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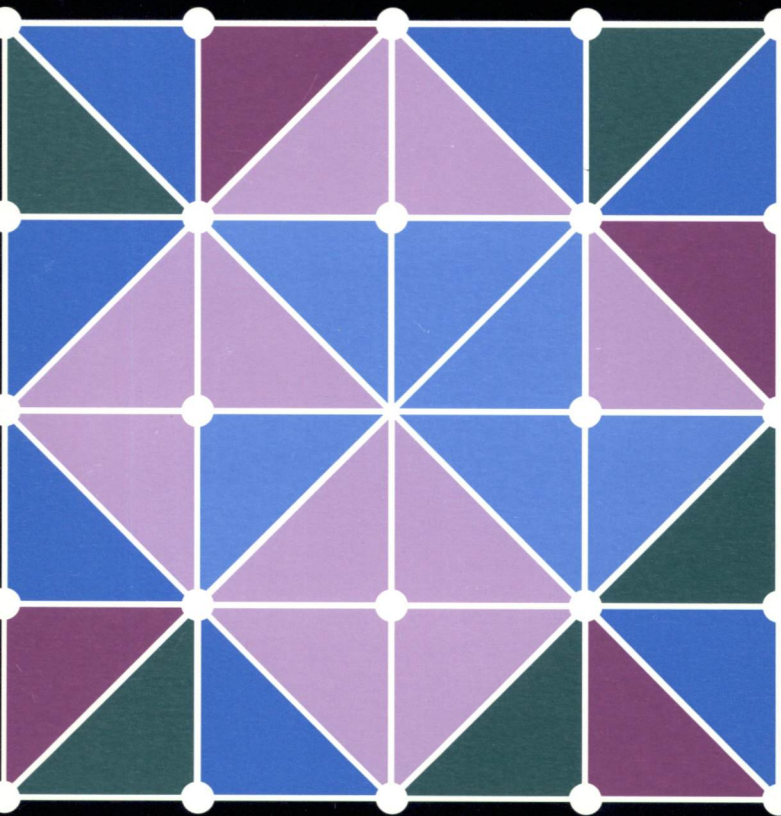
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Science and Technology



EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

Science and Technology

A REPORT TO THE CONGRESS

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

THE WHITE HOUSE

WASHINGTON

For Immediate Release

March 17, 1992

TO THE CONGRESS OF THE UNITED STATES:

I am very pleased to submit the Science and Technology Report and Outlook: 1989–1990 as required by the National Science and Technology Policy, Organization, and Priorities Act of 1976 (42 U.S.C. 6615).

The report reinforces and highlights that strong and vigorous support for our Nation's science and technology has been one of the central policies of this Administration. In addition to providing a general record of accomplishments, the report also suggests a number of possibilities in the form of an outlook for the future in key areas of science and technology.

The Federal Government's science- and technology-related activities support our Nation's quest to ensure a high quality of life for current citizens and future generations by meeting national needs, investing for the future, exploring intellectual, social, and physical frontiers, building on the fundamentally international character of science and technology, and strengthening math and science education.

The various chapters illuminate selected areas essential for meeting national needs. There is a focus on international competitive advantage, national security, global environmental needs, foreign policy, biotechnology, and information technology. Each chapter describes the area's key features, its policy relevance, and major components for which detailed strategies, policies, programs, and budgets have been or are being designed and implemented.

Science, as Vannevar Bush pointed out nearly half a century ago, is an endless frontier. Exploiting the opportunities in science and technology and securing their benefits to the United States require policies that are forward-looking and reflect a rapidly evolving world. This Administration also believes that these objectives require vigorous initiatives in the private sector, continued excellence in academic research, and sustained progress in education.

In many ways, investment in science and technology reflects a deep-seated American belief in the possibility of a better future. With concerted action, that future—that endless frontier—lies within our reach.

GEORGE BUSH

THE WHITE HOUSE
March 17, 1992

Science and Technology

A Report to the Congress



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Preface



The Science and Technology Report and Outlook is submitted biennially to Congress by the Office of Science and Technology Policy in conformance with Public Law 97-375. The report is designed to further the ongoing national dialogue about the past contributions, current status, and future roles of science and technology in our Nation's growth and prosperity.

In accordance with this purpose, the report highlights broad themes and priorities in national science and technology efforts and seeks to convey a context for their consideration. The focus on selected topics and issues allows for the examination of recent developments and possibilities for the future in a number of exciting areas of science and technology. The report is not comprehensive nor is it intended to serve as a Federal R&D program catalogue or a budget document; both of these types of information are readily available elsewhere. To best serve as a complement to these technical budget and program documents, this report is written to be accessible to both technical and non-technical audiences. While major coverage is for the period 1989-1990, updated events and initiatives are included for selected areas.

