowledge and providers of key components for their products. These linkages serve several purposes for the innovating firm, allowing it to: 1) spread the costs and risks associated with innovation among a greater number of organizations; 2) gain access to new research results and technological capabilities for innovation efforts; 3) acquire key components of a new product or process; and 4) gain access to complementary assets in manufacturing, marketing, and distribution. Acquiring such resources means linking with other developers of similar products, suppliers of critical components, and university researchers.

Firms often link together to share the cost and risk associated with innovation. New commercial aircraft easily cost over $1 billion to develop, as do the jet engines that power them. Estimates of the R&D costs required for next-generation semiconductor manufacturing, which will use 10- to 12-inch wafers of silicon, start at $3 billion, and

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[58] General Electric's CF6 engine and Pratt & Whitney's JT9, both used to power the 747 aircraft, derive from engines designed or built for military transports. The core of GE's newest engine, the CFM-56, built in collaboration with the French firm, SNECMA, derives from the engine used on the B-1 bomber. Jerry Sheehan, *Commercialization and Transfer of Technology in the U.S. Jet Aircraft Engine Industry,* unpublished master's thesis, Massachusetts Institute of Technology, June 1991.

[59] Alic et al., op. cit., footnote 17.

[60] FFRDCs are research organizations owned and operated by nongovernment organizations (industry or universities) that receive their funding from the federal government.

[61] National Science Foundation, *National Patterns of R&D Resources,* 1994 (Arlington, VA: 1995), table B-2. The figure is the sum of R&D performed by government and by university-run FFRDCs.

the cost of individual semiconductor fabrication facilities tops $1 billion.[62] Pharmaceuticals companies often spend more than $200 million to get a new drug to market.[63] At the same time, innovators face numerous uncertainties in developing new products and processes. The innovation may not work as expected, or it may not be possible to manufacture it with the right combination of price and performance. The market may not develop as rapidly as anticipated—or to the size needed to support profitable manufacture.

Few companies can afford to assume these risks alone. As a result, they rely on alliances, consortia, and suppliers to shoulder some of the burden. Large systems integrators such as Boeing use subcontracting arrangements to spread risk among a large number of suppliers and subcontractors, each of whom is responsible for a portion of the final product that Boeing itself will integrate. Sometimes competitors form alliances to jointly conduct R&D that no one firm could support single-handedly. Even large, diversified firms are finding such alliances necessary to develop next-generation technology. In the semiconductor industry, for example, IBM has teamed with Toshiba and Siemens to develop memory chips capable of storing 256 million bits of information (256 Mbit DRAMs).

Firms also form consortia, such as SEMATECH, the Semiconductor Manufacturing Technology consortium, which finances R&D projects of joint interest to its 11 member companies. Consortia are similar to subcontracts in that multiple participants each perform a part of the overall task; however, they differ in that responsibility for overall project initiation and design is shared, rather than controlled by the system integrator. In some industries, such as aircraft and portions of the electronics industry, international consortia are common. Because these industries have strong economies of scale and high R&D costs, typically just one leading company, or at most a few, resides in any one country. Airbus Industries, for example, is a consortium of several European countries. None was able to independently sustain a viable international presence in large commercial aircraft, but together they formed a viable competitor to Boeing and displaced McDonnell-Douglas as the world's second largest producer of commercial jet aircraft.[64]

Interfirm linkages are also a response to the increasing complexity of new products and processes. Many new products incorporate a large number of individual components. A personal computer, for example, contains a microprocessor, memory, a hard disk drive, a floppy disk or diskette drive, a keyboard, and a monitor. Manufacturing each of these components requires its own individual expertise, as does the process of linking them together in a properly functioning computer. The maker of microprocessors must be skilled in logic design, circuit layout, timing analysis, and semiconductor manufacturing techniques. The disk drive manufacturer must understand the fabrication and operation of read/write heads, servo mechanisms, controllers for maintaining alignment of the read/write heads and the disk, and precision assembly.

Complex technologies such as these—containing many components with numerous linkages between them—now account for the majority of world trade. Between 1970 and 1990, complex products manufactured with complex processes are estimated to have grown from 31 percent to 51

[62] "Scaling the Silicon Summit," *Electronic Engineering Times*, Apr. 4, 1994, p. 30.

[63] This figure represents an average cost for new product development that incorporates both successes and failures. Joseph A. DiMasi, "Risks, Regulation, and Rewards in New Drug Development in the United States," *Regulatory Toxicology and Pharmacology*, vol. 19, 1994, pp. 228-235. For a more detailed discussion of pharmaceuticals' R&D costs, see U.S. Congress, Office of Technology Assessment, op. cit., footnote 12.

[64] It should be noted, however, that Airbus often receives subsidies and preferential treatment from national governments of participating companies.

