Science, Technology, and the Federal Government: National Goals for a New Era

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SCIENCE, TECHNOLOGY, AND THE FEDERAL GOVERNMENT

National Goals for a Near Era

Committee on Science, Engineering, and Public Policy
National Academy of Sciences
National Academy of Engineering
Institute of Medicine

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PREFACE

For the past half-century, federal science and technology policies have been strongly influenced by two important forces: the promise of fundamental scientific research, which was described in the 1945 report *Science, the Endless Frontier,* and the demands of the Cold War. These influences contributed to the establishment of the preeminent U.S. research and development enterprise and to an unprecedented cascade of scientific and technological accomplishments.

During recent decades, a series of political and technological revolutions have significantly changed the context in which science and technology policy is made in the United States:

- The products of science and technology have become prominent elements of the world economy and of everyday life.
- The Cold War has been superseded by the collapse of the Soviet Union and the emergence of many newly independent nations.
- Our abilities to process and communicate information have transformed the creation and sharing of new knowledge.
- Our ability to diagnose and to treat disease has been greatly advanced.

As we approach the new millennium, these broad changes have recast the framework in which the U.S. research and development system functions. As representatives of the scientific and engineering communities, the members of this committee have attempted to understand that new framework and to describe ways in which science and technology can respond to it. We have tried to evaluate the role of the federal government in supporting research and development and to suggest better ways of translating that support into a higher quality of life.

The result is this report, which proposes a renewed and strengthened covenant between science, technology, and society. The report recognizes that public support of science and technology is justified by the eventual benefits to humanity. It also recognizes society's concern that scientific and technological progress should demonstrably lead to improvements in the quality of life. It reaffirms the generative role of scientific research within the research and development system, describing the connections between scientific research and several broad national objectives. It also points toward the key role of technology in transforming scientific discoveries into wealth-generating commercial products and services. It proposes specific national goals for science and technology, designed to ensure leadership in areas essential to the national well-being.

Our nation's economic performance and security depend on several key factors, including the ability to make better use of our world leadership in science and the innovative capacity of engineering. A renewed partnership between science, technology, and the federal government could quicken the movement of ideas from the laboratory and foster the use of new technologies throughout the economy. The government, with its overarching responsibilities for planning, budgeting, and review, is uniquely suited to promote—though not manage—this process. The benefits of such an approach would extend across the spectrum of short- and long-term national objectives.

By working together to strengthen federal policy, the government and the scientific and engineering communities can ensure that the goals of the research establishment are aligned with the continuing forces of change within our borders and around the world. These actions will not only perpetuate our national leadership in research but will help translate that leadership into the tools, goods, services, and prosperity that we as a nation require.

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CHAPTER 1

THE CHANGING CONTEXT FOR SCIENCE AND TECHNOLOGY

In recent years, the contexts in which science and technology are performed in the United States have undergone fundamental changes—changes that will continue into the future. Each aspect of the research and development (R&D) system—from the source of its funding to the ways in which it contributes to broad societal objectives—is now receiving critical attention. Americans continue to support the R&D enterprise as a whole, but they require both greater accountability and a rationale for research that reflects today's new circumstances.

America's strong public support for scientific and technological research is a somewhat recent phenomenon. Before World War II, the United States built its strength largely on new techniques of mass production, its large and rapidly expanding domestic market, the availability of inexpensive raw materials, and lively entrepreneurial traditions. Much of our basic science was imported from Europe, and many technologies were borrowed from abroad or based on research done elsewhere.

World War II dramatically altered the relationship between science, engineering, and the government. The atomic bomb, radar, nylon, penicillin, electronic computers, and a host of other products demonstrated the power of fundamental research when combined with engineering skills. Americans emerged from the war with a wholly new appreciation of the research enterprise and of the products it could generate.

This new appreciation was focused and elaborated in Vannevar Bush's 1945 report *Science, the Endless Frontier*.[1] Bush, who was head of the federal Office of Scientific Research and Development during the war, argued that new knowledge generated by basic scientific research was essential to the national defense, the war against diseases, and the creation of new products, new industries, and new jobs. Traditional patronage of basic science—primarily from philantropies and other private sources—was no longer sufficient; only the federal government had the resources and the broad public mandate to take full advantage of the promise offered by science.

During the decades after the war, the vision of Vannevar Bush was prominently realized.[2] Basic research was championed by both the federal government and private industry. It was nourished in industrial laboratories and in America's rapidly expanding network of colleges and universities.[3] (The appendix describes the federal government's current role in supporting research and development.) The quick expansion of research and of scientific and technical personnel brought dramatic results, from a vaccine against polio to versatile new plastics, from transistor-powered electronic devices to the human exploration of space.

A CHANGING WORLD

Today's relationship between the research community and the public is more complex. It is the product of many changes— in science, in engineering, in modern society, and in the relations among nations. These changes have weakened some of the premises underlying the federal support of science and technology while reinforcing others.

Economically, the most important new reality is the intensification of international competition. In the past two decades, as transportation and communication costs have declined, trade barriers have fallen, and industries around the world have developed, the volume of world trade has risen sharply. New automobiles, agricultural products, and consumer electronics arrive daily from foreign lands. The development of foreign economies has been an important element of postwar U.S. foreign policy. But the development of these economies has diluted an important element of America's trade advantage: dominant access to its own large domestic market.

At the same time, science and engineering capacities have strengthened swiftly in other countries. Much of the scientific knowledge and many of the technologies developed here since World War II have diffused to other countries through technology licensing, the growth of transnational corporations, publication in the open literature, and other routes of technology transfer. Other nations have invested heavily in the research, advanced training, institutions, and infrastructure needed to use existing technologies and to generate new skills and technologies. Foreign companies have become adept at absorbing technologies developed elsewhere and at bringing their own improvements to those technologies. In many of these countries, technology transfer has been enhanced through governmental measures, such as support and coordination of research and development and protection of domestic markets.

In addition, global political changes have given the United States the opportunity to redefine its military objectives and other important governmental policies, including those that involve science and technology. The collapse of the Soviet Union has decreased the importance of military power relative to economic power as the source of world leadership. International flows of people, capital, and ideas have all increased, creating new wealth in some nations and severe problems in others. Economic crises have destabilized the political structure of many countries. America's leadership in this chaotic environment will be critically important for international stability, and America's own economic strength is the key to maintaining that leadership.

NEW QUESTIONS FOR SCIENCE AND TECHNOLOGY

Powerful trends in the United States have shaped public attitudes toward science and technology. The need to provide better health care at affordable cost has challenged both the technical and political communities. Citizens question the effectiveness of our education systems. Broad concern for the environment has generated a demand for new methods of manufacturing, energy generation, and waste disposal.

The intertwined economic, political, and social changes of recent years have had direct consequences for the public's support of science and technology. In the past, this support has rested largely on the assumption that science and technology would contribute to national objectives by helping to ensure security and by generating new products, services, and economic growth. Today, this assumption is being questioned. Primacy in science has not prevented the loss of international market share. Continued biomedical advances have failed to produce uniformly affordable health care. Environmental threats persist despite our greater ecological knowledge and analytical skills. Although science and technology are but two facets of these complex problems, the persistence of these problems has moved the relationship between science, technology, and society onto new and uncertain ground.

The research and development conducted by industry also has come under pressure.[4] Because of corporate restructuring and the slowdown in productivity and economic growth, some companies have reduced their commitment to fundamental research to concentrate on short-term objectives. Private U.S. funding for research and development has barely kept up with inflation in recent years, while R&D funding has surged in other countries.

Science and technology themselves have been changing. The extension of knowledge in some areas now depends on large and costly projects, and even comparatively small projects require costly instrumentation and other expensive inputs.[5] Federal investment in scientific and technological megaprojects has generated tensions between the proponents of these projects and the great majority of scientists engaged in work requiring less-intensive capital investments. As other demands on the federal budget increase, the funding of one expensive activity can lead to cutbacks for many smaller activities, even though these smaller activities generate the bulk of new scientific knowledge.

Other changes have brought new stresses to particular areas of science and engineering.[6] Some fields have more scientists than can be adequately supported even though the total federal R&D budget has been growing. A belief among some scientists that all excellent science should be supported has led to increasing demands on the federal budget. An increased competition for limited funds may have persuaded many researchers to be more cautious in their work and thought. Some scientists and engineers engaged in research say that their profession is no longer as fulfilling as it once was—a message that seems to be reaching young Americans who express less interest in pursuing careers in science and engineering.