The Federal government's science- and technology-related activities support our Nation's quest to ensure a high quality of life for current citizens and future generations by meeting national needs, investing for the future, exploring intellectual, social, and physical frontiers, building on the fundamentally international character of science and technology, and strengthening math and science education.

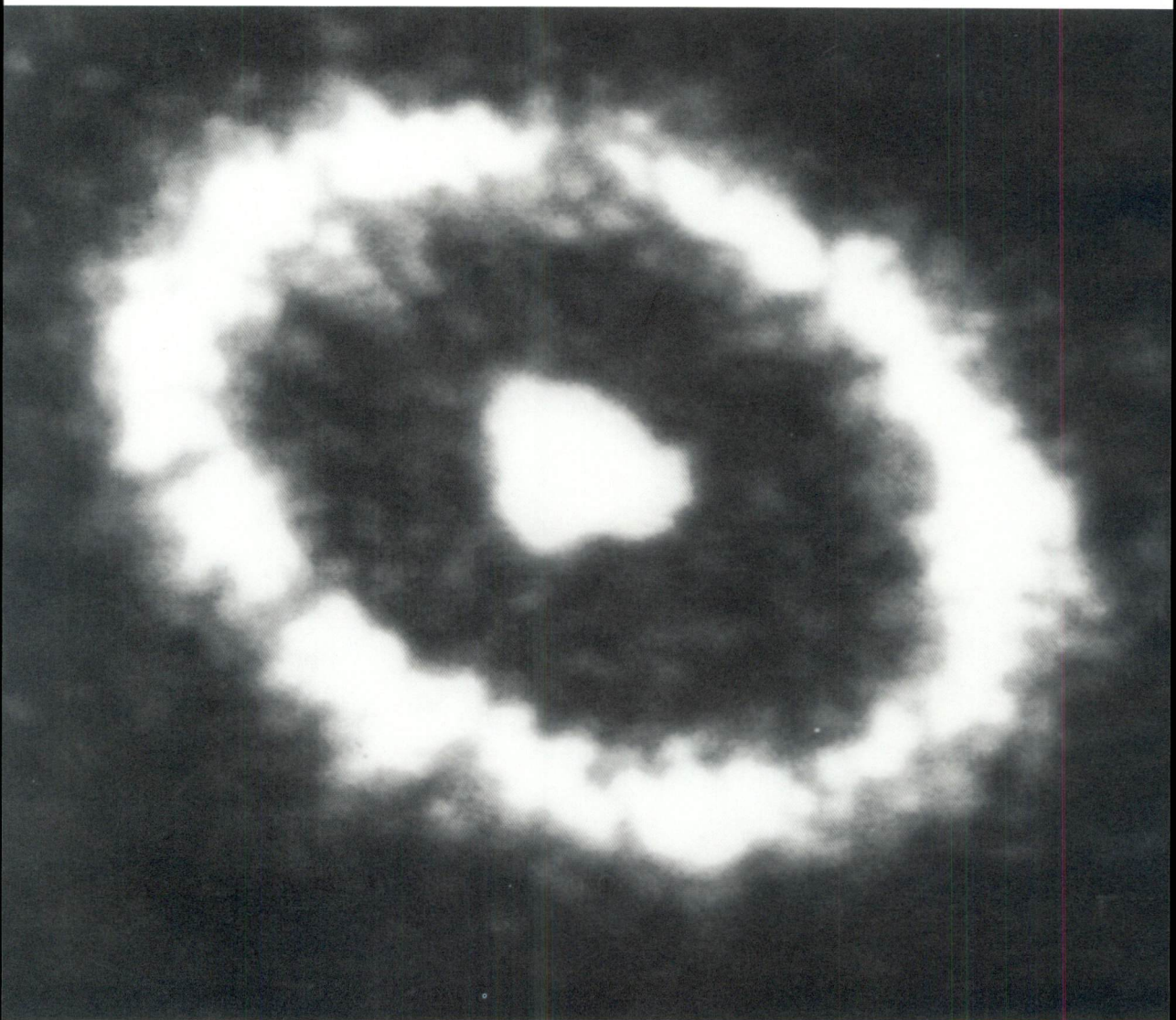
Part I of this report focuses on science and technology's role in society and how science and technology are shaping and being shaped by current events.

Part II examines the critical role of science and technology in enabling the Nation's future well-being and prosperity. The two areas of focus are the Nation's investment in basic research and the importance of educating our Nation's youth.

Part III illuminates several priority areas essential for meeting national needs. Chapters focus on information technology, biotechnology, national security, foreign policy, international competitive advantage, and global environmental needs. Each chapter describes the area's key features, its policy relevance, and major components for which detailed strategies, policies, programs and budgets have been or are being designed and implemented.