TABLE 3-6: Source of Innovation for Selected Technologies

	Innovation developed by:			
Innovation type	User	Manufacturer	Supplier	Other
Scientific instruments	77%	23%	O%	O%
Semiconductor and printed circuit board processes	67	21	0	12
Pultrusion processes	*90*	10	0	0
Tractor shovel-related	6	94	0	0
Engineering plastics	10	90	0	0
Plastics additives	8	92	0	0
Industrial gas—using	42	17	33	8
Thermoplastics—using	43	14	36	7
Wire termination equipment	11	33	56	0

SOURCE: Eric von Hippel, *The Sources of Innovation (New* York, NY: Oxford University Press, 1988), table 4-1, pp. 44.

percent of the value of the top 30 exports in world trade. Simple products declined from 58 percent of exports in 1970 to just 12 percent in 1990.[65] Complexity challenges the capabilities of individual companies, often prompting interfirm collaboration. Suppliers are one source of expertise. Not only do they improve the performance or cost of the components they produce, but they often generate innovations in end products that, in turn, stimulate demand for their own components. One study found that suppliers of electrical connectors developed 56 percent of the innovations in wire termination equipment; machine manufacturers developed only 33 percent.[66] Customers or end-users can also be the source of innovation, providing feedback to manufacturers on product improvement (see table 3-6).

MARKETS

Although most new products are developed in response to expressed or anticipated market demand, firms must still actively cultivate markets for their products, especially for those that represent a large departure from current offerings. Sometimes demand is latent. Potential customers may not understand the uses and advantages of a new technology. Or an innovation's usefulness to a customer is dependent on the presence of other users (e.g., a fax machine is only useful if others have fax machines); other technologies (e.g., computer hardware needs software); or other changed circumstances (e.g., a cleaner production process may be more attractive if pollution standards have tightened). Cost can also deter consumers. Technologies that are interesting or products that are technically superior to existing alternatives do not necessarily become market successes. Technical successes can easily be market failures.

Though generally associated with the private sector, market creation can be—and is—influenced by numerous government activities. Institutional arrangements-sometimes involving government policy, as in the case of health care—shape markets for new technology. Regulations, such as those to promote environmental protection and safety, often create incentives to purchase new types of products or services, or

[65] Don Kash and Robert W. Rycroft, "Nurturing Winners with Federal R& D," *Technology Review*, November/December 1993, pp. 58-64. Complex technologies are those with numerous components assembled together, such as computers, automobiles, and industrial machinery. Simple technologies have few assembled components, such as chemicals, drugs, foods, and metals. Simple technologies can sometimes be "high-tech," as in the case of biotechnology-derived drugs and chemicals, and advanced materials.

[66] Eric von Hippel, *The Sources of Innovation* (New York, NY: Oxford University Press, 1988), pp. 36-38.

adopt new manufacturing processes. Government procurement frequently provides initial markets for new products and processes, giving manufacturers an incentive to invest in production capacity and an opportunity to demonstrate product performance and reliability. Changes in the tax code create incentives for users to purchase particular types of products or to vary their consumption patterns accordingly. Many of these influences result from the day-to-day activities of government and exemplify the close intertwining of public- and private-sector forces in shaping technology development and implementation. Although at times government activities have retarded the development of commercial technologies, they also have played a critical role in launching many of the nation's most important industries, from aircraft to semiconductors.

Institutional Issues

Institutional arrangements, often involving government, shape markets for innovative technologies. For instance, the market for medical technologies is shaped by a system in which those who prescribe treatment (physicians and other providers), pay for treatment (usually insurance, Medicare, Medicaid, or health maintenance organizations), and seek treatment for health concerns (patients) are different parties with different incentives. Because of this third-party payer system, markets exist for expensive drugs, devices, and procedures that might otherwise be unaffordable to many who need them. The growing cost-consciousness of payers, consumers, and government is motivating medical technology innovators to analyze coverage and reimbursement issues earlier and more carefully in the development of drugs and devices and in the approval process.

In commercial satellite communications, users benefited from federal establishment of the Communication Satellite Corp. (COMSAT) as a quasi-public company to guide communication satellite system development and oversee U.S. participation in INTELSAT, an international consortium.[67] Leasing arrangements may promote or impede new technologies, depending on circumstances: landlords have little incentive to improve the energy efficiency of their buildings when tenants pay for energy, and tenants may balk at improving a landlord's property at their own expense. In contrast, leasing arrangements for capital goods and office equipment can facilitate the demand for new or upgraded technologies. For potential users, such arrangements lower the costs and risks of trying new technology without diminishing producer incentives for innovation.

Regulation[68]

Regulations can create markets for new technologies by requiring products and processes to meet certain standards. Technological responses to regulation sometimes take the form of discrete devices or services for meeting regulatory requirements (e.g., pollution control devices, safety apparel, automatic seatbelts, or aircraft flight data recorders). In other cases, regulations induce modifications to core products and process technologies, such as "no clean" soldering to avoid solvents, energy-efficient appliances, less toxic pigments, automated processes to avoid worker exposure to hazardous chemicals, and cleaner burning motor fuels. The distinctions between add-on devices and core product or production technologies are fuzzy. It is difficult to discern, for instance, whether redundant avionics and electronic fuel injectors are add-on or integral technologies for aircraft and automobiles, or whether their markets are determined by regulatory demands or good engineering design.