Finally, the ongoing changes in science, technology, and society have affected the relationship between scientists and the general public, including the public's representatives in Congress.[7] Some members of the public are dissatisfied with the quality and cost of education in many research universities, saying that academic scientists spend too much time in the laboratory and not enough in the classroom. Other citizens blame scientists and engineers when technological change brings social disruption or personal distress, such as the loss of jobs; these negative effects of new technologies can contribute to public skepticism about claims of future progress. Changes in society have created problems that cannot be resolved through new scientific and engineering knowledge alone, yet public expectations for technical solutions persist.

THE FUTURE

The changes that are affecting the relationship between science, engineering, and society, though in many cases disconcerting, are laying the foundation for that relationship in the twenty-first century. It is not possible to predict in detail how science, technology, and society will evolve. But, by extrapolating from powerful present-day trends, we can anticipate an even greater interdependence between science, engineering, and society. We can also imagine some of the challenges that will accompany this interdependence:

- Industrial productivity, fueled by advances in technology, will continue to increase, bringing many benefits to businesses, consumers, and economies. But higher productivity does not necessarily mean more jobs; it may mean fewer. For example, the high productivity of U.S. agriculture has changed this nation from a country populated largely by farmers to a country in which 3 percent of all Americans can grow enough food for everyone else in the country and for export as well. Changes in technology are understood to be a potent generator of new jobs but also bring about short-term job dislocations.[8] Where will people find employment in the future?
- Information technologies will continue to change the ways we work, learn, and interact with others. Many of these technologies are likely to reach the most remote places on our planet. Who will control these technologies and the information they convey, and to what ends?
- Science- and technology-based industries will continue to spread internationally. Governments will compete across the R&D spectrum as they seek to encourage the development of proprietary products and new knowledge. For example, the countries of the Pacific Rim, which once depended heavily on technology transfer from other countries, are already rapidly building up their basic research capabilities while they continue their focus on technological development. How will countries unable to develop modern industries or research capabilities compete?
- All levels of education will undergo revolutionary changes as information technologies come to permeate instruction. Children in this country and in other countries who are unable to

take advantage of new technologies risk being left behind. What will be the long-term effects of a shift away from traditional teaching?

These are difficult questions that cannot be completely answered today. But they make it clear that, as science-driven technologies continue to grow in importance, they will transform the ways people communicate, do business, and conduct their lives. The pace of discovery in science is accelerating, as is the pace of technological advance and the adoption of new technologies. Some of the changes that these new technologies cause in human life will be disruptive, but these technologies also offer the potential for great improvements in the quality of our lives.

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CHAPTER 2

SCIENCE AND TECHNOLOGY IN MODERN SOCIETY

About 200 years ago the pace of technological change in western society began to quicken. Wind, water, and animal power, with their limitations of place and capacity, were supplemented and then replaced by the steam engine, which went on to power the factories of the industrial revolution. The railroad made it possible to move things and people quickly over great distances. The telegraph and, later, the telephone carried communications across the countryside. Electric lighting supplanted the dim glow of candles, kerosene, and gas lights.

By the beginning of the twentieth century, the notion of progress was closely linked with technological development, and that linkage intensified in the following decades. The automobile and the airplane changed not only travel but the nature of our cities and towns. Radio and then television brought more of the outside world into everyone's homes. Knowledge about the causes of diseases brought new treatments and preventive measures. Computers appeared, and soon the transistor made them smaller, more powerful, more accessible, and cheaper.

Today, the system by which research and development leads to new products is fundamentally different than it was in the nineteenth century. To the role of the individual inventor has been added the power of organized scientific research and technological innovation. Organized research and development, which are increasingly international in character, have greatly increased the production of new knowledge. Deeper understanding of living organisms is leading toward cures of diseases once thought untreatable. Basic insights in materials science enable the development of structures that are lighter, stronger, and more durable than anything available before. The computer and novel modes of communication, such as optical fibers, bring new, interactive modes of work and more capable machinery. These new devices and new ways of working, in turn, speed the growth and dissemination of new knowledge.

The accumulation of scientific knowledge and new technologies has transformed human life. echnologies have helped provide many—though far from all—people with standards of warmth, cleanliness, nutrition, medical care, transportation, and entertainment far beyond those of even the wealthy two centuries ago.[1] They have also presented us with difficult questions about how to use science and technology most effectively to meet human needs.

The rapid rate of material progress can continue, but it is not inevitable. The extent to which the products of science and technology are useful depends on the needs of society. Each of the four areas discussed in this chapter—industrial performance, health care, national security, and environmental protection—uses these products in different ways. Progress is more likely if we understand these differences. Only then can we effectively translate scientific and technical understanding into the techniques, tools, and insights that improve the quality of our lives.

THE ROLE OF SCIENCE AND TECHNOLOGY IN INDUSTRY

Industries differ in the manner and extent to which they use the results of research. Some, such as the semiconductor industry, the biotechnology industry, and parts of the chemical industry, were created and shaped almost entirely by ideas that grew out of science. The technologies at the heart of these industries were initially characterized more by promise than by real products. Semiconductors were in this stage right after the invention of the transistor; more recently, biotechnology went through this stage after the development of recombinant DNA techniques. High-temperature superconductivity is a scientific discovery that shows promise of leading to new industries and is in this stage today.

As science-based industries continue to develop, they remain closely dependent on continuous inputs of new science, often produced by university researchers. These industries depend as well on the technological development of these ideas in order to grow and to widen their range of products. At an early stage, these industries tend to be small, to move at a fast technical and competitive pace, and to have enormous potential. Biotechnology is now in this stage.

In a more mature stage, a science-based industry may still be growing quickly, but it depends ess on the progress of academic scientists. The semiconductor industry, for example, moves at a fast technical pace and requires increasingly detailed knowledge of its materials and, as the individual transistors buried in its chips become ever smaller, even of new quantum phenomena. But its scientific needs are met almost entirely by the work of semiconductor scientists and engineers working in the plants and laboratories of the semiconductor companies. Indeed, industry scientists are often the only ones with the detailed knowledge needed to make incremental improvements in the technologies.

Another example of an industry at a mature stage is the aircraft industry, where thousands of scientists and engineers are required to deal with the enormous complexities of new plane design. Investments in manufacturing tools and plants are often measured in hundreds of millions of dollars. Only major companies can act on this scale, and only they have the technological knowledge and experience needed to design these complex products.

The most mature industries—for example, the automobile or construction industries—move at a slower technological pace and require fewer inputs from current science, whether generated by their own laboratories or by university research. Many of these were not based on science even at their birth. They do, however, require the highest levels of technological and production know-how.

For industries that rely on high technology but are technically self-contained (such as the semiconductor industry) and industries that do not depend heavily on current science (such as the automobile industry), the results of current fundamental research are generally not decisive. Japan, which has not been a leading research power, has exhibited great strength in such industries. In these areas, productivity gains and product leadership can be attained by a number of strategies largely separate from scientific research but highly dependent on engineering, such as developing new technology in corporate laboratories, improving the development cycle to hasten the marketing of improved products, better coordination of design and manufacture, maximizing the creative capabilities of employees, and responding quickly to changes in consumer preferences. Additional university research can help, but it will be of peripheral importance to such industries. Nor can research rescue a failing industry that has difficulties in other areas.

THE ROLE OF SCIENCE AND TECHNOLOGY IN MEETING OTHER NATIONAL OBJECTIVES

In addition to their influence on industrial performance, science and technology are directly involved in efforts to achieve a number of other important national goals. As in the case of industry, many other factors must also be in place for the goals to be achieved, but science and technology provide many of the crucial insights and techniques that enable progress. The following sections briefly describe some of the linkages between science and technology and several of these goals.

Health Care

Maintenance of health and prevention of illness are among the highest goals of our society. cience and technology have become critical factors in achieving those goals, and the health sciences—including the life sciences, health services research, and public health research—will remain vital elements in the promotion of the nation's well-being.

In health care, as in other areas, science and technology are embedded in much broader social and institutional structures. For example, a research discovery can lead to experimental products in a very short time. Yet those products may require very long lead times to bring to market because of the need to ensure their safety and efficacy.

