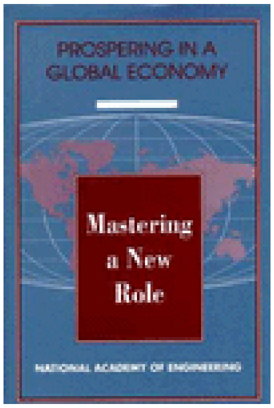

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Mastering a New Role

Shaping Technology Policy for National Economic Performance

Committee on Technology Policy Options in a Global Economy

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Preface

In recent years the national debate about technology policy has revolved around the relative roles of government, industry, and universities; of science and technology; and of defense and nondefense agencies. Governmental, academic, and industrial institutions, at the heart of our nation's technological enterprise, are midstream in a profound and sometimes wrenching reexamination of their missions and responsibilities as they seek changed roles in a new and unfamiliar world—a world without a Cold War but with new levels of global economic integration and and technological interdependence. There is a widespread recognition that U.S. economic performance and national security are intimately tied to the nation's ability to adjust its government policies and private-sector practices to a world economy rapidly being changed by transborder flows of goods, services, technology, and capital.

This report of a committee of members of the National Academy of Engineering addresses both goals for national technology policy and promising paths along which to pursue those goals. The report reaches back in time to World War II and examines the genesis of our nation's current policies. With that background, and bringing to bear some of the most recent experience and scholarship about how technology is used by successful companies to drive economic growth, the report argues that it is time for the U.S. government to master a new and unfamiliar role in helping the private economy develop and diffuse technology *explicitly* for purposes of enhanced economic performance.

On behalf of the National Academy of Engineering, I would like to thank the cochairmen—John Foster and Harvey Brooks—and the other members of the committee (named on p. iii) for their considerable efforts on this

project. In particular, I would also like to thank Proctor Reid, the study director, who managed the project and helped elicit consensus among the committee members. Alexander Flax, NAE senior fellow, and Bruce Guile, director of the NAE Program Office, provided their valuable insights to the committee and the study director over the course of the project. Kathryn Jackson, former NAE fellow, contributed to the committee's work during the early stages of project, and several members of the NAE Program Office, past and present, deserve thanks for their help, including Barbara Becker, Penelope Gibbs, Margery Harris, H. Dale Langford, and Annemarie Terraciano. Funding for this effort was provided by the Alfred P. Sloan Foundation and the National Academy of Engineering Technology Agenda Program.

ROBERT M. WHITE
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Executive Summary

Increasing both the productivity and the growth rate of the U.S. economy are priority national goals. The performance of the nation's technology enterprise—its collective capacity for creating, developing, and deploying new technology—is a key factor in the attainment of these goals. The principal challenge facing the U.S. technology enterprise is to work with other elements of the national economy to improve U.S. economic performance. The burden of meeting this challenge lies primarily with private companies operating in competitive markets. However, both state and federal governments must contribute significantly to this mission by stimulating more effective development and use of technology throughout the economy.

This report describes the demands placed on the U.S. technology enterprise as a consequence of changes in the global economy. It proposes a national technology strategy explicitly aimed at advancing national economic development and recommends policies to pursue that strategy.

TRENDS AND CHALLENGES

The competitive environment for U.S.-based companies is being recast by a number of powerful trends:

- The technical intensity of most manufacturing and service industries will continue to grow at an accelerating pace, and commercial technology will become increasingly science-based and interdisciplinary (Chapter 2, pp. 29–31).
- National security's claims on the U.S. technology base will continue to diminish, and national defense capability will become increasingly dependent on technologies developed and applied first in the commercial sphere (Chapter 2, pp. 52–54).

- The current revolution in production systems will continue to transform product and service companies and bring a new level of attention to the optimal use of human talents in the workplace (Chapter 2, pp. 31–40).
- International competition will continue to intensify as world industrial and technological capability becomes increasingly distributed among industrialized nations (Chapter 2, pp. 40–44).
- Local and regional clusters of industrial activity—and their associated human, material, and institutional capabilities—will continue to play a major role in national economic performance and exert a countervailing force to rapid internationalization (Chapter 2, pp. 37–40).
- Internationalization of economic and technological activity will, however, continue, deepening the interdependence of national economies and blurring the distinction between the domestic and foreign policies of nations (Chapter 2, pp. 44–52).

These trends reveal weaknesses in the U.S. technology enterprise that compromise the nation's ability to develop, acquire, and use technology to economic advantage. The most important of these weaknesses are

- Outmoded public- and private-sector management philosophies, organizational frameworks, and human resource strategies (Chapter 3, pp. 69–71).
- Insufficient investment in, and poor quality of, U.S. work force training and continuing education, particularly at the nonsupervisory level (Chapter 3, pp. 71–74).
- Inadequate investment by U.S.-based companies in competitive production processes, plant, and equipment (Chapter 3, pp. 74–76).
- Low civilian R&D intensity of U.S. economic activity and the insufficient breadth of the nation's civilian R&D portfolio, including underinvestment in growth- and productivity-enhancing technologies that are high-risk or whose benefits are difficult for individual investors to appropriate (Chapter 3, pp. 76–80).
- Insufficient awareness of, and interest in, technology originating outside their institutional boundaries on the part of many U.S. companies and federal laboratories (Chapter 3, pp. 80–83).
- Lack of a strong institutional structure for federal technology policy in support of economic development and the segregation of technology policy from domestic and foreign economic policy at the federal level (Chapter 1, pp. 18–20, and Chapter 3, pp. 83–84).

GOALS AND POLICY RECOMMENDATIONS

These challenges demand a combined response from the public and private sectors that is more aggressive, coherent, and broadly dispersed across economic sectors than has been the case in the United States in recent decades. If the country is to reverse its recent competitive decline, it must integrate technology policy with domestic and international economic policy more directly while creating working relationships between government and the private sector. Public technology policies for economic development should be shaped by market forces and should enlist market mechanisms and the capabilities of the private sector to the greatest extent possible. Given the difficulty of the task, and the federal government's relative inexperience in technology policies designed explicitly to foster national economic growth, the U.S. approach to technology policy in this arena should be one of aggressive experimentation and continuous learning. This report identifies four specific goals and makes recommendations for the active pursuit of those goals.

Goal: Foster the timely adoption and effective use of commercially valuable technology throughout the U.S. economy.

The committee recommends that the federal government focus the nation's effort to (1) improve business practices that drive the development and application of technology, and (2) increase the scope and effectiveness of the nation's investment in its nonsupervisory work force (Chapter 4, pp. 94–97).

RECOMMENDATION 1: Catalyze the development of a dense national network of public and private providers of industrial modernization services that is capable of meeting the diverse needs, including training, of 20–25 percent of the nation's small and medium-sized manufacturing companies by the year 2000. Expand the National Institute of Standards and Technology's Manufacturing Technology Centers program and State Technology Extension Program as a first step toward this objective.

RECOMMENDATION 2: Support experimentation with a wide range of public and private initiatives at the federal, state, and local levels to increase the quantity and improve the quality of school-to-work transition programs and of job-related training and continuing education for the nation's nonsupervisory work force.

RECOMMENDATION 3: Establish a high-prestige national fellowship program, to be administered by the National Science Foundation, for advanced study of the technical and organizational aspects of manufacturing. Structure the program not only for university graduate students and faculty but also for practitioners from industry.

Goal: Increase civilian R&D investment in the U.S. economy and close emerging gaps in the nation's civilian technology portfolio.

If the United States is to remain a leader in the development and commercialization of new product and process technologies, it must take immediate steps to increase civilian R&D investment (business-funded R&D in particular) in the nation's economy. U.S. companies must expand the scope of their R&D activities in areas downstream from proof-of-concept and integrate R&D with design, production engineering, production, and distribution. In addition, the nation must move to bridge widely acknowledged gaps in the development of growth- and productivity-enhancing technologies. Such technologies often fail to attract adequate private-sector investment because they are high in technical risk or their resulting benefits are widely diffused and difficult for individual investing firms to appropriate. These include high technical risk "pathbreaking" technologies that create new industries or transform existing industries, and low technical risk, difficult-to-appropriate, "infrastructural" technologies that enhance the performance of a broad spectrum of firms or industries.

For these reasons, the committee recommends that the federal government, building on the lessons of recent policy experiments, take the following actions (Chapter 4, pp. 97–99):

RECOMMENDATION 4: Replace the incremental Research and Experimentation (R&E) Tax Credit with a permanent tax credit on the total annual R&D expenditures of a company. Extend the R&E tax credit to cover industry-sponsored R&D in universities and other institutions, and the industrial contribution to R&D performed as part of a consortium that involves government laboratories.

RECOMMENDATION 5: Use public procurement, tax credits, accelerated depreciation schedules, regulation, and other demand-oriented policy instruments to pull innovation and increased private-sector investments in technologies expected to yield particularly high returns to U.S. society as a whole. These include technologies that produce environmentally benign and energy-efficient products and services and technologies that reduce the cost of health-care delivery.

RECOMMENDATION 6: Experiment aggressively with options for direct federal support of the development and diffusion of a broad portfolio of commercially relevant or promising "infrastructural" and "pathbreaking" technologies. Rely on industry leadership and involvement in project initiation and design, and on significant private-sector cost sharing to ensure commercial relevance. Options include expansion of the Advanced Technology Program and the Small Business Innovation Research program, support of additional private-sector managed industrial consortia like SEMATECH, creation of an independent federal Civilian Technology Corporation, and expansion of the measurement, standards, and testing activities of the National Institute of Standards and Technology.

Goal: Access and exploit foreign technology and high-tech markets more effectively to advance the interests of U.S. citizens.

All too many U.S.-based firms remain insufficiently aware of, and alert to, the threats and opportunities presented by foreign technical capabilities. This deficiency is compounded by a lack of coordination between technology policy and foreign economic policy.

Therefore, the committee recommends three policy actions. All three are consistent with the objectives of an open world trading system and current U.S. obligations under international treaties and agreements (Chapter 4, pp. 99–101):

RECOMMENDATION 7: Stimulate the expansion and institutionalization of U.S. public- and private-sector capabilities for global technological scanning and benchmarking. Most of these activities should be carried out by industry associations or industrial consortia with some sharing of costs and planning responsibility with federal government agencies.

RECOMMENDATION 8: Develop a capacity within the federal government for seeding and stimulating international R&D consortia (private-sector, public-sector, or mixed) in areas of recognized foreign technological strength where gains to U.S. participants are expected to be substantial. This is an important subset of the options for direct federal support of commercially promising "infrastructural" and "pathbreaking" technologies recommended above.

RECOMMENDATION 9: Improve coordination and cooperation between federal agencies with lead responsibility for domestic and foreign economic policy and agencies with lead responsibility for science and technology policy by (1) rotating high-quality midlevel staff between these agencies, (2) establishing a technology and trade committee of the Federal Coordinating Council for Science, Engineering, and Technology, and (3) making the integration of technology policy with domestic and foreign economic policy an explicit objective of the newly created National Economic Council.

Goal: Create a strong institutional framework for federal technology policy in support of national economic development, and integrate the planning and implementation of federal technology policy with that of national domestic and foreign economic policy.

The federal government's response to the technology and competitiveness challenges facing the nation's economy and its civilian technology enterprise has been poorly coordinated and inadequate to the task. Although many existing federal programs have been judged successful, they are limited and do not serve as a basis for learning by experience.

To create a strong institutional framework for federal technology policy in support of national economic development, the committee recommends that Congress and the administration take the following action (Chapter 4, pp. 101-103):

> RECOMMENDATION 10: Establish an institutional focus within the federal government to monitor, harness, and supplement the many existing federal programs and capabilities that currently support, or could support, more effective development, use, and diffusion of technology throughout the U.S. economy. This institutional focus should work for the early incorporation of technological considerations into the formulation and implementation of U.S. economic policy.

Whether it resides in an existing or a newly created agency or department, this new institutional focus should have a leadership role in the highly decentralized federal technology policy apparatus. In addition to any specific programs it may undertake, this new institutional focus should

- Develop and articulate an internally consistent national techno-economic strategy for the benefit of the United States.
- Monitor transnational public and private technology alliances to develop reliable methods of evaluating the benefits and costs of such alliances.
- Analyze the effects of differences in business practices among countries and their consequences for the competitive performance of U.S. companies, industries, and workers, and develop recommendations for (1) unilateral changes in U.S. practices and (2) changes to be negotiated in the practices of other countries to level the competitive playing field.
- Promote the coordination of trade policy, foreign investment policy, macroeconomic policy, tax policy, public-sector procurement, regulatory policy, work force training, technology extension, public technology investment selection, and other elements of U.S. economic and technology policy.

1

Background: The Postwar U.S. Technology Enterprise

The United States' collective capacity to create, develop, and deploy new technology constitutes its national technology enterprise. The nation's human, physical, and financial capital, and the publicand private-sector institutions (firms, universities, government agencies, nonprofit research laboratories, financial and regulatory systems, etc.) that organize and direct these resources in service of the interests of U.S. citizens, are all elements of the U.S. technology enterprise. Since World War II, the U.S. technology enterprise and the private and public strategies that have sustained it have been profoundly shaped by the nation's unique economic and geopolitical position in the decades immediately following the war (Nelson, 1990). This period of unchallenged U.S. economic and commercial technological preeminence was a time when the most urgent scientific and technological challenges to the nation were defined by the Cold War, the space race, a domestic war on cancer, and the quest for world leadership in virtually all areas of scientific research.

For most of the past 40 years, the U.S. technology enterprise and supporting public- and private-sector technology strategies have served the interests of U.S. citizens—their security, their economic welfare, their global influence, and their many other needs and wants—quite effectively. Recent changes in the global political and economic environment, however, have raised serious doubts about the adequacy of public- and private-sector institutions, actions, and assumptions that have characterized the U.S. approach to technology development and deployment for the last four decades. The Cold War is over. Meanwhile, other industrialized nations, led by Japan and Germany, have caught up with the United States, first in manufacturing performance, and more recently in some pivotal areas of product technology.

To better understand the significance of these and other challenges currently facing the U.S. technology enterprise, it is useful first to examine the distinguishing characteristics of that enterprise as they have evolved since the Second World War.

FOUR DISTINGUISHING CHARACTERISTICS OF THE U.S. TECHNOLOGY ENTERPRISE

As in all market economies, a vast majority of the resources and operational intelligence of the U.S. technology enterprise has resided in private companies and has been organized and driven by the logic of markets. At the same time, the structure, goals, and performance of the U.S. technology enterprise as well as its foreign counterparts have been heavily influenced by the contributions of other publicand private-sector institutions, such as government laboratories, universities, and not-for-profit research institutes. Beyond these broad commonalities, however, the U.S. technology enterprise has been most distinguished from that of other industrial countries by the following four characteristics since World War II:

1. The federal government has focused on mobilizing technical resources to further specific national missions. These missions, undertaken by federal agencies, have included national security, the cure of disease, space exploration, food production, and world leadership in basic science. National economic development and international competitiveness have rarely been explicit objectives of federal technology policies and investments.[1]
2. Technology strategies of federal government agencies and some of the most rapidly expanding segments of U.S. industry have focused on R&D-driven breakthroughs in product technology as the key to sustained technological and economic leadership. At the same time, process-related R&D and the organization of technical activities downstream from R&D that drive continuous improvement of existing products and processes have received considerably less public- and private-sector attention (Ergas, 1987; Florida and Kenney, 1990).
3. The federal government and the private sector have maintained a division of roles with regard to the funding of research versus the funding of development and deployment of technology for most sectors of the nation's economy.[2] Basic research and the development and application of technology relevant to accepted federal agency missions (though conducted principally by private-sector actors) have been regarded as legitimate activities for funding by the public sector. The identification, development, and adoption of technology for commercial products and services not directly associated with public missions has been seen as the legitimate preserve of the private sector.

4. Responsibility for making and implementing science and technology policies has been dispersed among a diverse collection of federal agencies, state and local governments, and private-sector participants; U.S. science and technology policy is explicitly pluralist, only loosely coordinated, and, at the federal level, largely disconnected from economic policymaking as well as highly influenced by constituency politics (Cohen and Noll, 1991).

These fundamental characteristics of the U.S. technology enterprise—each of which is discussed in more detail below—form an important background for understanding the policy challenges facing the United States in the 1990s.

The Primacy of Public Missions

For more than 40 years, federal government support of the U.S. technology enterprise has had a persistent focus on mobilizing technical resources for national security, space exploration, the cure of disease, the exploitation of nuclear energy, world leadership in basic science, and the other primarily public missions.[3] With few exceptions it has been assumed that national economic development need not be specifically addressed by federal science and technology policies. Federally funded basic research would provide a rich feedstock of new science for industry to exploit. "Spillover" technologies—those technologies discovered or developed in the pursuit of public missions and subsequently picked up and applied by private companies driven by market incentives alone—would do the rest.

The extent to which national security and other federal agency missions have set R&D priorities for the nation's technology enterprise is well documented (see Table 1.1). Although 80 to 90 percent of all research and development performed in the United States over the past four decades has been performed by private-sector entities (companies, universities and colleges and nonprofit institutions), the federal government has directly funded more than half of the nation's total R&D for most of this period. Since 1960, on an annual basis federal mission agencies have accounted for

- 60 to 70 percent of the nation's total investment in basic scientific and engineering research,
- 35 to 56 percent of the nation's total applied research investment, and
- 40 to 68 percent of the total U.S. investment in technology development.

During the past three decades, the federal government's share of the nation's total research and development investment (basic research, applied research and development) has declined significantly—from 65 percent in 1960 to 43 percent in 1992. However, at 43 percent it remains proportionally more than twice as large as that of the Japanese government, which at present accounts for only 20 percent of all Japanese R&D spending, and a fifth again as large as that of the German government, which funds 36 percent of all German R&D (National Science Board, 1991; National Science Foundation, 1992).

TABLE 1.1 Federal Government Role in the U.S. R&D Enterprise, Shares in Percent

	1955	1960	1970	1980	1992 (est.)
Federal R&D spending as share of total R&D spending	57	65	57	47	43
Federal share total U.S. spending:					
basic research	*	60	70	70	61
applied research	*	56	54	45	37
development	*	68	55	43	41
Federal defense-related R&D as share of total R&D	48	52	33	24	26
Federal health-related R&D as share of total R&D	2	3	4	6	6
Federal space-related R&D as share of total R&D	1	3	10	5	5
Federal energy-related R&D as share of total R&D	*	3	2	6	2
Federal R&D funding as share of total R&D performed by U.S. industry	47	59	43	32	28
Federal R&D funding as share of total U.S. academic R&D	54	63	71	68	57

* Data not available.

SOURCES: National Science Foundation (1990a, pp. 55; 1992, pp. 46–48, 52, 56, 60, 62, 69).

The most direct involvement of the federal government in the nation's R&D enterprise is through the national system of federal laboratories established to serve federal agency missions. Federal agencies currently support more than 700 federal laboratories with a combined budget for FY 1991 of $20.9 billion. These laboratories employ roughly 120,000 R&D scientists and engineers nationwide.[4]

The reach of federal agencies, however, extends well beyond the federal laboratories to large segments of U.S. industry and U.S. universities. During the past 40 years, publicly supported R&D in the service of federal missions and federal procurement of technologically advanced products, systems, subsystems, and components have contributed significantly to the development of some of the most successful and rapidly growing commercial industries in the United States. These include aerospace, communications, and biomedical and pharmaceutical industries.[5] It is estimated that in 1992 over $31 billion of federally funded mission-oriented R&D was performed by U.S. private industry, which, in turn, represented more than 30 percent of all R&D performed by U.S. industry that year (National Science Foundation, 1992a).

Throughout the postwar period, federal mission agencies, in particular, the National Institutes of Health (NIH), the National Science Foundation (NSF), and the Department of Defense (DOD), have provided the vast majority of funding for U.S. university-based research[6] (see Table 1.2). Although federal agencies' share of total university-based research has declined in recent years, as of 1991 these agencies collectively funded nearly $10 billion, or 56 percent, of all research on American campuses (National Science Board, 1991).

Through their funding of university-based research and their pull on labor markets for advanced-degree scientists and engineers, federal mission agencies also contributed significantly to the expansion of the nation's science and engineering work force during the 1950s and 1960s.[7] Most notably, rapid growth of the U.S. defense-related R&D effort during this period helped to create and sustain a much larger population of R&D scientists and engineers than in any other Western country. In 1965 the ratio of R&D scientists and engineers to total work force in the United States was nearly three times that of its major industrial competitors (see Figure 1.1). Not until the late 1980s did Germany, Japan, and other industrialized nations achieve ratios approaching those of the United States.[8]

Driven by the imperatives of the Cold War, national security has long received the highest priority for federal R&D funds. In 1992, national

TABLE 1.2 Support for U.S. Academic R&D, Percent Shares by Sector: 1960–1991

	1960	1970	1980	1991(est.)
Federal government	62.7	70.5	67.5	56.1
State and local government	13.2	9.4	8.2	9.0
Industry	6.2	2.6	3.9	7.3
Academic institutions	9.9	10.4	13.8	19.7
All other sources	8.0	7.1	6.6	7.8
TOTAL	100.0	100.0	100.0	100.0

NOTE: Percentages may not sum to 100 because of rounding.
SOURCE: National Science Board (1991, p. 349).

security accounted for 59 percent of federal R&D spending and 26 percent of total national (public and private) R&D expenditures (see Table 1.3). Roughly 90 percent of defense-related R&D spending has been for "development, testing and evaluation" of weapons and other systems having no markets other than military.[9] To a large extent, the demands of the national security mission have determined the structure and objectives of the government's system of federal laboratories, particularly in the physical sciences and engineering research. In 1991 DOD laboratories accounted for nearly half of all federal laboratory obligated expenditures as well as 50 percent of all federal laboratory research scientists and engineers.[10]

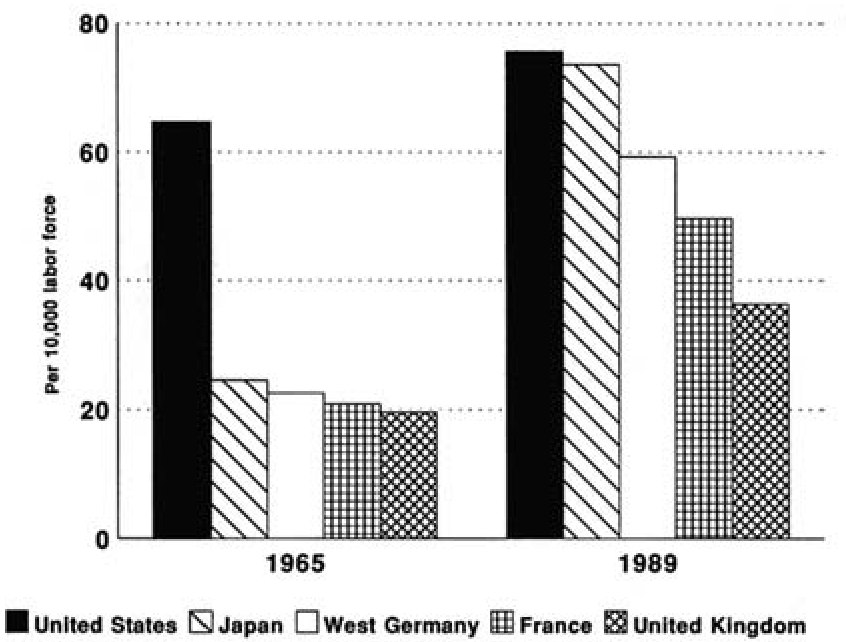

FIGURE 1.1 Scientists and engineers engaged in R&D per 10,000 labor force, by country: 1968 and 1989 NOTE: Latest available U.K. data is from 1988. SOURCE: National Science Foundation (1992, p. 67)

National security has also defined the focus of government support of much industrial and university-based engineering research and development. Most of the federally funded R&D performed by U.S. industry has been concentrated in a few industrial sectors such as aerospace and electronics that have both civilian and national defense components. In 1990, 63 percent of all federal funds for industrial R&D went to the aerospace sector, and 18 percent went to the electrical machinery and communications sector, accounting for 76 percent and 38 percent, respectively, of these industries' total R&D spending in that year (see Table 1.3). Although some of the industrial R&D supported by defense monies has yielded "dual-use" technology (having both civilian and military applications), the vast majority of defense-related R&D performed in these sectors has been for "development" of weapons and other systems having no markets other than military.

Although the share of total academic research supported by federal defense agencies has declined significantly during the last 30 years (from 60 percent of all federally supported academic R&D in 1954 to roughly 8 percent in the mid-1980s), the Department of Defense remains a major funder of university-based engineering research. During the late 1980s, DOD provided 32 percent of all funds for academic engineering research:

TABLE 1.3 National Security's Contribution to the U.S. R&D Portfolio, Shares in Percent

	1955	1960	1970	1980	1992(est.)
Defense R&D as share of federal R&D	85	80	58	51	59
Defense R&D as share of total U.S. R&D	48	52	33	24	26
Defense share of total federal support of academic engineering research	*	*	45[a]	55	46
Defense share of all government-funded R&D in U.S. industry [b]	*	81	68	63	68
Federal R&D funding as share of total R&D performed by U.S. industry	47	59	43	32	28
Federal share of total R&D funds in aerospace industry	88[c]	89	77	72	76[d]
Federal share of total R&D funds in electrical machinery and communications	66[c]	65	52	41	38[d]

NOTES:
* Data not available
[a] 1971 data
[b] Department of Defense only, data for 1962, 1970, 1981 and 1989
[c] 1957 data
[d] 1990 data
SOURCES: National Science Foundation (1990a, p. 55; 1991a; 1992, pp. 46–48, 62, 69 and unpublished data, 1993).

50 percent for electronics and electrical engineering research, 42 percent for aerospace engineering research, 20 percent for mechanical, 6 percent for civil and 4 percent for chemical engineering research (National Science Foundation, 1990a, 1992).[11]

Finally, national security has been a significant claimant on the nation's technological work force during the past three decades. Because of the high engineering intensity of defense-related economic activity, it is estimated that the national security mission currently commands roughly 18 percent of the total U.S. engineering work force. [12]

In summary, federal involvement in the technology enterprise through pursuit of agency missions has been extensive. Federal agencies, through their procurement of goods and services and their investment in R&D, have had a profound influence on the growth and direction of U.S. science and engineering research and education, on the growth and deployment of the nation's science and engineering work force, on the pace and direction of technical change in major sectors of the U.S. economy, and on allocation of technological and complementary investment resources throughout the economy (Casagrande, 1992).

The Priority of Research and Development in Postwar Policy

Throughout the postwar period, the U.S. public sector and some of the most rapidly expanding segments of U.S. industry have tended to focus on research and development aimed at technological breakthroughs as the key to sustained technological and economic leadership. In general, public and private technology strategies have been based on the (sometimes not fully acknowledged) premise that the supply of new technological ideas and concepts, rather than market demand, is the pacing factor in economic progress. Actual or potential market demand for products and services has been assumed to be sufficiently large and well-organized to pull substantial fractions of scientific and technological discoveries into use as fast as they emerged from the laboratory.

A driving force behind this post-World War II orientation toward R&D-driven new technology creation was the recognition that despite its industrial supremacy, the United States lacked a sufficiently broad-based institutional capacity for scientific research and development (Bush, 1945). For more than half a century before World War II, large sectors of U.S. industry had risen to global preeminence by drawing extensively on the results of foreign research and development. The spectacular productive performance of the United States in World War II, confirmed U.S. superiority in technical areas downstream from research, such as design, development, engineering and production. However, despite major gains in domestic R&D capability during the war, the U.S. government and many sectors of U.S. industry and academe considered the nation's science and engineering research base inadequate to the nation's new economic and geopolitical role.

During the 1950s and 1960s, public- and private-sector leaders assumed that unparalleled capacity to generate new science and technology was not only a necessary but also a sufficient condition for the maintenance of U.S. technological and economic leadership in newly emerging industrial sectors such as computers and semiconductors, or more established science-based industries such as pharmaceuticals or chemicals. The U.S. domestic market was by far the largest, wealthiest and most technologically sophisticated in the world. U.S. leadership in mass production and distribution, then the world's leading system of industrial production, was unchallenged. Foreign competition was minimal or nonexistent in most of the new high-tech sectors. These factors, when combined with an exceptionally large U.S. population of scientists and engineers, made it possible for U.S. firms in these high-growth industries to convert new technological ideas into commercially viable products more rapidly than their competitors as well as to translate that advantage into global market dominance in many R&D-intensive industries.[13]

Meanwhile, in less R&D-intensive manufacturing and service industries such as automobiles, steel, machine tools, construction and financial services, firm technology strategies, to the extent they were articulated at all, tended to be focused on incremental improvements in existing products with an emphasis on product design and marketing. Relatively immune to foreign competition as a result of the large economies of scale in production and distribution afforded by the U.S. domestic market, most firms in these industries devoted little attention and fewer resources to process innovation or the pursuit of product technology breakthroughs.

By the late 1970s, many of the deeply entrenched organizational and managerial practices of U.S. firms with regard to product development, design, production and marketing—practices that served these firms so effectively during the 1950s and 1960s—were beginning to handicap U.S. companies in several high-tech and non-high-tech sectors. Many U.S. companies were slow to pick up on major improvements in the pace and efficiency of product development and in the flexibility, efficiency and quality of production systems made by major Japanese firms and would later regret their relative inattention to process technology and the integration of R&D with its complementary downstream technical activities.[14] Nevertheless, in the unique circumstances pertaining for much of the postwar period, U.S. citizens and institutions enjoyed an unprecedentedly high but, as it proved, temporary probability of capturing virtually all the potential economic returns on the nation's large public and private investments in research and development.

The Division of Roles Between the Public and Private Sectors

The postwar U.S. technology enterprise has been characterized by a relatively sharp division of roles between the federal government and private-sector participants with regard to the funding of research and development and the application of commercial technology for most sectors of the nation's economy. Since the late 1940s it has been widely accepted that the federal government should play a central role in supporting the nation's basic research enterprise and its system of advanced scientific and engineering education (Bush, 1945). Like technology procured by the federal government to advance particular federal agency missions, basic research and advanced technical education have been viewed as essential public goods—goods that benefit society at large. Because of their public goods character, these areas of technological activity have not attracted sufficient investment from the private sector alone to meet societal needs, and have, therefore, been deemed appropriate areas for government intervention and support.

In contrast, nearly all technology not directly procured for use by the government has been perceived to be a private good that—like equipment or real estate—could be treated by a company as an asset (all or most returns on investments in technology were assumed to accrue to the investor). Likewise, technical activities beyond basic research, or not directly associated with the specific public missions, have been viewed as the exclusive responsibility of private-sector participants operating within competitive markets; the identification, development and adoption of commercially useful technology has been left to private companies.[15] The federal government has, of course, set the climate for these private-sector technical activities through pursuit of growth-oriented macroeconomic policies, the regulation of markets, the guarantee of intellectual property rights, and other critical market-sustaining policy actions.

A similar public-private division of roles has been assumed for "spin-off" benefits from public science and technology missions, such as technologies emerging from federally funded space, defense and biomedical research programs. Here again, it was generally accepted that market incentives alone were sufficient to motivate the private sector to pick up and adapt these developments for commercial use.[16]

The notion of a clean dichotomy of public-sector responsibility for basic research and private-sector responsibility for commercial development and use of technology has been an important signpost in U.S. debates over the role of government in civilian technology. Economic theory and historical experience argue that many areas of commercially relevant technological activity beyond basic research yield, or promise to yield, high returns to society as a whole yet pose risks too high or offer private returns too low to attract sufficient private-sector investment (Brooks, 1986; Nelson, 1989; Nelson et al., 1967). These activities include

- Research and development related to "pathbreaking" technologies that might give rise to a major new industry or transform existing industries. Pathbreaking technologies are characterized by high technical risk and by uncertain and possibly long-delayed economic payoffs, which may discourage private-sector investment (Alic et al., 1992). Examples of past and present pathbreaking technologies include nuclear medicine, biotechnology, semiconductors, aircraft engines and communications satellites.
- Research, development and institutional and technical support related to "infrastructural," or "generic," technologies—generally low technical risk, relatively low-cost technologies that enhance the performance of a broad spectrum of firms in the near to midterm, but whose benefits cannot be predominantly captured by any one firm. [17] Infrastructural technologies include the development of engineering methods; compilation and validation of technical data; development and characterization of materials, measurement tools and instrumentation; and refinement of manufacturing processes.
- Investments in research, development, institutional and technical support and complementary assets that facilitate the timely identification, adoption and diffusion of new scientific and technological knowledge throughout the national economy. These include investments in work force training, travel budgets for resident research and advanced production personnel, development or use of information data bases and networks and provision of technical or industrial extension services.