Markets for energy and environmental technologies are especially influenced by regulations, at both the federal and state levels. The Public Utility Regulatory Policy Act (PURPA) of 1978, for example, requires electric utilities to buy power

[67] That industry also benefited from NASA support, including the use of federal launch and other facilities.

[68] This section concentrates on regulations pertinent to the environment, health, and safety.

from nonutility heat and electricity cogenerators and from small power producers at the avoided cost of the utility's power. By doing so, the legislation spawned the establishment of independent power producers and stimulated markets for cogeneration equipment, gas turbines, and certain renewable energy technologies.[69] In a similar vein, California's new automobile regulations (also adopted by Massachusetts and New York) require that zero-emission vehicles account for at least 2 percent of automobile sales from major producers by 1998 and 10 percent by 2003. This policy has led to significant efforts by vehicle manufacturers, suppliers, and industry outsiders to develop automobiles with alternative fuel and power systems. Likewise, the Energy Policy Act of 1992 requires certain federal, state, and private fleets to choose alternatively fueled or powered vehicles for certain percentages of their new vehicle purchases during the late 1990s and early 2000s.[70]

Regulations can also impede technological innovation; in fact, some critics argue that regulatory impediments to innovation undermine the health, safety, and environmental goals they are meant to further.[71] This can happen if particular technologies or products do not meet the requirements of new regulations, or if the costs of doing so are so great as to impede technology development. Product approval requirements, as in the case of pharmaceuticals and pesticides, can delay or prevent new products from coming to market, though such delays are intended to minimize the chance of dangerous or ineffective products being marketed. Regulatory systems that grandfather existing facilities may dissuade investments in new or upgraded technologies if such changes trigger more stringent standards or lengthy permitting processes.

Furthermore, regulations can be written or administered in ways that favor tried-and-true technologies over more uncertain innovations. When permitting procedures are lengthy, costly, or uncertain, firms cannot easily alter processes or introduce new products.[72] Product reviewers and permit writers may act conservatively because of professional risks associated with approving untried technologies. Separate permitting procedures for each state or locality—as is common under environmental regulations—adds cost, time, and uncertainty. Such differentiation fragments the market and burdens new technology vendors—particularly small companies—and can diminish the interest of venture capitalists and other investors.[73] Also, most regulations do not reward innovators who exceed performance requirements.

Regulations that are overly prescriptive can lock in existing technologies to the detriment of other technologies that might also meet or exceed

[69] A number of utilities claim, however, that PURPA and state provisions led them into long-term supply contracts with independent power producers that became less economical as energy prices decreased. Agis Salpukas, "70's Dreams, 90's Realities—Renewable Energy: A Luxury Now. A Necessity Later?" *New York Times*, Apr. 11, 1995, pp. D1, D8; U.S. Congress, Office of Technology Assessment, *Energy Efficiency: Challenges and Opportunities for Electric Utilities*, OTA-E-561 (Washington, DC: U.S. Government Printing Office, September 1993), p. 41. PURPA, the Public Utility Holding Company Act, the Energy Policy Act, state law, and state public utility commissions impose numerous economic regulations regarding rate-setting, utility planning, competition, and other aspects of utility governance. These significantly influence the market for energy efficiency and alternative energy technologies.

[70] It is too early to measure the costs or effectiveness of these vehicle technology mandates. It is worth noting that these vehicle- and power-purchasing requirements do not mandate purchases of a particular narrow technology. Most of the requirements can be met through a variety of technical routes. One exception is the California zero emissions vehicle standard, which effectively mandates electric vehicles. Even here, however, a number of competing battery, recharging, and propulsion technologies vie for the prospective market. Another OTA assessment, "Advanced Automotive Technologies" (forthcoming), examines technological possibilities for future automobiles.

[71] For example, Sam Kazman, Competitive Enterprise Institute, presentation at "BioEast'95," Washington Hilton and Towers, Washington, DC, Jan. 10, 1995.

[72] For permitting barriers to innovative environmental technologies, see U.S. Environmental Protection Agency, op. cit., footnote 19.

[73] Dag Syrrist, Technology Funding, testimony before the Senate Committee on Environment and Public Works, May 21, 1993.

requirements. Some U.S. environmental, health, and safety regulations mandate the use of particular devices or methods (so-called technology- or design-based standards), though most regulations are theoretically performance-based (i.e., they establish a standard to be met, rather than a means for meeting the standard). However, even performance-based standards are frequently based on established reference technologies. In such cases, companies and regulators are likely to prefer reference technologies they are confident will meet standards, rather than innovative approaches that are less certain.