**Perspectives
on
Science and Technology**



NASA

Building on Science and Technology



THE HUMAN SPECIES has always been curious about the world around us and the antecedents of science as a rational inquiry into the properties of nature date back several thousand years. But modern science has become an important force in the beliefs of educated individuals only in the past few hundred years. The systematic harnessing of scientific discoveries as sources of economic development has an even shorter history, beginning with the 19th century.

Yet in the brief span of their existence, modern science and technology have proved to be powerful social and economic forces, and this impact is growing at an accelerating rate. In the second half of the twentieth century alone, it has transformed air travel, telecommunications, and many other existing industries and has given birth to entirely new sources of products and services, such as the semiconductor, computer, and biotechnology industries. It has dramatically improved health care and the quality of life and has provided a continuing supply of military technologies critical to national security. It has enabled the U.S. to become a space-faring Nation and at the same time to probe the essence of human life itself—the genome.

In addition, science has helped to satisfy human curiosity and expand intellectual horizons. Science is the Grand Adventure of our times: exploring the Solar System and beyond, the secrets of the sub-atomic world. The success of the scientific method has made it a model for rational thought and a common culture that binds together an international community of scientists.

TRENDS

We live in a time of unprecedentedly rapid change. These transformations include worldwide political change; changes in the nature and intensity of global economic competition; and changes in the nature of scientific research, the development of new technologies, and their employment. These changes are profound and closely linked and carry significant implications for current policy and for the Nation's future.



Political Changes—Revolutionary, largely peaceful changes in political and social organization are occurring as new freedoms and more democratic regimes arise in Eastern Europe, Africa, South America and Asia. These changes have been facilitated by the rapid dissemination of information within countries and across national borders and between continents. The proliferation of such new technologies as facsimile machines, satellite television and telephone links, copiers, and personal computers has made centralized control by authoritarian governments ever more difficult.

Political and social change have been further motivated by the increasingly obvious advantages—in technology, in economic well-being, in quality of life—of the industrial democracies over other governmental forms, providing models that virtually all nations now aspire to emulate.

It is no accident that the scientific and technological dynamism portrayed in this report has taken place largely within the industrial democracies, or that they have emerged as models for other nations. The basic values of science—freedom of inquiry, openness of expression and publication, and peer review—fit comfortably within the political framework of the democracies and only with difficulty under more authoritarian governmental forms. The scientific and political freedoms of the industrial democracies and the concomitant economic and technological decentralization have proved to be powerfully synergistic in building strong economies and improving the welfare of their citizens.

Economic Changes—In the new global economy, science and technology have become key factors in a sharpened, more intense competition that now includes not only Japan and the emerging European Community but also many of the newly industrializing nations. In part, this heightened importance of science and technology stems from the role of fundamental advances in knowledge as a basis for economic growth. As research has demonstrated, the social rate of return from academic research is extraordinarily high, averaging about 28 percent annually (Chapter 2). Social investments in the creation of new knowledge are increasingly recognized as an essential source of economic growth.

A second factor is the growing significance of new technology in gaining market share within established sectors and in creating entirely new markets for goods and services. This reflects the emergence of a capacity for commercially competitive R&D in



many countries of the world and the growing realization within multinational firms of the need to adopt a global viewpoint in the development of technology. Just as firms face a unique set of opportunities and threats stemming from the globalization of both markets and competitors, they also face the need to manage their technological investments internationally. Success or failure in this endeavor may determine a firm's ability to successfully exploit technology opportunities and thus survive in a new era of competition.

A recent survey of some 240 European, Asian, and North American firms found that Chief Executive Officers expect competition to intensify and to bring new pressure on U.S. technological leadership. The strategic importance of technology for the growth of individual firms is particularly apparent in high-tech fields such as computing and telecommunications. A similar pattern is increasingly evident in more traditional economic sectors such as automobiles and basic manufacturing because of technology driven changes in manufacturing processes.

Such changes reflect a rapid and profound transformation of the technological structure of industrial societies. New technologies are developed and deployed to a global marketplace on an increasingly short time scale. Moreover, the spread of scientific and technological competence to many nations and the efficacy of modern communications and information processing techniques means that technological innovations diffuse rapidly throughout the global marketplace. They are swiftly duplicated by competitors, necessitating continual innovation to maintain a competitive advantage.

Moreover, the application of computers and information processing techniques is creating a revolution in the way in which manufacturing processes are organized and operated to produce goods and services. A recent five year study of the global automotive market illustrates the extent of this paradigm shift in manufacturing. Reorganized factories and advanced techniques reduce the time (and hence labor and other costs) required to manufacture a car by a factor of two or three over traditional methods. The competitive advantages conferred by such increased productivity and greater flexibility in production may well outweigh the importance of advanced materials and other new technologies incorporated into the products themselves. As such advanced manufacturing techniques proliferate throughout the economy, they will have profound implications for the skills and education required in the work force of the future.