Despite the compelling logic for public-sector intervention to compensate for these market failures—articulated by many scholars and political and industrial leaders over the last 40 years—efforts to develop an explicit federal role in this area have rarely taken hold.[18] As a result, federal support for commercially relevant technological activities has not been broadly institutionalized. That is not to say that the federal government has not contributed, in some cases significantly, to the development and diffusion of pathbreaking and infrastructural technologies through its advancement of federal agency missions. Clearly, it has.[19] In general the federal government has not considered the development of commercially relevant technologies or commercial technology diffusion a legitimate part of its technology investment portfolio. Notable exceptions are the relatively small-scale industrial technical support (standards, testing, and evaluation) provided historically by the National Bureau of Standards (renamed the National Institute of Standards and Technology in 1989), and more recent, limited initiatives such as the Advanced Technology Program and the Small Business Innovation Research (SBIR) program, or the cultivation of industry-federal laboratory cooperative research and development agreements (CRADAs).[20]

The reluctance of the federal government to explicitly breach the division of responsibilities between public research and private technology in the commercial sphere since World War II can be explained by a number of factors. Throughout the 1950s and 1960s, the relatively impressive performance of the U.S. commercial technology enterprise had not suggested any obvious gaps in the nation's commercial technology portfolio. U.S. leadership in new high-technology industries and in the development of new products and services was taken for granted. Certainly, several major U.S. high-technology industries benefited greatly from federal mission-related R&D and procurement during their rise to commercial dominance. Recognition of this fact in the absence of clear threats to the nation's commercial technology base, however, did not translate into a persuasive call for a larger, more explicit federal role in support of commercial technology development and diffusion.

Yet, in recent decades, even as the existence of important gaps in the nation's commercial technology portfolio has gained wider credence, the analytical and political impediments to an expanded federal role in this area have remained formidable. The strong ideological commitment of American government to the power of free markets and limited government intervention in the nation's economy has for the most part contained congressional attempts to expand the government's role in civilian technology.

At the same time, many of those who acknowledge the need to redress gaps in the commercial technology portfolio in principle have been reluctant to take concrete policy actions. This is, in part, because the theoretical and empirical bases for identifying, setting priorities for, and deciding at what level to fund worthy areas of infrastructural or pathbreaking technology are not well established. An even greater impediment to policy action, however, is the fact that the benefits of public-sector investments in these areas of commercial technology are hard to measure, slow to diffuse and slow to mature. In short, the need for elected representatives and government officials to demonstrate concrete, short-term results to their constituencies may discourage them from investing much political capital in such diffuse, long-term yield initiatives. A corollary to this political imperative is the fear that direct industry funding might be yet another breeding ground for "pork."[21]

The "Nonsystem" of U.S. Science and Technology Policymaking

A final distinguishing feature of the postwar U.S. technology enterprise has been the pluralist, decentralized, loosely coordinated structure of U.S. science and technology policymaking. This structure has been characterized by the lack of an explicit commitment at the federal level to supporting technology development and deployment for economic development, and by the corresponding divorce of science and technology considerations from the making of federal economic policy. In addition, there has been little effort to coordinate or consolidate the autonomous yet often overlapping science and technology policies of the diverse federal mission agencies that collectively define U.S. federal technology policy overall. For example, it is only in the last three to four years that the federal government has begun to take stock of (let alone, begin to coordinate) the investments of various mission agencies in technology areas of mutual interest, such as manufacturing and advanced materials.[22]

The fragmented nature of science and technology policymaking at the federal level, its disconnectedness from economic policymaking, and the federal structure of the U.S. political system have contributed to even greater decentralization and fragmentation of U.S. science and technology policymaking at the subfederal level. With the explicit objective of advancing economic development within their jurisdictions, many state, regional, and local entities have pursued science and technology policies of their own (Carnegie Commission, 1992a; Clarke and Dobson, 1991; Feller 1992a,b; Plosila, 1987; Shapira et al., 1992).

Today at least 46 states and countless municipalities and counties pursue a range of policies aimed at promoting the creation, dissemination, and application of commercial technology within their jurisdictions. [23] Funding for these efforts involves much more modest resources than those invested by the federal government in mission-oriented R&D; state governments' spending for research and development and R&D plant totaled a mere $1.2 billion in fiscal year 1988, compared with a federal R&D investment that year of approximately $58 billion.[24] Historically, there has been little coordination (formal or informal) among these subfederal programs or between them and federal agency efforts, though this is beginning to change.[25]

In many respects, the pluralist nature of U.S. technology policymaking has both reflected and reinforced the pluralist structure of the technology enterprise proper. To an extent far greater than in other industrialized nations, operational responsibility for research, technology development, and technology application in the United States is distributed among a large, highly diverse population of public- and private-sector participants. These include private companies, trade and industry associations, universities, private research institutes, community colleges, professional associations, private or private/public consortia, and local, state, and federal government agencies. Moreover, the fact that the nation's science and technology capabilities are dispersed over a large number of regions and political constituencies has greatly increased the importance of constituency politics in federal technology policymaking and implementation.

On the one hand, the decentralized nature of U.S. science and technology policymaking has allowed diverse and locally adaptive policy responses to technology-related challenges at the federal and the subfederal levels. On the other hand, this same highly distributed, highly fragmented quality of U.S. science and technology policymaking, in combination with the near total divorce from economic policymaking at the federal level, have greatly impeded collective action on issues and problems that cut across political jurisdictions, and inhibited cooperation in the setting and implementation of national priorities.

THE POSTWAR PERFORMANCE OF THE U.S. TECHNOLOGY ENTERPRISE IN PERSPECTIVE

Throughout much of the past 40 years, the distinguishing features of the U.S. technology enterprise have served the nation's multiple interests effectively. By and large the most important goals of mission-oriented publicly funded research and development have been achieved. The United States has achieved and sustained preeminence in defense-related technologies, which it has used effectively to strengthen U.S. national security and U.S. influence throughout the world. The United States has been on the forefront of biomedical research, leading the world in the ability to treat and control many diseases.[26] As a result of heavy, sustained federal support, the U.S. basic research enterprise and U.S. advanced science and engineering education, after World War II, quickly achieved and continue to enjoy world leadership status.

Furthermore, the direct and indirect contributions of defense and other public missions to U.S. civilian technology development *have* been substantial. Federal agency R&D and large-scale federal procurement of advanced technology products generated important spin-offs. Some of those spin-offs were seminal to the growth and development of industries that have been major engines of U.S. and world economic growth, such as the aerospace, microelectronics, telecommunications, and computer industries.[27] Heavy federal mission agency funding of university science and engineering research departments helped to provide the intellectual underpinnings and the highly skilled human capital base for many newer, high-growth, science-based industries (computer science, pharmaceuticals, chemicals, and technical advances in many other areas).

Likewise, throughout the 1950s and 1960s, the performance of U.S. companies at home and abroad tended to confirm belief in the effectiveness of the nation's division of responsibility between the public and the private sectors with regard to research, development, and the commercial application of technology as well as its collective focus on research and development as the key to technological leadership. As of the early 1970s, U.S. productivity (gross domestic product per capita) was one and a half times that of Germany and Japan, and U.S. industry accounted for half of world high-tech production, more than a quarter of global high-tech exports, and nearly half of the total world stock of foreign direct investment (Maddison, 1989; National Science Board, 1989; U.S. Department of Commerce, 1989b) (see Figure 1.2).[28] The U.S. domestic market appeared to be largely immune to foreign competition, and the nation's ability to spawn new products, services, and industries was unrivaled.[29]

The 1970s and 1980s witnessed growing concern in the United States about the health and performance of the nation's commercial technology enterprise. As major U.S. manufacturing industries were outdone by foreign competition, both U.S. industry and the federal government sought to understand better the changing nature of international competition and its implications for U.S. competitiveness. This, in turn, led to a series of reevaluations of the private-public division of labor with regard to civilian technology development.[30]

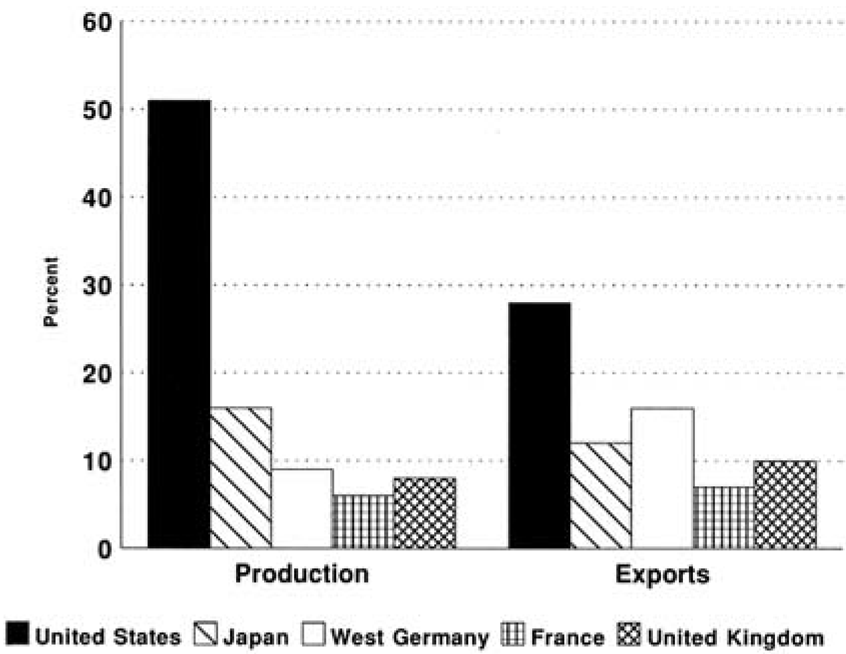

FIGURE 1.2 National shares of world high-tech production and trade, by country: 1970. NOTE: Based on data valued in current U.S. dollars; uses OECD definition of "high intensity technology products," see Chapter 1, note 28. SOURCE: National Science Board (1989, pp. 371, 377).

Nevertheless, even as the nation's vision of the federal role in the commercial development and application of technology began to be questioned, the focus of both public- and private-sector technology strategies has remained on research, early development, and acceleration of the rate of generation of new technology as the principal technological response to early signs of the nation's declining competitiveness. The concentration on invention and new technology development also resonated with a deeply ingrained "product-cycle" view of national industrial evolution. As U.S. companies lost market share to foreign competitors in what were considered "technologically mature" or lower valued-added industries or segments of industries, it was assumed that U.S. economic preeminence would be continually renewed (Kodama, 1991; Thurow, 1980; Vernon, 1966). This renewal would be achieved chiefly by exploiting the perpetual ability of the nation's technology base to create new, technologically dynamic, high-growth industries, such as computers, telecommunications, commercial aircraft, and pharmaceuticals. In short, U.S. national interests were thought to be best served by technology strategies that focused on maintaining U.S. leadership in the creation of new ideas and new technologies. These, in turn, could be counted on to seed new industries and new, higher value-added markets to compensate for "old" industries and markets lost to foreign competition.

During the past 10 to 15 years, however, the global political and economic environment has undergone a profound change. As a result, the strategies and tactics that have guided U.S. investment in science and technology over most of the second half of the twentieth century have become less effective and are likely to become even less so during the next 50 years. The next chapter discusses changes in the global context that challenge the adequacy of established U.S. public-and private-sector approaches to technology development and deployment.

NOTES

1. Henry Ergas (1987) has classified national technology strategies as "mission-oriented," "diffusion-oriented," and "hybrid." The United States, Great Britain, and France are cited as examples of "mission-oriented" strategies, Germany, Sweden, and Switzerland as examples of "diffusion-oriented" strategies, and Japan as somewhere in between.

2. This sharp division has frequently been stricter in theory and rhetoric than in practice since World War II. See Brooks (1986), Cohen and Noll (1991), Kash (1989), Mowery and Rosenberg (1989), and Nelson (1989).

3. During this period, federal support for mission-oriented research and development has been diminishing in defense, steadily rising in public health, and highly volatile in other public mission areas such as space, energy, environment, and housing (National Science Foundation, 1990a).

4. This total includes intramural agency laboratories as well as federally funded research and development centers (FFRDCs). FFRDCs and many intramural agency laboratories are government-owned, contractor-operated laboratories managed by universities (Los Alamos,

Lincoln Laboratory), university consortia (Brookhaven, Fermilab), industrial contractors on a not-for-profit basis (Oak Ridge National Laboratory administered by Martin Marietta,) and independent nonprofits (MITRE Corporation, Draper Laboratory, RAND). Other intramural agency laboratories are government-owned and government-operated (National Institutes of Health, NASA's space flight and space science laboratories, National Institute of Standards and Technology, Naval Research Laboratory, Naval Surface Weapons Center). In addition to these differences in management structure, federal laboratories are very diverse in size, character, and purpose. Most are single-office facilities employing a small number of researchers, whereas others are large organizations that employ thousands of scientists and engineers (Committee on Science, Engineering, and Public Policy, 1992, pp. 67–79).

5. Several recent studies have noted that the "spillovers" from defense and other federal agency missions were greatest during the early postwar period, when many of the technologies that later became new and highly competitive commercial industries were in the early, more "fluid" stage of their technology life cycle. In most cases, these mission-related spillovers have declined in importance as these industries and their relevant technologies have matured. However, there are notable exceptions. Aerospace technology generally, and aircraft engine technology in particular, remain as "dual-use" as ever. The massive federal investment in health-related research clearly continues to yield significant spillovers to the biomedical and pharmaceutical industries. See Chapter 2, pp. 53–54 below for further discussion. See also Alic et al. (1992); Mowery (1987); Committee on Science, Engineering, and Public Policy (1992); Utterback (1987).

6. The National Institutes of Health and the National Science Foundation came to account for the largest shares of federal support for academic research during the 1960s and 1970s, paralleling growth in academic life sciences research both absolutely and as a share of total academic research. In 1989 NIH accounted for 47.9 percent of total federal obligations for academic research and development, NSF for 14.5 percent, and DOD for 13.7 percent. In 1989 life sciences research accounted for 54 percent of academic science and engineering research expenditures (National Science Board, 1991, pp. 355, 360, appendix tables 5-6, 5-8; Government-University-Industry Research Roundtable, 1989, p. 2–23).

7. The Servicemen's Readjustment Act of 1944 (the G.I. Bill of Rights), which provided funds for World War II veterans to continue their education, contributed significantly to the early growth of the nation's advanced technological work force. The G.I. Bill enabled more than 2.2 million ex-servicemen to attend colleges and universities; see Ginzberg (1986).

8. As of 1989, the United States had 76 scientists and engineers engaged in R&D per 10,000 labor force, compared with Japan's 74, Germany's 59, and France's 50 per 10,000 labor force (National Science Foundation, 1992, p. 67).

9. It is worth noting the large contrast in the distribution of effort between publicly funded defense and nondefense research and development. Ninety percent of public funding for defense-related R&D is for development, testing, and evaluation, with applied research, basic research, and R&D plant accounting for the remaining 10 percent. In contrast, public nondefense R&D spending is divided more evenly among the 3 major categories with 30 percent for development, 30 percent for applied research, and 30 percent basis research, with the remaining 10 percent for R&D plant (National Science Board, 1991, pp. 94–95).

10. If Department of Energy (DOE) laboratories that focus primarily on nuclear weapons research are added to those of DOD, the national security mission laboratories account for roughly 55 percent of total federal laboratory expenditures and 60 to 70 percent of total laboratory researchers. At present slightly less than half of all DOE laboratory resources are dedicated to weapons research (Committee on Science, Engineering, and Public Policy, 1992, pp. 68, 74, tables 2-1, 2-3).

11. Alic et al. (1992) note that most of the university-based engineering research sponsored by DOD, DOE, the Atomic Energy Commission (AEC), and the National Aeronautics and

Space Administration (NASA) "was 'engineering science'—i.e., investigations of natural phenomena underlying engineering practice—rather that engineering design, manufacturing operations, or the construction and testing of prototype equipment."

12. The U.S. Congress, Office of Technology Assessment (1992a) estimates that 342,000 engineers were engaged in defense work in 1990 out of total U.S. engineering work force of 1.86 million. Henry and Oliver (1987) in their survey of the U.S. defense build-up from 1977 to 1985 and its claims on the U.S. labor force estimated that 15 percent of the nation's "technical professionals" were employed in defense-related economic activity.

13. Ergas (1987), Florida and Kenney (1990), and Nelson (1992) all note the mutually reinforcing character of U.S. technology strategies (public and private) and the postwar evolution and development of a broader set of U.S. institutions—research universities, venture capital markets, regulatory agencies, company law, etc.—with regard to the U.S. focus on technological breakthroughs and resulting comparative advantage in new science-related technologies and industries.

14. The preoccupation with R&D has been reflected in the technical "caste" systems and reward systems of companies in these industries under which conceptualizers and analysts involved in marketing, invention, and research have enjoyed considerably greater status and financial rewards than their colleagues in design, development, and manufacturing who transform broad concepts into working systems.

15. There are three recent exceptions to this characterization. First, following on legislation of the early 1980s that made technology transfer from federal agency laboratories to the private sector an explicit objective of federal policy, the 1986 Federal Technology Transfer Act authorized the establishment of cooperative research and development agreements (CRADAs) between government-operated laboratories and industry. Second, the National Institute of Standards and Technology, NIST, (formerly the National Bureau of Standards, NBS) has recently had its mission expanded to include support of "generic" advanced technologies important to certain sectors of the civilian economy with the establishment of the Advanced Technology Program. And third, the Small Business Innovation Research (SBIR) program was created in 1982 to direct a small share (not less than 1.25 percent) of each major mission agency's total annual R&D budget to fund R&D at small and medium-sized firms and to stimulate the commercialization of new products and services. The SBIR program was significantly expanded by Congress in the fall of 1992. For further discussion of these initiatives see Committee on Science, Engineering, and Public Policy (1992) and U.S. General Accounting Office (1992c). See also the Small Business Research and Development Enhancement Act of 1992 (P.L. 102-564).

The SBIR program, CRADAs, and the expansion of NIST's mission beyond the much narrower standards-oriented mission of NBS are in an infant stage. The NIST/NBS budget has been virtually level for most of the last 10–15 years, reflecting a long-standing low priority given to insfrastructural research and technology. However, significant increases in NIST funding in the fiscal 1992 and 1993 federal budgets reflect a growing recognition in Congress and the administration of the increased importance of NIST's charge.

16. Among industries that serve accepted public missions as well as commercial markets, the division of responsibility among private firms and government with regard to research, technology development, and technology deployment has varied considerably from industry to industry. Unlike defense, which has been a purely public mission monopolized by public funding, a natural division of labor developed between the government and industry in other fields such as agricultural and health. In these two fields, government provided funding primarily for the life science aspects where it was to develop appropriable knowledge, while the private sector funded the physical sciences and engineering, where the knowledge has tended to be more appropriable. Thus, in biomedicine and agriculture there developed private sectors whose R&D expenditures approximated in magnitude federal expenditures but

were complementary. A somewhat different division of labor developed in aeronautics. Here the government provided generic knowledge and testing facilities such as wind tunnels, which became a source of public knowledge available to all competitors, while industry carried out the design and development work and took responsibility for commercialization of actual aircraft.

Similarly, the markets for these industries have been "mixed" (public and private) to varying degrees. The aircraft industry's market has consisted largely of regulated air carriers and the military, where government had control of the market ground rules. For space technologies, the market has been virtually synonymous with the federal government. Even in satellite communications, where the products are sold by private companies, the market was a regulated monopoly throughout most of its postwar development. In the pharmaceutical and agricultural sectors, the market ground rules have been heavily regulated by government—with price supports in agriculture, and safety and efficacy regulation in pharmaceuticals and medical devices. In the latter two industries, there has been a substantial government market from Medicare, Medicaid, and the Veterans Administration (probably a good deal more than 30 percent of the total market, with much of the rest determined by third-party payers, which were subject to price regulation by the states).

Somewhat similar considerations would apply to nuclear power where the government provided a great deal of R&D funding and some infrastructure, while the heavily regulated electric utilities financed the development of, and capital investment in, actual power reactors. Here again is a case of mixed economy, ostensibly private, but with heavy government regulation and complementarity between the public and private roles.

For further discussion of the diverse mix of public and private roles in these industries, see Brooks (1982), Committee on Science, Engineering, and Public Policy (1992), and Kash (1989).

17. The concepts of "pathbreaking" and "infrastructural" technologies were taken from Alic et al. (1992, chapter 10).

Fundamental technical problems can and do arise at any stage of the technological life cycle, not just in the conceptual or exploratory phase; the lack of critical knowledge, empirical or theoretical, can appear as a barrier to incremental improvement even in a nominally mature technology. The research necessary to turn a new technological concept into a commercial product may or may not be a private good. Such research creates useful technical knowledge, which contributes to the function of the product or service, or contributes to reducing the cost or otherwise improving the efficiency of producing a product or service. If the results are widely applicable to many products or even several different industries, the payout may not be sufficient for any single company to support the work. For example, if the knowledge is in the form of data such as characteristics of materials or aerodynamic performance of wing shapes, or flow characteristics of various shapes of orifices, it is simply a fact of nature and can seldom be held proprietary and hence economically appropriable to the creator of the knowledge. In such cases, there may be sufficient mutual advantage among many product lines and industries to justify a collective or shared investment (perhaps with additional government support) in acquiring the relevant knowledge even if the demand for that knowledge is generated by immediate commercial concerns. See Brooks (1991).

18. Congress refused to support the Kennedy and Johnson administrations' attempts to develop modest research support programs within the Department of Commerce for textile, building, and machine tool industries during the early 1960s (Economic Report of the President, January 1963; Katz, 1982; Nelkin, 1971). The Nixon administration's grandiose federal initiative to use government-generated technology to bolster the competitiveness of the U.S. economy during the early 1970s produced only a few small pilot programs in the National Science Foundation and the National Bureau of Standards (including the limited, yet rather successful NBS Experimental Technology Incentives Program) that were never followed up (Lewis, 1975, 1976; National Research Council, 1976). See also the Carter administration's

1978 initiative to study the impact of federal policies on national economic competitiveness and to make recommendations for changes in federal policy to improve incentives for private-sector technological innovation and industrial investment in R&D (U.S. Department of Commerce, 1979).

19. For further discussion, see pages 9-16 and note 16 above. For an overview of the role of the Advanced Research Projects Agency and its successor the Defense Advanced Research Projects Agency in the development of dual-use technology, see also Mowery and Rosenberg (1989).

20. See Chapter 1, note 15, for further discussion.

21. It should be noted, however, that all of the uncertainties and risks associated with targeting specific technology areas as worthy of public support have not deterred major trading partners of the United States from doing so, albeit with mixed success. See Keck (1993), U.S. Congress, Office of Technology Assessment (1991b), and U.S. Department of Commerce (1992b).

22. In 1989 President Bush's new science and technology adviser and Office of Science and Technology Policy (OSTP) director, D. Allan Bromley, reestablished the dormant Federal Coordinating Council on Science, Engineering, and Technology (FCCSET) as a means to get federal agencies to coordinate their R&D programs. Since then FCCSET has launched six assessments of federal agency R&D programs in particular technology areas (technology "crosscuts"), including advanced materials and processing, biotechnology, global change, high-performance computing and communications, math and science education, and advanced manufacturing.

23. State-level industrial extension and economic development programs are long-standing. It was not until the 1980s, however, that state governments launched major initiatives emphasizing technology development, the search for new products and processes, and the launching of new spin-off firms (Carnegie Commission. 1992a; Clarke and Dobson, 1991; Feller, 1991, 1992; Osborne, 1989; Plosila, 1987; State of Minnesota, 1988).

24. In its recent report entitled *Science, Technology, and the States in America's Third Century*, the Carnegie Commission on Science, Technology, and Government (1992a) estimates that the total public and private resources leveraged by state spending (mostly matching investments by private industry) in fiscal 1988 was in excess of $2 billion. See also National Science Foundation (1990b).

25. Often, matching funds from state or federal resources are required by one or both parties for the financing of broad-based research centers.

26. Nevertheless, as recent analysis and debate of the U.S. "health care crisis" suggest, it would be wrong to claim that the United States actually leads in bringing to bear this superior capability in delivering health benefits to all its heterogeneous population.

27. While the spin-off benefits of national security spending have been larger than they would have been had no federal money been spent, they are almost certainly smaller than they would have been had comparable amounts of money been invested directly with an explicit mission of economic development. In other words, the spin-off benefit per dollar of expenditures is probably tiny compared with the potential benefit of a comparable amount of commercial industrial R&D and capital investment. This may constitute a politically unrealistic standard of comparison, because it is hard to construct a counterfactual political scenario in which the U.S. body politic could have been persuaded to devote similar amounts of money to commercially oriented R&D. Nevertheless, it is an important point that has been poorly understood by both sides in the spin-off debate. See Alic et al. (1992), especially pp. 54–81 for further discussion.

28. The OECD classification of "high intensity technology products" relies on directly applied R&D expenditures in its calculation and includes those products with above-average R&D intensities. Direct R&D expenditures are those made by the firms in the product group. The OECD classifies the following industries as high-tech: drugs and medicines (ISIC 3522);

office machinery, computers (ISIC 3825); electrical machinery (ISIC 383 less 3832); electronic components (ISIC 3832); aerospace (ISIC 3845); and scientific instruments (ISIC 385).

The Department of Commerce definition of high-technology products (DOC-3 high-technology products) includes products that have significantly higher ratios of direct and indirect R&D expenditures to shipments than do other product groups. Direct R&D expenditures are those made by the firms in the product group. Indirect R&D describes the R&D content of input products. The DOC-3 industries include guided missiles and spacecraft (SIC 376); communication equipment and electronic components (SIC 365–367); aircraft and parts (SIC 372); office, computing, and accounting machines (SIC 357); ordnance and accessories (SIC 348); drugs and medicines (SIC 283); industrial inorganic chemicals (SIC 281); professional and scientific instruments (SIC 38 less 3825); engines, turbines, and parts (SIC 351); and plastic materials and synthetic resins, rubber, and fibers (SIC 282). Comparisons of U.S production data for "high-intensity technology products," as reported to the OECD, with U.S. total shipment data for "high-technology" products—as reported to the Department of Commerce according to DOC-3 definition—show that the OECD data represented 96 percent and 100 percent of the DOC-3 data in 1980 and 1986, respectively (National Science Board, 1989, pp. 149–150).

29. Imports accounted for less than 5 percent of total U.S. domestic consumption of high-tech products in 1970 (National Science Board, 1989, p. 375, table 7-7).

30. Among the most important and influential studies were the 1979 report entitled *Domestic Policy Review of Industrial Innovation* from the U.S. Department of Commerce and the Office of Science and Technology Policy; the report of the President's Commission on Industrial Competitiveness (1985); and the formal statement of U.S. technology policy by the Bush administration (Executive Office of the President, 1990). See also Council on Competitiveness (1991) and National Academy of Engineering (1988). For a review of recent reports on U.S. technology policy, see Mogee (1991).

2

The Changing Demands on National Technology Policy and Strategy

Three important changes in the global political and economic environment have recast the central technology-related challenges facing the United States and thereby exposed major vulnerabilities in the U.S. technology enterprise. First, there have been steady and rapid changes both in industrial and corporate structure and in the nature of competition in many industries. In particular, the technical intensity of many manufacturing and service industries has increased dramatically at the same time that a revolution in production systems, both the human and the technical elements, has redefined the standard of competitive organizational and managerial performance for most companies.

Second, there has been a long-term shift in the global economic and technological position of the United States. Twenty years ago the preeminence and comparative self-sufficiency of the U.S. economy and technology enterprise could be taken for granted. Today the United States has become but one of several major economic and technological powers in a much more tightly integrated and interdependent world economy.

Third, the end of superpower military and geopolitical rivalry has placed a growing premium on economic and commercial technological strength as a source of national power and political influence worldwide. This geopolitical shift comes at a time when civilian technological advance, driven by global economic competition, is pacing technological advance in many fields critical to the national defense.[1]

These three changes are simultaneously creating a new set of challenges for U.S. public and private agendas for technological advance and application. They raise serious questions concerning the current scope and composition of the nation's portfolio of technological activities, including the breadth and relative self-sufficiency of R&D effort, and the strength of technical, organizational, and managerial capabilities that complement R&D and are essential to the effective application of technology. Together these three trends challenge the utility of many of the underlying assumptions and distinguishing features of the postwar U.S. technology enterprise discussed in Chapter 1.

RISING TECHNICAL INTENSITY AND THE REVOLUTION IN PRODUCTION SYSTEMS

Global competition and rising technical competence worldwide are changing the intensity, pace, and character of technological innovation in nascent, developing, and mature industries in important ways. Historians of business and technology have described the rise of complex, private-sector managerial bureaucracies that have emerged in parallel with the development of an ever more powerful global transportation and communications infrastructure. They have documented how the complexity of products and services, the size and diversity of markets, and the economies of scale and scope in R&D, production, distribution, and sales—each of which has several technological elements—are driving changes in the nature of competition. It is beyond the scope of this report even to catalog the full range of changes in marketplace competition; a virtual flood of scholarly analysis and popular journalism explores how industries vary as a function of their history, the technologies that they embrace, the dynamics of competition among leading players, and the characteristics of buyer-supplier relationships, to name just a few.[2] A couple of trends, however, seem universal, important, and undeniable, namely, the increasing technical intensity of important manufacturing and service industries and the revolution in production systems.

The Rising Technical Intensity of Industries

In many industries commercial technology is increasingly "science-based," that is, drawing to an increasing extent on codified and systematized knowledge rather than craftlike, experiential know-how (Alic et al., 1992).[3] In a few cases this is largely new science, but more generally it is based on a broad mix of old science, new science, and technological know-how from many different sources.

Also, in the development of promising new industries or in the transformation of major existing industries, more engineering and technological resources are being brought to bear than ever before. The result is a quickening of the pace of commercial technology development and diffusion accompanied by shorter product life cycles. In this context it is easy to understand how, in certain high-potential, technology-intensive industries, the capital and skill requirements for market entry and competitive survival of individual firms have risen dramatically. The financial and scientific or technological resources necessary for a firm to enter marketplace competition in, for example, bioengineered products or optoelectronic devices, regional banking or package delivery are substantial (Burrill and Lee, 1991; Kodama, 1991; Quinn, 1992; U.S. Congress, Office of Technology Assessment, 1987, 1991a).

The development and commercialization of new products and services have always been a multidisciplinary effort. The most successful practitioners in one field are likely to be those who can identify and draw upon complementary or supporting technical advances in other fields. In a new manufactured product, for example, the challenge is to determine simultaneously—at a minimum—good choices for materials, product features, manufacturing processes and technology applications, and the most promising approaches for product improvement after its introduction. In the last half century, in particular, the absolute volume of specific knowledge *within* technical disciplines has grown tremendously, and the resources required to attack problems with the best and newest tools of several disciplines have grown commensurately. In other words, the scope of the scientific and engineering basis for making a "good" competitive decision is often both larger and richer than it was a generation ago.