Many of these problems can be overcome with proper formulation, interpretation, and enforcement of regulations. In the environmental arena, several proposals and regulatory experiments have been implemented to simultaneously lower compliance costs, maintain or improve environmental performance, and improve the climate for technological innovation. Some of the approaches give companies flexibility to meet overall facility emissions and effluent requirements without requiring detailed permitting of each source at the facility. In New Jersey, for example, a pharmaceutical plant was recently issued a single permit in place of numerous individual air, water, and waste permits. In Minnesota, the state's environmental agency issued a flexible permit for certain air pollutants to a 3M plant in St. Paul. It allows the firm to modify processes without requiring repermitting if it gives the agency 10 days' advance notice and stays within facility-wide emissions limits.[74] Tradable pollution allowances, such as those authorized under the Clean Air Act Amendments of 1990 to govern sulfur dioxide emissions from power plants, also add regulatory flexibility and may lower compliance costs, although the effect on innovation is not yet clear. In the pharmaceutical arena, the FDA has proposed dropping preapproval requirements for certain changes in pharmaceutical production processes.[75] These and other related efforts do not directly promote markets for innovative technologies, but they may remove impediments to changes.

Another approach is to offer companies waivers that allow limited environmental noncompliance, or reduced penalties for noncompliance, when innovative technologies are tried or developed, but do not quite meet the mark.[76] Such "fail-soft" approaches would still need safeguards to ensure protection of public health and the environment, and to prevent abuse. Participation might be limited to firms with good compliance records, similar to the Occupational Health and Safety Administration's (OSHA's) Star program that allows eligible firms greater compliance flexibility.[77] Overall, such efforts could enable regulators to protect public safety and the environment, while encouraging technological innovation.

Government Procurement

Government procurement can also create markets for new technologies. Aircraft, integrated circuits, computers, satellites, biotechnology products, and some energy technologies all received significant boosts from government purchases. Such procurement can provide potential developers of new technology with sufficient assurances of a market to make it attractive for them to invest in production facilities. By acting as a launch customer, the government provides manufacturers with the early revenues, scale economies, experience, and user feedback they need to improve their products and make them affordable for commercial users. Early government use may also demonstrate the performance of new technology for

[74] U.S. Congress, Office of Technology Assessment, op. cit., footnote 18, p. 275.

[75] David J. Hanson, "Clinton Unveils Environmental and Pharmaceutical Regulation Reform," *Chemical and Engineering News*, vol. 73, No. 14, Apr. 3, 1995, pp. 15-16.

[76] U.S. Environmental Protection Agency, op. cit., footnote 19.

[77] U.S. Congress, Office of Technology Assessment, op. cit., footnote 18, p. 277.

potential commercial users, stimulating future demand. Nevertheless, there are limitations to relying on government procurement to commercialize new technologies to civilian markets.

Federal purchases were a major impetus for the commercialization of integrated circuits (ICs). Though integrated circuits were developed by private industry without government funding or direction, commercial firms were hesitant to use them because of their higher cost and uncertain long-term reliability. IBM, for example, opted to use "hybrid" integrated circuits—a stepping stone between discrete components and full integration—in its 360 series computers because existing vendors had not yet demonstrated an ability to manufacture ICs at the scale and quality IBM required.[78] The first uses of ICs were in the guidance system of NASA's Apollo spacecraft and DOD's Minuteman intercontinental ballistic missile systems.[79] Government users were willing to pay high prices for the miniaturized components because they provided a capability essential to the success of government missions.[80] These early government markets provided manufacturers with early incentives for investing in production facilities, and funded further improvement in IC capability and great decreases in cost. This led to a greatly expanding commercial IC market. During the decade from 1962 to 1972, the government share of the IC market dropped from 100 percent to one-third or less, while IC capabilities increased greatly and costs decreased (in current dollars) from $50 to a little more than $1 per IC.[81]

Military procurement has benefited other industries as well. Innovation in the aircraft industry was strongly influenced by military demand, although postal air mail contracts in the 1920s also provided a market. Commercial satellites, computers, and a host of other products are regarded as spin-offs of military and space efforts. Penicillin was first produced in large quantity for defense needs, although its initial development was not a military project. During World War II, the federal government bought all American production of penicillin at very high prices.[82] Although the market price for penicillin collapsed after the war, a firm foundation for innovation and commercial leadership in antibiotics and pharmaceuticals generally had emerged in the United States.

Civilian government procurement also has an impact. For instance, the National Institutes of Health (NIH) and other federal agencies support a market for biotechnology products, specialized reagents, and instruments to fill research needs. Such products are now sold to commercial researchers and for diagnostic and clinical use. In the case of alglucerase, an enzyme used for treating a rare genetic ailment called Gaucher disease, NIH procurement from an academic laboratory led to the creation of a biotechnology company that used the revenues and its increasing expertise

[78] Charles H. Ferguson and Charles R. Morris, *Computer Wars: How the West Can Win in a Post-IBM World* (New York, NY: Random House/ Times Books, 1993), pp. 8-9.

[79] Thomas R. Howell, Brent L. Bartlett, and Warren Davis, *Creating Advantage: Semiconductors and Government Industrial Policy in the 1990s* (Semiconductor Industry Association and Dewey Ballantine, 1992), pp. 25-26, fn. 35.

[80] A Philips executive is reported to have said: "This thing [a very early integrated circuit from Texas Instruments] only replaces two transistors and three resistors and costs $100. Aren't they crazy!" See Ernest Braun and Stuart Macdonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics* (New York, NY: Cambridge University Press, 1978), p. 113.