The most visible public policy issue in health care today is cost.[2] Many of the medical products generated by research and development, such as vaccines, actually reduce total health care costs. Other new products derived from research and development, such as complex imaging devices and expensive surgical procedures, raise costs in the short term while enhancing overall care. Still other procedures reduce unit treatment costs, but these reductions make treatments more available and thus increase demand and total costs.

The development and pricing of health care products are unusual for a number of reasons. In a normal market economy, differences in the costs of technologies are reflected in the level of use. But our current system of health care reimbursement insulates patients from the true costs. In addition, the government directly regulates many aspects of medical technology to ensure safety and control costs, further distorting market signals. Finally, health care involves such basic human conditions as birth, disease, and ultimately death. Under such conditions, individual consumers often ignore economic considerations; yet the total cost of health care is a matter of enormous national concern.

The effects of technical progress on costs depend to a large extent on the social and institutional structures surrounding the health care system. As the nation undertakes a broad reassessment of its health care system, a central challenge is to create administra tive structures that promote the *development* of medical technology while improving care and containing costs.

National Security

Since World War II, the United States has sought military advantage through technological rather than numerical superiority. For example, technological superiority in the hands of a well-trained military contributed greatly to the success of the Persian Gulf War.

The United States will continue to rely on this strategy to retain military advantage, but the sources of new military technology are shifting.[3] In the past, the segment of industry that has supplied both hardware and software to the U.S. military has been largely separate from civilian industry. This segment of industry has had essentially one customer, and its requirements were focused on product performance more strongly than on cost.

In the 1950s and 1960s, the defense industry produced much technology of value to civilian industry. But today the technological sophistication of civilian industry in many cases surpasses that of the defense industry. As a result, the military has become more dependent on civilian technologies. This trend will make improvements in national security more dependent on overall national economic performance.

A major challenge facing the military today is to maintain technological superiority in the face of declining defense budgets. Meeting this challenge will require a reexamination of the broad scientific and technological base that contributes to military needs, including research and development in government laboratories, in industry, and in universities.

Environmental Protection

Over the past two decades, the United States has recognized and has made substantial progress in curbing the degradation of the environment. Nevertheless, difficult problems remain.

Environmental degradation continues to accompany many aspects of economic growth. Emissions and effluents of contaminated materials continue, waste disposal plagues urban areas, forests continue to be devastated, and biodiversity losses are growing. At the same time, science and technology have exposed new issues of great complexity and uncertain consequences, such as global warming, acid precipitation, the destruction of the stratospheric ozone layer, and the contamination of water supplies.

By the middle of the twenty-first century, the human population is projected to double to around 11 billion people, and, to meet their basic needs, the global economy will need to be several times larger than it is now.[4] Many industrial and agricultural practices and products used today in energy and food production, transportation, and manufacturing will need to be restructured to prevent pollution if sustainable economic growth is to be achieved. In some situations, existing technologies can be made cleaner and more efficient; in others, entirely new technologies, including energy technologies, will be needed.

Almost all fields of science and technology can contribute to the reduction of environmental degradation. Biotechnology, materials science and engineering, and information technologies can enable the efficient use of raw materials and prevent pollution at the source. Reducing and preventing pollution is an important goal of the new field of industrial ecology, which, by examining industrial processes, strives to maintain sustainable technological growth.[5]

COMMON THEMES

These examples demonstrate that science and technology are powerful determinants of the conditions of modern life but that they clearly are not the only determinants. Nevertheless, even if science and technology are not sufficient by themselves to resolve societal issues, they are necessary for progress. Industry, for example, now relies heavily on technology to raise productivity;

economic studies show that more than half the per capita productivity increases in the United States since World War II have come from technological advances. Although such factors as better skills among workers and new methods of organizing production will continue to contribute to economic expansion, new technologies will continue to be the major force behind the generation of new wealth.

Similarly, many new technologies are increasingly reliant on science—whether the new science emerging from research laboratories or the well-established science available to everyone with the necessary training. Engineering, increasingly science-based, could not have achieved its present level of sophistication without its base of scientific knowledge. This increasing integration of science and technology also applies in reverse: technological problems now inspire important areas of science, even as science broadens the scope and capabilities of technology.

Given the fact that science and technology are necessary, but not sufficient, elements of human progress, we as a nation face important questions: How great an investment in science and technology should we make to meet national needs? How can we best measure national performance in science and technology? The committee turns to these questions next.

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CHAPTER 3

NATIONAL GOALS FOR SCIENCE

Science and technology are closely linked to important national objectives in such areas as economic growth, health care, national security, and environmental protection. These linkages implicitly raise the question of what goals the nation should have for science and technology and how those goals should be reflected in levels of investment, organizational arrangements, and subjects for research and development. In this chapter, we examine these issues for science; in the next chapter, we do so for technology.

In setting national goals for science, several observations must be kept in mind. The first is that it has proved impossible to predict reliably which areas of science will ultimately contribute to important new technologies. History is rich in examples of scientific research that have led to practical applications in areas far removed from the original work. Fundamental research on electromagnetism contributed directly to the development of modern communications. Investigations in solid-state physics enabled the invention of the transistor. The recombinant DNA technology that led to the biotechnology industry arose from studies of unusual enzymes in bacteria. Mathematics, often regarded as highly abstract, is at the core of applications as diverse as aircraft design, computing, and predictions of climate change.

The second observation involves the importance of research for which applications are not yet known. For investigators who do such fundamental research, primarily in universities, the original motivation is seldom to develop new applications; rather, it is the desire to discover and to understand natural processes.

Nevertheless, this motivation—enlarging the store of human knowledge—in the end brings advances and applications that cannot be made any other way. A substantial redirection of such fundamental research toward goal-directed work would reduce the potential for advances of economic and social importance without necessarily leading to solutions for the problems being addressed.[1]

A third observation concerns the cultural significance of science. The application of modern scientific research, beginning in the seventeenth century, is one of the most profound events in human history. Modern research has done more than change the material circumstances of our lives. It has changed our ideas about ourselves and our place in the universe, about human history and the human future.

A final observation has to do with leadership. The great modern expansion of scientific knowledge has led to changes that have been of enormous benefit to humanity. Adjusting to these changes has in some cases proved disruptive to society. Nonetheless, leadership in science has become one of the defining characteristics of great nations. The United States has risen to a position of global prominence in part through its strengths in science and technology. Those strengths can continue to contribute greatly to U.S. leadership.[2]

In light of the above observations, we believe that the federal government, in partnership with the private sector and with other levels of government, should adopt explicit national goals for science. Our first recommendation is:

The United States should be among the world leaders in all major areas of science.

"Major areas" refers to broad disciplines of science (such as biology, physics, mathematics, chemistry, earth science, and astronomy) and to their major subdisciplines (such as the neurosciences, condensed-matter physics, and seismology). "Among the world leaders" means that the United States should have capabili ties and infrastructures of support that are not exceeded elsewhere. Of course, there will be specific areas or skills in which other nations lead the world. But in considering the major subdisciplines in which such areas belong, the United States should meet world standards.

There are several rationales for this goal:

- *Excellence.* When U.S. researchers are working at world levels in all disciplines, they can bring the best available knowledge to bear on problems related to national objectives, even if that knowledge appears unexpectedly in a field not traditionally linked to that objective. For example, by being among the world leaders in the areas of virology, immunology, and molecular biology, U.S. researchers were able quickly to devise a test for AIDS antibodies that helped ensure the safety of the blood supply.
- *Receptiveness.* By being among the world leaders in all disciplines, U.S. researchers can quickly recognize, extend, and utilize significant research results that occur elsewhere. For example, high-temperature superconductivity was discovered in Switzerland, but U.S. researchers were able to repeat and extend these findings within a matter of days.
- *Education.* Only by working in the presence of world leaders can students in American colleges and universities prepare to become leaders themselves and to extend and apply the frontiers of knowledge.
- *Personnel.* Maintaining excellence in a field is the best way to attract the brightest young students to that field and thus ensure its continuing excellence.

In general, being among the leaders in each area of science means that U.S. scientists understand and participate in expanding the frontier of human knowledge. The United States could not have been the early home of the semiconductor industry without having been among the world leaders in solid-state physics. It could not have been the home of the emerging biotechnology industry without having been a world leader in molecular biology.

In addition to being among the world leaders in all areas of science, the United States will wish to excel in certain areas on a national level. Therefore, the committee's second recommendation is:

The United States should maintain clear leadership in some major areas of science.