Competition among companies that have the resources and ability to manage such a demanding, rapidly evolving, multidisciplinary process is driving a higher degree of interdependence among fields in commercial applications. Technology fusion, or the marriage of disparate technologies from different industries to create new products, new services, or new systems, is becoming an increasingly important source of product and process innovation in all industrialized economies. For example, the marriage of electronic and mechanical technologies, or "mechatronics," has led to the creation of such products as numerically controlled machine tools and industrial robots. Optoelectronics, the fusion of electronics and optics technologies, has yielded major commercial products, including optical fiber communication systems. Similarly, the coevolution and combination of computerized inventory systems and universal telephone service has revitalized both the retail and the catalog sales industries.[4]

The implication of such technology fusion is that, in many industries, technological advance depends increasingly on the effective technical interaction and collaboration of equipment vendors, component suppliers, system assemblers, private and public research laboratories, other service providers, and consumers in complex networks or "organizational complexes" of innovation. Not only is the process of successful commercial innovation becoming much more technology-intensive and fusion-oriented, but this same phenomenon means that established industries and technological niches are much more vulnerable to "invisible competitors," that is, new combinations of technologies once considered beyond the scope of interest and concern of a given industry (Kash and Rycroft, 1992; Kodama, 1991; Rycroft and Kash,1992).

These developments place new demands on the technological capabilities of companies and of nations. To compete effectively companies must coordinate and integrate their advanced technical activities much more fully with the rest of the production system, pushing R&D activity further downstream into design, production, and marketing, as well as factoring production and marketing considerations into the earlier phases of upstream development activities. Likewise, they must look beyond their own corporate, industry, and national borders for technology that might yield competitive advantage, and develop the capacity for rapidly assimilating and mastering it. Faced with high costs and uncertainty associated with the development and commercialization of many promising areas of technology, a growing number of companies are entering into R&D consortia, joint ventures, or alliances with other firms (domestic and foreign), with universities, and with government agencies in an effort to share risks and costs for the sake of mutual benefits (Hagedoorn and Schakenraad, 1993; Mowery, 1987; Tassey, 1992; Vonortas, 1989).

The increasing technical intensity of industries and the growing importance of technology fusion in the context of stiff international competition also place a premium on broadening a nation's overall R&D portfolio, in effect, hedging against unforeseen opportunities and challenges. These changes demand particular attention to the widening spectrum of industrial technologies whose development and diffusion are beyond the capabilities of individual firms operating in competitive markets. Governments worldwide are defining more industrial technology as "generic," or "precompetitive," and therefore a legitimate target for private-sector consortia and public-sector support.[5] To strengthen their domestic generic technology base and help resident companies capture the benefits of that base, many governments are helping to cultivate linkages and collaboration across the diverse spectrum of domestic R&D institutions—corporations, universities, national laboratories, and private research laboratories. At the same time, the nature of global technology-intensive competition demands that a nation's technology enterprise become more effective at tracking and acquiring new technology from outside national borders.

The Revolution in Production Systems

The rapid growth in technical intensity of many industries coincides with a radical shift in the organization of production and innovation that is redefining the standard of competitive performance in most manufacturing and many service industries. Characterized as a revolution in production systems, this organizational and managerial shift is captured by such concepts as just-in-time, total quality management, design for manufacturing, and concurrent engineering. Many successful producers of complex products and services are now combining aggressive R&D and technology outreach strategies with organizational changes that make possible more rapid, continuous, incremental and concurrent improvements in products and processes. While demanding more effective integration of all elements in the product-realization process—including R&D, design, engineering, production, marketing, and in-field support—this approach tends to be less disruptive in the short term and often yields large improvements in the system of manufacture or service delivery (as an integrated part of the production process) over longer periods of time (Barkan, 1991; Bowen, 1992; Dertouzos et al., 1989; Lee, 1992; Quinn, 1992).

A continuous incremental improvement strategy leads to the possibility of inserting new component and subsystem technology as it becomes available, thereby capitalizing on new technical advances more rapidly. [6] The technical resources and capabilities of suppliers and vendors, therefore, have become far more critical elements in the manufacturing firm's product and process development strategies than was true two decades ago. These closer linkages to suppliers contribute to both higher quality of products and increased performance of the production system. This gives advantage to firms with strong cooperative relations with suppliers, workers, and potential customers (Lundvall, 1992; von Hippel, 1988).

Much of the change is a result of greater appreciation of the demonstrated efficiencies of modern Japanese production methods, sometimes gathered under the rubric of "lean production" and "flexible manufacturing." In contrast with traditional mass production, lean production refers to a constellation of new organizational relationships both inside and outside the firm, to a new way of viewing workers, customers, and suppliers, and to a different understanding of how technologies change and improve (Hill, 1991; Kline, 1991; Womack et al., 1990). The goal of lean production—in comparison with mass production—is to use less labor, materials, plant, equipment, and time at all levels in the firm to produce a greater variety of high-quality products, while continuously accommodating rapid changes in product design and performance.[7]

Table 2.1 sets out the most salient differences between the new "lean" or "flexibly decentralized" model of industrial production and the more traditional model of "mass" or "robust" production. As this comparison highlights, a lean production system is organized and managed to seek perfection the first time, to avoid wasted time and materials, and to understand and meet or exceed customer expectations. The lean production work force combines the multiple skills of the craft worker with the scale advantages of

TABLE 2.1 Changing Organizational Patterns in U.S. Industry

Old model	New model
Mass production, 1950s and 1960s	Flexible decentralization/Lean production 1980s and beyond
Overall strategy	
• Low cost through vertical integration, mass production, scale economies, long production runs.	• Low cost with no sacrifice of quality, coupled with substantial flexibility, through partial vertical disintegration, greater reliance on purchased components and services.
• Centralized corporate planning; rigid managerial hierarchies.	• Decentralization of decision making; flatter hierarchies.
• International sales primarily through exporting and direct investment.	• Multi-mode international operations, including minority joint ventures and nonequity strategic alliances.
Product design and development	
• Internal and hierarchical; in the extreme, a linear pipeline from central corporate research laboratories to development to manufacturing engineering.	• Decentralized, with carefully managed division of responsibility among R&D and engineering groups; simultaneously product and process development where possible; greater reliance on suppliers and contract engineering firms.
• Breakthrough innovation the ideal goal.	• Incremental innovation and continuous improvement valued.
Production	
• Fixed or hard automation.	• Flexible automation.
• Cost control focuses on direct labor.	• With direct costs low, reductions of indirect cost become critical.
• Outside purchases based on arm's-length, price-based competition; many suppliers.	• Outside purchasing based on price, quality, delivery, technology; fewer suppliers.
• Off-line or end-of-line quality control	• Real-time, on-line quality control.
• Fragmentation of individual tasks, each specified in detail; many job classifications.	• Selective use of work groups; multiskilling, job rotation; few job classifications.
• Shopfloor authority vested in first-line supervisors; sharp separation between labor and management.	• Delegation, within limits, of shopfloor responsibility and authority to individual and groups; blurring of boundaries between labor and management encouraged.

Old model	New model
Mass production, 1950s and 1960s	Flexible decentralization/Lean production 1980s and beyond
Hiring and human relations practices	
• Work force mostly full-time, semi-skilled.	• Smaller core of full-time employees, supplemented with contingent (part-time, temporary, and contract) workers, who can be easily brought in or let go, as a major source of flexibility.
• Minimal qualifications acceptable.	• Careful screening of prospective employees for basic and social skills, and trainability.
• Layoffs and turnover a primary source of flexibility; workers, in the extreme, viewed as a variable cost.	• Core work force viewed as an investment; management attention to quality-of-working life as a means of reducing turnover.
Job ladders	
• Internal labor market; advancement through the ranks via seniority and informal on-the-job training.	• Limited internal labor market; entry or advancement may depend on credentials earned outside the workplace.
Governing metaphors	
• Supervisors as policemen, organization as army.	• Supervisors as coaches or trainers, organization as athletic team. (The Japanese metaphor; organization as family.)
Training	
• Minimal for production workers, except for informal on-the-job training.	• Short training sessions as needed for core work force, sometimes motivational, sometimes intended to improve quality control practices or smooth the way for new technology.
• Specialized training (including apprenticeships) for gray-collar craft and technical workers.	• Broader skills sought for both blue-and gray-collar workers.

SOURCE: U.S. Congress, Office of Technology Assessment (1990b, p. 115).

the mass producer. Multiskilled workers use increasingly automated and more flexible machines and tools to make a greater variety of products with the same capital equipment, for example, by software rather than hardware modifications. Inside the lean production organization, the division of labor is organized around cooperative cross-functional teams at all levels, thereby encouraging sharing of responsibility and close integration of different parts of the product realization process (Hill, 1991). Cooperative work groups on the factory floor can coordinate work more effectively and make incremental changes directly and quickly.

These techniques tend to be linked and interdependent. Therefore, it is critical that those who organize and arrange the production and delivery of goods or services understand the complexity of the production/delivery system that their decisions affect when considering improvements to that system. For instance, although just-in-time production techniques are often praised for their contribution to lowering inventory investment, these techniques have also provided powerful incentives for firms to achieve higher component quality. While elevating the importance of supplier relationships, these techniques also allow firms to reduce investment in material-handling equipment and to decrease warehouse storage requirements as well as material buffers in the assembly process. Conversely, just-in-time practices, if divorced from strong cooperative relations with suppliers, workers, and customers, are unlikely to work well, and may even be counterproductive. The new "lean" system needs to be implemented as a whole. Beyond these gains, a greatly increased flexibility of product manufacture allows rapid response to new orders (Heim and Compton, 1992; Hill, 1991; Lee, 1992).

Indeed, well-executed, lean production of products with a high piece count has enabled manufacturers to cut production costs by up to 50 percent while simultaneously yielding much higher product quality than older production processes. When a Xerox benchmarking team compared their company's performance against that of their Japanese affiliate and other Japanese photocopier manufacturers in the late 1970s and early 1980s, they were astonished by the differential between Japanese and U.S. firms. Japanese manufacturers were producing significantly higher quality products than Xerox with half the manufacturing costs (Bebb, 1990).

A similar gap between Japanese and U.S. automakers in quality and cost was documented during the mid-1980s. More recent data show that some plants of U.S. automakers have nearly caught up with Japanese in the number of labor hours required to assemble a car. Nevertheless, many other U.S. plants continue to lag far behind their Japanese counterparts in labor productivity, in some cases requiring 50 percent more labor hours to produce a comparable number of automobiles (Womack et al., 1990; Clark and Fujimoto, 1991).

In addition to the gains cited above, when management practices adhere to the human resource principles of lean production, significant gains in worker satisfaction can also be realized. The record of the General Motors-Toyota joint venture, New United Motors Manufacturing, Inc. (NUMMI), in Fremont, California, demonstrates that significant quality and productivity improvement can be accompanied by major increases in worker satisfaction under lean production (Adler, 1993; Vierling, 1992), NUMMI was established in 1984 in the Old GM-Fremont plant, hiring 85 percent of the unionized work force that had worked in the plant under GM's traditional mass production organization. By the end of 1986, productivity at the NUMMI plant was higher than all other GM plants and twice that of its predecessor, GM-Fremont. At the same time, absenteeism at the NUMMI plant fell to a steady 3 to 4 percent, down from levels of 20 to 25 percent under the old GM-Fremont management, and the number of worker grievances filed under NUMMI management dropped to a fraction of those filed during the GM-Fremont era. By the end of 1991, over 90 percent of NUMMI employees described themselves as "satisfied" or "very satisfied" (Adler, 1993).[8]

Although the NUMMI experience demonstrates that the improvement of worker welfare and the other productivity and quality objectives of lean production can be mutually reinforcing, it should be noted that "lean" approaches that neglect the human component of production systems can have the opposite effect. One recent study of other Japanese auto transplants in North America concluded that these companies' commitment to conserving resources or "leanness" did not extend to their work force, citing a relatively high incidence of work-related injuries such as repetitive stress injury at a number of plants (Berggren, et al., 1991).[9] Although many changes in production systems during the industrial age have led to less desirable conditions for workers in the factory, the committee notes that the opposite *can* be true with a shift to lean production if increased participation and enhancement of firm's most valuable asset—its work force—are central to its strategy.

In a similar manner, many of the principles of lean production can be applied to the new product development process. Several studies have shown in detail that the more systematic approach to the integrated, concurrent design and development of products and their related processes, known as "concurrent engineering," can significantly reduce product lead times and increase engineering productivity while maintaining, if not improving, product quality. It does so by the use of multifunctional teams in each phase of product development along with much-improved methods of communication and documentation. A study of production and product development performance in the photocopier industry during the late 1970s and early 1980s concluded that Xerox, the leading U.S. producer of photocopiers, took twice as long and twice as much engineering manpower to develop a new product as Fuji Xerox and other Japanese competitors (Bebb, 1990).

Likewise, in a comparative study of 29 major new car development projects in 20 companies (three American, eight Japanese, and nine European), Clark and Fujimoto (1991) showed that Japanese firms employing concurrent engineering techniques were able to complete a development project with, on average, one-third the engineering hours and two-thirds the lead time of their U.S. and European competitors. Similarly, Sullivan's (1987) two-company comparison of the process of developing a new model automobile showed that major design changes peaked for the Japanese firm about 35 percent of the way through the process, whereas the design changes of the U.S. firm peaked just before and after the new model's release and were much more numerous overall. [10] See Figure 2.1.

Finally, there is broad evidence that the principles of lean production and concurrent engineering have the potential for widespread application in the production and delivery of services such as accounting, banking, retail sales, package delivery, health care, insurance, and telecommunication services. Indeed, service firms can be said to have pioneered in some forms of lean production and concurrent engineering, especially in new ways of using computer and communications systems to develop and deliver new services as well as to redesign existing services to suit new forms of delivery, all while reducing the cost and raising the quality of services delivered to customers (Barkan, 1991; Drucker, 1991; Enderwick, 1990; Guile and Quinn, 1988a,b; Lee, 1992; Quinn, 1992; U.S. Congress, Office of Technology Assessment, 1987).[11] As in the production of manufactured goods, lean production of services is driven by attention to the value added at each stage of the product-realization process. In both cases, the focus is on eliminating steps and activities that do not contribute sufficient value to justify the cost of their inclusion in the process.

All of these factors together make the advantages deriving from economies of scale alone much less significant than they once were in many industries. The ability to respond quickly and flexibly to changing customer demands and the importance of rapidly absorbing new technologies in both product and process design require a revolution in both the internal communications of the firm and in its relationship with customers and suppliers, as well as a new level of attention to the optimal use of human talents in the work force. To compete in this new context, companies need to embrace continuous improvement of product and production processes, integrating R&D effectively with design, production, and marketing. It is also critical that they move away from their traditional arm's-length, adversarial relationships with suppliers and customers and toward more cooperative, mutually beneficial relationships with these important "external" sources of innovation. At the same time, they should rely less on managerial hierarchy and focus instead on cooperative work teams, employee empowerment, and continuous skill building at all personnel levels.

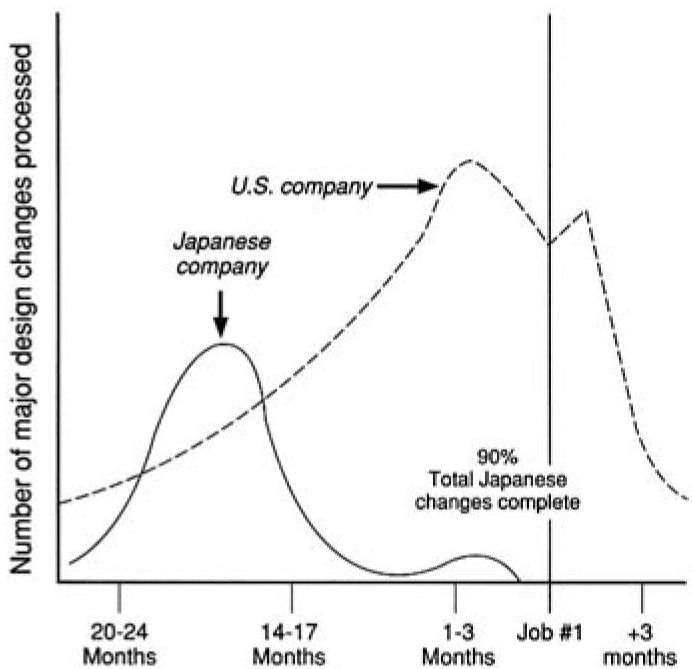

FIGURE 2.1 Rate of issuance of design changes, patterns of U.S. and Japanese auto manufacturers. SOURCE: After Sullivan (1987, p. 39).

Many features of the Japanese production system have been successfully adapted to the U.S. workplace by a number of U.S. and Japanese-owned firms. Reinforced by public- and private-sector initiatives, such as the Malcolm Baldrige Quality Award, the National Center for Manufacturing Sciences consortium, and the dissemination of International Organization for Standardization (ISO) 9000 quality standards by a host of private-sector industrial associations and management consulting firms, many U.S.-based manufacturing and service companies have begun to embrace such concepts as total quality management and concurrent engineering.[12] Nevertheless, the spread of modern production practices throughout U.S. industry, beyond a relatively small group of U.S. and foreign-owned multinational companies, has been very slow.

Average U.S. industrial performance in this regard is particularly troubling, given that Japanese manufacturers continue to advance the competitive standard by investing considerably more than their U.S. counterparts in advanced manufacturing technologies and automation (See Table 2.2).[13] Moreover, the rapid spread of lean production practices and advanced manufacturing technology through multinational companies to production facilities

TABLE 2.2 Use of New Technology in Manufacturing, Japan and the United States: 1988

Type of New Manufacturing Technology	Technology Users as a Percentage of Small and Large Manufacturing Enterprises[1]				Large/Small Ratio		Japan/U.S. Ratio	
	Japan		U.S.		Japan	U.S.	Small	Large
Japanese definition (closest U.S. definition in parentheses)	(a) Small	(b) Large	(c) Small	(d) Large	(e)	(f)	(g)	(h)
Numerically controlled and customized numerically controlled machine tools (NC.CNC machine tools)	57.4	79.4	39.6	69.8	1.4	1.8	2.0	1.1
Machining centers (FMS cells or systems)	39.4	67.4	9.1	35.9	1.7	4.0	7.4	1.9
Computer-aided design (and computer-aided engineering)	39.1	75.2	36.3	82.6	1.9	2.3	2.1	0.9
Handling robots (pick and place robots)	22.6	62.2	5.5	43.3	2.8	7.8	11.2	1.4
Automatic warehouse equipment (automatic storage and retrieval)	10.9	44.9	1.9	24.4	4.1	13.1	24.1	1.8
Assembly robots (other robots)	8.3	41.4	3.9	35.0	5.0	8.9	10.6	1.2

NOTES:

[1] The comparisons between Japan and the U.S. are approximate since differences exist in technology definitions and employment size categories. Additionally, the Japanese data are enterprise-based, while the U.S. data are establishment-based. The Japanese define a small manufacturing enterprise as having less than 300 employees and a large enterprise as having 300 employees or more. The U.S. government defines small enterprises as firms with 50 to 499 employees and large enterprises as firms with 500 employees or more.

(e)=(b)/(a).
(f)=(d)/(c).
(g)=(a)/(c).
(h)=(b)/(d).

SOURCES: After Shapira et al. (1992, p. 5).
(a),(b) Ministry of International Trade and Industry (1989).
(c),(d) U.S. Department of Commerce (1989a).

in developing countries, where wages are anywhere from one-fifth to one-tenth those of the U.S. work force, suggests that the pressures on U.S.-based companies to modernize their organization, management and plant will intensify greatly in the coming decade.[14]

At the level of national technology strategy and policy, the revolution in production systems places a growing premium on the rapid and widespread diffusion of "best practices" in the management of human capital and the production process as a whole throughout a nation's economy. It also reveals the importance of building and strengthening local or regional clusters of complementary skills, human resources, and technical infrastructure (Porter, 1990; Womack et al., 1990).

TOWARD A TECHNOLOGICALLY MULTIPOLAR AND INTERDEPENDENT WORLD

In parallel with the revolution in production systems and the changing character of technology-based competition in many industries, the past two decades have witnessed pervasive changes in the global distribution and organization of technological capabilities among nations. First, there has been a major shift in the postwar technological balance of power around the world. Whereas the United States in the early postwar period was both technologically and economically preeminent in almost every field, technological and economic power is now much more evenly distributed among North America, the Pacific Rim, and an increasingly integrated European Community. Whether the measure is investments in R&D as a share of gross national product, patent shares, or successful launches of new technology-intensive products and services, it is clear that the United States no longer dominates the world in scientific and engineering prowess. This is especially true if domination is defined as organizational mastery of technology development and application in all its aspects rather than merely being first to demonstrate new technologies in the laboratory or in prototype form.

Accompanying the gradual but steady equalization in basic national technical competence has been an unprecedented trend toward internationalization of production and associated technological activities through the expansion of international trade, investment, and cross-border corporate alliances. Capital, technology, industrial management systems, people, products, and services cross the borders of industrialized countries at unprecedented rates as part of everyday commerce. As a result, the process of technological innovation itself is becoming increasingly internationalized, and the pace at which new technology diffuses throughout the advanced industrialized world is accelerating. A product sold in France, Japan, the United Kingdom, or the United States is likely to be a global product—developed in one country, based on research or design done in another, assembled by one multinational company from components made around the world, and sold and serviced by still another multinational company that has name recognition in a particular country's market.

Converging Capabilities in Technology Creation and Commercial Use

The nature and significance of the shifting global balance of technological power are illustrated by various comparative indicators of national scientific and technological strength. Comparisons of national trends in R&D investment, R&D work force expansion, patenting, and the publication of the results of scientific and technological research show that other industrialized nations are closing the gap with the United States in the capacity to produce and absorb new scientific and technological knowledge.

In total dollars invested in research and development, both defense and nondefense-related, the United States remains without rivals (see Figure 2.2). In 1990 the United States invested more money in research and development

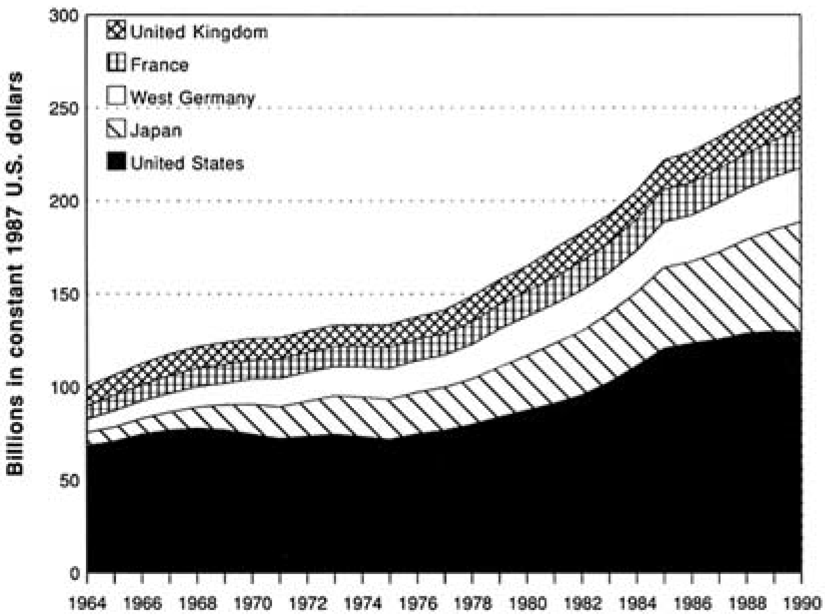

FIGURE 2.2 National R&D expenditures, by country: 1964-1990.
SOURCE: National Science Board (1992, p. 73).

than Japan, Germany, France, and the United Kingdom combined. Similarly, total U.S. investments in basic research (research that advances scientific knowledge yet does not have specific commercial objectives) roughly equals the combined basic research investments of these four countries.[15]

At the same time, international comparisons of trends in the ratio of total R&D investment to gross national product (GNP)—the R&D intensity of a nation's economic activity—show that Japan, Germany, and Sweden have surpassed the United States during the last decade. As of 1990 the United States invested 2.7 percent of its GNP in total R&D while Japan, Germany, and Sweden invested 3.1, 2.8, and 2.9 percent, respectively. However, since the contribution of defense-related R&D to the technology needs of the civilian economy is much more limited today than 20 years ago (see pp. 53–54 below), the more relevant measure of an economy's technical strength is its ratio of nondefense, or civilian, R&D investment to GNP. International comparisons of civilian R&D intensity document a large and widening gap between the United States and some of its major industrial competitors (see Figure 2.3).[16] This ratio has remained fairly constant for the

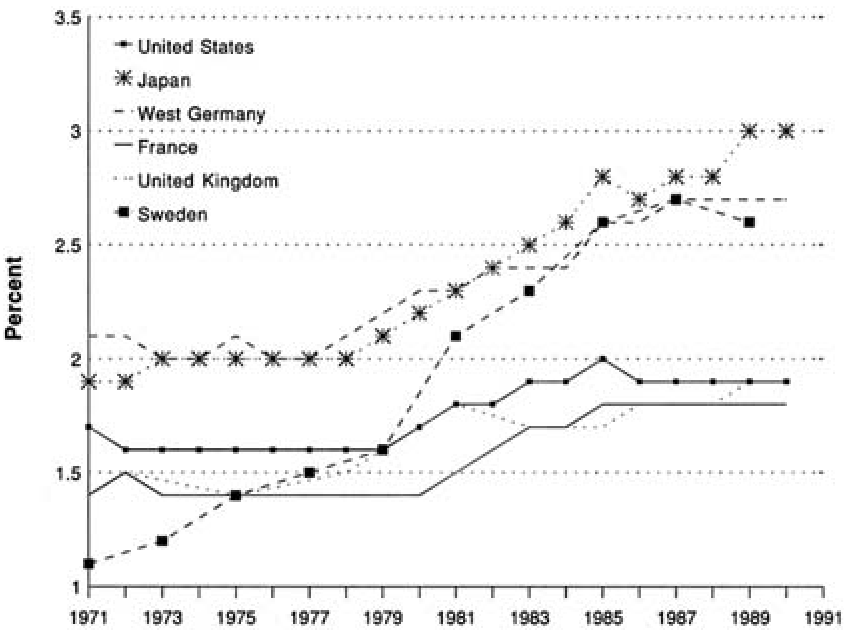

FIGURE 2.3 Nondefense R&D expenditures as a percentage of gross national product, by country: 1971–1990. NOTE: Based on data valued in constant 1987 U.S. dollars. SOURCE: National Science Board (1992, p. 74).

United States, ranging between 1.6 and 2.0 percent for the past 20 years. In contrast, over the same period, Germany, Sweden, and Japan have increased the civilian R&D intensity of their economies significantly. As of 1990 the United States invested 1.9 percent of its GNP in nondefense R&D, while Germany, Sweden, and Japan invested 2.7, 2.6, and 3.0 percent of their respective GNPs on nondefense R&D.[17]

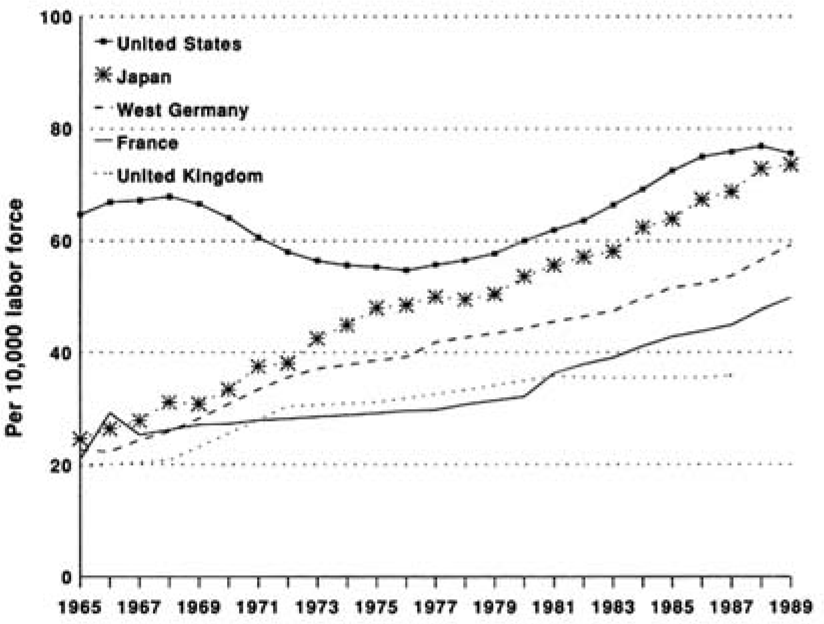

FIGURE 2.4 Trends in employment of scientists and engineers in R&D, by country: 1965–1989. NOTE: Latest available U.K. data is from 1988. SOURCE: National Science Foundation (1992, p. 67).

Similarly international comparisons of R&D scientists and engineers as a share of the total work force of industrialized nations show that the distinctiveness of the U.S. postwar position has eroded in recent decades (see Figure 2.4). By 1989 Japan had nearly closed the gap with the United States, fielding 74 R&D scientists and engineers (most of whom were engineers.[18]) per 10,000 workers, compared with 76 in the United States.

In the area of production technology and associated methodologies, Japan has emerged as a world leader. As noted above, Japan has done more than any other nation to advance, codify, and disseminate a revolution in production systems captured by such concepts as just-in-time, total quality management, design for manufacturing, and concurrent engineering. Japan's leadership in, and mastery of, these modern production methodologies have been well documented. In the automotive and photocopier industries, Japanese firms have demonstrated that they can develop new products in half to two-thirds the time with half the engineering work-hours required by their leading U.S. or European competitors (Barkan, 1991; Bebb, 1990; Clark and Fujimoto, 1991; Imai, 1990).[19] As of the mid-1980s, Japanese industry already enjoyed the world's highest density of advanced manufacturing technology embodied in production equipment such as industrial robots, numerically controlled machine tools (NCMTs), and flexible manufacturing systems (FMS) (Edquist and Jacobsson, 1988; Shapira et al., 1992). see Table 2.2.

The redistribution of shares of world production and trade in high-technology manufacturing industries over the past decade is another proxy measure of the shifting balance of technological power.[20] Between 1980 and 1990, world production of high-tech manufactures (calculated in 1980 dollars) more than doubled, while high-tech trade grew fourfold. The United States continues to host a larger share of world high-tech production than any other nation. However, between 1980 and 1990, its share of global shipments of high-tech manufactures fell 4 percentage points from 40 to 36 percent, while that of Japan increased from 18 to 29 percent (see Figure 2.5). Over the same period, high-tech manufacturing as a share of total U.S. manufacturing grew from 20 to 30 percent while it more than doubled in Japan from 16 to 35 percent. Between 1980 and 1988, the U.S. share of world high-tech exports fell from 27 to 23 percent, while Japan's rose from 10 to 15 percent. [21]

In summary, the wide postwar gap between the United States and its major industrial competitors in both the creation and the commercial application of new technology has been closed in many areas of technology and is closing in others. Hence, the U.S.-dominated, technologically unipolar world of the 1950s and 1960s has given way to a world in which there are now multiple poles of technological power distributed throughout the globe.

Deepening Economic and Technological Interdependence

The past decade has seen an acceleration of the transition from a world of relatively discrete national technological systems toward one of globally interconnected and interdependent national technological systems. The internationalization of technology development and diffusion is following upon a profound deepening of international economic interdependence during the past 15–20 years, as evidenced by the growth of world trade, a virtual explosion of foreign direct investment, and the associated proliferation of international technical and logistical networks of firms. Nevertheless, the transition to a fully globalized world economy is still far from complete (Freeman and Hagedoorn, 1992; Patel and Pavitt, 1991, 1992; Pavitt, 1992).