[81] Ibid.

[82] Basil Archilladelis, "The Dynamics of Technological Innovation: The Sector of Antibacterial Medicines," *Research Policy*, vol. 22, 1993, pp. 279-308. During the war, the federal government paid producers cost plus $20 per dose. When commercial sales were permitted in 1946, prices dropped to $1 per dose and, by 1949, to 10 cents.

to commercialize the drug.[83] Federal funding of academic institutions, as well as government laboratories, also promotes initial markets for high performance computers and scientific instruments that may then be adapted for commercial requirements.

The day-to-day operations of government—as a major user of energy, motor vehicles, buildings, office equipment, paper, and so on—also open up opportunities for using the government's buying power to facilitate new technology commercialization. As the federal government is the largest user of energy in the nation, a number of laws and Executive Orders have been promulgated since the mid-1970s to try to improve federal energy efficiency.[84] The most recent examples are the Energy Policy Act (EPACT) of 1992 and Executive Order 12902 on Energy Efficiency and Water Conservation in Federal Facilities. By serving as a testbed for innovative technologies, government facilities may reduce the federal government's energy bill and demonstrate performance for wider markets (though many of the cost-effective energy efficiency options are already commercially available[85]). Executive Order 12873 on Federal Acquisition, Recycling and Waste Prevention, which promotes federal purchases of environmentally preferable goods, may also stimulate markets for new technologies and products, though it is difficult to predict the effectiveness of such procurement standards in areas in which the federal government represents only a small portion of the market.

While the ability of government to pay a premium for products that meet defense and space program needs can be a springboard for commercial technology spin-offs, government market needs can also lead producers away from commercial markets. Military needs are often specialized or unique, and may not match civilian market demands. High technology military production often occurs at relatively low production rates and emphasizes product characteristics that have little commercial utility. Commercial producers, in contrast, usually look for frequent process improvements that allow lower cost, high-volume manufacturing. These and other differences between military and civilian needs suggest important limitations to relying on defense-related procurement, and more generally, defense-related technology transfer for spin-offs to the commercial sector.[86] Overreliance on specialized government markets has been implicated in the demise of some firms and technologies. For instance, Thinking Machines Corp., a developer of high-performance computer systems, was forced into bankruptcy reorganization at least in part because it concentrated its efforts on the needs of government clients instead of potential commercial users of scalable parallel computers.

Tax and Credit Provisions

Tax provisions, subsidized or facilitated tax credits, loan guarantees, and other subsidies also influence commercialization by channeling economic activities. Some provisions specifically target technological change, while others address broader economic activities (e.g., capital investment)[87] that indirectly provide incentives for new technologies. Such provisions may simultaneously serve a goal of stimulating new technology markets

[83] U.S. Congress, Office of Technology Assessment, *Federal and Private Roles in the Development and Provision of Alglucerase Therapy for Gaucher Disease*, OTA-BP-H-104 (Washington, DC: U.S. Government Printing Office, October 1992).

[84] U.S. Congress, Office of Technology Assessment, *Energy Efficiency in the Federal Government: Government By Good Example?* OTA-E-492 (Washington, DC: U.S. Government Printing Office, May 1991).

[85] Ibid., p. 3.

[86] Alic et al., op. cit., footnote 17, pp. 43-44.

[87] For instance, capital investment may be affected by tax rates on income and capital gains, by depreciation and amortization provision, and—in the past when they were in force—investment tax credits.

while assisting certain user industries, such as small business. For instance, the Japanese government and some quasi-public bodies have provided subsidized credit and leases since the 1980s to help small and medium-sized companies modernize. These measures also stimulated markets for advanced manufacturing technologies such as numerically controlled machine tools, robots, and computers.[88]

Tax provisions can interact with consumer preferences and other market factors to propel markets for certain technologies in some countries, while demand remains low in others. A case in point is the commercialization of electronic fuel injection (EFI) for automobiles (see box 3-6). Taxes on automobiles by engine displacement and high taxes on fuel were significant factors leading to earlier commercialization of EFI in Europe than in the United States. They also may have contributed to a foreign EFI supplier capturing the technological lead from an American innovator.

Tax and other provisions work on both the supply side and demand side of technology development, as exemplified by the research and experimentation tax credit on the one hand, and tax credits for purchase or use of particular types of technologies in certain industrial sectors on the other. The current tax code contains at least 17 provisions that may affect technological development through incentives for research, purchases of particular products, or investments in certain industries, not including general provisions such as tax rates and alternative minimum taxes (see table 3-7). Many of these provisions are related to energy and environmental technologies, reflecting the strong regulatory role the government maintains in these areas and the energy crisis of the 1970s, which placed a premium on developing alternative energy sources and reducing energy consumption. Only the research and experimentation tax credit is more widely applicable to U.S. industry.