The rationales for maintaining a clear lead in selected areas of science go beyond those listed above. Among the criteria that would call for clear leadership in a field are the following:

- The field is demonstrably and tightly coupled to national objectives that can be met only if U.S. research performers are clear leaders. For example, the field of condensed-matter physics drives technological advances in such industrial sectors as microelectronics, advanced materials, and sensors.
- The field so captures the imagination that it is of broad interest to society. An example in astronomy is the recent detection of differences in the cosmic background radiation related to the creation of the universe.
- The field affects other areas of science disproportionately and therefore has a multiplicative effect on other scientific advances, especially those where clear leadership is the objective. For example, molecular biology is critical to advances in health care, biotechnology, agriculture, and industrial processes.

The selection of those fields in which the United States wishes to maintain clear leadership ill be made by government decisionmakers with appropriate advice from various interested groups. These decisions must be fully informed by the comparative assessments of different scientific fields, discussed below, and by the extent to which different fields meet the criteria for clear leadership. These decisions thus differ in character from decisions about the most promising directions for research *within* an area of science, which are made most effectively by researchers themselves and should be insulated from the political process.

IMPLICATIONS OF THE PERFORMANCE GOALS

The federal government needs a better way to gauge the overall health of research—as a whole and in its parts—and to determine whether it is adequately supporting broad national objectives. Such indicators as dollars spent or numbers of scientists supported are, by themselves, inadequate. Nor can such indicators determine the adequacy of overall funding or the appropriate distribution of funds among different fields.

The committee believes that comparative international assessments of scientific accomplishment are a better yardstick for policy decisions. This concept, like others in this report, has been discussed in theory and applied in specific cases,* but the committee believes that it now deserves a central place in national considerations of science policy. To this end, we have developed it in much greater detail.

The committee believes that it is feasible to monitor U.S. performance with field-by-field peer assessments. Researchers in many fields have, in recent years, identified research opportunities and even set funding priorities. The processes that they have used could be adapted for more general application.

The committee recommends the establishment of independent panels consisting of researchers who work in a field, individuals who work in closely related fields, and research "users" who follow the field closely. Some of these individuals should be outstanding foreign scientists in the field being examined.

The panels would assess the performance of U.S. research

* See Ralph Gomory, "Goals and Priorities for the U.S. Government's Role in Science and Technology," testimony before the Subcommittee on Science of the House Committee on Science, Space, and Technology, April 28, 1992; and William J. Clinton and Albert Gore, Jr.,*Technology for America's Economic Growth, A New Direction to Build Economic Strength.* Washington, D.C.: Executive Office of the President, 1993.

scientists in a given field and compare it with performance of researchers in other nations. To do this, the panels might, for example, judge where the most exciting and promising ideas are emerging, consider where the best new talent is locating, and examine the comparative capabilities of research facilities or equipment. The panels could identify key factors enhancing—or blocking—performance within different fields and project trends into the future. They would assess both the internal performance of the field and its relationship to other fields of science. Finally, the panels could recommend actions for both the performers and the supporters of research (see box).

Quantitative measurements, such as movements of individuals, literature citation counts, and quantity and quality of instrumentation, would be important tools for the panels. But the most valuable contribution by the panels would be the qualitative judgments of panel members working in each field. Scientists immersed in a particular field are best qualified to appraise the true quality of the work being done, to identify the most promising and exciting advances, and to project the status of the field into the future. The participation of representatives from other fields of science and from the users of research would help to allay concerns that the panels' recommendations are self-serving.

We believe that assessments of fields will prove useful in the allocation of resources both within and among fields. Within fields, the assessments will help identify the key factors affecting the comparative performance of its researchers. The assessments will be much more useful than current budgetary criteria for analyzing issues such as the adequacy of the infrastructure and the optimal number of students entering the field. By providing long-term perspectives, the assessments will increase the predictability and stability that are essential to a focused and sustained effort in science.

Assessments of resolve debates over the support of megaprojects. research performance would also help The costs of a megaproject would be assessed in terms of the performance goals. If the area of the megaproject was one in which the United States chose only to be among the leaders, participation would almost certainly depend on international collaboration and cost sharing. For an area where clear leadership is justified, the United States might choose to pursue a megaproject even without international partners. One could envision this process being applied, for instance, to the Human Genome Project, the Superconducting Supercollider, NASA's Mission to Planet Earth, fusion reactors, synchrotron radiation light sources, and so on.

RESULTS OF THE PANELS' DELIBERATIONS

The independent panels of researchers and research users, drawing on their assessments of the comparative performance of U.S. researchers, could make several kinds of reports to the broader research community and to the federal government. Here are three hypothetical outcomes:

1. In one area of science, an assessment panel might find that the U.S. research effort is not at world levels of performance. The panel would diagnose the reasons for the deficiency—perhaps inferior facilities or a shortage of qualified young researchers. It could then translate its findings into proposals for the funders, performers, and users of research that would help bring U.S. performance up to world standards.
2. In another field, an assessment panel might find that U.S. performance is at world levels and does not seem to be in danger of falling behind. In this case, the group could recommend actions that would keep the United States among the world leaders.
3. In yet another area, an assessment panel might conclude that the United States leads the rest of the world. If that area is not one in which the United States should maintain clear leadership, the panel might recommend reductions in funding, which could then be applied to areas requiring additional support.

The goals that we recommend also have implications for the research infrastructure. Meeting the goals requires that appropriate elements of the U.S. research infrastructure remain second to none. Educational institutions are essential to this infrastructure;

only by providing the finest instruction in mathematics and science can the United States produce world class young scientists and engineers.

The committee believes that these goals can be met within the existing overall federal R&D budget. First, because of its traditionally strong support for science, the United States is already a leader in most areas of science. Second, through the application of the goals outlined above, the federal government is likely to find that the United States has clear leadership in some areas of science in which we need only to be among the leaders; funds can be redistributed accordingly. Third, relatively minor reallocations of the federal government's R&D budget, which now exceeds $70 billion per year, could have a major effect on the research portion of the budget.

A NEW FRAMEWORK FOR FUNDING

The performance goals stated above would provide the basis for a new approach to designing and enacting federal research budgets.[3] Today, the federal R&D budget emerges from a process that is only loosely coordinated. Each federal agency supports research in pursuit of its individual mission, and research is often a relatively small part of that mission.

Guided by the performance goals of being among the world leaders in all areas of science and maintaining a clear lead in some, the Executive Branch and Congress could take a more coherent approach to setting R&D budgets. In the Executive Branch, the assessments of scientific fields could guide initiatives designed to achieve specific scientific or technological goals. In the past few years, initial steps in this direction have been taken by the Federal Coordinating Council for Science, Engineering, and Technology under the Office of Science and Technology Policy. If a major field of science were found to be behind world standards, the Executive Branch could boost funding across all the agencies that support research in the field.

When the budget reaches Capitol Hill, the House and the Senate would conduct comprehensive reviews of the proposals for science and technology before disaggregating the budget for agency-by-agency examination. Limited versions of such reviews now take place in both houses, but they need to be structured so that their results have more impact on the decisions of individual appropriations subcommittees.

PRINCIPLES TO BE FOLLOWED IN ACHIEVING THE GOAL OF NATIONAL LEADERSHIP

Scientific research, like any large social endeavor, is influenced by a set of principles that distill the experience of the past into guidelines for today. These principles take on new significance in light of the goals discussed above.

The Need for Quality

Research that is not creative and innovative has very little impact on society. The funders, erformers, and users of research therefore need to adopt and enforce procedures that ensure the quality of research.

Since World War II, the process of ensuring quality in federally funded research has been shared by the federal government and the research community. The federal government has established broad priorities and criteria for the distribution of its funds. Individual projects have then been funded based on an assessment of their merit, commonly using advice from peer reviewers outside government. The government has solicited this advice on the belief that the public interest is best served by letting scientists decide, on the basis of their experience, which research is most qualified for support.

In recent years, this partnership has become strained on both sides. The scientific community has criticized the federal government for appropriating over a billion dollars a year for specific R&D projects and facilities that have undergone little or no formal assessment of quality. Representatives of the government have criticized the scientific community for defending certain programs with arguments that are subjective or self-serving.