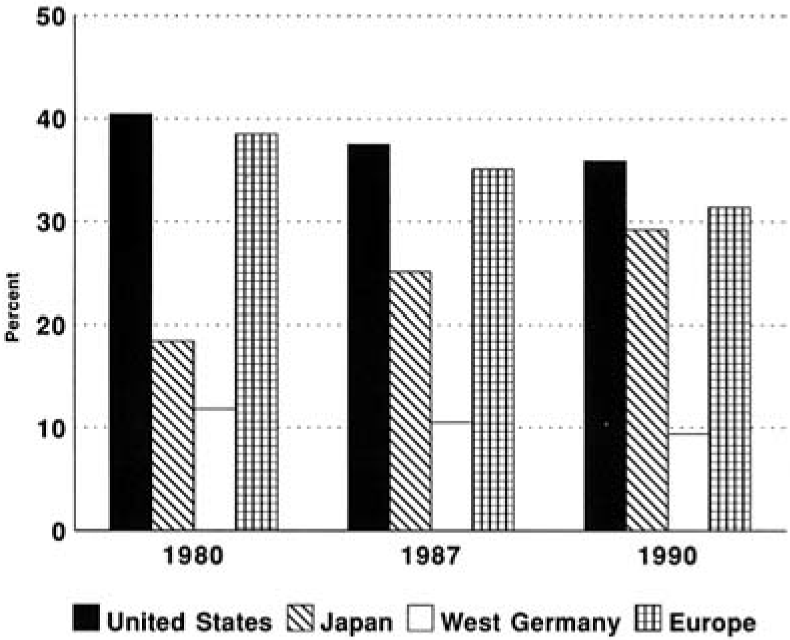

FIGURE 2.5 Shares of global market for high-tech manufactures: 1980, 1987, 1990. NOTE: Based on data valued in constant 1980 U.S. dollars. SOURCE: National Science Board (1991, p. 402).

During the 1980s, trade in manufactured goods as a percentage of total manufacturing output of the 25 leading industrialized nations grew from 20 to 35 percent. Over the same period, trade in high-tech manufactures grew from 19 to 27 percent of these countries' total high-tech production. By the late 1980s, U.S.-based high-tech manufacturers were exporting more than 20 percent of their total output, while their Japanese and German counterparts were exporting 24 percent and 60 percent of their respective high-tech output.

Likewise, between 1980 and 1990, U.S. imports of high-tech products as a share of total U.S. domestic consumption of these goods nearly doubled from 8 to 14 percent (National Science Board, 1991). See Table 2.3. Over the same period, high-tech import penetration of the major European economies, already on average 3 to 4 times the U.S. level in 1980, increased

TABLE 2.3 Import Share of Domestic Market for High-Tech Manufactures, by Country: 1980, 1986, 1990

High-Tech Manufactures	1980 (percent)	1986 (percent)	1990 (est.) (percent)
United States	8.0	12.1	13.8
Japan	6.6	8.4	9.2
West Germany	25.1	31.2	41.2
France	33.2	45.1	55.2
United Kingdom	29.1	38.8	42.1
Italy	29.3	44.5	43.6

SOURCE: National Science Board (1991,p.405).

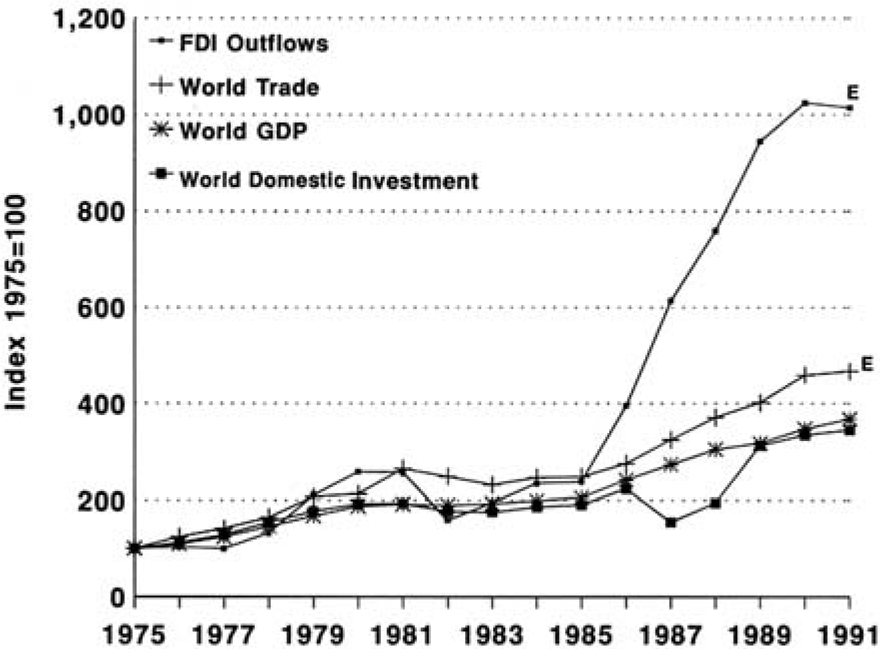

FIGURE 2.6 Growth in world trade, output, domestic investment, and foreign direct investment: 1975–1991. NOTE: E based on 1991 estimates. SOURCE: U.S. Department of Commerce, International Trade Administration, Office of Trade and Economic Analysis, unpublished data, 1993.

significantly to more than 40 percent in Germany, Italy, and the United Kingdom, and more than 55 percent in France. Japan, on the other hand, which began the decade with an absolute level of high-tech import penetration below that of the United States, experienced much slower growth of import penetration during the 1980s than any other major industrialized country.[22] Trade data by themselves, however, grossly understate the deepening of international economic interdependence over the past decade.

Since the mid-1970s the main driver of global economic integration has been the growth of foreign direct investment or multinational corporate enterprise.[23] In the past decade alone, world flows of foreign direct investment have tripled, growing two and one-half times faster than world trade since 1983 (see Figure 2.6). More than three-fourths of the growth in world stock of foreign direct investment was accounted for by non-U.S. companies, and nearly a quarter of the growth was absorbed by the United States.

During the past decade, foreign direct investment has assumed an increasingly important role in all major industrialized economies, again, with the notable exception of Japan. As the data in Table 2.4 show, most of the United States' major trading partners except Japan were significantly more

TABLE 2.4 Foreign-Controlled Firms' Share of Total Business Enterprise R&D Expenditure, Employment, and Product Shipments in Manufacturing Enterprises in Six Countries

	% Share Business Enterprise R&D Expenditure 1989	$ Share Employment 1989	% Share Product Shipments 1989
United States	8.8	10.0	14.9
France	12.4	22.1	26.7
United Kingdom	17.0	14.8	23.5
Sweden	13.6	14.0	15.1
Germany	*	18.1	21.7
Canada	52	34.0[a]	48.6[b]
Japan	1.0	1.1	2.3

NOTE: The United States defines foreign-controlled firms as nationally incorporated and unincorporated business enterprises in which foreign persons have at least a 10 percent interest. Some nations define foreign-controlled firms at a higher level of equity interest.

* Data not available

[a] 1986 data

[b] 1987 data

SOURCES: Organization for Economic Cooperation and Development (1992b, Table 59 and 60, and unpublished data, 1993).

dependent on foreign direct investment by the late 1980s than the United States itself. The affiliates of foreign-owned companies accounted for 21 percent or more of the total domestic sales of manufactured goods in the United Kingdom, Germany, France, and Canada, and only 15 percent of total U.S. manufacturing sales. Nevertheless, no other major industrialized nation experienced growth in its dependence of foreign direct investment during the 1980s as rapid as that of the United States.

TABLE 2.5 Measures of the Proportion of Foreign Direct Investment in the U.S. Economy

	Percent
Foreign direct investment position in the U.S. economy as a proportion of total U.S. domestic net worth (1991)	5.3
Total assets of U.S. affiliates in manufacturing as a proportion of total assets of all U.S. manufacturing companies (1990)	18.6
Stockholder's equity of U.S. affiliates in manufacturing as a proportion of stock-holder's equity of all U.S. manufacturing companies (1988)	12.9
Sales of U.S. affiliates in manufacturing as a proportion of sales of all U.S. manufacturing companies (1990)	16.4
Employment of nonbank U.S. affiliates as a proportion of total U.S. private nonbank employment (1990)	5.0
Employment of U.S. affiliates in manufacturing as a proportion of all U.S. manufacturing companies (1990)	10.8
Value added of nonbank U.S. affiliates as a proportion of U.S. gross domestic product (1989)	5.1
Value added of U S. affiliates in manufacturing as a proportion of all U.S. manufacturing companies (1989)	13.4

SOURCES: From U.S. Department of Commerce (1991, and unpublished data, International Trade Administration, Office of Trade and Economic Analysis, 1993).

Between 1980 and 1991, foreign direct investment in the United States expanded nearly fivefold.[24] By 1990 foreign-owned companies controlled more than $1.5 trillion in assets in the United States and employed roughly 4.7 million Americans. In manufacturing alone the U.S. affiliates of foreign-owned firms accounted for approximately 19 percent of total U.S. manufacturing assets, 16 percent of U.S. manufacturing sales, 13 percent of U.S. manufacturing value added, and nearly 11 percent of U.S. manufacturing employment in 1990 (see Table 2.5). [25] Currently the subsidiaries of foreign-owned firms operating in the United States are estimated to account for more than one-third of U.S. imports and one-fifth of U.S. exports (U.S. Department of Commerce, 1991).

Likewise, the multinational presence of U.S.-owned companies has expanded greatly during the past decade both in dollars invested abroad and in the number of U.S. companies that have gone multinational. In 1990 the assets of overseas affiliates of U.S. companies were in excess of $1.5 trillion, and more than one-third of U.S. multinationals' earnings came from overseas operations. That year, U.S.-owned operations abroad employed more than 6.7 million people, drawing heavily on local production, technical, and management talent. Already in 1986, sales by the foreign affiliates of U.S. high-tech companies were twice as large as U.S. high-tech exports, and foreign affiliate assets represented more than 40 percent of the total assets of U.S. high-tech manufacturing industries (Conference Board, 1992; Julius, 1990; National Science Board, 1989; U.S. Department of Commerce, 1992c).[26]

In summary, economic and technological interdependence among industrial nations is deep and likely to continue to deepen. The depth of interdependence experienced by the major industrialized nations varies considerably—from the highly "internationalized" economies and national technology enterprises of Western Europe, to the historically more autonomous yet rapidly internationalizing U.S. economy and technology enterprise, to the relatively autonomous and more slowly internationalizing Japanese economy and technology enterprise. Although trends in the global economy suggest that these asymmetries in dependence will diminish with time, they are unlikely to disappear in the short term.

The Internationalization of Technology Development and Diffusion

The rapid expansion of foreign direct investment during the 1970s and 1980s was accompanied by major changes in the conduct and spatial organization of corporate technical activities worldwide. From the mid-1950s to the late 1970s, the development of new product and process technology was, for the most part, an exclusively "domestic" as well as "in-house" activity for U.S. companies.

Since the late 1970s, however, changes in the global competitive environment have fostered an increasingly international approach to technology development and application on the part of U.S. and foreign multinationals. While affecting different industries to different degrees, increased global competition, the advantages of collocating production and R&D in many industries, national "managed trade" or "industrial" policies of varying scope, the promise of wider markets, and the availability of cost-effective sources of new technology and specialized technical competence overseas have all played a role in shifting corporate technology strategies. Responding to the challenges and opportunities associated with this new environment, multinational companies in many industries have begun to reorganize their technical activities to optimize them on an international basis.

In 1990 U.S. companies invested more than $10 billion in R&D overseas, nearly 14 percent of total company-financed industrial R&D in the United States that year. Leading the charge have been U.S. multinational companies in the computer, telecommunications, microelectronics, pharmaceuticals, and automotive industries, which now conduct anywhere from one-quarter to one-third of their R&D work abroad (U.S. Department of Commerce, 1992c). However, foreign multinationals, whose ranks expanded dramatically during the last two decades, have also increased their overseas R&D spending since the early 1980s. In the United States alone the U.S. subsidiaries of foreign firms accounted for more than $11 billion, or more than 15 percent of total U.S. company-financed industrial R&D in 1990. By 1990 at least 115 foreign companies had established 254 R&D facilities in the United States; 150 of these R&D facilities were established by Japanese companies, 95 by European companies, 6 by Korean companies, and 3 by Canadian companies (Dalton and Serapio, 1993).[27]

Multinational R&D spending alone, however, clearly understates the extent to which private-sector technology development, application, and diffusion are internationalizing. As the population of U.S. and foreign multinational companies has mushroomed, these firms have, in turn, helped cultivate increasingly dense global technical and logistical networks of companies that include a much broader population of "domestic," technically innovative suppliers, vendors, and distributors.

One measure of the growing importance of these global networks is the rapid growth in volume of intermediate inputs for final production obtained from international rather than domestic sources (see Figure 2.7).[28] A recent study of sourcing patterns for manufactured intermediate inputs in six industrialized countries from the early 1970s to the mid-1980s has shown that the direct import of these inputs from abroad increased more rapidly than domestic sourcing in all of the countries surveyed. As a result, by the mid-1980s, foreign sourced manufactured inputs were 50 percent of domestically sourced inputs in Canada and between 30 and 40 percent of domestically sourced inputs in France, Germany, and the United Kingdom. Much lower levels of foreign sourcing were observed for the United States and Japan, although both countries experienced significant increases in foreign sourcing between the mid-1970s and the mid-1980s (Wyckoff, 1992).

Another window on the growth of collaborative sourcing and development of technology by firms is provided by the surge in the number of corporate technical alliances (such as patent licensing and joint R&D) during the past decade. One recent survey has documented a steep rise in the number of transnational technical alliances among companies since the late 1970s (Hagedoorn and Schakenraad, 1993). While three broad industrial areas—information technology, new materials, and biotechnology—have experienced a particularly high level of alliance activity since 1980, other industries such as aerospace, automotive, and chemicals have also experienced growth in the number of international corporate alliances in recent years (see Figure 2.8).

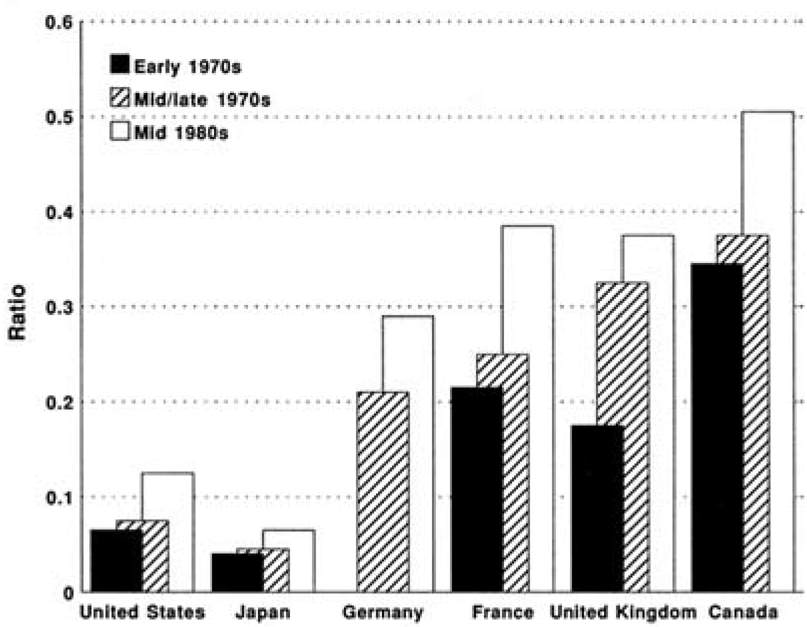

FIGURE 2.7 Ratio of imported to domestic sourcing of inputs, average of manufacturing goods, by country. NOTE: Early 1970s information for Germany is not available. SOURCE: Wyckoff (1992, p. 6).

Collectively the internationalization of R&D, the growth of global technical and logistical networks, and the rapid expansion of world high-technology trade define a powerful and pervasive trend toward internationalization of technology development and diffusion. While the current extent of internationalization is greater in certain industries and certain countries than in others, and should not be overstated, the trend is well established and gathering momentum. [29] In many sectors new technological knowledge is becoming a global commodity, rapidly accessible to any organization with sufficient incentive and technical sophistication to absorb it. In this new environment, U.S. prosperity, military security, and other vital national interests will depend increasingly on the ability of U.S. public- and private-sector actors to access and harness the technological output and capabilities of other nations as well as on that of global technical networks that defy national classification.

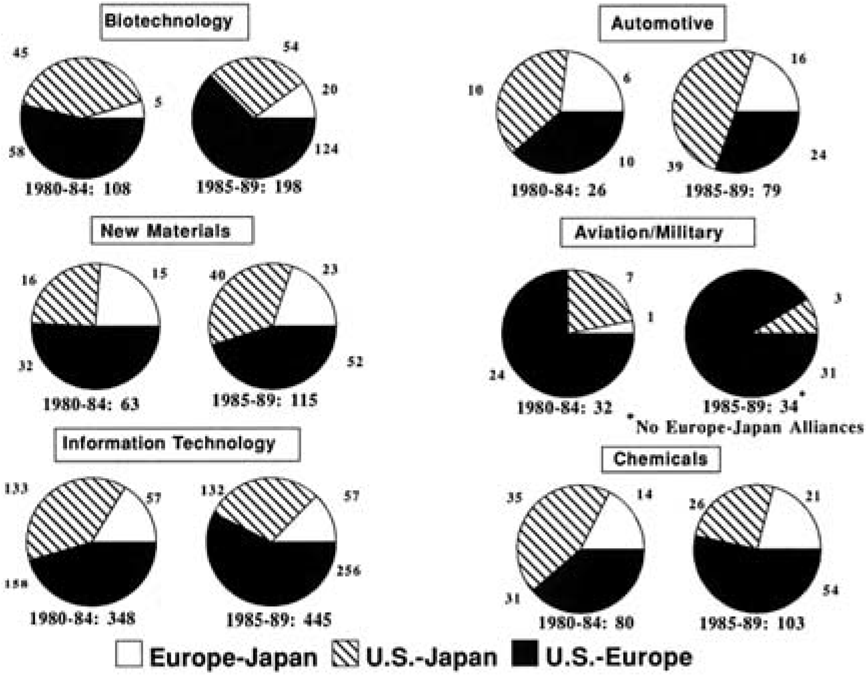

FIGURE 2.8 Number of new transnational corporate technology alliances, by industry: 1980-1989, SOURCE: Hagedoorn and Schakenraad (1993).

THE GEOPOLITICAL PREMIUM ON ECONOMIC STRENGTH

For more than four decades the military and geopolitical rivalry between the United States and the Soviet Union defined the global balance of power and served as a major driver of U.S. science and technology policy. U.S. military strategy and national security have been based on the development of U.S. superiority in military technology and on the strength of the U.S. industrial base. Throughout the 1950s and 1960s U.S. military strength and the nation's economic and commercial technological muscle were, for the most part, mutually reinforcing; public-sector investments in defense-related technologies complemented private-sector investment in commercial technological preeminence. In turn the growth of new industries and the U.S. economy overall ensured that the resources needed to maintain the nation's military strength and defense technology base were available.

During the 1960s and 1970s, even as other advanced industrialized nations closed the gap with the United States in economic prosperity and technological competence, the United States was able to continue to leverage its military superpower status to advance U.S. economic and political interests in negotiations with its allies and trading partners. The 1980s, however, were a time of dramatic change. As recently as 1980 the Cold War was in full swing and substantial increases in U.S. government defense spending (including defense R&D) were based on arguments setting forth the Soviet threat. At the same time, the exposure of the United States to foreign trade and investment (in particular, by Japanese companies.[30]) was just beginning to be felt. Over the course of the 1980s, the perceived threats to U.S. prosperity and security switched positions. On the one hand, the collapse of the Soviet Union seems to have put military security within reach. On the other hand, seemingly intractable U.S. trade and fiscal deficits, intensive foreign competition both at home and abroad in many major industries, and growing U.S. dependence on foreign sources of capital and technologically advanced products and components have raised concerns about U.S. economic security.[31] These changed national priorities suggest the need to reevaluate U.S. technology policy and strategy.

In this new world, leadership in military technology will remain critical to U.S. national security and U.S. influence abroad, but the level and nature of demands on the nation's defense capability have changed. Defense budgets are contracting and are likely to continue to do so for the foreseeable future. As a result, the U.S. national security missions' claims on, and contribution to, the nation's technology enterprise are likely to decrease.[32]

It has also become apparent that leadership in critical military technologies will be increasingly built on, and sustained by, leadership in the development and competitive commercial application of their corresponding, and often "progenitor" civilian technologies. This is because civilian technological advance—driven by global economic competition—is now pacing technological advance in many fields critical to the national defense, especially in respect to materials, components, and subsystems.

In the 1950s and 1960s, when the relative national investment in space and defense R&D was much larger than it is at present, many building-block technologies (solid-state electronics, computer technology, aeronautics and jet propulsion, and nuclear power) were in an early phase of their technological life cycle. This situation was favorable to the spin-off approach that U.S. technology policy had grown to rely on, implicitly if not explicitly, for substantial contributions to the generation of new commercial technology in the postwar period.

Beginning in the mid-1960s, many of these new technologies moved into more mature phases in which advances became more applications-specific and technologies derived from military R&D and procurement in the earlier period had already been adopted by civilian industries. Thus, in semiconductors and computers especially, the growth rate of commercially oriented R&D supported by industry, both in the United States and worldwide, far outpaced the growth of government-funded R&D in these technologies. As this change has occurred in more and more sectors, "spin-off" has been transformed into "spin-on" in all but a few sectors that are highly specialized to military requirements (such as nuclear weapons design and fighter aircraft). Indeed, only in aerospace, gas turbines, jet engines, specialized sensors, laser applications, and techniques of systems engineering and systems integration has the military provided a significant impetus for technological advance in recent years. In most other frontier areas the primary impetus to technological advance has been provided by commercial markets and economic competition.[33]

Since the late 1970s four new generic areas of technological advance have opened up: optoelectronics and fiber optics, advanced engineered materials, biotechnology, and software engineering, including artificial intelligence. With the exception of health-related research in biotechnology, which has been driven largely by public support from the National Institutes of Health, advances in these technological areas have been driven primarily by commercial demand. None of these new technologies has depended to more than a limited degree on support from the nation's military and space missions.[34]

These new areas of technological advance have been characterized by two conditions. First, military and space investments (both R&D and procurement) by the federal government have generated much less comparative advantage for the United States in recent years than earlier generic technology investments. Second, such advances as occurred in these newer technologies have at the outset been much more market-driven than earlier advances in integrated circuits, computers, and nuclear power.

In summary, (1) the particular demands on the U.S. national defense capability are substantially changed, (2) the national security mission's claim on, and contribution to, the nation's technology enterprise are dropping, and (3) the importance of defense-specific technologies has declined while the dependence of defense technology generally on technologies developed first in the commercial sphere is rising. [35] As a result, the nation's traditional approaches to defense procurement and defense research and development need to be reexamined—the old strategies seem unlikely to yield the same national security benefits as they did in the past. The increasing dependence of U.S. military leadership on the commercial economy, and specifically on commercially driven technological advance (a growing fraction of which is occurring outside the United States), should stimulate fresh thinking about the current composition and strategy of public-sector investment in science and technology (Carnegie Commission, 1990, 1992b; Center for Strategic and International Studies, 1991; Moran, 1993).

CONCLUSION: WEAKNESSES EXPOSED

Broad changes in the global environment—the revolution in production and innovation systems, the shift in the global balance of technological power in the context of deepening economic interdependence, and the end of the Cold War—alter the context for national technology strategy and policy and require rethinking of appropriate policies.

- First, the accelerating pace and the increasingly multidisciplinary an science-based character of technological change call for greater breadth and better balance in the R&D portfolio of companies and the nation. Ensuring competitive capability across a broad range of industrial technologies (including infrastructural and pathbreaking technologies) demands a higher degree of collaboration among firms, and between firms and other private and public R&D institutions. Tracking and acquiring new technology from outside corporate and national borders have become a necessary complement to internal technology development.
- Second, the revolution in production systems demands that companies (supported by government policies) adopt new organizational structures that rely less on managerial hierarchy and functional compartmentalization and focus instead on improved intrafirm communication and coordination, teamwork, employee empowerment, and continuous skill building at all personnel levels. It also places a premium on public policies that support the creation and development of local or regional clusters of particular complementary skills, human resources, and technical infrastructure.
- Third, the shift to a technologically multipolar world, increasing global competition, and the trend toward internationalization of production and innovative activity have made it imperative that individual companies and national economies (supported by government policies) work to harness global technology and high-technology markets more effectively to advance their respective interests.
- Finally, the breakup of the Soviet Union and the changed relationship between commercial and military technologies have substantially changed the demands on the U.S. national defense capability, reduced the number of defense-specific technologies, and dramatically increased the opportunity for defense technology to come from the commercial sphere. Moreover, current and ongoing U.S. defense cuts may displace a significant fraction of the nation's advanced technical work force and thereby risk dissipating their accumulated skills and competencies. [36]

Each of these broad changes in the global political and economic environment exposes serious weaknesses in the United States' current portfolio of technological activity. The revolution in production systems focuses attention on what many view as a legacy of underinvestment in, and managerial inattention to, process technology, human resources, and the social organizational aspects of technology's introduction and use in the workplace. Ongoing defense cuts, the changing relationship between civilian and defense technology, and the changing nature of industrial innovation more generally raise serious concerns about the present size, composition, and intensity of the nation's civilian R&D effort. And the shifting balance of technological power and deepening technological interdependence expose a parochialism in U.S. private and public technology strategies and policies that could easily undermine the nation's ability to harness global technology and markets.

Collectively the challenges and opportunities presented by these changes in the global context underscore the need for the United States to make national economic development an explicit objective of federal technology policy. The following chapter examines the major strengths and weaknesses of the U.S. technology enterprise as revealed by these global trends.

NOTES

1. This is true for two reasons. First, the fields that are most unique to defense and that may be regarded as single-purpose are largely concentrated in the area of strategic systems, which are most likely to be of lower priority in the coming defense environment. Second, the coming era of "smart" conventional weapons is more dependent on "dual-use" technologies, where commercial R&D is driving the pace of advance to an increasing degree. At the same time, these technologies were in a much earlier stage of their "technological life cycle" when defense was the driving force in their development, which was much less application-specific.

2. See, for example, Chandler (1962, 1977, 1990); Hughes (1983); Porter (1990); Rosenberg (1982); Scherer (1980).

3. Despite the increasingly science-based quality of commercial technology, there is still a large component of tacit knowledge embodied in the actual practice of all technology. Indeed, this is even true in the laboratory practice of the purest science. Hence, it is easy to overstate the science-based nature of technological competition.

4. For a comprehensive discussion of technology fusion as it applies to manufacturing industries, and the revolutions in mechatronics and optoelectronics, see Kodama (1991, chapter 5). For other examples of technology fusion in the service sector, consider the many service industries that have sprung from or have been radically transformed by the fusion of information technology and telecommunication. See Guile and Quinn (1988a,b) and Quinn (1992).

5. During the past decade other industrialized nations have greatly increased their collective public- and private-sector investments and overall strength in many areas of pathbreaking and infrastructural technology. See Chapter 1, p. 17, for definition of these types of technology. U.S. public- and private-sector investment in these technologies, however, is generally seen as inadequate to the needs of U.S. industry (Tassey, 1992; U.S. Department of Commerce, 1992b).

6. Part of the problem is the different natural cycle time of various elements in the new product development and manufacturing process. Generations of components and subsystems follow each other in much shorter succession than the overall design of a more complex piece of equipment. Thus, it is often important to configure the whole product development and manufacturing process to absorb incremental improvements of many different rates, resulting in an integrated process of "continuous improvement" rather than large individual leaps.

7. Womack et al. (1990) and Jaikumar (1989) have shown that Japanese companies often get a lot more mileage out of flexible manufacturing systems (FMS) than U.S. companies using the same equipment. In particular, the Japanese make a much larger variety of products on the same system, thus taking much greater advantage of its flexibility feature.

8. Interviews by several independent observers of workers who have worked under both systems at NUMMI support the statistical evidence in the sense that workers express far more satisfaction with the new system (often in very strong language). See, for example, Adler (1993) and Vierling (1992).

9. The study by Berggren et al. (1991) also challenged the assertions of other "lean production" studies regarding the productivity and profitability of "lean" Japanese transplants. Among other things Berggren et al. suggest that the heavy focus on the productivity consequences of workplace organization has led lean production advocates to overlook the fact that Japanese transplants have invested heavily in new process technology and that many of them are world leaders in automation. Furthermore, the authors assert that the bookkeeping practices of some of these transplants raise questions regarding their claims of high profitability.

10. Barkan (1991), Clark and Fujimoto (1991), Lee (1992), and others have documented the importance of high relative productivity of engineering services in product development and design to the superiority of the Japanese system of manufacture. They have also observed that the Japanese principles of product design are heavily derived from Japanese experience in manufacturing systems. In other words, the social system of manufacturing seems to have come first, and the lessons learned from that experience were then applied "upstream" in the design and development process.

11. Consider, for example, the rise of Federal Express to the pinnacle of the package delivery business (Nehls, 1988, Quinn 1992), or the organizational revolutions at American Express, the General Mills Restaurant Group, and Wal-Mart. Organizational changes made possible by the effective use of information and telecommunications technology and the application of customer-focused, lean production principles have allowed these companies to deliver a wider range of better quality services to customers at lower costs (Quinn, 1992, pp. 136–145, 319–320). With regard to Wal-Mart stores, the fastest-growing, most profitable major U.S. retail chain of the past decade, Quinn notes that the retailer has "perhaps the best technology-based communications system in its field, including satellite and interactive video links to many stores. With its detailed stock management systems, it can delegate and control to the counter level. This allows its personnel to run a 'store within a store' for better personal motivation and more focus on the customer."

12. For further discussion of these and other initiatives, see National Center for Manufacturing Sciences (1992a,b), Peach (1992), U.S. General Accounting Office (1991).

13. See also Chapter 3, pp. 74–76.

14. A recent U.S. Congress, Office of Technology Assessment (1992b) report on U.S.-Mexico trade found that export-oriented Mexican firms undercut U.S. wages for production workers by at least 5 to 10 percent, while in some cases achieving comparable levels of quality and productivity. The report concluded that in the future, multinational firms would have increasing latitude in locating production where labor is cheap and other conditions for modern manufacturing can be met. For a more optimistic assessment of the current and future attractiveness of the United States as a location for manufacturing activity by multinational corporations, see National Research Council (1992a).

15. See Irvine et al. (1990) and Chapter 3, Figure 3.1.

16. More than one-quarter of U.S. R&D investment is dedicated to national security needs—that is, researching and developing technologies of limited applicability to the civilian economy. For this reason, the committee considers the ratio of civilian or nondefense R&D to the gross national product a more meaningful measure of the relative technical intensity of national economies than the ratio of total R&D to GNP. Moreover, while it can be argued that economies of scale in R&D yield particular advantages to the United States because of its large

overall investment in nondefense R&D (more than that of Japan and Germany combined), the committee does not believe that these advantages compensate for the U.S. disadvantage in civilian R&D intensity to any significant degree. For further discussion of the diminishing relevance of national security-related R&D to the nation's commercial technology base, see Chapter 2, pp 53–54.

17. The latest year for which total and nondefense R&D data for Sweden are available is 1989.

It is worth noting that those countries that invest the highest proportion of their GNP on nondefense-related R&D are also countries noted for their policy emphasis on (and relative success with) the adoption and diffusion of technology—Switzerland, Germany, Sweden, and Japan. This line of argument suggests differences in the "character" of R&D and the organization of innovative activities between these countries and the United States. For further discussion, see Edquist (1990); Ergas (1987); Kodama (1991); Nelson (1993); and Patel and Pavitt (1992). Mansfield's comparative research on the allocation and productivity of industrial R&D resources among matched sets of U.S. and Japanese firms notes that the Japanese firms devote considerably larger shares of their total R&D investment to scanning and assimilating technologies developed beyond the firm, incremental improvement of existing products and processes, and process technology in general (Mansfield, 1988a, b). Also see Chapter 3, pp. 76–83 below, for further discussion of the composition and management of the U.S. civilian R&D portfolio.

18. Despite gray areas in definition and classification of scientists and engineers, the disparities here are so great they cannot be offset.

19. See discussion of concurrent engineering on pp. 36–37 above.

20. For definition of high-technology products, see Chapter 1, note 28.

21. See National Science Board (1991, pp. 401–407. appendix tables 6-2, 6-3, 6-4, 6-7). High-tech production data for 1988–1990 are estimates. All production and trade data are figured in constant 1980 dollars.