Tax provisions that favor certain activities or industries are often considered market distortions that produce an inefficient allocation of resources; some tax provisions, however, correct for costs borne by those outside a particular market or by society as a whole, such as pollution costs or national security costs associated with high reliance on imported petroleum. Often such negative externalities are dealt with through regulations; in some cases, fiscal incentives in the form of taxes and tax breaks may yield results that are more cost-effective and promote innovation more than conventional regulatory approaches.[89] Fiscal incentives can allow firms to be more flexible in the means by which they meet standards and can give companies incentives to do better than standards require.

Tax credits or deductions can be costly to government. Every dollar of forgone tax income is equivalent to an additional dollar of expenditures. The investment tax credit cost between $13 billion and $37 billion each year between 1979 and its elimination in 1987. Accelerated cost recovery, which is still available for some classes of assets, cost as much as $64 billion in 1987.[90] Also, taxes forgone may or may not efficiently lead to desired innovation or investment. For instance, the investment tax credit stimulated between $0.12 to $0.80 in additional equipment investment for every dollar forgone by the Treasury, according to a number

[88] U.S. Congress, Office of Technology Assessment, *Making Things Better: Competing in Manufacturing*, OTA-ITE-443 (Washington, DC: U.S. Government Printing Office, March 1990), pp. 162-166.

[89] A discussion of this can be found in U.S. Congress, Office of Technology Assessment, op. cit., footnote 18, ch. 9; and another OTA assessment, *Environmental Policy Tools: A Users Guide* (forthcoming).

[90] Joint Committee on Taxation, Estimates of Federal Tax Expenditures, Fiscal Years, Annual.

BOX 3-6: Electronic Fuel Injection: Tax Provisions and Market Forces

Electronic fuel injection (EFI) for gasoline-powered automobile engines, while patented by a U.S. firm, was commercialized more quickly in Europe. To some extent, institutional factors were responsible. In the vertically integrated U.S. auto firms, carburetor divisions resisted EFI because it would make their technology obsolete; European auto manufacturers, on the other hand, outsourced carburetors and could readily switch to EFI. For the most part, however, the faster commercialization in Europe resulted from more favorable market conditions.

U.S. and European firms developed mechanical fuel injection first for airplanes and then for racing cars. Users were willing to accept the fuel injectors' high cost and weight because they provided engine power critical to their missions. Bendix Corp. patented the first EFI system for automotive use in 1961, having transferred the technology from its aerospace division to its automotive division.

While EFI promised several advantages over carburetor technology in automotive applications—smaller size, improved performance (faster acceleration), improved fuel efficiency, and reduced exhaust emissions—these attributes were not valued highly by either manufacturers or drivers in the United States. Most drivers were content to purchase larger cars with larger engines in order to get improved performance; interest in fuel efficiency did not grow until the oil shocks of 1974 and 1979 and the imposition of CAFE (corporate average fuel efficiency) standards in 1975. Though the U.S. Environmental Protection Agency (EPA) promulgated emission regulations in 1970, they could be easily met by adding electronic controls to carbureted engines. Only in the mid-1980s—when European and Japanese manufacturers demonstrated that properly designed and tuned EFI systems could meet more stringent fuel economy and emissions standards, while improving performance without Increasing manufacturing costs---did EFI become popular in the United States.

EFI achieved earlier success overseas because of differences in market demand. European drivers typically valued performance and handling more than American drivers, and saw the benefit of extracting greater power from a smaller engine. This tendency was reinforced by taxes assessed on vehicles in proportion to engine displacement in Europe during the 1960s and 1970s. Higher gasoline taxes in Europe also gave drivers an incentive to seek improved fuel economy even without government regulation. Bosch GmbH, a German auto parts supplier, licensed EFI from Bendix in 1967, and began supplying the technology to Volkswagen in 1968 (and later to other European manufacturers). By the time U.S. consumers demanded EFI in their vehicles, Bosch was well positioned to capture a large share of the global market.

SOURCE: Kevin Beaty, "Electronic Fuel Injection, " unpublished contractor report prepared for the Office of Technology Assessment, U S Congress, Washington, DC, June 1995

of estimates.[91] Increased income and tax revenues resulting from the additional capital investment are less certain.

Inadequate design of tax provisions can limit their effectiveness in achieving a desired policy goal. For example, federal tax credits for residential investments in renewable energy and energy efficiency between 1977 and 1985 were limited to add-on equipment such as weather-stripping, storm windows, and solar water heaters. Certain energy-efficient and solar features integrated into building architecture to serve both energy and

[91] Joseph J. Cordes, "The Effect of Tax Policy on the Creation of New Technical Knowledge: An Assessment of the Evidence," in Richard M. Cyert and David C. Mowery (eds.), *The Impact of Technological Change on Employment and Economic Growth* (Cambridge, MA: Ballinger, 1988), and Robert Chirinko and Robert Eisner, "Tax Policy and Investment in Major U.S. Macroeconomic Models, ''*Journal of Public -Economics.* March 1983.