To be among the world leaders in all major areas of science, our nation must ensure quality by more objective means. Merit review must be safeguarded from political distortions. If Congress cannot stop the earmarking of R&D funds, it should isolate these appropriations from the rest of federal science and technology and openly establish a different set of criteria. For its part, the scientific community must do a more equitable job of setting priorities within areas of science.

Adequacy and Stability of Funding

Scientists and engineers conducting research sponsored by the government have been under increasing financial pressure. As a result, they have been spending more time writing proposals and less time at work in their laboratories. Furthermore, when funding is tight, they tend to produce more conservative proposals. This discourages venturesome, long-term work—the kind of research that may lead to major advances.

A more cost-effective and productive funding strategy would be to provide stable, multiyear funding based on a system of evaluation and support that identifies the most qualified investigators and minimizes their administrative burdens. This would apply both to established investigators and to young researchers. Year-to-year funding levels would be more stable, bringing a degree of predictability to research that would make it more attractive to talented American students.

The financial support provided to a field and the manner in which it is allocated among training, salaries, equipment, facilities, and so on would be based on the assessment of the field's comparative performance and whether the goal for the field is to achieve world standards or clear leadership. On this basis, support for a field might be reduced, maintained, or increased.

Organization of Science

Traditionally, science has been organized into specific disciplines. However, science, by its nature, is in continual flux. New disciplines emerge at the edges or intersections of existing ones. Old disciplines are transformed by new knowledge and new techniques, while new disciplines draw knowledge and techniques from the old.

Furthermore, many of the problems that scientists are now trying to solve require contributions from more than one discipline. For this interdisciplinary research to succeed, scientists must be able to extend their knowledge to new areas and work effectively as members of teams.

The performers and funders of research must allow these dynamics of science to drive its organization. They must remove barriers to emerging areas of research and encourage permeable institutional structures that allow for the flow of interdisciplinary opportunities.

The Synergy Between Research and Education

Achievement of our national objectives in science and technology must be supported by continuous development of human resources. Research that includes an explicit educational component contributes to these objectives more powerfully than research done independently of education. But the quality of research should not —and need not—be subordinated to education. In evaluating the merits of research, its educational component should be an explicit criterion.

Much of the discussion about reaching and research has missed an essential point. The two skills are not necessarily congruent. Skill at research does not guarantee skill at teaching. But teaching is a skill that almost always can be greatly improved with effort. And excellence in research can enhance the value of what is taught. In this sense, participation in work that extends the frontiers of knowledge can magnify the effectiveness of a committed teacher. The committee returns to this subject briefly in Chapter 5.

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SUMMARY OF SCIENCE GOALS

For half a century, the federal government has strongly supported basic research in science and engineering. However, the government has never formulated an explicit policy for setting the level of that support. We have recommended two performance goals for science that would allow the appropriate level of support to be determined.

The first goal is that the United States should be among the world leaders in all major areas of science. Achieving this goal would allow this nation quickly to apply and extend advances in science wherever they occur.

The second goal is that the United States should maintain clear leadership in some major areas of science. The decision to select a field for leadership would be based on national objectives and other criteria external to the field of research.

The comparative performance of U.S. research in a major field would be assessed by independent panels of experts from within and outside the field.

The implementation of these goals for science requires more coherent federal budgetary procedures. We have suggested a framework for action based on mechanisms already in place. Allocations across fields would be guided by the two performance goals. Allocations within fields should be guided by scientists in those fields.

CHAPTER 4

THE FEDERAL ROLE IN THE DEVELOPMENT AND ADOPTION OF TECHNOLOGY

The United States has a predominantly private system for promoting and rewarding the development and adoption of new technology. The federal government's primary roles in this system have been to foster a stable economic and financial environment; to encourage investment in plant, equipment, human resources, and intellectual resources; and to regulate companies and markets when necessary to meet public objectives.

However, the federal government has a long history of involvement in some matters affecting industrial technology. Through its support of research and development at universities, government laboratories, and industries, it has helped generate much of the new knowledge and educated people critical to industries at the cutting edge of technology. This contribution is best seen in areas widely recognized as appropriate federal responsibilities, such as public health, national security, energy development, environmental protection, or interstate transportation. In selected cases, such as agriculture and aviation, the government has also helped fund research and development to meet specific commercial objectives with outstanding success.

In the past, this predominantly private system has worked well. Propelled by new technologies, industrial productivity has been higher in the United States than in any other country throughout the twentieth century. The government's support of technology for public missions has also led to pioneering achievements in military technology, space exploration, medical technologies, and other areas.

The United States still has the highest overall industrial productivity in the world. However, the rate of productivity growth is higher in some other nations, and the gap between U.S. performance and performance in other countries has been narrowing. Some of this erosion of advantage was inevitable. U.S. industry could not have remained as far ahead of industries in Europe and Asia as it was at the end of World War II. Nor would this have been desirable, given the larger markets created by expanding economies abroad.

As described earlier, the new knowledge resulting from scientific research and development has become a major contributor to industrial success. But new scientific discovery by itself is rarely enough to raise industrial performance. Scientific knowledge must be effectively extended and applied through engineering into successful technologies.

For commercial technologies, the federal government traditionally has chosen to support basic research and mission-driven research and to leave the development and application process largely to industry. In today's more competitive and technologically interdependent world, this approach may no longer be sufficient. Companies in other countries, sometimes favored by national industrial policies, are equaling and in some cases surpassing U.S. firms in specific areas of industrial technology, which has helped them capture market share and high-paying jobs.[1] The federal government increasingly requires strong U.S. industries to meet national objectives in such areas as defense, public health, and environmental protection.[2] And many corporate R&D programs are now focusing more on shorter-term objectives with financial returns that the research-performing company can capture rather than on longer-term objectives with less easily captured benefits but where returns to the nation may be substantial. For these reasons, the government should now take a more forceful approach to the development and adoption of technology than it has in the past.

That approach, however, must be channeled. Given the vast array of current and prospective technologies that may compete for attention and resources, and the diverse federal agencies and programs that need to be enlisted in the effort, a focused strategy is needed. The committee thus recommends a national goal for technology that in some respects parallels our goal for science.

> **The federal government should cooperate with the private sector to ensure that the United States maintains a position of technological leadership in those technologies that promise to have a major and continuing impact on broad areas of industrial and economic performance.**

The philosophy guiding this recommendation is that a large and diverse economy such as that of the United States should not allow technological backwardness to be the decisive factor in the loss or failure of important industries. We recognize that firms and industries rise and fall for many reasons aside from technology, depending on their own capacities and practices, and that these capacities and practices have not generally been the object of public policy in the United States. But the national interest in technological improvement may extend beyond that of any individual firm or industry.

Because new technologies so often form the basis of internationally significant new industries or help ensure the survival of existing ones, the federal government should help foster such technologies. Normally, the United States will already be a participant in the relevant industry, but there will be some occasions when it is not.

As with our national goal for science, the goal of being in a leadership position does not require that the United States be preeminent in each designated technology. But it does mean that the United States should be close enough to the frontiers in these areas that it can promptly take advantage of developments that occur in the United States or in other countries.

This national goal for technology can be effective only if it is applied selectively. We suggest three guidelines for identifying key technologies.

First, the nation should actively seek to preserve its traditional leadership in the development of technologies that *create major new markets.* Historically, these technologies have often had a base in recent advances in research. Major current industries— among them computers, semiconductors, and advanced materials— did not exist in earlier decades, but now they are of major economic importance, are expanding rapidly, and provide large numbers of skilled jobs. The United States—with its well-trained labor force and large domestic market for new products—has a natural competitive advantage in pioneering new industries, and this nation should maintain its traditional leadership in creating and driving new high-technology markets.

Second, the United States needs to emphasize technologies for which the relevant firms have a *demonstrated capacity to convert technology into a marketable product* ; one indicator of such capacity is that such firms are already competing in global markets. Our most successful industries have the familiarity with changing world markets and the technical know-how needed to convert development ideas into products and services, and these industries should not founder because of a lack of technology. U.S. policy should ensure that industrial and governmental leaders are alert to technological developments, wherever they take place, that can contribute to the continued success of major industries in world markets.

Third, there are occasions when *national strategic considerations,* rather than economic factors, lead the government to identify technologies where it is essential that the United States remain competitive with other nations. One example is the recent initiative, based in part on national security grounds, to improve manufacturing technologies for semiconductors.