22. Intra-industry trade data also underline the anomalous position of Japan among advanced industrialized countries. See Lincoln (1990). It should be noted that there is considerable debate as to the magnitude and causes of these apparent differences in the level of foreign penetration of national economies, and hence, whether it is even useful or accurate to explain these differences as asymmetries of access. For a sampling of this debate, see Japan Economic Institute (1991); Krugman (1991); Lawrence (1991a,b); Lincoln (1990); Saxonhouse (1989, 1991).

23. Foreign direct investment in the United States, as defined by the U.S. government for reporting and statistical purposes, is the ownership by a foreign person or business of 10 percent or more of the voting equity of a firm located in the United States. An equity interest of 10 percent or more is considered evidence of a long-term interest in, and a measure of influence over, the management of the company (U.S. Department of Commerce, 1992d, p. m-1). Although some nations define foreign direct investment at a somewhat higher percentage of voting equity than the United States, analysts of global foreign direct investment trends do not consider these differences to be very significant.

24. In 1990 total foreign direct investment inflows into the United States fell dramatically from $72 billion in 1989 to $26 billion, the smallest amount since 1985. In 1991 and 1992 the downward trend continued in foreign direct investment inflows. There is some debate whether 1990 marks a fundamental turning point or an aberration in the long-term growth trend (U.S. Department of Commerce, 1992a).

25. Foreign-owned firms' share of manufacturing value-added is for 1989 (U.S. Department of Commerce, unpublished data, 1993).

26. According to data presented in Julius (1990), U.S. companies' foreign affiliate sales in some countries were much larger than U.S. exports to these countries (five to one in United

Kingdom). In other countries, however, foreign affiliate sales were only marginally greater than U.S. exports (only about 10 percent larger in Japan).

27. Industries or technology areas with the largest number of foreign R&D facilities include biotechnology (74 facilities), automotive (35 facilities), computer software (26 facilities), and computer peripherals (26 facilities) (Dalton and Serapio, 1993, p. vi).

28. Much of the growth in the volume of international sourcing follows from growth of foreign direct investment and concomitant growth of intrafirm trade (Wyckoff, 1992).

29. Tyson (1991) has noted that the U.S. domestic market still absorbs 80 percent of all high-tech production by U.S.-based (U.S. and foreign-owned) companies. Reviewing U.S. patent data, Patel and Pavitt (1991) conclude that industrial R&D is still predominantly national in character. As of the mid-1980s, 91 percent of total industrial R&D expenditures by U.S.-based companies were made in the United States; 92 percent of patenting by U.S. firms was from the United States, while the Japanese firm have done 99 percent of their patenting from their home country (National Science Board, 1991; Pavitt, 1992).

Research on patenting shows that even basic research—supposedly the purest form of public knowledge—is significantly more likely to be used effectively in proximity, either organizational or geographic, to where it is generated. The notion that private entities will tend to underinvest in basic research because they cannot be assured of capturing the economic benefits therefore is true in an average sense; nevertheless organization and countries that engage in basic research are able to absorb and benefit from new technological knowledge more rapidly and successfully than those that do not, even though involvement in R&D does not guarantee its appropriability (Jaffe et al., 1993; Pavitt, 1992; von Hippel, 1988).

There are still significant barriers to the movement of both scientific and technological knowledge across national boundaries and even between organizations or between regional agglomerations of technological competence in specific fields. There is ample evidence that the capacity to absorb new science and new technology is significantly dependent on the level of performance of research and development in the recipient organization, country, or region. The formal mechanisms of communication—publications, technical meetings, even electronic networks—are not by themselves sufficient to move technology, which requires movement of people and mutual participation in joint enterprises. There is still much we do not know about the mechanism of, and barriers to, movement of knowledge and skills.

30. The timing was not an isolated happenstance. The revolution in production systems (see pp. 31–40 above) led by Japan had permeated most Japanese export industries by the 1980s, providing "lean" Japanese manufacturers with significant advantages over their U.S. competitors in many industries.

31. The committee defines U.S. economic security as the ability of U.S.-based companies to access key components and subsystems required to make their major products competitive with those of foreign competitors. For further discussion of the changing nature of international economic competition and the concept of economic security see Moran (1993).

32. In the early 1950s the Pentagon's R&D expenditures accounted for about 35 percent of the total R&D expenditures of all advanced industrialized countries (OEEC/OECD). By 1990 this had dropped to about 12 percent and will probably shrink to less than 10 percent in the next five years. So, quantitatively, defense would have become a less important factor in world R&D as a whole even if its contribution to the commercial technology base per dollar of outlay had remained constant over that period.

The nature of defense R&D expenditures has also changed, being more concentrated on specific weapons systems engineering with a smaller fraction devoted to "generic," general-purpose R&D, which is more likely to have commercial benefit. Relative expenditures in U.S. budget categories 6.1 and 6.2 have shrunk to about one-third of what they were in the 1960s. However, the development portion of defense R&D is so large that there is undoubtedly some leakage into the commercial technology base even from the nominally "pure" weapons development programs. As weapons technologies have matured, and emphasis has shifted more and more to strategic systems related to the U.S.-U.S.S.R nuclear rivalry, the relevance of the overall R&D and procurement program to the commercial sector has declined. For example, in the early days of the semiconductor industry's development, the Pentagon accounted, for virtually 100 percent of the demand for semiconductors, and this has now dropped to around 8 percent. Thus, the commercial spin-off from both defense R&D and defense procurement, per dollar, has undoubtedly declined, probably severalfold.

Despite its diminished contribution to the global commercial technology base, the U.S. national security mission continues to lay claim to roughly 26 percent of all U.S. R&D spending (public and private) and 18 percent of the U.S. engineering work force. Given that national security activities remain five to seven times as R&D intensive as commercial activities on average, a relatively small shrinkage of economic activity in defense-related sectors translates into a far larger shrinkage in the national security mission's claim on the nation's technical resources. Hence, anticipated cuts in defense spending are likely to result in significant dislocation of highly skilled technical personnel (scientists and engineers and skilled manufacturing labor) and a corresponding decline in systems engineering and production activities in the U.S. economy. For further discussion see Henry and Oliver (1987), and U.S. Congress, Office of Technology Assessment (1992a). The recent decision within the Department of Defense to allocate more resources to research, exploratory development, advanced technology development, and prototyping at the expense of production is intended to moderate the effect of defense procurement cuts for the defense R&D base.

33. Because of the rapid pace of commercial product development cycles and the relatively slow pace of military system modernization cycles, it is becoming increasingly important for military systems designers to keep abreast of state-of-the-art commercial technology and find ways to incorporate it on an ongoing basis into the design of defense weapons systems. The very-high-speed integrated circuit (VHSIC) program, for example, had its origins mainly as an effort to get military systems designers to incorporate more state-of-the-art commercial semi-conductor technology into the design of weapons systems. To do this effectively, the government would have had to find ways to break down the barriers between commercial and defense technology development and procurement, and to provide for more frequent, modular replacement of military subsystems over the life cycle of individual weapon systems. Although some technological advances in semiconductor design and fabrication were accelerated, realization of the original purpose has been more doubtful.

34. Advanced engineering materials used in the production of aircraft and aircraft engines are an important exception. This subset of engineered materials is quintessentially "dual-use" technology, in which technology inputs and outputs are shared between the military and commercial sectors.

35. The nation's strategic nuclear weapons systems may on average require more defense-unique technology (thermonuclear weapons, precision long-range missile guidance, MIRV technology, directed-energy weapons, etc.) than conventional weapons do.

36. See note 32 above.

3

Strengths and Weaknesses of the U.S. Technology Enterprise

The revolution in production systems, the shifting global balance of technological power in the context of deep interdependence, and the rising geopolitical premium on economic strength, together present major challenges as well as opportunities to the U.S. technology enterprise. Considering the U.S. economy's recent legacy of large fiscal and trade deficits, slow productivity growth, and the slow growth of U.S. living standards, these trends demand that economic development become a priority objective of U.S. national technology strategy. If the nation is to address and master this new economic imperative, it must first take stock of the strengths and weaknesses of the nation's technology enterprise as revealed by the recent political, economic, and technological trends in the global economy.

STRENGTHS OF THE U.S. TECHNOLOGY ENTERPRISE

Among the many strengths of the U.S. technology enterprise, four warrant particular attention in light of the global trends examined in Chapter 2:

1. The large scale, broad scope, and relative openness of the U.S. basic research enterprise.
2. The size, wealth, openness, and technological sophistication of the U.S. domestic market.
3. The nation's capacity for spawning new technology-intensive industries, products, and services.
4. The continuing competitive strength and global reach of many U.S. high-tech industries.

As the following discussion makes clear, these four strengths are closely interrelated. Each both contributes and attests to the nation's deep-seated institutional and human resource capacity for creating new scientific and technological knowledge, new products, and new industries. Although the committee firmly believes these strengths should be sustained and built upon, it is now clear that these strengths alone will not enable the United States to meet successfully the technology-related challenges of a global economy. The committee also notes that most of these strengths, when pushed too exclusively, may, in fact, create deficiencies in other parts of the nation's technology enterprise.

A Large, Productive Basic Research Enterprise

Largely a product of decades of generous funding by federal mission agencies, the U.S. basic research enterprise has the potential to continue to provide the country with unique advantages in both the creation and the assimilation of new scientific and technological knowledge (see Figure 3.1).

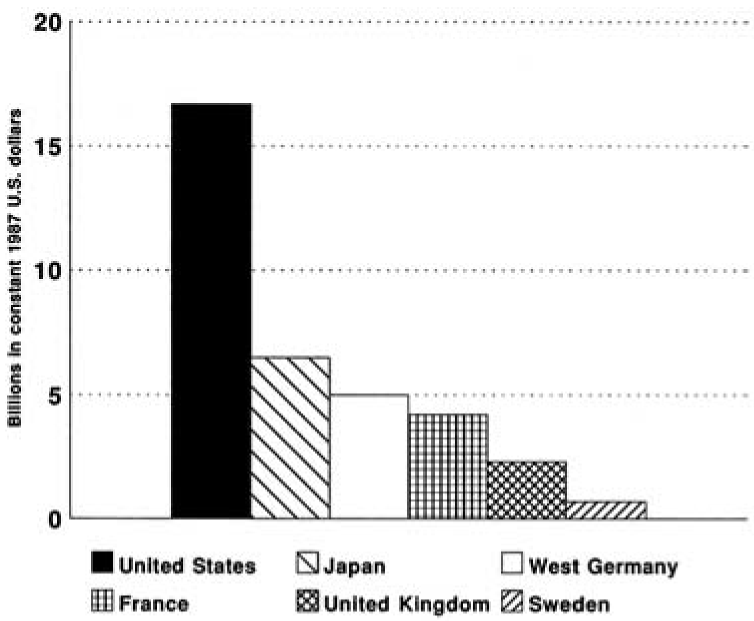

FIGURE 3.1 Basic research expenditures, by country: 1988. NOTE: Data represents total 1988 R&D expenditures multiplied by latest available ratio of basic research to total R&D spending. Latest ratio for Germany and Sweden is from 1987; the U.K., 1981. SOURCE: National Board (1991, p. 344; 1992, p. 73).

The U.S. basic research enterprise draw its strength from many sources, including

- The sheer magnitude of financial and human resources dedicated to research.[1]
- The multiplicity and diversity of U.S.-based research organizations, including universities, government laboratories, industrial laboratories, and independent research institutes, each characterized by different modes of setting research agendas.
- The high mobility of U.S. technical personnel.[2]

A particularly important factor in the strength of the U.S. basic research enterprise is that its largest, broadest,and probably most creative segment resides primarily within U.S. universities. The openness of the U.S. academic research enterprise to the free flow of ideas and talent from throughout the world, its integral relationship with advanced scientific and technical education, and the large scope it provides for initiative of individual scientists at relatively early stages in their careers have all contributed to U.S. preeminence in the creation of new scientific and technical knowledge.

The scale and character of U.S. academic research, in turn, have given the United States distinct qualitative and quantitative advantages in the cultivation of a large, diverse population of highly skilled research scientists and engineers. The outstanding reputation of U.S. universities in scientific and engineering research has been a magnet for some of the very best international scientific and engineering talent.[3] Throughout the 1980s, U.S. universities awarded over half of all doctoral degrees in engineering and nearly a third of all doctoral degrees in the sciences to foreign-born students, many of whom have stayed to work in the United States (National Research Council, 1988; National Research Council, Office of Scientific and Engineering Personnel, unpublished data, 1992). Thus, the strength of the U.S. university-based research enterprise has contributed significantly to the infusion of diverse cultures, intellectual traditions, and technical practices into the U.S. technology enterprise, thereby enriching it.

Clearly the United States' unrivaled capacity for basic research and the human resource dividends it yields are major assets for the U.S. technology enterprise. However, the often single-minded pursuit of excellence and leadership in basic research within academia spills over into an undervaluation of other types of technical activity in industry, thereby indirectly weakening the ability of U.S. industry to develop, assimilate, and manage technology effectively for economic advantage. The preoccupation with technical originality throughout academic science and engineering and the preoccupation with phenomenological research and development of tools for analysis within engineering have led to an underemphasis on holistic design experience, manufacturing, and technology management in the curricula and research portfolios of U.S. engineering schools, particularly those that tend to be pacesetters.[4] By equating innovation with R&D and overvaluing the pursuit of original knowledge relative to excellence in execution, many engineering schools have helped to create, or at least to sustain, dysfunctional walls between research and other downstream technological activities in American industry.[5]

A Large, Sophisticated Domestic Market

The size, affluence, and sophistication of the U.S. domestic market continue to provide a rich test bed and large demand for technologically advanced products and services. Despite its relatively slow growth in recent decades, U.S. per capita income (measured in purchasing power parity) is still the highest of the world's seven largest industrialized economies. The U.S. economy is still more than two and half times the size of Japan's. And the U.S. market continues to absorb more than 35 percent of world's total output of high-technology products (see Figure 3.2). U.S.-based

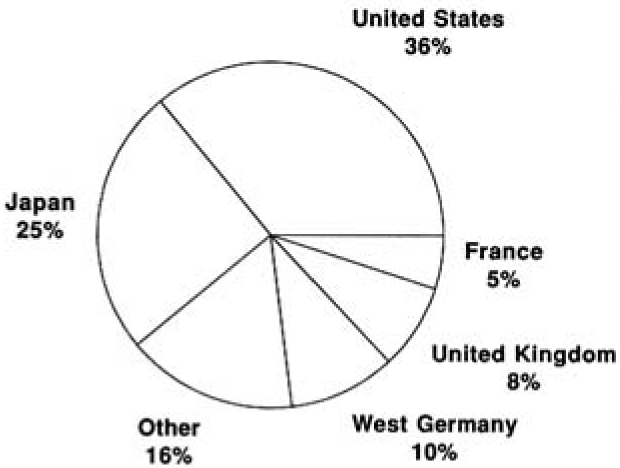

FIGURE 3.2 Home market share of world consumption of high-tech products: 1988.
NOTE: Total high-tech consumption by the 25 member countries of the Organization for Economic Cooperation and Development are used as a proxy for world consumption. SOURCE: Data from National Science Board (1991, pp. 401, 409).

companies should have an advantage in exploiting the strengths of this market for new product development and market growth, especially through the opportunity for collaboration between producers and sophisticated user firms.

The openness of the U.S. economy to foreign direct investment and trade has greatly increased the exposure of U.S-based industry and U.S. consumers to foreign technology and know-how, and promises to increase technology transfer into the United States from abroad as foreign technical competence and economic strength increase. Moreover, together with the nation's comparatively strong antitrust laws and efficient factor market,[6] the U.S. government's commitment to open markets has ensured a high level of competition within most sectors of the U.S. economy, thereby providing a powerful stimulus to productivity-enhancing innovation throughout U.S. industry.

At the same time, many of the major strengths of the U.S. domestic market have also contributed (albeit indirectly) to current vulnerabilities of the nation's technology enterprise. For most of the past 40 years, the United States has been the only country in the world with a large enough domestic market to sustain numerous scale-intensive industries. For much of this period, exports and the sales of foreign affiliates of U.S.-based companies were perceived as a bonus to corporate strategies focused heavily on the large and prosperous U.S. market.[7] Import penetration of the U.S. economy was minimal during most of the postwar period, and the challenge of foreign competition was perceived as minor compared with that of other domestic firms.[8] As a result, until recently there have been few strong incentives for the vast majority of U.S.-based companies to adapt their products to different requirements of foreign markets, or look abroad for new product or process technology.

Moreover, the very openness of the U.S. domestic market to foreign competition has also proved a double-edged sword. The committee is convinced that foreign competition has stimulated much productivity-enhancing innovation throughout U.S. industry, and, on balance, has greatly benefited U.S. consumers as well as the management, stockholders, and work force of U.S.-based companies that have been able to respond effectively to the challenge. Yet foreign competition has also inflicted heavy economic adjustment costs on many American companies, industries, and communities that have for one reason or another been less successful at meeting the foreign challenge. In a few cases, failed adjustment to foreign competition (whether "fair" or "unfair") has resulted in serious decline of resident technical and manufacturing capability in areas deemed important to the nation's long-term technical, economic, military, or political interests—for example, in semiconductor manufacturing equipment.[9]

Incubator of New Industries, Products, and Services

The strength of the basic research enterprise, and the size and wealth of the domestic market, together with the highly entrepreneurial character of U.S. capitalism, have fostered an unrivaled indigenous capacity for creating new technology-intensive products, services, and industries. The U.S. political economic system affords many institutional and regulatory incentives for the creation of new businesses. Strict antitrust laws, forgiving bankruptcy laws, a host of financial intermediaries willing and able to supply capital for new ventures, and a deep-rooted culture of entrepreneurship have all contributed to a U.S. capacity for new business creation (and destruction) unequaled throughout the world (Ergas, 1987; Florida and Kenney, 1990).

Building on this strong base, the U.S. system of support for basic research, with its strong dependence on the initiative of individual investigators, has also fostered a strong entrepreneurial culture among academic scientists and engineers. Many universities have become incubators of small, high-tech firms built around new products or services that have occasionally given rise to entire new industries, such as biotechnology and magnetic resonance imaging. To an extent far greater than their counterparts abroad, U.S. private investors have long demonstrated a willingness to support the start-up of high-tech companies. In addition, the United States has the world's largest and most highly developed venture capital market, which not only makes capital available to high-tech start-ups, but also serves as an effective mechanism for information networking among small firms (Bygrave and Timmons, 1992).[10]

The downside of this "high-tech" subset of U.S. entrepreneurial culture with its focus on being first to create a new product or service is that it is often associated with a lack of follow-through in downstream engineering and continuous improvement, especially in manufacturing, after initial success. To a large extent, this lack of follow-through can be attributed to the managerial and organizational shortcomings of U.S. companies (which are discussed at greater length below). However, it is also evident that the U.S. system of allocating investment capital, despite its unrivaled capacity for spawning new companies, does not do as good a job as it should at making available to technology-oriented businesses the patient capital they need to commercialize their technologies, to grow, or to modernize (National Academy of Engineering, 1992; Porter, 1992). Whether the product of poor management, the inaccessibility of patient capital, or other factors, the end result has been that market leadership has migrated abroad in many high-growth, high value-added industries or products that were pioneered by U.S. high-tech start-ups (Florida and Browdy, 1991; Florida and Kenney, 1990).

The Strength of U.S. High-Tech Industries

The continuing competitive strength and global reach of many U.S.-owned companies in high-tech industries, such as aerospace, pharmaceuticals, chemicals, oil refining, computers, and software, contribute greatly to the strength of the nation's technology enterprise. These firms, which continue to excel in the "high end" of their respective global product markets, cultivate organizational competence and human technical resources worldwide. Although their contribution to the technological capability of other nations is significant and growing, these firms conduct the vast majority of their technically advanced, high-value-added work in the United States.[11] They generate financial resources that are reinvested in their corporate technology bases and through them in the nation's technology base. These firms account for a large share of U.S. manufactured exports and imports (much of this trade is intracompany, between the U.S. parent companies and their affiliates abroad). They represent major vectors for technology diffusion into and out of the United States, as do, increasingly, the U.S. affiliates of foreign firms. Admittedly, the flow of technology through multinational companies has been predominately one-way out of the United States in the past.[12] However, as the level of technological capability abroad continues to rise, both U.S.-owned multinationals and the U.S. affiliates of foreign-owned firms are likely to draw increasingly upon technological capabilities abroad to augment the industrial innovative capacity of the U.S. economy.

In certain respects, however, the early dominance of U.S. high-tech firms in world markets has weakened the U.S. technology enterprise. In the 1970s many of these firms took too much comfort in their dominance of the most technically sophisticated high end of their product markets (for example, customized microprocessors as compared with dynamic random access memory chips, or DRAMs; sophisticated computers as compared with consumer electronics; customized, numerically controlled machine tools as compared with standardized tools) (Alic et al., 1992). In the process, they overlooked the fact that the necessary financial resources and manufacturing knowledge for maintaining their strength in high-end, low-volume, and high-margin product markets could not be sustained without a continuing presence in important related mass markets. This strategic miscalculation has helped undermine the long-term technological competitiveness of many of these firms and of the broader base of U.S. industries to which they are closely tied.

WEAKNESSES OF THE U.S. TECHNOLOGY ENTERPRISE

Ultimately the ability of the United States to exploit the strengths of its technology enterprise for sustained economic development will depend on how rapidly and effectively the nation redresses the major weaknesses of the enterprise. The committee identifies the following six closely interrelated weaknesses as the greatest technology-related obstacles to meeting the nation's economic development challenge:

- Outmoded management philosophies, organizational frameworks, and human resource strategies of many U.S. public- and private-sector producers of goods and services.
- Insufficient investment in, and poor quality of, U.S. work force training and continuing education, particularly at the nonsupervisory level.
- Inadequate investment by U.S.-based companies in competitive production processes, plant, and equipment.
- Low civilian R&D intensity of U.S. economic activity and insufficient breadth of the nation's civilian R&D portfolio, including underinvestment in growth- and productivity-enhancing technologies that are high-risk or whose benefits are difficult for individual investors to appropriate.[13]
- Insufficient awareness of, and interest in, technology originating outside their institutional boundaries on the part of many U.S. companies and federal laboratories.
- Lack of a strong institutional structure for federal technology policy in support of national economic development, and the segregation of technology policy from domestic and foreign economic policy at the federal level.

While the strengths are relatively discrete and well documented, the weaknesses of the U.S. technology enterprise are more subtle and interconnected. They are one step removed from easily measurable performance indicators that would directly demonstrate them. There are no comparative measures that directly show the relative decline in the ability of U.S.-based companies to generate, absorb, master, and manage technology to achieve sustainable competitive advantage in world markets—only anecdotal evidence or case histories. Furthermore, even in industries in which most companies have lost market share or withdrawn from the market, there are usually one or two companies that are still world competitive. Nevertheless, these weaknesses have manifested themselves collectively in indicators such as the following:

- A decline in global market share of some U.S. high-tech industries during the past two decades and a significant reduction in the nation's long-standing trade surplus in high-tech products.[14]
- Prolonged low U.S. productivity growth rates (for both labor and total factor productivity) relative to a number of its major industrial competitors (Organization for Economic Cooperation and Development, 1992a).
- Slow product-development and innovation cycle time of U.S. companies

in a number of large industries in comparison with their Japanese counterparts (Bebb, 1990; Clark and Fujimoto, 1991).

- A "quality" gap that emerged between U.S. firms and their foreign competitors in a number of industries during the 1970s and 1980s.
- Slow adoption of advanced production technologies by U.S. manufacturers relative to their Japanese competitors.[15]

The following discussion addresses each of the six major weaknesses in the U.S. technology enterprise that have collectively contributed to the lackluster performance of many U.S.-based firms and the U.S. economy overall as revealed by these indicators. While the six weaknesses are addressed in sequence, the committee considers all six to be closely interrelated and, to a large extent, mutually reinforcing.

Outmoded Managerial and Organizational Approaches

Many U.S.-based companies are having great difficulty in their efforts to increase productivity, improve quality, lower costs, and increase the speed with which they develop and deliver competitive new products and services. Primary responsibility for this decline rests with outdated managerial and organizational practices of U.S. companies with regard to production, innovation, and human resources. Although there has been some progress in recent years, a considerable fraction of American industry and government has yet to respond to an ongoing revolution in production systems that has been gathering momentum since the early 1970s.

The prevailing managerial and organizational practices in U.S. industry developed in response to the rapid diffusion of mass production technology around the turn of the century and have not changed significantly since that time. Admittedly, there has always been considerable variation in organizational practice among firms within a given industry as well as across industries. However, the dominant organizational framework in most sectors of American industry for at least the last half century has been one of rigid, large decision-making hierarchies overseeing a functionally compartmentalized production system and work force. Within this framework the many constituent functions in the product realization process—R&D, design, industrial engineering, production, and marketing—have often been treated as discrete activities linked in sequence to reduce the need for interfunctional communication and to lower intrafirm transaction costs. Innovation within this organizational framework has also been treated as a sequential process; the development of new product or process technologies has been regarded as the preserve of a relatively insulated R&D department, or, as in the case of many manufacturing and service companies, an activity performed by outside vendors and suppliers but not in-house (Gomory, 1989; Kline, 1990; Lee, 1992).

The functional compartmentalization between innovation and production has, in turn, involved a high degree of functional specialization of the work force in many industries. In the highly trained technical work force (scientists and engineers), excessive specialization has contributed to a widening cultural, or communication, gap between R&D personnel and production engineers (Armstrong, 1993; Gomory, 1992). As noted above (pp. 63–64), this cultural gap has been perpetuated, if not exacerbated, by the way in which would-be industrial scientists and engineers are educated and trained in American universities. All too many U.S. university science and engineering faculties continue to prepare R&D scientist and engineers with little appreciation or understanding of design and production engineering. At the same time, many practicing design and production engineers in U.S. companies are ill-prepared to work effectively with R&D personnel either to help shape the company's research agenda or to absorb and apply the results of research performed in-house or outside the firm.

For the vast majority of the industrial work force, functional specialization has led to increasingly narrow job classifications, a generally low expectation of what a nonsupervisory worker can contribute, and a failure to take advantage of the firsthand experience and ideas of frontline workers. Within his context, much of American corporate management has come to regard investments in technology as a way to substitute for rather than upgrade the skills and performance of the work force. Management of a functionally specialized work force and compartmentalized production systems, in turn, has required large managerial bureaucracies (relative to a firm's total work force) in which responsibility and authority are centralized. Furthermore, the organization of work has demanded managerial strategies that emphasize vertical "top-down" control rather than horizontal coordination (Carnevale, 1991; National Center on Education and the Economy, 1990).

Many of these same organizational and managerial practices that structure production and innovation in a majority of U.S. companies are also reflected in these firms' arm's-length, adversarial relationships with customers and suppliers. Some companies value suppliers primarily for their ability to meet customer specifications at lowest cost and view them as easily replaceable. Similarly, customers for final products and services are often viewed as undiscriminating in areas other than price and incapable of articulating their needs and preferences except through market transactions. Although the number of notable exceptions is growing, a majority of U.S. companies continue to show little appreciation for sources of innovation beyond their own R&D laboratory or company borders (Kodama, 1991; Roussel et al., 1991; von Hippel, 1988).

Although oversimplified and overgeneralized, this summary of the distinguishing features of the way a majority of U.S. companies organize and manage production, innovation, and their work force explains why so much of U.S. industry is having difficulty developing and using technology to sustained competitive effect. Companies will not achieve the fundamentals of competitive performance in this new environment—continuous improvement of product quality, shorter product development cycles, higher rates of productivity growth, continuous product and process innovation, and rapid response to changing markets—unless they radically change the way they organize and manage the product realization process in its entirety, particularly their most valuable assets, human resources (Dertouzos et al., 1989; Heim and Compton, 1992; Kline, 1991; Quinn, 1992; Womack et al., 1990).

Although most of the attention of late has been focused on these issues of organization and management as they apply to production, work, and innovation in manufacturing firms, it is increasingly apparent that these same organizational and managerial problems also plague the majority of U.S. service providers (private and public).[16] A number of service industries have achieved impressive productivity growth through the application of new information and transportation technologies. However, the U.S. service economy as a whole, which at present accounts for more than 74 percent of U.S. gross national product and 77 percent of U.S. employment, has experienced levels of productivity growth significantly below that of the U.S. manufacturing sector over the past decade (Kendrick, 1988; Quinn, 1988; Roach, 1988, 1991).[17]

The broad outlines of the changes needed are generally understood and have been collected and broadly disseminated throughout the United States under various concepts such as total quality management, concurrent engineering, flexible manufacturing, or lean production. However, the following impediments to widespread adoption and diffusion of modern organizational and managerial methods in U.S. industry remain formidable:[18]

- Widespread managerial resistance to change.
- A legacy of mutual mistrust between labor and management.
- A work force often ill prepared by education, training, and managerial expectations to participate more broadly and flexibly, and assume greater responsibility in new work organizations.
- A lack of appropriate metrics and "benchmarks" against which to measure the new parameters of organizational performance.
- An entrenched reluctance to look beyond company boundaries for sources of useful innovation.

Gaps in Work Force Training and Continuing Education

The committee believes that the skills, capacity for continuous learning, and effective management of a nation's work force largely determine that nation's ability to attract and retain high-value-added, high-skill industries as well as its ability to absorb and exploit new technology for economic benefit. As the preceding discussion makes clear, U.S. producers of goods and services must adopt more productive approaches to the organization of work and the management and motivation of their work force if they expect to cultivate and take full advantage of their skills, ingenuity, and creativity. Indeed, a number of recent studies suggest that the greatest impediments to improving the performance of U.S. labor markets have more to do with inadequate demand for high-skilled labor than with inadequate supply (Carnevale, 1991; Mishel and Teixeira, 1992). Nevertheless, the changing nature of work organization and content in many industries, and the new demands these changes place on the U.S. work force, underline major weaknesses in the scope and quality of the nation's efforts in job-related training and continuing education.

The United States has one of the largest, most diversified, though poorly coordinated training enterprises in the world. In the United States, work-related training and continuing education are provided by a broad spectrum of private and public institutions, including two-year colleges and technical institutions, noncollegiate postsecondary vocational schools, four-year colleges and universities, apprenticeship programs, professional associations, unions, vendors, and employers. However, across this vast and diverse U.S. training enterprise, there are few common standards, the quality of training is uneven, and important subsets of the nation's current and potential work force are poorly served, particularly with regard to job-related training and continuing education within industry (Carnevale et al., 1990a,b; Lynch, 1992; National Center on Education and the Economy, 1990; U.S. Congress, Office of Technology Assessment, 1990b; U.S. General Accounting Office, 1992b).[19]

On average U.S. companies invest slightly more than 1 percent of payroll on training in comparison with competitors in other countries that invest on average as much as 6 percent of their payrolls (Marshall and Tucker, 1992a).[20] One-half of 1 percent of U.S.-based companies account for nearly all of the $30 billion currently invested by U.S. industry in formal training, and only 10 percent of the nation's work force participates in company-financed training activities (Carnevale et al., 1990a; Marshall, 1992). Moreover, as Figure 3.3 shows, most of U.S. industry's training dollars are used to provide training and continuing education for its college-educated supervisory and professional work force, while relatively little is allocated to its non-college-educated and, for the most part, nonsupervisory work force.[21] The U.S. allocation of training resources stands in marked contrast to that of its major industrial competitors (including Germany and Japan) that have developed extensive training programs for nonsupervisory workers in general and for new entrants to the work force, in particular (Organization for

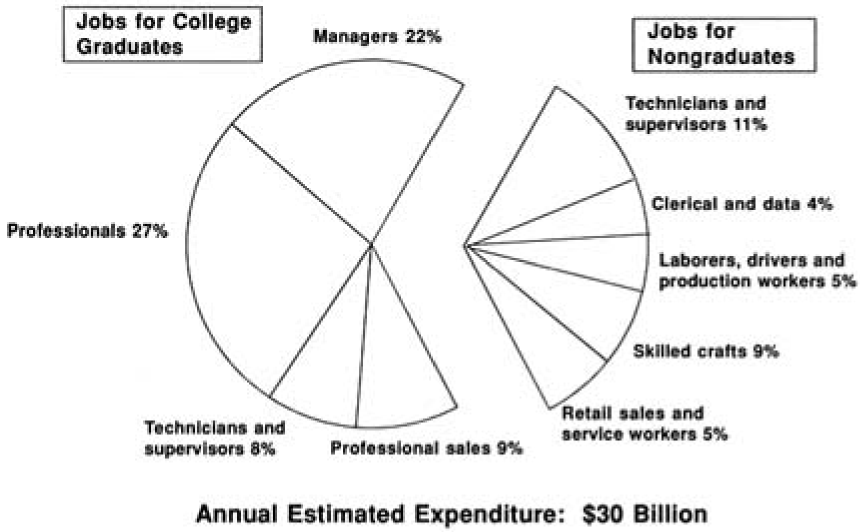

FIGURE 3.3 Distribution of U.S. private-sector expenditure on formal training.
SOURCE: After National Center on Education and the Economy (1990, p. 49).