TABLE 3-7: Tax Code Provisions for New Products and Technologies

U.S. Code Annotated, title 26, section(s):	Section title and description
23	*Resident/a/Energy Credit (repealed Nov. 5, 1990 by Public Law* 101-508)—provided nonrefundable credits of 15% for energy conservation and 40% for renewable energy for qualified residential investments,
28	*Clinical Testing Expenses for Certain Drugs for Rare Diseases or Conditions*—nonrefundable 50% credit for clinical testing expenses for orphan drugs; such expenses cannot be applied to research tax credit (section 41) simultaneously, although it counts toward base expenses,
29	*Credit for Producing Fuel from a Nonconventional/ Source—$3* per barrel of oil equivalent credit adjusted for Inflation and real 011 prices for certain unconventional oil and gas production; repealed for certain biomass energy; credit reduced by value of other federal, state, or local credits, grants, subsidies, and tax-free bonds,
30	*Credit for Qualified Electric Vehicles*---- 10% of cost, up to $4,000 per vehicle put in service, credit phases down during years 2002 to 2004.
40	*Alcohol Used as Fuel*— $0.60 refundable credit per gallon for alcohol used as or in fuel; $0,45 per gallon for 150-190 proof alcohol; an additional $0.10 per gallon for qualified small producers; terminates Dec. 31,2000,
41	*Credit for Increasing Research Activities*-----20% refundable credit on qualified research and experimentation expenses above a base amount (this credit has required annual renewal).
43	*Enhanced Oil Recovery Credit*—-- 15%. refundable credit on qualified enhanced (tertiary recovery) 011 recovery costs; phased down as real oil price increases,
45	*Electricity Produced From Certain Renewable Resources*—$0.015 per kilowatt hour for electricity generated by wind or closed-loop biomass systems; credit good for the first 10 years of a facility built before July 1, 1999; phased down with real electricity price increases; credit reduced by value of other government credits, grants, subsidies, tax-free bonds.[a]
48(a)	*Energy Credit*— 10% credit on portion of energy facility for certain solar heat, hot water, cooling, electric and geothermal electric investments; credit reduced by value of other government credits, grants, subsidies, tax-free bonds
136	*Energy Conservation Subsidies Provided by Public Utilities* - deductions for utility subsidies for purchase and Installation of listed industrial, commercial, and residential energy conservation equipment; 100% for residential equipment, for nonresidential equipment, 40% in 1995, 50% in 1996, 65% thereafter
174	*Research and Experimental Expenditures*— such expenditures can be treated as deductible expenses
179A	*Deduction for Clean-Fuel Vehicles and Certain Refueling Properties*----up to $2,000 per car, $5,000 per medium truck, $50,000 for heavy trucks and buses; deductible for acquisition or retrofit to run on certain alternative fuels other than electricity; deduction phases down *25%* in 2002, 50% in 2003, 75% in 2004; up to $100,000 deductible per location for alternative fuel refueling and electric vehicle recharging facilities,
193	*Tertiary Injectants*— deduction for certain materials injected for tertiary oil recovery
611, 612, 613, 613A	*Depletion allowances* for mines, oil and gas wells, other natural deposits, and timber.
616, 617	*Deductibility of certain development and mining exploration expenses.*
4041	*Lower taxes for alcohol fuels relative to gasoline and diesel fuel.*
4064	*Gas Guzzler Tax*— schedule of excise taxes on automobiles rated at fewer than 22.5 miles per gallon; tax Increases from $1,000 to $7,700 as fuel economy decreases,
4681, 4682	*Tax on Ozone-Depleting Chemicals*--- taxes on ozone depleting chemicals phased out under *law.*

[a] The Energy Policy Act of 1992 (Public Law 102-486), Section 1212, provides for the Department of Energy to pay $0.015 per kilowatt hour for qualified renewable electricity production for the first 10 years of production.

NOTE: This list is not necessarily complete. Other general provisions of the tax code and Alternate Minimum Tax provisions may affect new technology markets. Some of the provisions listed above directly affect incentives for research and development, rather than the purchase of new technologies.

SOURCE: Office of Technology Assessment, 1995.

structural purposes were disallowed by the Internal Revenue Service (IRS)—even though integrated features were a more efficient means to achieve national energy goals.[92] Also, credits were offered on the basis of dollars spent on certain technologies, rather than on the performance (amount of energy saved) of those technologies. Even if Congress and the IRS considered these issues at the time residential energy credits were in force, it might still have been difficult for the IRS to decide whether or not a window should be considered a passive solar energy collection device and to determine the actual energy savings resulting from residential energy investments.