The implementation of this national goal for technology, including the application and refinement of these guidelines, will require a process that combines the expertise and views of government policymakers, private-sector leaders in technology-intensive business, and relevant economic, technological, and other experts.

EXAMPLES OF TECHNOLOGIES WHERE LEADERSHIP IS IMPORTANT

1. An example of a technology that may have the capacity to transform a major sector of the global economy is advanced power battery technology. The U.S. Advanced Battery Consortium recently was established to unify private and governmental efforts to extend significantly the range and performance of electric vehicles. Costs are shared among the major U.S. auto makers, the private Electric Power Research Institute, battery companies, and the Department of Energy.
2. The tools and techniques that underlie the biotechnology industry are examples of technologies based extensively on federally supported research and development. Federal funding has traditionally focused on health-related areas, but the government has recently begun to expand its support for research in areas such as agriculture, bioprocessing, and environmental remediation.
3. Another example of an advanced technology that may stimulate entirely new markets is broadband communications, including fiber optic networks, especially as they relate to the local delivery of massive data bases. This is an area of traditional leadership by the private sector, and the appropriate amount of government involvement remains to be determined. An argument for government investment is that some potential applications—the delivery of data to schoolrooms, the exchange of large data sets among collaborating researchers—are nationally important applications that are not well reflected in the economic marketplace.

The fundamental difference between our national goals for technology and science is that the technology goal cannot be achieved primarily through federal policies. Technological leadership in the commercial marketplace is the responsibility of the private sector. Therefore, as the federal government seeks to promote technological leadership more actively, it has available only the economic policy levers that permit market forces to play a major role. In practice, this means that private sector initiative should normally determine which ideas to support. In particular, support for R&D projects should derive from competition among industry-generated proposals and should require cost-sharing from industry as a test of market value. Because the goals can be distorted by political influence, the government must strive to minimize such influences in federal actions.

We envision a role for the federal government in promoting—through technological advance—national economic performance where the government itself is not the customer. This role must be discharged in partnership with industry. Policy measures should embrace a diversity of experiments in how to carry out this role successfully, because at this stage the effects of various policy mechanisms are incompletely understood and only a fragile national consensus exists on the limits of government latitude in this area. The government must be prepared to discard programs that do not work and reallocate resources to those that do.

This chapter focuses largely on the performance of the general economy and not on the public missions (such as national defense and public health) that the federal government has traditionally pursued. With the end of the Cold War, and with the rapid technological advances in the private sector, public missions will depend more heavily on advances in the private sector. To the extent that we maintain a strong civil technology base, these broad public missions will also benefit. For example, to promote technologies needed for national defense, the federal government will need to devote special attention to the growing number of national technologies that both serve civilian markets and have military importance.

We do not attempt, in this document, to provide a detailed prescription for executing a federal technology policy. Rather, we seek to explore some of the tools that the federal government can use to achieve the stated technology goal. Nor can we, at this time, gauge the resources needed to implement this strategy. Two recent reports from the National Academy of Sciences complex analyze existing federal programs and provide recommendations for change: *The Government Role in Civilian Technology: Building a New Alliance*[3] by a panel organized under this committee, and *Mastering a New Role: Shaping Technology Policy for National Economic Performance*[4] by a committee of the National Academy of Engineering.

CREATING A FAVORABLE ENVIRONMENT FOR THE DEVELOPMENT AND ADOPTION OF TECHNOLOGY

Because the development and adoption of technology are largely private responsibilities, the most important task of the federal government remains that of creating an environment in which technology can flourish. Doing so is a complex challenge. Many federal policies influence the development and adoption of new technologies, including federal policies that affect investment, taxes, trade, antitrust restrictions, intellectual property rights, environmental protection, health regulations, and product liability. Government support for the infrastructure of our society—schools and universities, transportation and communication networks, health care and social services—also has an important indirect influence on technology.

Governmental policies in these areas have seldom been designed to meet technological goals. As a result, the effects of these policies on the development, adoption, and application of technology have been uneven and sometimes contradictory. Even those policies and programs more explicitly focused on technology are, by American tradition, decentralized and pluralistic. For example, the federal government does not have a unitary Department of Technology or a Department of Science. Individual agencies pursue their own missions, with more or less detailed oversight from the White House or the Congress. Coordination between state and federal programs for the general promotion of technology is likewise haphazard.

On the positive side, pluralistic policies at the federal and state levels allow industry to be flexible and adaptable in the face of change. But as technology has become more important to both public and private missions, a need for coordination has become plain. A similar need has arisen to integrate the planning and implementation of federal technology policy with both domestic and foreign economic policy.

Specific institutional reforms can bring greater coherence to policy considerations that affect technology both in the Executive Branch[5] and in Congress.[6] The recent creation, in the Executive Office of the President, of the National Economic Council and its close working relationship with the Office of Science and Technology Policy can be important steps in this direction.

FEDERAL SUPPORT FOR THE DEVELOPMENT AND ADOPTION OF TECHNOLOGY

Between the federal government's two traditional forms of support for research and development—basic research and mission-oriented research and development—there lies an important gap. This is the area where private industry is active but may fail to pursue some commercially promising technologies because the necessary research and development may be too costly, lengthy, or risky for an individual company. When these considerations hinder the development of a new technology, a role for the federal government can make good sense.

There is a strong argument for government involvement in important areas of technology that contribute to the technology goal enunciated above, but that are not aggressively pursued by private industry, even though the economic return to the nation as a whole may be great.

History offers many examples where federal investments in technology have paid off handsomely. The federal government's support, for national security reasons, of aeronautics, semiconductors, computers, and satellite communications helped produce thriving U.S. industries. On the other hand, the federal government has supported large projects that failed. It has spent billions of dollars on such technologies as the breeder reactor and synthetic fuel production that have fallen far short of their original ambitious aims.[7] Some failures, of course, are inevitable. Policymakers must both expect and learn from them.

When the federal government chooses to foster the development and adoption of technology, it can do so by a number of routes. It can further ease antitrust restrictions to allow companies to cooperate on precompetitive research. When appropriate, it can also catalyze these consortia through partial funding. The government can direct agencies that support mission-driven research and development to seek broader applications for the technologies developed. It can also use its procurement policies to boost fledgling technologies or clear new paths for technology development.

The government can also directly support commercially important research and technology development in universities or in industry. Federal programs that provide a base for these efforts include the Advanced Technology Program at the Department of Commerce, the Advanced Research Projects Agency in the Department of Defense, and the Science and Technology Centers and Engineering Research Centers supported by the National Science Foundation. An additional approach that has been suggested by this committee's Panel on the Government Role in Civilian Technology is the formation of a Civilian Technology Corporation designed to stimulate investment in civilian technologies with high social rates of return (see note 3).

The network of hundreds of federal laboratories that conduct both basic and mission-driven research represents an additional resource. The federal government invests over twice as much money in these laboratories as it does in university research, and the largest laboratories are among the nation's largest employers of scientists and engineers. More than half of these government laboratories conduct defense-oriented research. With the end of the Cold War, many of them are looking for new missions. Some are likely to shrink substantially, and others are likely to close. But some defense-oriented laboratories, as well as some laboratories with other missions, may have the potential to contribute to the nation's civilian technology base. Such new missions will need to be discharged in close collaboration with the relevant private-sector entities. In view of the difficulty of meshing the cultures of the laboratories and business organizations, performance must be closely evaluated to ensure that the funds could not be spent more productively in other ways.

PRINCIPLES TO OBSERVE IN THE FEDERAL SUPPORT OF TECHNOLOGY

Whatever routes the government chooses in its support of commercially promising research and development, it can increase the probability of success by following certain principles.

Responsiveness to Market Signals

First, federal efforts to support commercial technologies should be inspired by marketplace demands as interpreted by industry rather than by political or special-interest pressures. There are several promising approaches.

The first is to let industry take the lead in initiating and designing collaborative efforts. Industrial leadership will help ensure that programs are driven by market forces and will keep the government from inappropriately specifying which technologies or companies should be supported.

The second is to insist that industry share costs to a meaningful degree. Jointly funded research and development help to link projects closely to market signals and to industrial efforts. When a company or industrial sector is willing to put up its own funds, its commitment to an undertaking is likely to be greater. This is the case, for example, with cooperative R&D agreements between federal laboratories and industry, and with the new technology programs being advanced by the current administration.