Economic Cooperation and Development, 1991a; U.S. Congress, Office of Technology Assessment, 1990b).

Although the United States sends a larger percentage of its high-school graduates to colleges or universities than any other industrialized nation, non-college-bound U.S. high-school graduates have few opportunities to participate in school-to-work training programs (Lynch, 1992; U.S. General Accounting Office, 1990b). It is estimated that U.S.-based apprenticeship programs and similar school-to-work transition programs involve less than 2 percent of all 17-to 25-year-olds and less than 0.3 percent of the total U.S. civilian work force. In contrast, German apprenticeship programs engage roughly 75 percent of all German 17-to 25-year-olds, and over 60 percent of the German work force has completed an apprenticeship (Marshall and Tucker, 1992b; U.S. Congress, Office of Technology Assessment, 1990b).[22]

The liabilities that follow from the low level of U.S. investment in training and continuing education for the nation's nonsupervisory work force (both entry-level *and* established workers) are further compounded by the excessively narrow, task-specific focus of the relatively limited amount of training this segment of the work force receives.[23] Because of its narrow focus, such training does little to prepare workers to broaden their skill base or to participate and contribute more broadly to the overall organizational goals of their employer. When combined with the lack of industrywide standards for training and apprenticeship, such a narrow training curriculum makes it increasingly difficult for these workers to move to other companies and areas of work. In marked contrast to the U.S. approach, job-related training and apprenticeship programs in Germany, Japan, and a number of other industrial countries offer better balance between general competence training and job-specific training (Northdurft, 1989; U.S. Congress, Office of Technology Assessment, 1990b).

Underinvestment in Production Processes, Methods, and Equipment

In addition to placing a premium on changes in work organization and investments in work force development, global competition and the revolution in production systems have also underlined the importance of sustained investment in production processes, methods, and equipment to corporate and national productivity and competitiveness.[24] Recent U.S. industrial history is replete with examples of companies that have failed to reap adequate returns on extensive investment in automated production equipment because they failed to attend to the socio-organizational aspects of the effective use of the new capital equipment within the production system as a whole.[25] Nevertheless, international comparisons of rates of private industry investment in plant and equipment in general, and equipment embodying advanced manufacturing in particular suggest that on average U.S. industry is falling behind its major foreign competitors in capital investment per employee.

U.S. private-sector fixed investment in plant and equipment has fluctuated around 12 percent of GDP during the last decade, following roughly the same pattern as Germany. However, at 12 percent in 1990, the U.S. rate of investment was little more than half that of Japan (see Figure 3.4). The results of a comparative international survey of diffusion rates for a number of advanced manufacturing technologies (numerically controlled [NC] machine tools, industrial robots, computer-aided design [CAD], flexible manufacturing cells and systems) indicate that the diffusion of most of these technologies was much less advanced in the United States than in Japan as of 1988 (see Chapter 2, Figure 2.2).[26]

More recent surveys indicate that while U.S. investment rates in computer-integrated manufacturing equipment (CAD, programmable controllers, local area networks, and NC machines) grew rapidly during the 1980s, most of this investment was accounted for by large firms, firms with more than 500 employees (Kelley and Brooks, 1988, 1991; U.S. Congress, Office of Technology Assessment, 1990b). Small U.S. companies continue to be particularly slow at adopting these advanced manufacturing technologies, not only relative to their large U.S. counterparts but also relative to small foreign firms (Shapira et al., 1992; Tornatsky and Luria, 1992).[27]

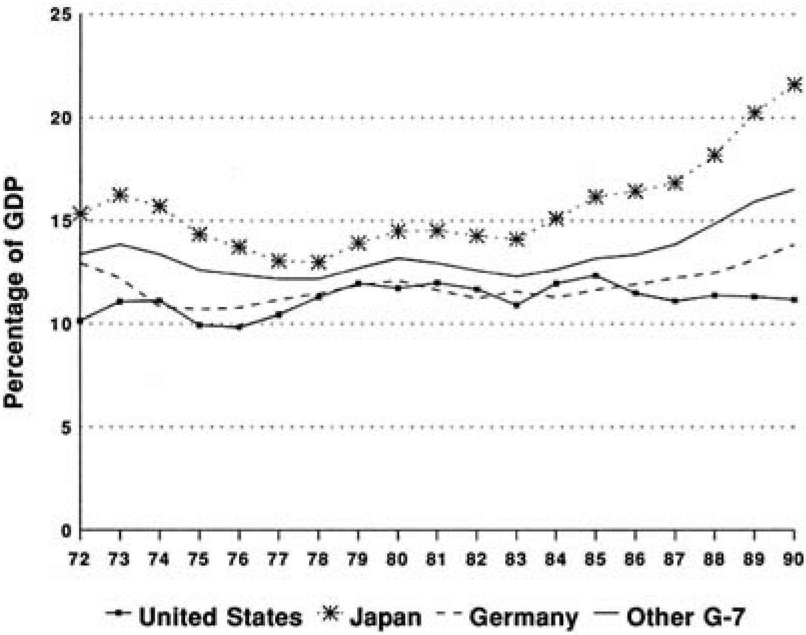

FIGURE 3.4 Private industry expenditure on plant and equipment as a percentage of gross domestic product: 1972–1990. NOTE: G-7 (Group of Seven) countries are Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States.
SOURCE: Council on Competitiveness (1992).

The causes of low investment and slow diffusion rates are hotly debated and complex. The most frequently cited explanations are the nation's low savings rate, the comparatively high cost of patient capital, the relative inaccessibility of capital for many small technology-oriented businesses, and the short-term planning and performance criteria of U.S. businesses with regard to technology investments (i.e., poor management of technology) (National Academy of Engineering, 1992; Porter, 1992). Clearly, all of these factors contribute to the problem, although some (managerial behavior and capital access for small firms, for instance) may be more politically tractable than others (raising the nation's savings rate or reducing the cost of patient capital). In any event, failure to address these impediments to sustained investment in the modernization of U.S. industry's capital plant can only further diminish the nation's ability to use technology effectively to increase its overall economic and technological strength.

The Economy's Low Civilian R&D Intensity and Narrow R&D Portfolio

Changes in the character of global competition and innovation, declining defense budgets, and the shifting relationship between military and civilian technology have posed challenges to the U.S. R&D enterprise. Shrinking defense procurement, the diminished contribution of defense R&D to the nation's commercial technology base, and the recent slowdown in U.S. industrial R&D spending have all focused attention on a growing disparity between the intensity of civilian R&D (business-funded R&D in particular) in the U.S. economy and that of its foremost competitors abroad, as documented in more detail in Chapter 2, pp. 41–43.

Imbalances and Gaps in U.S. Company R&D Portfolios

The committee is convinced that many sectors of U.S. industry are not investing enough in research and development to remain internationally competitive over the medium to long term. Furthermore, the committee believes that the majority of U.S. industrial R&D performers are not managing their current R&D portfolios as effectively as they should. There is considerable evidence to suggest that the portfolios of U.S. companies engaged in R&D may be characterized as follows:

- Too little R&D related to scanning and assimilating new technological knowledge relative to total company investment in "original" in-house R&D (Mansfield, 1988a,b: Mathis, 1992; Roussel et al., 1991).
- Too little process-related R&D relative to product-related R&D (Caravatti, 1991; Dertouzos et al., 1989; Mansfield, 1988b).
- Too little R&D related to incremental improvements of existing products and processes and to downstream follow-through on new product breakthroughs (Florida and Browdy, 1991; Florida and Kenney, 1990).

Just as private industry bears the principal responsibility for increasing its investment in research and development overall to meet the demands of global competition, so too are private companies chiefly responsible for overhauling their commercial R&D strategies and restructuring their R&D portfolios to this end. But it is clear that U.S. public policies and the U.S. higher education system have an important impact (both positive and negative) on the level, composition, and management of private-sector commercial R&D. For instance, the committee believes that current U.S. tax treatment of private-sector R&D does not provide sufficient incentive to private-sector investment in commercial R&D. The incremental approach of the current U.S. Research and Experimentation (R&E) Tax Credit, though fiscally "cheap," does little to encourage sustained R&D investment across business cycles. Moreover, the R&E Tax Credit cannot be extended to industry-sponsored R&D in universities and other institutions, or the industrial contribution to R&D performed as part of a consortium that involves government laboratories. In this manner, federal tax policy may discourage the very leveraging, networking, and refocusing of the national R&D infrastructure so greatly needed for sustained economic development.

Similarly, federal procurement practices that force companies producing for both commercial and defense markets to erect walls between R&D and downstream activities make it difficult and expensive for these firms to manage their total R&D resources effectively (Adelman and Augustine, 1992; Center for Strategic and International Studies, 1991; Gansler, 1992). Finally, many observers contend that U.S. engineering and management schools have aggravated the problems of technology management within many U.S. companies by failing to teach effective technology management to their students.

Gaps in the Nation's R&D Portfolio: The Generic Technology Challenge

The committee believes the nation is underinvesting in a number of generic infrastructural, pathbreaking, and otherwise high-leverage technologies that could greatly increase the productivity and long-term growth of the U.S. economy, as well as the competitiveness of U.S.-based industry.[28] As argued in Chapter 2, rising technical intensity and complexity in many industries have raised the cost and uncertainty of many technology-related investment opportunities to the point where individual firms are increasingly likely to underinvest in promising areas of industrial technology (Tassey, 1992). A growing number of private companies have responded to this challenge by engaging in R&D alliances, joint ventures, and consortia to share risks and costs associated with the development of a broad spectrum of generic technologies (Hagedoorn and Schakenraad, 1993; Mowery, 1987; Organization for Economic Cooperation and Development, 1991b; Tassey, 1992; Vonortas, 1989).

Accordingly, with varying degrees of intensity and effectiveness, governments in industrial nations have actively fostered, and in some cases partially underwritten, collaborative arrangements within the private sector and between the public and the private sectors in many areas of generic technology. Nevertheless, recent assessments of the current and projected position of the United States in many important areas of generic technology confirm that the combined U.S. public- and private-sector effort in generic technologies is inadequate to maintain or improve the nation's current geopolitical and global economic position (Council on Competitiveness, 1991; Gamota and Frieman, 1988; National Critical Technologies Panel, 1991; Rogers, 1991; Tassey, 1992; U.S. Department of Commerce, 1990, 1992b) (see Table 3.1).

There are currently many avenues through which the U.S. federal government provides limited support to the development of commercially relevant generic technology. The spin-off from defense-related R&D to civilian infrastructural and pathbreaking technology development has declined significantly in recent decades. But the U.S. Department of Defense continues to support dual-use technology development in a number of specific technological areas critical to aerospace, semiconductor manufacturing, computing, display technology, advanced manufacturing, and other sectors.[29] The National Institutes of Health continue to underwrite much of the R&D infrastructure for the emerging biotechnology industry. There are also long-standing as well as recent, albeit limited, initiatives by the government to support development of commercially relevant generic technologies through other federal agencies. These include the intramural research programs in the areas of standards, measurement and testing at the National Institute of Standards and Technology (NIST), the establishment and growth of NIST's young Advanced Technology Program, the promotion of Cooperative Research and Development Agreements between select federal laboratories and U.S. firms, and the establishment of university-based Engineering Research Centers by the National Science Foundation.[30]

Nevertheless, despite a plethora of old and new programs, the share of total federal government investment in R&D directly relevant to the needs of industrial and general economic development (with the notable exceptions of aerospace and biotechnology) remains minuscule, particularly in comparison with that of other nations (see Table 3.2).[31] In 1989 the federal government allocated only 0.2 percent of its total R&D budget explicitly to "industrial development" and less than 8 percent of the total to all socioeconomic objectives related to economic development (agriculture, energy, industrial development, and infrastructure). By comparison, Japan spent more than 32 percent and Germany, France, and the United Kingdom between 19 and 23 percent of their respective public R&D monies on "economic development" activities. Between 5 and 13 percent of their public R&D budgets were dedicated to "industrial development" alone.

Despite a growing consensus regarding the need for greater public-and private-sector effort to close the emerging generic technology gaps in the nation's civilian technology base, formidable political as well as analytical impediments to public-sector action remain. Political resistance to an expanded federal government role in civilian technology has weakened. However, the benefits of public-sector investments in areas of commercially relevant infrastructural and pathbreaking technology are diffuse, hard to

TABLE 3.1 U.S. Competitive Position in Critical Technologies

Technologies in which the United States is Strong	Technologies in which the United States is Competitive
Materials and Associated Processing Technologies	**Materials and Associated Processing Technologies**
Bioactive biocompatible materials	Catalysis
Bioprocessing	Chemical synthesis
Drug discovery techniques	Magnetic materials
Emissions reduction	Metal matrix composites
Genetic engineering	Net shape forming
Recycling and waste processing	Optical materials
	Photoresists
Engineering and Production Technologies	Polymers
	Polymer matrix composites
Computer-aided engineering	Process controls
Systems engineering	Superconductors
Electronic Components	**Engineering and Production Technologies**
Magnetic information storage	
Microprocessors	Advanced welding
	Computer integrated manufacturing
Information Technology	Human factors engineering
Animation and full motion video	Joining and fastening technologies
Applications software	Measurement techniques
Artificial intelligence	Structural dynamics
Computer modeling and simulation	
Data representation	**Electronic Components**
Data retrieval and update	Logic chips
Expert systems	Sensors
Graphics hardware and software	Submicron technology
Handwriting and speech recognition	
High-level software languages	**Information Technologies**
Natural language	Broadband switching
Neural networks	Digital infrastructure
Operating systems	Digital signal processing
Optical character recognition	Fiber-optic systems
Processor architecture	Hardware integration
Semantic modeling and interpretation	Multiplexing
Software engineering	Spectrum technologies
Transmitters and receivers	
	Powertrain and Propulsion
Powertrain and Propulsion	Alternate fuel engines
Air-breathing propulsion	Electrical storage technologies
Low emission engines	Electric motors and drives
Rocket propulsion	

Technologies in which the United States is Weak	Technologies in which the United States is Losing Badly or has Lost
Materials and Associated Processing Technologies	**Materials and Associated Processing Technologies**
Advanced metals	Display materials
Membranes	Electronic ceramics
Precision coating	Electronic packaging materials
	Gallium arsenide
Engineering and Production Technologies	Silicon
	Structural ceramics
Design for manufacturing	
Design of manufacturing processes	**Engineering and Production Technologies**
Flexible manufacturing	
High-speed machining	Integrated circuit fabrication and test equipment
Integration of research, design, and manufacturing	Robotics and automated equipment
Leading-edge scientific instruments	
Precision bearings	**Electronic Components**
Precision machining and forming	Electrolminescent dislays
Total quality management	Liquid crystal displays
	Memory chips
Electronic Components	Multichip packaging systems
Actuators	Optical information storage
Electro photography	Plasma and vacuum fluorescent displays
Electrostatics	Printed circuit board technology
Laser devices	
Photonics	
Powertrain and Propulsion	
High fuel economy/power density engines	

SOURCE: Council on Competitiveness (1991, pp. 31–34).

measure, and slow to mature, and this diminishes their political appeal. The need for elected representatives and government officials to demonstrate concrete, short-term results to their constituencies may discourage them from investing much political capital in such initiatives. Moreover, the theoretical and empirical bases and the institutional frameworks for identifying and deciding how much to fund worthy areas of infrastructural or pathbreaking technology are weak and poorly developed.[32]

Underinvestment in Technical Outreach

The growth of technical competence abroad, the revolution in production systems, and the increasing pace, intensity, and multidisciplinary character of technological innovation in general have all underscored the importance of greater interaction among the many public- and private-sector actors (domestic and foreign) involved in the creation, development, and use of technology.[33] Yet, there is evidence to suggest that the vast majority of U.S.-based companies have little interest in technology originating outside their own institutional boundaries, beyond U.S. borders, or outside the normal technological scope of the company.[34]

During the postwar era of U.S. technological preeminence, the costs to the nation of the widespread reluctance of individual U.S.-based firms to tap domestic sources of innovation beyond their own in-house R&D labs were barely perceived (Mathis, 1992; Roussel et al., 1991). With foreign technical capabilities lagging most U.S. industries, there were rarely strong incentives for U.S. firms or the U.S. government to look abroad for improved technology. However, in a technologically multipolar world, the persistence of U.S. industry's "not-invented-here" outlook, which is mirrored in a number of federal mission laboratories, represents a serious liability of the U.S. technology enterprise (Lee and Reid, 1991).

Today, the flow of new ideas, technology, and know-how through global networks of firms, universities, and other institutions is anything but

TABLE 3.2 Government R&D Support by Socioeconomic Objective, by Country: 1989

	Percent				
	United States	Japan	Germany	France	United Kingdom
Defense	65.5	9.0	19.0	41.9	55.2
Health	12.9	4.8	5.2	3.7	6.2
Civil space	7.3	11.1	8.5	8.7	3.8
Advancement of knowledge	3.8	13.8	20.7	17.5	5.8
Agriculture, forestry, and fishing	1.9	6.5	3.1	4.6	5.5
Energy	3.9	39.2	9.5	4.0	4.0
Infrastructure	1.8	1.7	2.0	0.9	1.5
Industrial development	0.2	8.1	19.0	15.0	10.3
Other	2.7	5.9	12.9	3.6	7.7
Total	100.0	100.0	100.0	100.0	100.0

NOTE: Data adjusted to exclude general university funds for Japan (43 percent of the government-funded R&D total), West Germany (33 percent), the United Kingdom (18 percent), and France (12 percent) Percentages may not sum to 100 because of rounding.
SOURCE: National Science Board (1991, p. 344).

"one-way" out of the United States. As documented in Chapter 2, the competitive strength of many U.S.-based companies depends in no small way on their ability to access technically demanding markets and technological assets abroad. Furthermore, the contribution of foreign-owned multinational companies to the U.S. technology base is significant and growing.[35]

Ultimately, the nature of high technologies is such that the nation as a whole can no longer hope to retain world leadership in more than a few key "technology clusters." The breadth of high technologies necessary for competitive performance in a dynamically evolving world economy with a growing multiplicity of players is such that the United States must be prepared to remain close to the world frontier in a wide range of advanced technologies to be able to exploit them rapidly when unexpected opportunities present themselves. In many new or technologically revitalized industries where the product cycles are rapid or the up-front costs of market entry are high, "catch-up" strategies are so costly as to be unviable if the U.S. position lags the world frontier to any significant extent (Ross, 1992).

Nevertheless, despite these trends there is considerable evidence that many U.S.-based firms are less interested and less effective at harnessing foreign technological capabilities and markets than their major foreign competitors. Despite widely acknowledged foreign competence and leadership in many areas of high technology, the United States continues to lead the world in disembodied technology exports (patents, licenses, etc.) and runs a large surplus in its technological balance of payments (see Table 3.3). Meanwhile its principal economic rivals, Germany and Japan, though major creators of new technology in their own right, remain among the world's largest importers of disembodied technology and continue to run overall technological balance-of-payments deficits.[36]

Long-standing, large imbalances in the exchange of scientific and engineering personnel between the United States and other countries also attest to a relative lack of interest in foreign technological competence on the part of U.S. industry and the U.S. technological work force more generally.[37] Finally, despite continuing growth in the U.S. population of multinational companies, trade and foreign direct investment data show that the vast majority of smaller U.S. manufacturing enterprises, not to mention service providers, are only marginally, if at all, involved in foreign markets (Nothdurft, 1992).[38]

While firmly convinced that many of the impediments to the exploitation of foreign markets and technology of U.S. firms are self-imposed, the committee also recognizes that structural or policy-induced asymmetries of access among national markets and technology enterprises often disadvantage U.S.-based firms in their international competition. [39] Regardless of their causes, in an age of deepening economic and technological interdependence among nations, international asymmetries of access to markets and technology affect the course of international competition. Ultimately, they also affect the comparative advantage of nations in ways that increase international political and economic friction and threaten to undermine the existing world trading system.

TABLE 3.3 International Patent and License Transactions, Selected Countries: 1990 (in billions of U.S. dollars)

Country	Receipts	Expenditure	Balance
United States	16.4	3.1	13.3
Japan	2.3	2.5	-0.2
Germany	5.4	6.5	-1.1
France	1.8	2.5	-0.7
United Kingdom[a]	1.9	2.0	-0.1

[a] 1989 data.
SOURCE: Organization for Economic Cooperation and Development, unpublished data, 1993.

Improving the long-term access of U.S.-based firms to foreign high-tech markets and technology in a way that continuously upgrades U.S. industrial and technological portfolios and strengthens the international trading system will not be accomplished easily or quickly. It will require an aggressive and long-term commitment by the U.S. government to leadership, negotiation, and mutual accommodation on a broad range of policy issues, from trade and direct investment to intellectual property rights, international technical standards, and national R&D subsidies. Nevertheless, the committee believes there is much U.S. industry and government can do together to harness global technology and markets more effectively. Specific goals and policy actions toward this objective are addressed in Chapter 4.

The Nonsystem of Technology Policymaking

During the past decade, changes in the global economic and technological environment and the continuing relative decline of U.S. economic competitiveness have amplified liabilities associated with the highly decentralized, poorly coordinated nature of U.S. technology policymaking and its historically weak links to U.S. economic policymaking (domestic and foreign) at the federal level. These liabilities, in turn, have challenged U.S. policymakers to look for new ways to organize or coordinate federal technology policy at the federal level and to focus it more effectively on stimulating technology development and deployment for civilian economic growth and development. Although a number of creative and modestly successful initiatives to this end have been launched by the federal government since the late 1970s, the problems of poor communication and coordination and weak integration of federal technology policy with federal economic policy persist.

As discussed in Chapter 1, the intelligence and operational responsibilities for informing, formulating, and implementing public- and private-sector policy responses to the diverse and rapidly changing technology-related challenges facing the U.S. economy are highly dispersed. A multitude of private-sector think tanks, university-based analysts, and industry associations, as well as municipal, state, and federal government agencies are involved in technology-related data collection, analysis, and policy formulation and implementation. During the past decade, state governments, in particular, have amassed considerable experience with policies and programs designed to harness technology for economic development (Carnegie Commission, 1992a; Clarke and Dobson, 1991; Feller, 1992a,b; Shapira et al., 1992). In many respects, this decentralized, distributed nonsystem of analysis and policy action remains a source of great strength; it continues to provide for high-quality analysis and a unique breadth of public and private policy experimentation.

Nonetheless, communication, coordination, and institutional learning among the constituent elements of the enterprise (at both the federal and state levels) remain weak. As a result, the lessons of successful or failed policy initiatives are poorly disseminated throughout the enterprise as a whole and often quickly forgotten. In addition, the system is poor at identifying and setting priorities among challenges to the technology enterprise with direct consequences for national economic performance, and particularly poor at building constituencies in support of action at the national level.

CONCLUSION: THE NEED FOR CHANGE

Collectively, the strengths and weaknesses of the U.S. technology enterprise make clear that both private-sector technology strategies and public-sector technology policies need to change significantly for the nation to remain the world's leading economic and technological power. To harness and build on its areas of strength, the nation must redress the major weaknesses of the technology enterprise. In so doing the nation must also recognize that these weaknesses are closely interrelated and cannot be addressed effectively in sequence. Broadening the scope and improving the balance of the U.S. portfolio of technological activities to meet the challenges of a new global order require that the public and private sectors work together to achieve the following goals:

- Modernize the managerial philosophies, organizational frameworks, and human resource strategies of U.S. companies.

- Raise the level and quality of work force training and continuing education.
- Increase investment in production processes, methods, and equipment.
- Expand, diversify, and upgrade the nation's civilian R&D effort.
- Seek out and exploit foreign technology and markets more extensively and effectively.
- Develop a strong institutional framework for federal technology policy in support of national economic development, and integrate the planning and implementation of federal technology policy with that of national domestic and foreign economic policy.

Clearly, some of these weaknesses are more closely linked to public policy decisions than others. In many instances the primary responsibility lies with private company decisions or the leadership of the nation's universities. In no case does responsibility—for a weakness or a "fix"—fall exclusively to one group. In the following, concluding chapter of this report, the committee sets forth conclusions and policy recommendations it believes will help the nation meet these challenges.

NOTES

1. Although the gap between the United States and other industrial countries in basic research is narrowing, the United States continues to enjoy an impressive, absolute lead over its trading partners in total money invested in basic research, the number of scientists and engineers engaged therein, and the volume and quality of the U.S. basic research output. Throughout the 1980s, U.S. investment in basic research exceeded that of Japan, Germany, France, and the United Kingdom combined. As of the late 1980s, U.S.-based researchers accounted for over a third of the world's scientific and technological literature (National Science Foundation, 1991b).

2. Lerner (1990) documents remarkably high mobility of U.S. scientists and engineers between the military and civilian sectors during the 1980s.

3. The U.S. graduate academic research enterprise draws on a much larger pool of talent from abroad than from the United States, presenting the opportunity for much greater selectivity.

4. It is well established that the focus of federal funding for academic engineering research throughout most of the postwar period has been on engineering science with very little external support for activities involving engineering design and the design or layout of manufacturing systems. Thus, the heavy influence of federal funding on academic engineering research has skewed much of U.S. undergraduate engineering education toward the needs of the academic research enterprise itself and away from those of U.S.-based industry. Similarly, the focus on phenomenological, as opposed to applications-related, engineering research and on original discovery, as opposed to synthesis of disparate existing knowledge, diminish the contribution of academic engineering research to organizational learning and human resource development—i.e., the very returns from public investments in the U.S. academic research enterprise that are most readily captured by U.S. citizens and least likely to flow abroad (Alic et al., 1992, pp. 112ff).

5. For example, Ralph Gomory (1992), former vice president of technology at IBM, has described the mismatch between the "world-class" research of one of America's preeminent corporate research laboratories and the perceived needs of the very product divisions these laboratories were intended to serve. See also Armstrong (1993) and Florida and Kenney (1990).

6. Ergas (1987, p. 202) notes how the functioning of U.S. capital markets reinforces competition in U.S. product markets. For instance, well-developed venture capital markets increase the threat of market entry by new companies by reducing the costs of setting up and dissolving businesses. Ergas also notes that "the effects of potential competition are compounded by the far greater supply in the United States of potential entrants into advanced technology markets." As of the mid-1980s, he notes that "more than 15,000 firms in the United States [had] R&D laboratories, [compared] with about 1,500 in France and 800 in the United Kingdom."

7. In 1970, U.S. exports of high-technology products represented less than 10 percent of total U.S. high-tech production. As late as 1985, U.S. high-tech exports represented less than 15 percent of U.S. high-tech production. By way of comparison, high-tech exports represented 61 percent of West German, 54 percent of U.K., 38 percent of French, and 22 percent of Japanese high-tech output in 1985 (National Science Board, 1989, Appendix table 7–12, p. 378).

8. Data from the OECD Industrial Outlook Database (1988) set U.S. imports of high-technology products at less than 5 percent of the total U.S. market for high-technology products in 1970, and at 11.5 percent of the total U.S. high-tech market in 1980 (National Science Board, 1989, p. 374). Calculations in 1991 by Data Resources, Inc./McGraw-Hill, using OECD industrial structure statistics and series C trade data, estimate that high-technology imports represented only 8 percent of the U.S. domestic market for high-tech products in 1980 (National Science Board, 1991, p. 405).
The stock of foreign direct investment in the United States as of the early 1970s accounted for little more than 1 percent of U.S. gross national product. By 1977 the U.S. affiliates of foreign-owned firms accounted for roughly 1.7 percent of U.S. GNP, 5.2 percent of U.S. manufacturing assets, 3.7 percent of U.S. manufacturing value-added, and 3.5 percent of U.S. manufacturing employment (Graham and Krugman, 1989, pp. 13, 30).

9. The recent rebound of the U.S. semiconductor and semiconductor manufacturing equipment industries in world markets suggests that predictions of these U.S. industries' imminent demise were premature (Wall Street Journal, 14 December 1992, p. 1). Equally premature, however, is the conclusion, based on a relatively short positive trend, that these U.S. industries have successfully mastered the competitiveness challenge posed to them by Japanese and other Asian competitors. Whether or not U.S. firms in these sectors continue to gain ground, their precipitous decline in the face of Japanese competition during the late 1970s and 1980s cannot be ignored.

10. The National Science Board (1992, p. 158) notes that an overwhelming majority (70 percent) of high-tech companies formed in the United States during the 1980s relied exclusively on private investment for business start-up or expansion. Only 6 percent of these companies relied solely on venture capital investment. Eleven percent relied on a mix of private and venture capital investments.

11. Tyson (1991) has noted that the U.S. domestic market still absorbs 80 percent of all high-tech production by U.S.-based (U.S. and foreign-owned) companies. Reviewing U.S. patent data, Patel and Pavitt (1991) conclude that industrial R&D is still predominantly national in character. As of the mid-1980s, 91 percent of total industrial R&D expenditures by U.S.-based companies were made in the United States; 92 percent of patenting by U.S. firms was from the United States, while the Japanese firms have done 99 percent of their patenting from their home country (National Science Board, 1991; Patel and Pavitt, 1991).

12. See Table 3.3 for the magnitude of the U.S. technological balance of payments surplus (license and royalty receipts in excess of payments) in recent decades.

13. See Chapter 1, pp. 17–18, and note 28 below, for discussion of emerging areas of underinvestment in the U.S. technology base and definitions of "infrastructural" and "pathbreaking" technologies. These concepts were taken from Alic et al. (1992, chapter 10).

14. Between 1980 and 1988 the U.S. share of global markets for high-tech manufactured products declined from 40 to 37 percent. Most of the decline in U.S. market share occurred in three product groups—engines and turbines; office and computing machinery; and radio, television, and communication equipment (National Science Board, 1991, pp. 402–403).

15. See Chapter 2, pp. 38–39, 43–44, for further discussion.

16. Indeed, in many ways the boundaries between services and manufacturing are blurring; many service industries today draw on much the same technology base as manufacturing. For further discussion of the challenge to and potential of the U.S. service sector, see U.S. Congress, Office of Technology Assessment (1987); Guile and Quinn (1988a,b); Quinn (1992).

17. Data from the Organization for Economic Cooperation and Development indicate that U.S. manufacturing productivity grew about 55 percent between 1980 and 1991 compared with gains by Japan and Germany of less than 40 percent. However, significantly lower productivity growth in the U.S. service sector dropped U.S. overall productivity growth to about a third of the average 1.5 percent growth rate for all OECD or advanced industrialized countries as a whole. In February 1993 the U.S. Department of Commerce released production figures that showed the first significant jump in service sector productivity in decades in the fourth quarter of 1992. With service sector productivity rising, overall productivity growth for the U.S. economy rose 4 percent over the quarter, raising the annual rate to 2.7 percent (5 times the annual average for the preceding 5 years). The causes of the recent service productivity surge are not entirely clear. Nor is there cause for certainty that service sector productivity will continue to grow as fast in the future. However, the latest Department of Commerce productivity data highlights the extent to which improvements in service sector productivity can boost the overall productivity growth of the U.S. economy. See "U.S. Productivity Shows Best Gains in 20 Years," *Financial Times*, February 1993.