Other Market Incentives

Purchase commitments, bounties, and other incentives from potential users of a new technology can also speed commercialization. Such approaches may allow the private sector alone, or with some government support, to help bridge the gaps between R&D, manufacturing, and initial sales, while ameliorating risks for developers and earliest users. Several examples from the energy technology arena follow:

1) Following successful field demonstrations of gas-fired residential heat pumps, a consortium of gas utilities provided $14 million in incentives for the first three years' sales of the devices.[93] In return for the support of utility companies, the manufacturer will begin reimbursing utilities after the 50,000th unit is sold. The manufacturer benefits from promotion of the new technology by the gas utilities, who then benefit by being better able to compete with electric utilities. Early customers benefit from a utility subsidy, as well as any advantages the technology may offer over rival options.
2) Electric utilities took the lead in offering a $30 million bounty—termed a *golden carrot*—to manufacturers for developing and commercializing high-efficiency refrigerators that did not use chlorofluorocarbons as their coolant.[94] The winning manufacturer, Whirlpool, collects the reward as it markets the award-winning models in the service areas of the 24 participating utilities. Golden carrot competitions are planned for other appliances as well.
3) Energy utilities are also participating in innovative commercialization approaches for new power generation technologies. The Fuel Cell Commercialization Group (FCCG) links gas and electric utilities in the United States and Canada as a buyer's group.[95] FCCG members, a fuel cell manufacturer chosen by FCCG on the basis of a winning development and commercialization proposal, the Electric Power Research Institute, and DOE participate in technology development, demonstrations, exchange of information, and the establishment of project milestones. As an incentive to buy early demonstration and commercial units, manufacturers have agreed to pay FCCG members royalties on later sales. This arrangement helps defray the risks of early participation. The manufacturer agrees to meet certain cost and technical criteria before receiving payment from FCCG buyers.
4) The Utility PhotoVoltaic Group (UPVG) and the Utility Biomass Energy Commercialization Association (UBECA) are other utility-led efforts to move technologies out of the

[92] For instance, 26 CFR Part 1 Sec. 1.23-2(e)(3) disallows dual-use features such as windows and greenhouses as "solar energy properties" within the meaning of the tax provision.

[93] Howard Geller and Steven Nadel, "Market Transformation Strategies To Promote End-Use Efficiency," *Annual Review of Energy and Environment*, vol. 19, 1994, pp. 301-346.

[94] Ibid.

[95] Fuel Cell Commercialization Group, *FCCG Update*, vol. 5, No. 1, spring 1994.

laboratory and into the market by involving potential buyers in late development, demonstration, and early purchases.[96] UPVG plans to catalyze early sales of photovoltaic systems by sharing technical information with potential users, aggregating purchases for some small-scale applications, and proposing private-public cost-shared projects that can lead to wider, higher volume commercial markets.

Buyers' commitments to precommercial technologies do not guarantee successful commercialization. In the 1960s, U.S. airlines committed $60 million to develop the supersonic transport (SST), in partnership with airframe and engine manufacturers and the federal government (which spent nearly $920 million over about a decade).[97] At its peak in 1967, airlines reserved 129 delivery positions for the SST—most required $200,000 refundable deposits, although the last 16 positions required nonrefundable $750,000 payments. The SST project failed to meet technological and commercial goals and faced high cost overruns; nevertheless, the government did not terminate the program. The government continued to fund development of the SST despite industry's resistance to providing matching funds of 25 percent in 1963 and the lowering of the private cost-share requirements to 10 percent in 1967. In contrast, most recent U.S. public-private cost-shared technology programs have featured 50 percent or greater private shares.

The energy utility sector appears prominently in this discussion on commercialization incentives not because utility managers are necessarily more imaginative than executives in other sectors, but because energy utilities are highly regulated entities (financial as well as environment, health, and safety regulations) in which numerous technological, institutional, regulatory, and tax provision changes have recently or are currently taking place. In many states, public utility commissions have made changes in utility governance that make conserving energy an attractive alternative to increasing production capacity. In some cases, utilities are allowed to earn a financial return on energy saved; a number of other utilities are finding that increasing capacity can be costly, lengthy, and uncertain due to both regulatory requirements and the resistance of local residents to new facilities. Also, the federal tax code allows utilities to deduct certain energy-efficient subsidies provided to customers (26 U.S.C. 136). These circumstances have allowed or encouraged utilities to prime markets for new energy-efficient technologies through rebates, bounties, technical assistance, and bulk buying. Although energy utilities operate under conditions different from other industries, there may be opportunities for nontraditional commercialization approaches in other industries as well.

CONCLUSION

Successful innovation and commercialization depend on far more than a strong science and technology base. Commercialization is a business decision based on reasoned judgments about future returns from investments in product design and development, manufacturing, marketing, and distribution. The size of these returns—and hence the incentives for firms to commercialize new technology—depends on a number of factors beyond the boundaries of individual firms. The availability of capital, the size and nature of markets, and the existence of complementary assets all influence the ability of firms to commercialize new technologies. Firms often have little control over these factors, or little incentive to adapt them to their needs. The effort required is often too extensive and the benefits are often too diffuse for

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[96] Utility PhotoVoltaic Group, "The TEAM-UP Request for Proposals," fact sheet; Utility Biomass Energy Commercialization Group, *Biomass Bulletin*, vol. 1, No. 1, autumn 1994.

[97] Susan A. Edelman, "The American Supersonic Transport," in Linda R. Cohen and Roger G. Noll (eds.), *The Technology Pork Barrel* (Washington, DC: The Brookings Institution, 1991), ch. 6, pp. 97-147.

any one firm to capture. Attempts to improve U.S. capabilities in commercializing emerging technologies must recognize both the importance of such factors and the need for new forms of interaction among industry, government, and universities to address them.