The third is to apply frequent and rigorous evaluation, both technical and economic, to a project's promise and performance. These evaluations should be made by independent experts in relevant scientific, technological, and economic areas.

Complete insulation from politics is rarely, if ever, achievable. Wherever possible, however, institutional guidelines should be designed to minimize the intrusion of purely political influences into federal decisions involving technology.

The Importance of Stable Support and Long Time Horizons

In its support of scientific research, the government recognizes that social benefits may be widely separated in time from the work that makes them possible. But in the case of promoting new technologies, political pressures often demand unrealistically quick returns from federal investments. Of course, mechanisms need to be in place to terminate programs that have proven unsuccessful. But federal efforts to promote technology will be hindered unless the government can adopt a long-term perspective.

The evaluation process is the key to balancing patience with accountability. Technology development programs must have goals against which progress can be measured. Cutoff dates for federal funding may be appropriate mechanisms for limiting federal involvement. The lessons of early programs must be carefully studied to improve the design of subsequent efforts.

A Focus on Technology Adoption as Well as Technology Development

Federal assistance in developing world-class technologies is rarely sufficient to achieve national goals. The federal government must also work with the private sector to reduce the costs, create the skills, and increase the incentives needed to adopt effective technologies.

With a few important exceptions—most notably agriculture— the federal government has devoted much less attention to the adoption of technology than to its development. In recent years it has taken tentative steps in this direction through such programs as the Manufacturing Technology Centers of the National Institute of Standards and Technology and the State Technology Extension Program. But these programs reach only a small fraction of potential clients, particularly among small and medium-sized businesses. These programs should be substantially expanded, at least on an experimental basis.

The adoption of new technology is a costly and often knowledge-intensive process. Its success depends on such factors as the skills of workers, the availability of investment capital, and the foresight of management. But technology adoption is crucial to the strength of an economy because it is the means by which technologies diffuse from high-technology industries to firms in more mature and less R&D-intensive industries, including many of those in the service sector.

Recognizing the Growing Role of the States

State governments have invested in and experimented with a number of mechanisms to foster links between publicly funded research and particular industries. These efforts have led to a variety of state programs designed to boost economic competitiveness through science and technology.

Today, these programs are poorly coordinated with federal efforts. This leads to confusion over roles and to less-than-optimal investments. The federal government and the states should establish a mechanism through which information can be exchanged to leverage federal resources through state and local activities.[8]

OTHER INFLUENCES ON INDUSTRIAL PERFORMANCE

The importance of technology adoption reflects an important aspect of the overall role of technology in the U.S. economy. Cutting-edge technology is not enough to guarantee industrial success, just as frontier research is not sufficient to achieve national goals. Rather, the development of forefront technology must be combined with other factors to influence the performance of private industry. These factors include the availability and cost of investment capital, opportunities for profit, the skills of the work force, the regulatory environment in which companies operate, trade policies, and the physical infrastructure supporting the economy. Government has varying degrees of influence over these factors, but government policies in these areas are rarely determined by considerations of technology. Furthermore, in a given case, any of these factors can be more important than technology in determining the competitive status of a company or an industry.

The relationship of technology to industry is thus similar to that of science to technology: it is an increasingly necessary but not sufficient component of success.

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SUMMARY OF TECHNOLOGY GOAL

Although the federal government has had a policy of supporting research in basic science and engineering, it has regarded the development and adoption of technology as largely a responsibility of the private sector, except in such areas as defense, public health, and agriculture.

Present conditions warrant a reexamination of the federal government's policies toward technology development and adoption. We have recommended that the federal government adopt the goal of maintaining a leadership position in those technologies that promise to have a major and continuing impact on broad areas of industrial and economic performance.

These technologies should be in areas that could lead to major new industries, should be in areas where U.S. firms have demonstrated their ability to convert technology into marketable products, or should be based on national strategic considerations.

Achieving this goal requires a new partnership between the federal government and the private sector. This partnership should incorporate a responsiveness to market signals, stable support and long time horizons, a focus on technology adoption as well as technology development, and a recognition of the growing role of the states.

CHAPTER 5

CONCLUSION AND NEXT STEPS

The committee has discussed two broad components of the science and technology enterprise. The first is scientific and engineering research—the generation of new knowledge. The second is the development and adoption of technology—putting new knowledge to work. Together these components form part of a system—a system that works well when its components are strong and interact effectively.

A third part of the system is equally important—the education and training not only of future scientists and engineers but of the public in general. Our society is growing ever more dependent on the creation and flow of information. Throughout their careers, the members of an information-based culture will spend much of their time learning new information and new skills. The committee believes that the issues surrounding education and training in science, mathematics, engineering, and technology are sufficiently important to merit a separate report.

A number of important questions need to be answered. At the graduate level, students today tend to specialize early, prolong their studies, and strive for tenure in academic positions. How can graduate schools prepare their students for a world in which highly trained scientists and engineers move often among industry, academia, and government?

At the undergraduate level, the structure of science and mathematics curricula appears to discourage many qualified students from pursuing careers in science and engineering. How can colleges and universities present these subjects so as to make such careers more accessible? How can universities promote scientific literacy among their graduates? How can they improve the training of students who will become science and mathematics teachers in elementary and secondary schools?

Finally, at the precollege level, how can the schools best take advantage of information-based technologies to optimize teaching and learning? How can teachers best prepare students for further education and for careers where science, technology, and mathematics will play an increasing role?

The development of human resources is essential to meeting the fundamental challenge in the science and technology enterprise: that of maintaining and improving the linkages between research and the development and adoption of technology. If our scientific enterprise is to be more effective in a competitive world, these activities must be more effectively coupled. The principal link is through people—the scientists, engineers, and others who are trained in schools, colleges, and universities and then go on to work in industry, academia, and government.

The development of human resources is also related to another issue that warrants further examination: the increasingly international character of science and technology. A nation's work force is virtually the only factor of production in modern economies that does not move easily across international borders. Scientific knowledge, technical know-how, natural resources, and capital have increasingly become international commodities that flow quickly to those best able to use them. This report has focused predominantly on the national dimensions of science and technology, but the changing international context will have increasingly important consequences for national approaches to research and development.

TOWARD A NEW PARTNERSHIP

Despite the increasing internationalization of science and technology, the linkages between a nation's internal scientific and technological capabilities and its well-being will continue to be strong. The countries that best integrate the generation of new knowledge with the use of that knowledge will be positioned to be the leaders of the twenty-first century.

Each component of the science and technology system is important. The scientific research carried out in universities and in federal and industrial laboratories will continue to be essential in providing new knowledge and trained personnel. Today, society faces many problems whose solutions will depend on the knowledge generated by this research.

Of equal importance will be the transformation of new scientific knowledge through engineering into new technologies. This process will require an economic, managerial, and legal environment that fosters innovation and the adoption of new technologies. In today's world, the federal government must be a partner with industry in identifying and developing technologies essential to national needs. For more than a century, the United States has been at the world frontiers in many of the technologies that have transformed society. This country can and should continue to be a technological pioneer.

Finally, the science-driven knowledge of the twenty-first century will be successfully deployed only if our nation invests in human resources. This means more than just the production of future generations of scientists and engineers. The country needs a technically trained and flexible work force that can make use of new scientific and technological knowledge and can adapt to change in an increasingly dynamic economy.

Science and technology cannot solve all of society's ills, even if their benefits were distributed as widely as possible. But science and the technologies that increasingly flow from science are essential to generate the knowledge and the wealth that will be needed to address societal problems. This country therefore needs to explore how to ensure the progress of science and how to use new knowledge most effectively to meet human needs. If we succeed in doing so, human well-being will be greatly improved.

APPENDIX

FEDERAL FUNDING OF RESEARCH AND DEVELOPMENT IN THE UNITED STATES

The federal government finances somewhat less than half the research and development (R&D) conducted in the United States. Private industry funds about half; colleges, universities, and other nonprofit organizations such as foundations play smaller but still important roles (Figure 1).

The federal government funds R&D in four different types of organizations: industrial laboratories, laboratories owned by the federal government and managed either by the government or by contractors, colleges and universities, and other nonprofit organizations such as hospitals and museums (Figure 2). Most of the federally funded R&D conducted in industry is focused on the missions of federal agencies, particularly the Department of Defense and the National Aeronautics and Space Administration. The federal government is also the primary customer for the products of the national security and aerospace sectors, and therefore has a strong influence on private-sector R&D in these areas through its procurement policies. When federally supported R&D in industry is added to the R&D financed by industry itself, industry is the performer of almost 70 percent of all the R&D done in the United States (Figure 3).