18. The following list of impediments to technology adoption draws heavily on Heim (1992), and Heim and Compton (1992).

19. A recent study by the U.S. General Accounting Office notes that the federal government alone runs 125 programs spread across 14 agencies that provide employment and training services for adults and out-of-school youth. Many of these programs serve the same client groups with similar services. Adding to the chaos these programs operate for the most part without any uniform definitions or requirements (U.S. General Accounting Office, 1992b).

20. In a 1991 report, the Organization for Economic Cooperation and Development (1991a, p. 160) cautions that "[e]xisting statistics on training are not comparable, and often they are not particularly transparent with respect to what is or is not to be considered training. It currently makes little sense, therefore, to compare *levels* of descriptive statistics on training incidence or training expenditures from one country to another."

21. In 1990 the U.S. General Accounting Office (1990b) reported that public subsidies for U.S. college students were more than seven times larger than those of non-college-bound youth.

22. According to an analyst in the U.S. Department of Labor's Office of Work-Based Learning, there are more apprentice trainers and teachers in Germany than there are apprentices in the United States (personal communication, U.S. Department of Labor, 1992).

23. The German apprenticeship system does a much better job of developing the skills of technicians and craft workers than the more fragmented U.S. nonsystem of vocational education and training. Large Japanese firms rely heavily on supervisors and managers to provide instruction on the factory floor, but because of emphasis on long-term or lifetime employment

in Japan, there is also more emphasis on development of multiple skills and capabilities extending beyond the requirements of a particular job assignment (U.S. Congress, Office of Technology Assessment, 1990b, pp. 83–95).

24. There is a growing body of evidence that links higher rates of investment in process technology and production equipment with improved cost-competitiveness and higher rates of productivity growth in manufacturing (Edquist and Jacobsson, 1988; DeLong and Summers, 1990).

25. See, for example, Alic et al. (1992, chapter 10), Jaikumar (1989), and Tani (1989); for examples from the service sector, see Roach (1988, 1991).

26. See also Edquist and Jacobsson (1988) for a multicountry comparison of diffusion rates for advanced manufacturing equipment during the mid-1980s.

27. As of the late 1980s, it is estimated that no more than 10–12 percent of installed machine tools in the United States were numerically controlled. These surveys also show that (i) plants engaged in defense production adopt advanced manufacturing technology more readily than plants serving principally commercial markets; (ii) plants owned by firms with high R&D-to-sales ratios adopt these technologies more rapidly; and (iii) the relationship between plant age and technology usage is weak (Casagrande, 1992; Dunne, 1991; Kelley and Brooks, 1988, 1991; Kelley and Watkins, 1992).

28. The terms "generic technology" and "precompetitive technology" have been used loosely in much of the current discussion over the proper government role in civilian technology to describe a broad range of technologies for which the rationale and operational implications for government support vary considerably. The committee believes it is important to distinguish between various types of "generic" technology according to differences in time horizons, differences in the mix of business and technical risks and rewards, and differences in beneficiaries. The typology set fourth in the recent study *Beyond Spinoff* (Alic et al., 1992), which identifies three different types of generic technology, is particularly useful in this respect:

•**Pathbreaking technology**—emphasizing technical challenge;

•**Infrastructural technology**—emphasizing productivity improvement and breadth of application; and

•**Strategic technology**—emphasizing the importance to the nation of the industries to which the technology applies.

For elaboration of these types of three generic technology, operational criteria for identifying each type, and implications for public policy and public R&D investments, see Alic et al. (1992, chapter 12). See also Chapter 1, p. 17 for brief descriptions of pathbreaking and infrastructural technologies that draw on this taxonomy.

29. In the wake of the 1990 Congressional Budget Agreement, the Defense Department's role in support of "dual-use" technology received an additional boost. The budget agreement established "fire-walls" between the defense and nondefense budget categories for the purposes of allocating spending cuts to help reduce the federal budget deficit. Given the tight constraints on the nondefense portion of the budget and mounting pressures within Congress for action to redress emerging weaknesses in the nation's civilian technology base, a number of small-scale programs designed to strengthen the nation's industrial technology base were categorized as "dual-use" and written into successive defense authorization and appropriations bills. As a result, the Department of Defense now administers a number of programs that are closely related to the missions and competence of civilian agencies such as the Department of Commerce and the Department of Labor. See "Huge Funding Surge is Soon to Greet Dual-Use Programs," *New Technology Week* 7(7) (February 16, 1993):1–2.

30. For an overview of the history and recent evolution of the these programs, see Committee on Science, Engineering, and Public Policy (1992, pp. 65–67) and National Academy of Engineering (1989).

31. Because some nations define or classify R&D expenditures differently than others, international comparisons such as these are fraught with difficulties. Nevertheless, the very fact that the United States allocates such a relatively small percentage of its total public R&D dollars to objectives it classifies as "industrial development" sheds considerable light on international differences in public R&D priorities.

32. The nature of the civilian R&D investments needed to bridge emerging gaps in the nation's technology base poses serious challenges to sound public policy action in this area. Infrastructural R&D investments such as those aimed at the development of engineering methods, the compilation and validation of technical data, the development and characterization of materials, measurement tools, and instrumentation, and the refinement of manufacturing processes are generally low cost and low technical risk and are believed to have a high payoff to society as a whole. However, such R&D is rarely "high-profile," and the returns are cumulative over a number of years, widely diffused across a broad spectrum of firms or industries, and therefore difficult to measure. Research and development investments relevant to pathbreaking technologies, while perhaps more appealing to many because of their potentially high economic reward, are above all fraught with high technical risk and characterized by highly uncertain and possibly long-delayed economic payoffs. While these very characteristics of pathbreaking technology discourage adequate private-sector R&D investment and provide the rationale for public-sector support, they also ensure a high failure rate and make measurement of returns on such investments extremely difficult. See note 28 above for further discussion. For a useful survey of how the German and Japanese governments select technology areas for public R&D subsidies, see U.S. Department of Commerce (1992b).

33. By organizing to tap external sources of innovation, firms often become more effective at integrating the innovation process within their own corporate borders.

34. The preliminary results of an international survey of senior technical executives conducted by MIT's Industrial Liaison Program and PA Consulting Group suggest that U.S. firms have not taken advantage of outside sources of technology such as joint ventures, suppliers, and university-sponsored research to the same extent as their European and Japanese counterparts. However, U.S. executives interviewed expected to rely more on external technology in the future. For a review of the survey's findings as presented at a 10 December 1992 MIT symposium on Strategic Management of Technology: Global Benchmarking, see "How U.S. Companies Measure Up," *Science* vol 259, 1 Jan. 1993. p. 23. See also Mansfield (1988a,b).

35. In fact, R&D performed by affiliates of foreign multinationals in the United States is growing considerably faster than R&D performed by foreign affiliates of U.S. multinationals abroad as foreign companies move to take advantage of the excellent R&D capabilities in the United States (see Bureau of Economic Analysis, *Foreign Direct Investment in the United States* [ongoing series] and National Science Foundation, *Industrial R&D* [ongoing series]. See also Chapter 2, pp. 47–51 above.

36. This seems to suggest a U.S. lag in the adoption and use of new technology relative to its rivals despite its continuing strength in the origination of new technology licensed to others. Sweden, for example, has adopted process innovations far more rapidly in recent years than the United States, even though it has originated relatively few (Edquist, 1990).

37. Federal agencies and most U.S. corporations are notorious for cutting the travel budgets of their R&D personnel whenever general cost-cutting measures are called for. Despite the existence of National Science Foundation programs to support the exposure of U.S. industry-based scientists and engineers to foreign R&D enterprises, U.S. industry has not availed itself of these programs to any significant extent.

38. According to Nothdurft (1992) only 10 percent of U.S. firms are regular exporters and 15 percent of all exporting firms account for 85 percent of all exports.

39. For indicators of asymmetry of market access between Japan and other industrialized countries, see data on import penetration and the relative importance of foreign-controlled

firms (foreign direct investment) in the major industrial economies in Tables 2.3 and 2.4 in Chapter 2. Intra-industry trade data also underline the anomalous position of Japan among advanced industrialized countries. See Lincoln (1990). It should be noted that there is considerable debate as to the magnitude and causes of these apparent differences in the level of foreign penetration of national economies, and, hence, whether it is even useful or accurate to explain these differences in terms of asymmetries of access (Japan Economic Institute, 1991; Krugman, 1991; Lawrence, 1991 a,b; Lincoln, 1990; Saxonhouse, 1989, 1991; Takeuchi, 1989). For a discussion of structural differences between the U.S. and Japanese technology enterprises and how these differences affect access to the two technology enterprises, see National Research Council (1989,1992b,c) and Heaton (1991).

4

A New Mission for U.S. Technology

The United States has experienced more than two decades of declining economic performance relative to a number of its major trading partners as well as its own historical economic record. Since the mid-1970s, a number of public- and private-sector initiatives have been launched to reverse this decline. To date, however, these responses have been ad hoc and narrow, affecting too small a fraction of the economy and, in the opinion of the committee, not commensurate with the magnitude of the challenge facing the nation. Stronger measures are required. What and how strong these should be is a matter of judgment and cannot be determined without more aggressive experimentation and learning on the part of both public- and private-sector players. The committee is convinced that the long-term costs of inadequate measures are likely to be far greater than the consequences of "overdoing it" for a few years, especially if programs are structured to maximize the amount of organizational learning that takes place in the process.

The committee believes that the most challenging mission of the U.S. technology enterprise now and in the near future is to work with other elements of the national economy to arrest and reverse the recent relative decline of U.S. economic performance and lay the foundation for sustained national economic prosperity into the next millennium. Clearly, the burden of meeting this challenge lies primarily with the private sector. Nevertheless, the committee believes that both state and federal governments can and should contribute significantly to this mission by stimulating more effective development, use, and diffusion of technology throughout the U.S. economy through closer cooperation, coordination, and joint action with each other and with private-sector players.

UNDERLYING TRENDS AND RESULTING CHALLENGES

The committee believes that the trends (see Chapters 2 and 3) that have affected the competitive environment for U.S.-based firms in the last two decades will continue well into the next decade. These underlying trends can be summarized as follows:

- The technical intensity of most manufacturing and service industries will continue to grow at an accelerating pace, and commercial technology will become increasingly science-based and interdisciplinary.
- National security's claims on, and contributions to, the U.S. technology base will continue to diminish. National defense capability (and technological leadership) will become increasingly dependent on technologies developed and applied first in the commercial sphere.
- The current revolution in production systems will continue to spread throughout industrialized and industrializing economies, transforming the organization of effective product and service companies and their relationships with customers and suppliers, as well as bringing a new level of attention to the optimal use of human talents in the workplace.
- International competition will continue to intensify, as world industrial and technological capability becomes increasingly distributed among an expanding population of industrialized nations.
- Local and regional clusters of industrial activity and the associated human, physical, and social capital (accumulated work force skills and know-how, financial and educational institutions, supporting legal and regulatory structures, supplier and distributor networks, etc.) will continue to play a major role in the competitive economic performance of nations. They continue to provide a countervailing force to rapid internationalization.
- Internationalization of economic and technological activity will continue to grow, however, deepening the interdependence of national economies, and, to a significant extent, blurring the distinction between the domestic and foreign policies of nations.

These powerful trends have revealed and exacerbated major weaknesses in the U.S. technology enterprise, weaknesses that are closely interrelated and severely compromise the nation's ability to develop, acquire, and use technology to defend and advance the welfare of its citizens. The committee identified the most important weaknesses to be the following:

- Outmoded managerial philosophies, organizational frameworks, and human resource strategies of many U.S. public- and private-sector producers of goods and services.
- Insufficient investment in, and poor quality of, U.S. work force training and continuing education, particularly at the level of the nonsupervisory work force.

- Inadequate investment by U.S.-based companies in competitive production processes, plant, and equipment.
- The low civilian R&D intensity of the U.S. economy and the insufficient breadth of the nation's civilian R&D portfolio, including underinvestment in growth- and productivity-enhancing technologies that are high-risk or whose benefits are difficult for individual investors to appropriate—"infrastructural" and "pathbreaking" technologies. [1]
- In many U.S. companies and federal laboratories, lack of awareness of and interest in technology originating outside their institutional boundaries, beyond national borders, or outside their normal technological scope.
- Lack of a strong institutional structure for federal technology policy in support of economic development and the segregation of technology policy from domestic and foreign economic policy at the federal level.

These challenges demand a combined public- and private-sector response that is more aggressive, coherent, and broadly dispersed across economic sectors than has been the case in the United States in recent decades. If the United States is to reverse its recent relative competitive decline and restore its economic performance to a level commensurate with its geopolitical position, U.S. public- and private-sector participants must move collectively and forcefully to achieve the goals of the national technology strategy set forth below.

FOUR GOALS OF A NEW NATIONAL TECHNOLOGY STRATEGY

The committee identified four major goals for U.S. government technology policies and private-sector technology strategies. If the United States is to prosper and remain a world economic and technological leader, public- and private-sector participants must work together to achieve the following goals:

1. Foster the timely adoption and effective use of commercially valuable technology throughout the U.S. economy.
2. Increase civilian R&D investment in the U.S. civilian economy and close emerging gaps in the nation's civilian technology portfolio.
3. Access and exploit foreign technology and foreign high-tech markets more effectively to advance the interests of U.S. citizens.
4. Create a strong institutional framework for federal technology policy in support of national economic development, and integrate the planning and implementation of federal technology policy with that of national domestic and foreign economic policy.

Effective pursuit of these four goals demands that the nation's policy mechanisms address the intersection of technology policy with domestic and international economic issues more directly and build working relationships between government and the private sector. Since private companies and markets are the primary movers in the nation's commercial technology enterprise, public technology policies for economic development should be shaped by market forces and should enlist market mechanisms and the capabilities of the private sector to the greatest extent possible. Given the difficulty of the task and the federal government's relative inexperience in technology policies designed explicitly to foster national economic growth, the U.S. approach to technology policy in this arena should be one of aggressive experimentation and continuous learning.

RECOMMENDED POLICY ACTIONS

As first steps toward each of these four overriding goals, the committee recommends a limited number of specific, priority policy actions and guidelines.

Goal 1: Foster the timely adoption and effective use of commercially valuable technology throughout the U.S. economy.

The United States must move swiftly and successfully to (1) improve business practices that drive the development and application of technology, and (2) increase the scope and effectiveness of the nation's investment in worker training and continuing education, particularly for the nonsupervisory work force. These two areas of weakness are reflected in the low rate of investment of U.S. companies in modern production processes and equipment.

A revolution in industrial production systems, first cultivated by the Japanese, has been spreading throughout the industrial world since the late 1960s. During the past decade, this revolution and the wave of intense international competition it has helped engender have prompted a small yet growing population of U.S. companies to modernize their managerial and organizational practices as well as their production plant. In an effort to accelerate the widespread adoption of productivity-enhancing technology and organizational practices throughout the U.S. economy, several modest though promising initiatives have been launched at the state, federal, and regional levels. These have included publicly sponsored industrial and technology extension programs at both the state and the federal level, privately organized consortia and industrial networks, public finance companies designed to entrain private capital to help small companies overcome the obstacles to raising capital for technology investments, and many other imaginative and promising programs.[2]

Likewise, in an attempt to meet the human resource demands of modern production and innovation systems, U.S. state and federal governments, universities, and companies have all begun to take small steps toward redressing major gaps in U.S. work force training and education. These steps have included the development of manufacturing engineering curricula and research programs at a number of U.S. universities, the development of successful customized training and modernization programs administered by the states, municipal or regional vocational education and apprenticeship programs, and significant investment in new training technologies and methods by the nation's armed forces (Carnevale et al., 1990a,b; U.S. Congress, Office of Technology Assessment, 1990b). In addition, increased national interest in work force training as a result of the recent presidential campaign has provided new momentum to a number of more ambitious training and education proposals, including calls for the introduction of a training levy or training tax credits for U.S. companies and the development of a broad-based national apprenticeship program.

Given the apparent success of many relatively small public and private initiatives in technical extension and work force training and education, and the prospect of significantly increased federal action in these areas during the next few years, the committee recommends that the federal government take the following actions to build on existing successful efforts (both publicly and privately sponsored), and to accelerate and focus the nation's response.

Policy actions to achieve Goal 1:

> RECOMMENDATION 1: Catalyze the development of a dense national network of public and private providers of industrial modernization services that is capable of meeting the diverse technical, managerial, training, and related needs of 20–25 percent of the nation's small and medium-sized manufacturing companies by the year 2000. Expand the National Institute of Standards and Technology's Manufacturing Technology Centers program and State Technology Extension Program as a first step toward this objective.[3]

> RECOMMENDATION 2: Support experimentation with a wide range of public and private initiatives at the federal, state, and local levels to increase the quantity and improve the quality of school-to-work transition programs and of job-related training and continuing education for the nation's nonsupervisory work force. Such initiatives could include expanded support for apprenticeship programs, vocational training programs, cooperative work-study programs, training consortia, and training demonstration projects and outreach programs, as well as the development of training certification and standards schemes. The possibility of funding such initiatives with a combination of training levies and training tax credits should be explored.[4]

RECOMMENDATION 3: Establish a high-prestige national fellowship program, to be administered by the National Science Foundation, for advanced study of the technical and organizational aspects of manufacturing. Structure the program not only for university graduate students and faculty but also for practitioners from industry.[5]

The committee believes it is important that federal policymakers recognize what these programs and initiatives should, and should not, be called upon to address. An expanded federal role in industrial modernization should be defined in close collaboration with state governments and private-sector organizations that are, or should be, involved in the process. In particular, federal initiatives such as the MTC program should not seek to replace existing public- and private-sector providers of industrial modernization services, but rather to serve as a "reference librarian" or "broker" for their services, to help them learn from each other, and to stimulate local initiatives to increase the density in coverage of modernization services nationwide. Nor should federal programs in this area focus exclusively on stimulating the diffusion of technological hardware. Indeed, it is far more important that these centers support the widespread adoption of advanced, yet proven, production technology, including both modern production equipment and its essential complements, modern methods of work organization and management.[6]

In work force training and continuing education, the primary role of the federal government should be to help coordinate, rationalize, and identify gaps in the system, bearing in mind that close cooperation with state governments, private industry, educators, and organized labor will be crucial. Federal initiatives should give particular attention to approaches that combine the teaching of highly specialized (less transferable) job-related skills with curricula that cultivate the basic skills, education, and growth potential of the work force. Moreover, it must be recognized that such supply-oriented initiatives are unlikely to be effective without parallel efforts to expand demand for higher-skilled workers. These efforts include industrial modernization programs, such as the MTC network, that promote reorganization of the workplace to take advantage of enhanced and more broadly applicable skills.[7]

The manufacturing fellowship program should place as much emphasis on practice as on theory. It should be explicitly designed to break down dysfunctional cultural walls between scientists and engineers engaged in research, invention, and conceptualization and their counterparts engaged in transforming new ideas and broad concepts into products and production systems. The fellowship program should be designed to address all elements of manufacturing systems, including services delivery within these systems, and it should recognize explicitly that the production and innovation challenges to goods-producing industries are equally important for service industries.

Goal 2: Increase civilian R&D investment in the U.S. economy and close emerging gaps in the nation's civilian technology portfolio.

If the United States is to remain a leader in the development and commercial exploitation of new product and process technologies, it must take immediate steps to increase civilian R&D investment in the U.S. economy to a level more comparable with that of its foremost industrial competitors. U.S. companies must be encouraged to expand the scope of their R&D activities in areas downstream from proof-of-concept and to integrate R&D with design, production engineering, production, and distribution more than in the past. In addition, the nation must move to bridge widely acknowledged gaps in that part of the U.S. technology base whose benefits cannot be readily captured by single companies and therefore tend to be viewed as a "public good."

The committee applauds many recent efforts (both established and proposed) to stimulate private-sector R&D activity.[8] However, the committee is convinced that the United States cannot significantly increase civilian R&D intensity or close critical gaps in the nation's R&D portfolio unless the federal government experiments more aggressively with a wider range of policy options than it has to date and mounts stronger efforts to develop measures of their effectiveness. At the same time, the committee strongly believes that the guiding principle for public policies designed to raise the level or broaden the scope of U.S. industrially relevant research and development activity should be to harness market forces and distributed private-sector intelligence to the greatest extent possible.[9] Hence, in the committee's opinion, direct and indirect incentives to private-sector R&D investments are, in most cases, preferable to direct public subsidies of R&D. For these reasons, the committee recommends that the federal government take the following actions.

Policy actions to achieve Goal 2:

RECOMMENDATION 4: Replace the current incremental Research and Experimentation (R&E) Tax Credit with a permanent tax credit on the total annual R&D expenditures of a company to encourage an increase in the cycles. In addition, extend the R&E tax credit to cover industry-sponsored level and the stability of industrial R&D activity across business R&D in universities and other institutions, and the industrial contribution to R&D performed as part of a consortium that involves government laboratories.[10]

> RECOMMENDATION 5: Use public procurement, selective tax credits, accelerated depreciation schedules, regulation, and other demand-oriented policy instruments to pull innovation and increased private-sector investments in technologies expected to yield particularly high returns to U.S. society as a whole. These include technologies that produce environmentally benign and energy-efficient products and services and technologies that reduce the cost of health-care delivery.[11]

> RECOMMENDATION 6: Experiment more aggressively with options for direct federal support of the development and diffusion of a broad portfolio of commercially relevant or promising "infrastructural" and "pathbreaking" technologies. Rely on industry leadership and involvement in project initiation and design, and on significant private-sector cost sharing to ensure commercial relevance. Options include expansion of the Advanced Technology Program and the Small Business Innovation Research program,[12] public funding of additional private-sector managed industrial consortia like SEMATECH, creation of an independent federal Civilian Technology Corporation,[13] and significant expansion of NIST's measurement, standards, and testing activities.[14]

The committee believes that these three courses of policy action should form the core of the federal government's response to the nation's civilian R&D challenge. At the same time, the committee also cautions against a number of potential pitfalls that the government should seek to avoid.

First, the committee believes that aggressive efforts to raise the volume of national investment in civilian R&D without devoting greater attention to the relative productivity or "quality" of that increased investment would be a costly mistake. For this reason, it is important that the federal government monitor public R&D programs and private R&D practices more closely than it currently does, and adjust its programs as well as the official tax definition of R&D to prevent abuse and wasteful investments.

Second, all federal initiatives designed to influence the growth and direction of private-sector R&D investment through indirect demand-shaping policies should allow as much discretion as possible to private firms operating in competitive markets to determine the most effective technological path toward designated societal objectives. Initiatives involving direct federal subsidies should include an explicit "sunset" clause and exit plan for all participants, and should be required to show how U.S. companies that are not participants in the subsidized consortium will be able to gain access (for example, through purchase or license) at a reasonable price to the technology and expertise developed.[15] Moreover, to avoid pork barrel politics and the buildup of vested interests, the committee believes it is critical that the federal government develop explicit and objective criteria and processes for the selection and evaluation of projects or target technology areas.[16]

Finally, much can and should be done to enhance the useful supplemental role of many federal laboratories in "infrastructural" research and technological exploration of use to industry and to civilian missions of federal agencies. However, it would be unrealistic to expect a major contribution to more downstream commercial technology development from most of the nation's federal laboratories. With the exception of NIST, these laboratories lack a strong tradition of working closely with private-sector producers of commercial products and services. The recent proliferation of Cooperative Research and Development Agreements (CRADAs) between federal laboratories and private companies or consortia may help some of the participating federal laboratories develop greater competence in industrially relevant work. To the extent these public-private partnerships do not detract from the core R&D mission of participating federal laboratories, and meet the same criteria for other more direct federal subsidies of precompetitive R&D described above, their creation should be encouraged. However, since it is still too early to judge the overall effectiveness of CRADAs, the committee believes federal funding of mission-oriented laboratories for commercially relevant R&D should be approached with caution and in an experimental mode with periodic review to appraise its economic impact.

Goal 3: Access and exploit foreign technology and high-tech markets more effectively to advance the interests of U.S. citizens.

Although many U.S. multinational corporations have become more effective at tapping foreign technology and foreign high-technology markets—through transnational corporate alliances, joint ventures, and foreign direct investment—a majority of U.S.-based firms remain insufficiently aware of, and alert to, either the threats of the opportunities presented by foreign technical capabilities. This deficiency in the nation's technology enterprise and economic competitiveness is compounded by a lack of coordination between technology policy and foreign economic policy. While the committee believes that "not-invented-here" attitudes and shortsighted corporate strategies explain a great deal, it also recognizes that there are significant asymmetries of access among the national markets and technology enterprises that often disadvantage U.S.-based firms abroad. These issues can be addressed only through constructive international negotiation. The absence of adequate coordination between U.S. technology and foreign economic policies has so far made it very difficult for the U.S. government to assess the impact of actions in one policy area on outcomes in the other, and it has occasionally resulted in neglect of U.S. technological interests in U.S. trade negotiations.[17]

During the past decade, federal agencies such as the National Science Foundation, the Department of Commerce, and the Department of Defense have made numerous attempts to encourage U.S. citizens and companies to exploit more fully the acknowledged capabilities of foreign firms in particular technological areas. Examples include the international fellowship programs and the Japanese Technology Evaluation Program (JTEC) in the National Science Foundation and the Japanese Technical Literature Service and the U.S.-Japan Manufacturing Technology Fellowship program in the Department of Commerce.[18] At the same time, recent events and trends in international markets have prompted sporadic efforts at coordination of technology and foreign economic policymaking in the federal government. Intellectual property rights and government R&D subsidies have assumed an increasingly important status in U.S. international trade negotiations, whether as part of the latest round of multilateral negotiations under the General Agreement on Tariffs and Trade (the Uruguay Round) or in the negotiations of the North American Free Trade Agreement.

Building on these initiatives, the committee recommends three policy actions to increase U.S. access to foreign technology and markets, improve coordination of U.S. technology and foreign economic policy, and strengthen the U.S. position in future multilateral negotiations concerning technology and trade. All three are consistent with the objectives of an open trading system and current U.S. obligations under international treaties and agreements.

Policy actions to achieve Goal 3:

> RECOMMENDATION 7: Stimulate the expansion and institutionalization of U.S. public- and private-sector capabilities for global technological scanning and benchmarking. Most of these activities should be carried out by industry associations or industrial consortia with some sharing of costs and planning responsibility with federal government agencies. [19]

> RECOMMENDATION 8: Develop a capacity within the federal government for seeding and stimulating international R&D consortia (private-sector, public-sector, or mixed) in areas of recognized foreign technological strength where gains to U.S. participants are expected to be substantial. This is an important subset of the options for direct federal support of commercially promising "infrastructural" and "pathbreaking" technologies recommended above.[20]

> RECOMMENDATION 9: Improve coordination and cooperation between agencies with lead responsibility for domestic and foreign economic policy and agencies with lead responsibility for science and technology policy by (1) rotating high-quality midlevel staff between these

agencies,[21] (2) establishing a technology and trade committee of the Federal Coordinating Council for Science, Engineering, and Technology, and (3) making the integration of technology policy with domestic and foreign economic policy an explicit objective of the newly created National Economic Council.[22]

In general the committee believes that maintaining the openness of the U.S. market to foreign competitors that abide by existing international agreements on trade and investment provides incentives for U.S.-based firms to seek out foreign technology and markets and to innovate. At the same time, the committee also recognizes that some major differences in national business practices, industrial structure, and public policies are beyond the reach of existing international agreements. Such differences often result in significant asymmetries of access among national markets and national technology enterprises.[23]

Over the long term the United States must provide leadership in the negotiation, establishment, and administration of more far-reaching multilateral agreements and arbitration mechanisms to reconcile differences in national policies and business practices that distort trade, investment, and technology flows.[24] Nevertheless, given the relative openness of U.S. markets and the growing influence of foreign markets on the structure and health of the U.S. technology enterprise, it is essential that the federal government develop an interim strategy to advance U.S. national interests. Specifically, in seeking to reduce asymmetries of market and technology that disadvantage U.S.-based companies, the U.S. government should look for countering strategies that are more likely to lead to mutual benefits for the United States and its trading partners than to negative consequences for both sides. This may include unilateral actions, such as countering another government's trade-distorting R&D subsidies with its own R&D subsidies rather than restoring to retaliatory tariffs or quotas.[25]

Goal 4: Create a strong institutional framework for federal technology policy in support of national economic development, and integrate the planning and implementation of federal technology policy with that of national domestic and foreign economic policy.

The federal government's response to the technology and competitiveness challenges facing the nation's economy and its civilian technology enterprise has been inadequate. Many programs and initiatives dispersed throughout the federal government address various aspects of the nexus between technology and economic development. Some are clustered within the Technology Administration of the Department of Commerce, but many are appended to federal agencies whose primary missions and expertise have little to do with the technology needs of the U.S. civilian economy. Although many of these programs have been judged successful in their own right, they are ad hoc and limited, do not serve as a basis for learning by experience, and are largely peripheral to the concerns and interests of the federal government's principal domestic and foreign economic policy agencies.

In recent years there has been some movement in the federal government to improve coordination of federal technology policy initiatives among the diverse federal agencies through the revitalized Federal Coordinating Council for Science, Engineering, and Technology, administered by the Office of Science and Technology Policy. However, there have also been numerous calls for the establishment of an institutional focus for federal technology policy in service of national economic development that would go beyond coordination of the relevant efforts of multiple agencies.[26] Each of these proposals has defined the purpose, functions, and organization of the proposed institutional focus somewhat differently.

Drawing on what it perceives to be the strengths of existing initiatives and previous proposals, as well as its own understanding of the primary institutional challenges facing U.S. technology policy at the federal level, the committee recommends that Congress and the administration take the following action together.

Policy Action to Achieve Goal 4:

RECOMMENDATION 10: Establish an institutional focus within the federal government to monitor, harness, and supplement the many existing federal programs and capabilities that currently support, or could support, more effective development, use, and diffusion of technology throughout the U.S. economy. This institutional focus should work for the early incorporation of technological considerations into the formulation and implementation of U.S. economic policy.

The committee considers it essential that such an institutional focus, whether it resides in an existing or a newly created agency or department, assume a leadership role in the highly decentralized federal technology policy apparatus to advance U.S. economic growth and development and the broader societal goals that economic growth makes possible. In addition to any specific programmatic responsibilities that it may assume, this new institutional focus should include the following four functions in its core mission:

- Develop and articulate an internally consistent national techno-economic strategy for the benefit of the U.S. public and of all the various players who contribute to the U.S. technology enterprise and national economic development.

- Monitor transnational public and private technology alliances to develop reliable methods of evaluating the benefits and costs of such alliances to both the United States and foreign participants.
- Analyze the effects of differences in business practices among countries and their consequences for the competitive performance of U.S. companies, industries, and workers, and develop recommendations for (1) unilateral changes in U.S. practices and (2) changes to be negotiated in the practices of other countries to level the competitive playing field.
- Promote the coordination of trade policy, foreign investment policy, macroeconomic policy, tax policy, public-sector procurement, regulatory policy, work force training, technology extension, public technology investment selection, and other elements of U.S. economic and technology policy.

The committee believes that many of the capabilities required for the performance of these functions already exist, dispersed throughout the federal bureaucracy. However, no leading institution or forum helps coalesce, develop, and harness these pieces to inform and advance a more coherent national strategy for technology in service of economic development. The committee also believes that any of several existing or proposed government entities might fulfill the role of institutional focus, and it does not offer specific recommendations concerning the roles of, and relationships among, existing or proposed federal entities.

The committee strongly believes that as Congress and the administration address this institutional challenge, their principal concern should be with bringing technology most effectively to bear in pursuit of national economic development, not with advancing and diffusing technology in and of itself. For this reason, the committee recommends against institutional solutions that do not include strong linkages between technology policy and other domains of domestic and foreign economic policy.

While it makes the task of policy coordination more difficult, the highly distributed nature of both technology policymaking and economic policymaking in the United States is a source of U.S. strength that should be built upon. Accordingly, the committee considers it neither practical nor desirable for the new institutional focus to centralize the many existing programs and initiatives of a wide range of federal agencies that work with and support industry and universities to strengthen the civilian industrial technology base.

NOTES

1. See Chapter 1, pp. 17–18. and Chapter 3, pp. 76–80, for discussion of emerging areas of underinvestment in the U.S. technology base and definitions of "infrastructural" and "pathbreaking" technologies. These concepts were taken from Alic et al. (1992, chapter 10).

2. To promote the diffusion of advanced production technology and "best" managerial and

organizational practices throughout U.S. industry, the federal government has initiated a number of relatively small-scale programs. These include NIST's Manufacturing Technology Centers (MTC) program and State Technology Extension Program (STEP), NSF's Engineering Research Centers, the new DOD National Manufacturing Extension Program, DOD support for the privately organized and managed National Center for Manufacturing Sciences (NCMS) consortium, and the Department of Commerce's Malcolm Baldrige Quality Award and Baldrige Institute. For background information and evaluations of these and other initiatives, see Committee on Science, Engineering, and Public Policy, (1992); Manufacturing Technology Centers Third-Year Review Panel (1992), National Academy of Engineering (1984, 1989), U.S. General Accounting Office (1991).

For information concerning the many state level technology extension programs, see Carnegie Commission (1992a), Clarke and Dobson (1991); Feller 1992a,b; Shapira et al. (1992). For discussion of the current and potential role of regional industrial networks, see Hatch (1991), Rosenfeld (1992), Rosenfeld et al. (1992). For promising examples of ways state and federal funds might be used to focus the allocation of private funds on technology/industrial modernization investments by small manufacturing firms, such as Michigan's Business and Industrial Development Corporations (BIDCOs) or Pennsylvania's investments in private seed capital funds through the Ben Franklin Partnership Program, see Bygrave and Timmons (1992).

3. The MTC and STEP programs are essentially pilot projects. Since the MTC program's inception only seven Manufacturing Technology Centers have been established. The MTC program's fiscal 1993 budget authority was roughly $17 million in federal funds with centers attracting an approximately equal amount in cash or in-kind contributions. The five operational centers (two additional centers are in the startup phase) have provided some level of service to more than 3,500 companies since they were established. STEP is currently funded at little over $1 million dollars. Preliminary reviews of these programs have been favorable (Manufacturing Technology Centers Third-Year Review Panel, 1992; Shapira et al., 1992).

Many proposals have been made in the last two years for expanding the fledgling MTC and STEP programs into a more comprehensive national industrial extension network. See, for example, "Manufacturing for the 21st Century: Turning Ideas into Jobs," September 8, 1992, Clinton/Gore Campaign; National Center for Manufacturing Sciences (1992b); Shapira et al., (1992); U.S. Congress, House (1992b, 1993b), U.S. Congress, Senate (1993).

The committee applauds the administration, Congress, and other public-and private-sector contributors for their efforts to develop some form of national industrial modernization service network. It should be noted that among the proposals put forward by these parties, there is wide variation in estimates of how many MTCs and associated "outreach" satellite institutions are needed to meet the nation's needs and at what level of funding. Estimates vary according to different assumptions about what types and level of services the MTCs and associated local or regional entities should provide or broker, how they will interact with other public and private service providers, and the extent to which MTCs will be able to support their activities through user fees. The committee believes that the national industrial modernization network it proposes could assume any number of organizational forms, with different levels of claims on federal, state, and private-sector resources. Therefore, the committee does not make specific recommendations regarding the appropriate size of the MTC or STEP programs except that they should be expanded from their current pilot project scope. In any case, the committee believes it is essential to develop a systematic program to develop and apply criteria for monitoring the effectiveness of these programs before vested interest makes it politically difficult to phase out the less successful mechanism.

4. For further elaboration of these and other proposed initiatives, see Carnevale (1991); Carnevale et al. (1990a,b); Lynch (1992); Marshall and Tucker (1992 a,b); Mishel and Teixeira (1992); National Center on Education and the Economy (1990); U.S. Congress, Office of Technology Assessment (1990b); U.S. General Accounting Office (1990b).

5. Despite limited progress in recent years in increasing the scope and status of manufacturing education and research within U.S. universities, there remains a crying need to get both U.S. industry and U.S. universities to take manufacturing, in both its technical and organizational aspects, much more seriously. The committee believes that a relatively small, high-prestige fellowship program would go a long way toward helping to seed similar fellowship programs and greater university and industry interest and collaboration in the development of manufacturing studies.

6. In the design of industrial modernization services, it is best to recognize that small companies are not uniformly in need of technological help—many can afford to invest in new production technology, are technologically sophisticated, and can get good technical advice at a reasonable price. Most small companies to do not regard technology as a key to survival or business success. Therefore, the job of industrial extension is as much a job of basic business consulting/advising as it is of technology transfer, and the success of any individual extension operation will depend as much on the talent and experience of the personnel delivering services as on the policy design. The committee considers the 10 "best practices" for industrial modernization programs distilled by Shapira et al. (1992) as a particularly useful baseline for designing and evaluating federal and state programs designed to catalyze the national industrial modernization network:
1. Competent, quality, core staff is essential.
2. Programs should focus on the customer and meet the localized needs of existing small and medium-sized enterprises.
3. Programs need to go beyond problem solving and stimulate firms to pursue a technology upgrade path.
4. Technology should be pragmatic.
5. Programs should be integrated; services should be seamless to firms.
6. Public, private, profit, and nonprofit sectors and organizations all play important roles in modernization.
7. Industrial modernization needs to promote change as well as offer services.
8. Industrial modernization programs need scale, stability, and a long-term perspective. For this reason, MTCs should charge industrial clients reasonable fees for specific services rendered, but should not be expected to be self-supporting since they provide public as well as private benefits.
9. Industrial modernization has to work at the system level as well as the individual firm level.
10. Assessment and evaluation are critical.
For a review of the MTC program and an evaluation of the barriers to diffusion of advanced manufacturing technology and production methods among small and medium-size companies, see also National Research Council (1993).

7. In the national debate about training, there has been too little recognition that the problem of work force skills is as much one of demand as of supply. All too many U.S.-based businesses are not organized to take advantage of a higher-skilled work force. For further discussion of this point see Chapter 3, pp. 69–74, as well as Carnevale (1991) and Mishel and Teixeira (1992).

8. The federal government has adopted a number of recent programs to increase private-sector investment in R&D, bridge critical gaps in the nation's industrial technology base, and improve management of public- and private-sector R&D. These programs have included (a) support of industrial R&D consortia such as SEMATECH, the National Center for Manufacturing Sciences (NCMS), and the Battery Consortium; (b) promotion of Cooperative Research and Development Agreements (CRADAs) between federal laboratories and U.S. industrial enterprises; (c) launch of the Department of Defense's Computer-aided Acquisition and Logistics Supply System (CALS); (d) establishment of the Advanced Technology Program (ATP) in the National Institute of Standards and Technology; (e) establishment of dual-use critical

technology partnership programs administered by the Defense Advanced Research Projects Agency (DARPA); and (f) a significant increase in funding for the Small Business Innovation Research program. For information concerning these programs, see Committee on Science, Engineering, and Public Policy (1992), National Institute of Standards and Technology (1992), Public Law 102-484 (FY 1993 Defense Authorization Act), U.S. Congressional Budget Office (1990), U.S. General Accounting Office (1991, 1992a,c).

Proposed new initiatives in this area include increasing and making permanent the R&E Tax Credit to U.S. companies, plans for further changes to federal government procurement practices (particularly those of the Department of Defense) to draw more extensively and effectively on the U.S. commercial technology base, efforts to expand significantly the funding of "dual-use" technology development by DARPA, a tenfold expansion of NIST's relatively modest ATP program (currently funded at $6 million), and the establishment of a civilian technology corporation (a government-financed venture capital corporation). See, for example, Carnegie Commission on Science, Technology, and Government (1990), Bloch (1991), Committee on Science, Engineering, and Public Policy (1992), Hufbauer (1992), National Institute of Standards and Technology (1992), U.S. Congress, House (1992a,b; 1993a,b), U.S. Congress, Senate (1992, 1993).

9. A problem with the great majority of ongoing and proposed efforts in this area is the uncertainty in how and whether such publicly supported R&D initiatives will actually lead to commercialization. All of these initiatives involve the generation of technical knowledge that is largely in the public domain. The hope is that, by reducing the technical risks involved, the cost sharing by government will make follow-on private investments in commercialization less risky and hence more attractive to the private sector. But this depends on a favorable market and investment climate for follow-up. It remains to be seen whether events will work out this way, and private-sector follow-through needs to be carefully monitored. One of the most important functions of the "institutional focus" recommended later in this chapter (pp. 101–103) is to do this monitoring and evaluation of the initiatives with particular attention to understanding the incentives and disincentives to follow-on private investments in commercialization. Even if the technical risks are substantially reduced by federal cost sharing upstream, serious downstream market risks remain, and it is much more difficult for the federal government to find mechanisms for reducing these risks. Many of these mechanisms lie more in the domain of economic, regulatory, and other nontechnical policy areas than in the domain of technology policy. The government does, and should, create the climate and some ground rules in the area, but industry *must* take the direct action. This is one of the prime reasons for seeking better integration of technological and economic considerations in the development of an effective national competitiveness policy.

10. The current U.S. incremental R&E Tax Credit provides for a credit of 13.2 percent (or a 20 percent credit, of which 50 percent is treated as taxable income) for the excess of current R&D over the base amount for that year. The credit applies to 100 percent of in-house R&D and to 65 percent of contract R&D. This contrasts, for example, with a 20 percent tax credit for all company-financed R&D in Canada, a 50 percent incremental tax credit in France, and a 20 percent incremental tax credit in Japan, where small and medium-sized firms have the option of a 6 percent credit on total R&D expenditures.

While there remains some uncertainty over the exact effect of R&D tax credits on research spending by industry, recent studies by Bailey and Lawrence (1990, 1992) and Hines (1991) suggest that even modest tax incentives can have sizable impacts on private-sector R&D spending.

Arguing for a package of reforms in U.S. corporate tax law which he estimates will raise net U.S. tax revenues by more than $12 billion annually, Hufbauer (1992) estimates that a shift from the current 20 percent incremental R&D tax credit to a 10 percent tax credit on total corporate R&D would cost the U.S. Treasury roughly $7.5 billion in forgone revenues each year. While the committee has not studied Hufbauer's full package of proposed reforms in any detail, it considers Hufbauer's recommendations a useful starting point for policy discussions of this issue.

11. There are some interesting precedents in the old National Bureau of Standards' Experimental Technology Incentives Program (ETIP) for using both regulation and public procurement to provide initial markets for socially beneficial technology such as water heaters with minimal lifetime costs (as opposed to first cost). See Lewis (1975, 1976) and National Research Council (1976). Considering the total volume of federal government purchases of goods and services (including health care), the potential for pulling private-sector commercial technology investments in the direction of broad social and economic goals is significant. For discussion of the technological challenge facing U.S. health care delivery systems, see Carnegie Commission (1992b).

12. Since receiving its first appropriations in fiscal year 1990, ATP's funding level has increased from $10 million to $67.9 million in fiscal year 1993. The FY 1994 NIST authorization bill—which was not enacted—would have authorized $1.4 billion over five years for the program. NIST has noted that "strong arguments can be made for an ATP program with funding in the range of $500 million to $1 billion per year" (National Institute of Standards and Technology, 1992).

With respect to the appropriate level of funding for an expanded ATP program, the committee concurs in the following assessment by the Committee on Science, Engineering, and Public Policy Panel on the Government Role in Civilian Technology:

The ATP program has had a promising start. It is not possible, at this early stage, to determine the program's success; nor should congressional or executive branch policymakers expect to see immediate, dramatic results. The panel has concluded, however, that the ATP's budget in the past has been insufficient to have a significant impact on U.S. technology commercialization efforts. An evaluation of ATP by an independent panel of experts, on an ongoing basis, would permit periodic determination of the desirable size of the program (Committee on Science, Engineering, and Public Policy, 1992, p. 67).

Legislation introduced in 1992 in both House and Senate (H.R. 5631 and S. 3382) called for the establishment of an independent government Civilian Technology Corporation (CTC) and included a provision for absorbing the ATP into the new CTC if this were deemed advisable. Subsequent bills introduced by both the House and Senate in early 1993 call for major expansion of the ATP within NIST (U.S. Congress, House, 1993b; U.S. Congress, Senate, 1993). See note 13 below for further details.

The Small Business Innovation Research program was significantly expanded by Congress in the fall of 1992. See Chapter 1, note 15.

13. The establishment of a Civilian Technology Corporation "to increase the rate at which products and processes are commercialized in the United States," was first proposed by the Committee on Science, Engineering, and Public Policy Panel on the Government Role in Civilian Technology in its 1992 report. In 1992, both houses of Congress introduced bills (H.R. 5631 and S. 3382) "to establish an independent government Civilian Technology Corporation to support the efforts of American industry in the development of key technologies of the future." These bills proposed that a newly established CTC be funded at a level of $5 billion and be authorized to make technology development awards (in the form of grants, cooperative agreements, or contracts) for the purpose of supporting industry-led projects to develop critical civilian technologies. In addition, it proposed that the CTC be authorized to provide loan guarantees and loans (including conditional interest-free loans) and take warrants and voting and nonvoting equity in qualified joint ventures and qualified individual firms and equity investments in order to assist these private-sector parties to develop and commercialize critical civilian technologies. In January 1993 the House reintroduced the proposal in the

Civilian Technology Act of 1993 (U.S. Congress, House 1992a, 1993a; U.S. Congress, Senate, 1992).

The House and Senate versions of the National Competitiveness Act of 1993 (H.R. 820 and S.4), introduced in early 1993, contain provisions for a "Civilian Technology Loan Program" and a "Civilian Technology Development Program," to be administered by the Commerce Department, that would fulfill much the same role as the proposed CTC (U.S. Congress, House, 1993b; U.S. Congress, Senate, 1993).

14. NIST's direct appropriations for operating funds for fiscal year 1993 were about $300 million per year, and its total budget (including other agency funds) was approximately $450 million. NIST's intramural programs are funded at a level of $220 million for fiscal year 1993.

Another way in which the federal government currently supports industrially relevant "infrastructural" research and development is through the Cooperative Research and Development Agreements (CRADAs) between private companies and federal laboratories. See Chapter 1, note 15, and Chapter 4, p. 99.

15. The committee considers the following six guidelines for federal government support of precommercial research and development developed by the Committee on Science, Engineering, and Public Policy (1992) Panel on the Government Role in Civilian Technology to be very useful in this regard:

— Include significant private-sector cost sharing as well as strong industry leadership and involvement in project initiation and design to ensure the commercial relevance of the work.

— Ensure that project selection is based on technical and economic assessments of the merits of a specific program and is as insulated from distributional politics as possible.

— Develop a broad portfolio of investments across technical fields to complement federal mission-oriented research.

— Keep participation open to foreign-owned firms, provided they bring novel technological capabilities or other complementary assets to the enterprise and there is reciprocal access to the home country's indigenous consortia.

— Ensure rigorous, technical, and economic evaluation of all projects, taking into account the knowledge and experience of potential customers for the results.

16. See Alic et al. (1992, pp. 370, 374–379).

17. One example is the enforcement and interpretation of antitrust regulations without reference to international competition, although this has been largely remedied by recent legislation. A broader problem has been the tendency to extend U.S. domestic requirements to foreign subsidiaries of U.S.-headquartered corporations. Some of the worst effects, however, have arisen not from inconsistencies among different policy areas, but from misguided policies that have had opposite effects from those intended. Classic examples here include the use of "voluntary" import quotas for automobiles and the U.S.-Japan Semiconductor Trade Agreement, which have handed windfall profits to Japanese companies and enabled them to invest in up-market developments. See, for example, Crandall (1987), Flamm (1990), Mowery (1992). For more favorable assessments of the Semiconductor Trade Agreement, see Yoffie (1992) and Tyson (1992a,b). For several perspectives on the relationship between U.S. trade and technology policy, see Harris and Moore (1992).

18. For information on the JTEC (formerly JTECH) program, see Gamota and Frieman (1988) and Rogers (1991). For details on the recently announced U.S.-Japan Manufacturing Fellowship Program, see U.S. Department of Commerce (1993). The Japanese Technology Literature Act of 1986 (Public Law 99-382) amends the Stevenson-Wydler Act to direct the Department of Commerce improve availability of Japanese technical literature to U.S. businesses, scientists, and engineers. See also U.S. General Accounting Office (1990a).

19. Both the House and Senate versions of the National Competitiveness Act of 1993 contain provisions for expanding and better coordinating the federal government's "collection, evaluation and dissemination of information on foreign science and technology, specifically information assessing foreign capabilities relative to comparable United States capabilities," See U.S. Congress, House (1993b) and U.S. Congress, Senate (1993).

20. Presumably the proposed increase in federal benchmarking capabilities in the House and Senate versions of the National Competitiveness Act of 1993 would help federal agencies (in their close collaboration with U.S. industry) to identify potential areas for international R&D collaboration that might merit public-sector support. (See note 19 above.) Nonetheless, any arrangements of this sort may entail some risk of asymmetrical benefits; hence, they need to be justified by real potential mutual benefits. The federal government needs to be able to assess objectively both the mutual and the relative gains to the United States and its foreign partner, both retrospectively and prospectively, to provide guidelines for future policy in this area. The committee believes that this need constitutes an important argument for establishing some sort of institutional focus for economic or technological policy in the federal government. See the committee's final recommendation and rationale on pages 101–103.

21. The Senior Executive Service is ostensibly set up to do this, but, in fact, staff members do not rotate among the big federal agencies.

22. These initiatives should be viewed as a complement to the committee's final recommendation for the establishment of an institutional focus for federal technology policy in support of national economic development; see pp. 101–103.

23. It is important to recognize that some policy actions by the U.S. government have produced trade distortions disadvantageous to U.S. firms. See note 17 above for discussion of the unintended consequences of U.S. policy actions affecting trade in automobiles and semiconductors. Another often-cited example is Section 861 of the U.S. corporate tax code, which provides incentives for U.S.-owned multinational companies to locate a larger share of the research, development, and evaluation activities offshore than they would in the absence of these incentives. For further discussion of Section 861, See Bailey and Lawrence (1991) and Mettler (1992). The committee believes the federal government should work to identify and remove such policies.

24. Achieving stable international agreements in these areas represents a long-term challenge that will require considerable negotiation, policy experimentation, and learning. For further discussion of this challenge and possible U.S. responses to it, see Bergsten and Graham (1990), Moran (1992), Mowery (1992), Ostry (1990), Tyson (1992a,b), Yoffie (1992).

25. Tyson (1992a,b) argues for a similar "positive-sum" interim approach for U.S. foreign economic policy in general.

26. For example, in 1985 the President's Commission on Industrial Competitiveness called for the creation of a cabinet-level Department of Science and Technology. Others have proposed establishment of a civilian DARPA and a Civilian Technology Agency or a Civilian Technology Corporation. There have also been calls for reorganization of the Department of Commerce into a new Department of Technology, Industry, and Trade. For details see President's Commission on Industrial Competitiveness (1985). Carnegie Commission (1991), Committee on Science, Engineering and Public Policy (1992). See also Kline and Kash (1992). For a review of other recent proposals along these lines, see Mogee (1991).

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Biographical Information About the Committee

HARVEY BROOKS is Benjamin Peirce Professor of Technology and Public Policy (Emeritus) and former dean of Engineering and Applied Physics at Harvard University (1957–1975). Before coming to Harvard as professor of applied physics in 1950, he had been associate head of the Knolls Atomic Power Laboratory of General Electric in Schenectady, New York, from 1946 to 1950. Trained originally as a theoretical physicist at Yale, Cambridge, and Harvard universities, he is a member of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, and is a former president of the American Academy of Arts and Sciences (1970–1975). From 1975 to 1986, he headed the Science, Technology, and Public Policy Program of the Kennedy School of Government at Harvard.

JOHN S. FOSTER, JR., is a chairman of the Defense Science Board. He is a former vice president for science and technology of TRW Inc. He received his B.S. degree from McGill University in 1948 and his Ph.D. in physics from the University of California, Berkeley, in 1952. He then joined Lawrence Livermore National Laboratory, where he eventually became director while also being named associate director of Lawrence Berkeley National Laboratory. Foster joined TRW in 1973 as vice president for energy research and development. He retired from TRW in 1988 and at that time was elected to become a director of TRW Inc. He continues to serve TRW as a consultant. Foster has served as director of Defense Research and Engineering for the U.S. Department of Defense and has served on the Air Force Scientific Advisory Board, the Army Scientific Advisory Panel, the Ballistic Missile Defense Advisory Committee of the Advanced Research Projects Agency, and as a panel consultant to the President's Science

Advisory Committee. Foster is a member of the National Academy of Engineering.

H. NORMAN ABRAMSON is a retired executive vice president of Southwest Research Institute. He received his B.S. in mechanical engineering in 1950 and M.S. in engineering mechanics in 1951, both from Stanford University, and his Ph.D. in engineering mechanics from the University of Texas in 1956. Abramson's work on problems of dynamic behavior of liquid propellants in rockets and spacecraft have earned him an international reputation. He has also made important contributions in the field of ship structural analysis and dynamics, particularly as an authority in hydroelasticity. Besides serving as manager or principal investigator of more than a score of significant research projects, he has also been extensively sought after as a technical consultant by a large number of governmental agencies and industrial concerns. Abramson is a member of the National Academy of Engineering and has served as a member of numerous national and international professional, scientific, and governmental advisory committees.

JOHN A. ARMSTRONG is a member of the IBM Corporate Management Board and, as vice president of science and technology, is responsible for ensuring IBM's techonological excellence and leadership in research. He received his A.B. degree in physics from Harvard College in 1956 and his Ph.D. in 1961 from Harvard University for research in nuclear magnetic resonance at high pressures. He joined IBM in 1963. His current position at IBM includes management responsibility for the research division, technical strategy development, technical journals and professional relations, and technical personnel development. Armstrong was elected a member of the National Academy of Engineering in 1987. He has also served as chairman of the National Science Foundation's Advisory Committee for Physics and a member of its Special National Science Board Commission on the Future.

ERICH BLOCH is a Distinguished Fellow at the Council on Competitiveness. Until 1990 he was for six years director of the National Science Foundation. Before that he was vice president for technical personnel development at IBM Corporation, which he joined in 1952 as an electrical engineer. At IBM in 1962, Bloch headed development of the Solid Logic Technology program, which provided IBM with microelectronic technology for its System/360 computer. For his part in this achievement, Bloch received the National Medal of Technology in 1985. Bloch serves on the Council of the National Academy of Engineering.

MICHAEL L. DERTOUZOS is a professor of computer science and electrical engineering at the Massachusetts Institute of Technology, and director of the MIT Laboratory for Computer Science. Born in Athens, Greece, Dertouzos came to the United States for undergraduate study as a Fulbright Scholar. After receiving his Ph.D. from the MIT in 1964, he joined the faculty. In 1974 he was named director of the Laboratory for Computer Science, a center of some 500 researchers that spans the major research areas of computer science and technology. He is the author of six books, the most recent of which is *Made in America: Regaining the Productive Edge*, coauthored with Richard Lester and Robert Solow. The book compares European, Japanese, and U.S. manufacturing practices. Dertouzos is a member of the National Academy of Engineering and a corresponding member of the Anthens Academy of Arts and Sciences.

BOB O. EVANS is executive vice president of Technology Strategies & Alliances. Before assuming his current position, he was a general partner with Hambrecht & Quist Venture Partners, specializing in information systems and components investments. He then joined IBM where he held a number of R&D and general management positions, the last being vice president for engineering, programming, and technology. Evans was awarded the National Medal of Technology in 1985 and holds numerous professional awards. He is a member of the National Academy of Engineering and has served on several U.S. government advisory boards, as well as university and corporate boards. He holds a B.S. degree in electrical engineering from Iowa State University.

HAROLD K. FORSEN is senior vice president of Bechtel Corporation, responsible for the Bechtel Technology Group. He received his B.S.E.E. and M.S.E.E. degrees from the California Institute of Technology and his Ph.D. in electrical engineering from the University of California, Berkeley. The Bechtel Technology Group includes the Research and Development Operation, Geotechnical Services, Materials and Quality Services, and Bechtel Software, Inc. Before joining Bechtel, Forsen was vice president and director of Exxon Nuclear Company, responsible for the management and direction of their laser isotope separation program. Before that he was a professor of nuclear engineering and director of the Physical Sciences Laboratory at the University of Wisconsin at Madison. During this time, he also provided consulting services in applied physics and magnetic fusion to the Atomic Energy Commission, Energy Research and Development Administration, Argonne National Laboratory, and Oak Ridge National Laboratory. He is a member of the National Academy of Engineering and a fellow of the American Physical Society, the American Nuclear Society, and the Institute of Electrical and Electronics Engineers.

WILLIAM G. HOWARD, JR., is an independent consulting engineer with clients in microelectronics and technology-based business planning areas. Before beginning consulting practice, he was a senior fellow at the National Academy of Engineering from 1987 to 1990. His focus while at the Academy was in the area of technology commercialization in private industry. Prior to his fellowship at the Academy, Howard was senior vice president and director of research and development at Motorola, Inc. Before joining Motorola in 1969, Howard was an assistant professor of electrical engineering and computer sciences at the University of California, Berkeley, where he earned his doctorate. He has served on numerous government and private advisory panels and has served as chairman of the U.S. Department of Commerce's Semiconductor Technology Advisory Committee and chairs a working group of the Department of Defense's advisory group on electron devices. He is a member of the National Academy of Engineering and has held a variety of positions in the Institute of Electrical and Electronics Engineers.

STEPHEN J. KLINE is the Clarence J. and Patricia R. Woodard Professor of Mechanical Engineering and Values, Technology, Science and Society (VTSS) at Stanford University. Kline was one of the four founding members of the Stanford VTSS Program in 1970. Kline's technical interests encompass foundations of thermodynamics, heat transfer, and fluid mechanics. He has long been a consultant to a number of companies concerning complex problems in internal flows. The combination of this consulting experience and an interest in VTSS foundation concepts led Kline to create an improved model of innovation in industrial societies in 1984, a model now coming into use worldwide. This led to a concern and active interest in technology policy. Kline is an Honorary Life Fellow of the American Society of Mechanical Engineers and the American Association for the Advancement of Science, and a member of the National Academy of Engineering.

JAMES F. MATHIS is chairman of the New Jersey Commission on Science and Technology, which invests state funds in science and technology initiatives to help the state's economy. He received his B.S. degree in chemical engineering from Texas A&M University in 1946 and his M.S. and Ph.D. degrees from the University of Wisconsin in 1951 and 1953, respectively. He was employed by Exxon for 35 years, retiring in 1984 from the position of vice president of science and technology for Exxon Corporation. In that role he was responsible for overseeing more than $700 million in worldwide R&D programs. Since then, he has consulted with Arthur D. Little, Inc.; the Strategic Decisions Group; ChemShare, Inc,; and many others. In 1985–1986, he was a director of NL Industries. Currently he is a director of Laser Recording Systems, Inc., and the Hanlin Group, Inc. Mathis is a trustee of the Wisconsin Alumni Research Foundation and of the Rene Dubos Center for Human Environments, Inc. He is a fellow and former director of the American Institute of Chemical Engineers. He is a member of the National Academy of Engineering and many scientific, technical, and environmental organizations.

JOHN S. MAYO is president of AT&T Bell Laboratories. He received his B.S., M.S., and Ph.D. degrees in electrical engineering from North Carolina State University. Mayo joined Bell Laboratories in 1955 and throughout his career has played an important role in development of digital technologies. His early research was with the team that produced the first transistorized digital computer. He then worked on digital transmission technology, using the transistor to show the feasibility of T-1 Carrier, the first system for high-speed digital transmission in the telephone plant. Other Bell Labs projects in which Mayo was involved include high-speed pulse code modulation systems, the Telstar satellite, electronic systems for ocean sonar, the 4ESS digital switching system, and development of a wide range of electronic technologies with emphasis on systems assembly, integrated circuits, and photonics devices. Mayo is a fellow of the Institute of Electrical and Electronics Engineers and a member of the National Academy of Engineering. He received the IEEE's Alexander Graham Bell Medal, Simon Ramo Medal, and C&C Prize. He is a trustee of Polytechnic University and a member of the College of Engineering Advisory Board of the University of California, Berkeley.

M. EUGENE MERCHANT is a senior consultant to the Institute of Advanced Manufacturing Sciences. He received his B.S. degree in mechanical engineering from the University of Vermont in 1936, and his doctorate of science degree from the University of Cincinnati in 1941. He carried out basic and applied research in manufacturing science and engineering at Cincinnati Milacron, Inc. for 46 years, serving finally as that company's principal scientist. Upon retirement from Milacron in 1983, Merchant joined Metcut Research Associates, Inc. as director of advanced manufacturing research. He is member of the National Academy of Engineering and has been a recipient of a variety of honors and honorary degrees in various countries. Merchant's research has created important advances in the science of manufacturing, including the concepts of the systems approach to manufacturing and the computer-integrated manufacturing system.

JOSEPH E. ROWE is associate vice president for research and director of the Research Institute at the University of Dayton. He received his B.S.E.E., B.S.E., M.S.E.E., and Ph.D. degrees from the University of Michigan and also completed the Advanced Management Program at Harvard University. Before moving to the University of Dayton, Rowe was vice president and chief scientist at PPG Industries, Inc. in Pittsburgh. He acquired experience in teaching, research, and academic administration at the University of Michigan and Case Western Reserve University. His industrial career includes technology development and management in electronics, computers, glass, coatings, and chemical industries. Rowe has also been employed as a consultant by numerous companies, including ITT, Raytheon, MIT Lincoln Laboratory, Hughes Aircraft, Texas Instruments, and Westinghouse. As a consultant, his tasks included research and product development in the areas of microwave devices, gaseous plasmas, solid-state devices, integrated circuits, microwave communications, and computer applications. Rowe is a member of the National Academy of Engineering.

ERNEST T. SMERDON is dean of engineering and mines at the University of Arizona. He holds B.S., M.S., and Ph.D. degrees from the University of Missouri and completed a year of graduate study in meteorology at the University of Washington. A registered professional engineer, Smerdon was the first director of the Water Resources Institute at Texas A&M University from 1964 to 1968. He then moved to the University of Florida, where he was chairman of the Agricultural Engineering Department and then assistant dean for research in the Institute of Food and Agricultural Sciences. From 1976 until 1982 he served as vice chancellor for academic affairs for the University of Texas System. Smerdon is an active or former member of a number of scientific and affiliated honor societies. He has served as an officer in some of the nation's prominent scientific and education organizations and currently serves on the executive board of the Council of Deans of the American Society of Engineering Education. He is a member of the National Academy of Engineering.

ALBERTUS D. WELLIVER is corporate senior vice president of the Boeing Company. Welliver joined Boeing in 1962 and has held several management and executive positions. He was actively involved in developing new technology in commercial aircraft propulsion systems and engineering technology research and program development activities. His current responsibilities include all engineering and technology development for the Boeing Company. He holds a degree in mechanical engineering from Pennsylvania State University and participated in the Stanford Executive Business Program. Welliver is a member of the National Academy of Engineering.

STUDY DIRECTOR

PROCTOR P. REID is a senior program officer with the National Academy of Engineering (NAE) in Washington, D.C., where he directs a multiyear program of policy research on technology and economics entitled "Prospering in a Global Economy." During a postdoctoral fellowship with the NAE from 1988 to 1990, he served as study director for the NAE Committee on Engineering as an International Enterprise, whose report, *National Interests in an Age of Global Technology*, was published in 1991. In addition to his work with the Academy, Reid is a professorial lecturer in European studies at the Johns Hopkins University, Paul Nitze School of Advanced International Studies, where he received his Ph.D. in international relations in 1989. Before joining the NAE, he was an instructor in political economy at Oberlin College (1986–1987) and worked as a consultant to the National Research Council (1988) and the Organization for Economic Cooperation and Development.

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