Figure 3 also shows that government laboratories, including laboratories administered by industry, universities and colleges, and other nonprofit institutions, are the second largest performers of R&D in the United States. The Department of Defense funds about half of the R&D done in government laboratories. This work focuses largely on technology development to meet military needs.

In the Department of Energy, the national laboratories pursue both R&D driven by specific government missions, such as weapons development and energy development, and research related to general science in such areas as elementary particle physics research. The intramural laboratories of the National Institutes of Health make major contributions of knowledge to the health care system. NASA's laboratories focus on technologies needed for space exploration and for aeronautics, while those of the Department of Agriculture seek to extend and disseminate agricultural knowledge.

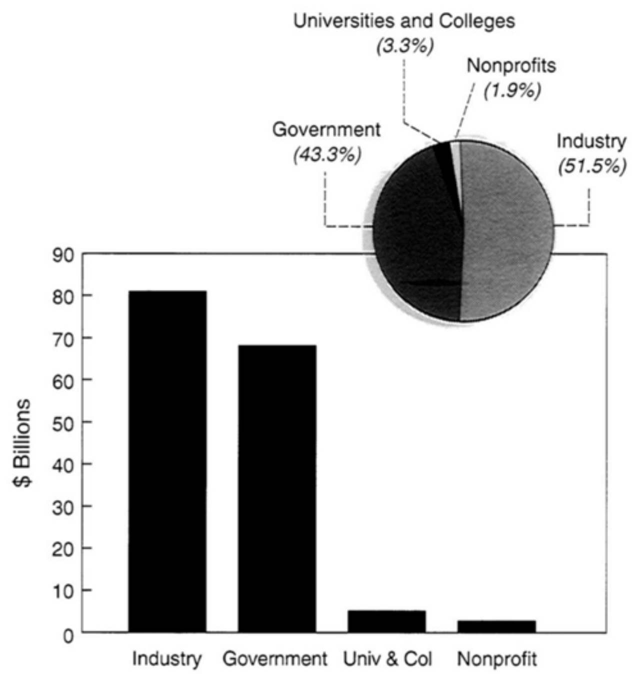

FIGURE 1 *Estimated funding of research and development in 1992 by industry, by the federal government, by colleges and universities, and by other nonprofit institutions. The total for colleges and universities includes state and local government funds separately budgeted for research and development. SOURCE: National Science Foundation,* National Patterns of R&D Resources: 1992, *Washington, D.C.: National Science Foundation, 1992*

In terms of overall expenditures, colleges and universities do somewhat less R&D than do government laboratories. Colleges and universities receive more than half their research funding from the federal government (Figure 4). Over 90 percent of the federal funding for R&D in universities comes from six federal agencies: the National Institutes of Health, the National Science Foundation, the Department of Defense, the National Aeronautics and Space Administration, the Department of Energy, and the Department of Agriculture.

The broad structure of the U.S. R&D system outlined above has been fairly stable in recent years. However, the period has seen some significant long-term trends. The percentage of federal R&D funds going for defense purposes has dropped, from 69 percent in 1986 to less than 60 percent in 1992. This percentage can be expected to drop further in the future.

Since 1985, academic R&D has expanded substantially, whereas R&D in industry and in government laboratories has grown less rapidly. The share of federal funds in academic R&D has declined over that period, from two-thirds of the total in the early 1980s to an estimated 57 percent today. This drop has been accompanied by an increase in funding from industry and from internal funds of universities and colleges.

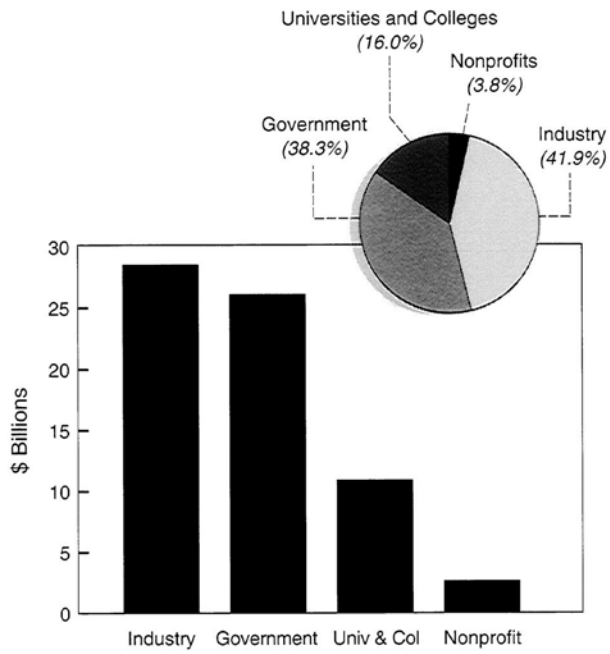

FIGURE 2 *Estimates of federally funded research and development done in 1992 in industry, in government laboratories (including laboratories administered by industry, by colleges and universities, and by other nonprofit institutions), in colleges and universities, and in other nonprofit institutions. SOURCES: National Science Foundation,* National Patterns of R&D Resources: 1992, *Washington, D.C.: National Science Foundation, 1992. Personal communication, John Jankowski, National Science Foundation, 993.*

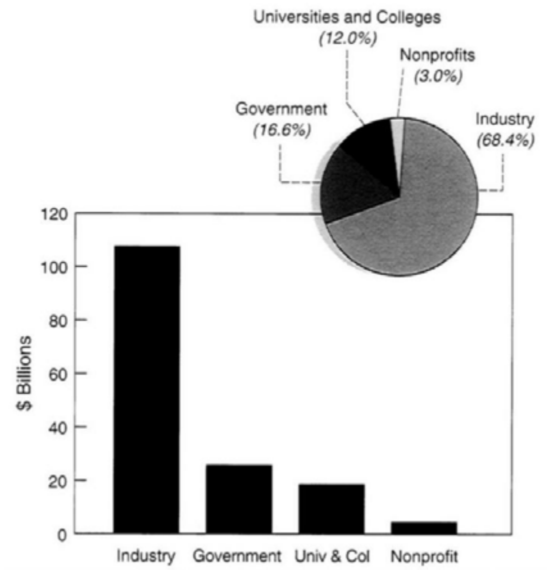

FIGURE 3 *Estimated performance of total research and development in 1992 by industry, by government laboratories (including laboratories administered by industry, by colleges and universities, and by other nonprofit institutions), by colleges and universities, and by other nonprofit institutions. SOURCES: National Science Foundation,* National Patterns of R&D Resources: 1992, *Washington, D.C.: National Science Foundation, 1992. Personal communication, John Jankowski, National Science Foundation, 993.*

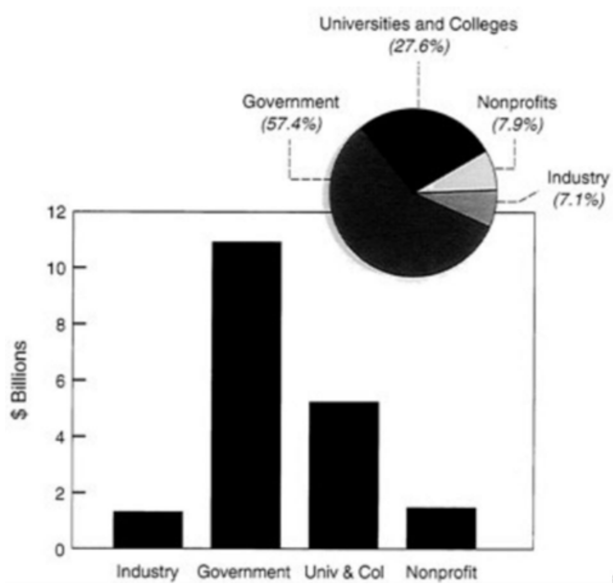

FIGURE 4 *Estimates of funding sources for academic research and development in 1992. Funding from universities and colleges includes state and local government funds separately budgeted for research and development. SOURCE: National Science Foundation,* National Patterns of R&D Resources: 1992, *Washington, D.C.: National Science Foundation, 1992.*