It is no accident that the scientific and technological dynamism portrayed in this report has taken place largely within the industrial democracies.



National Security Changes—Over the past two years, the world security environment has undergone a major transformation. Threats to key U.S. security interests have been greatly reduced by changes in East-West relations attributable to the failure of communism and the successful strategy of deterrence.

At the same time, significant challenges remain to the national security interests of the United States, which will require the vigorous and visionary application of science and technology (Chapter 6). The threat of a global war has sharply diminished, but newly emerging democratic institutions are fragile and regional threats of aggression and militarism are growing. The strategic nuclear arsenal of the former Soviet Union remains intact, while the political future of the Commonwealth of Independent States and other republics is unpredictable. Still other political uncertainties in much of the world, coupled with the diffusion and proliferation of high technology (especially weapons technology), further complicate national security strategy and requirements.

The United States has long depended on our qualitative superiority in science and technology for the advantages that ensure our freedom and protect the peace. The weapons systems that performed so admirably in Desert Storm, winning the war with minimal loss of life, were the results of far-sighted investment decisions made in decades past. "Time and again, we have seen technology revolutionize the battlefield," President Bush said recently. "To prepare to meet the challenges we must face in the future, we must focus on research—an active and inventive program of defense R&D." We also need wise policies to address a wide range of national security S&T concerns including weapons proliferation, technology diversion, and the nurturing and protection of our nation's scientific, technological and economic base.

Environmental Changes—Rising levels of "greenhouse gases" in the atmosphere have posed the threat of potential global warming and concomitant climate changes. Other potential or actual environmental changes caused by human activity have also been identified. Together these concerns raise the prospect of global changes of unknown scope and impact. Yet the existing knowledge base needed to evaluate and predict such changes and to quantify the results or costs of mitigation efforts is woefully inadequate. In effect, the world is faced with the daunting task of managing a planet that is still imperfectly understood.



One response to these new global environmental concerns must be a greatly expanded effort to improve knowledge of the fundamental processes that govern the biogeochemical cycles of the Earth. Likewise, there is a need to improve the ability to model and to predict the impact of human activities on these cycles (Chapter 9) as well as the economic and social impact of global environmental change on humankind. Such efforts require an unprecedented degree of coordination of research efforts spanning many fields of science and, indeed, many nations.

Changes in Science and Technology—In parallel with the expanded scope of science and technology in areas of national importance, the nature of science and technology development also changed, as has the structure of R&D activities and the interaction between science and technology.

One such change is the increasing sophistication of research and its dependence on more complex and powerful instrumentation. These advanced methods, themselves reflecting significant scientific advances and new technologies, have enabled scientists to understand the nature of materials, to probe the molecular basis of life, and to simulate and predict the outcome of natural processes on powerful computers. Since such methods are applicable both to fundamental and practical problems, the result has been a blurring of the boundary between basic and applied research.

A second change results from the complexity of the problems which science can attack and the need to bring to bear the insights and methods of many disciplines. Understanding the nature of the carbon cycle that underlies the greenhouse warming phenomenon, for example, requires the development and fusion of physical, chemical, and biological knowledge. Thus multidisciplinary approaches are often required to comprehend a facet of nature, even in basic research.

The nature of technology development also has changed. In the private sector, competitive pressures require that it proceed on far shorter time scales than ever before in order to establish early, strong market positions and allow for recoupment of rising investment. One consequence is to compress the period between the discovery of new knowledge and its application in technology and to increase the importance of the rapid transfer of basic knowledge from universities or government laboratories to the industrial sector. But if new knowledge increasingly feeds technology development, the converse is also true: technology

The United States has long depended on our qualitative superiority in science and technology for the advantages that ensure our freedom and protect the peace.



development not only poses new problems for scientific research but also gives rise to new and more powerful research tools. Thus science and technology interact more strongly and with greater synergism than in the past.

APPRAISAL

In 1991, it is estimated that over \$150 billion was spent on scientific research and development in the United States. At this level of investment, the U.S. scientific and technological enterprise is still by far the largest in the world. The United States spends more on R&D activities (civilian and military) than do France, Germany, Japan, and the United Kingdom combined. Research and development have fared better than many other components of the budget, reflecting the high priority assigned by the Bush Administration to investment in R&D.

Federal investment in basic research has grown in real terms by over 350 percent since 1960 and by more than 50 percent since 1980 alone (Chapter 2). The Federal government is the major source of support for basic research, providing about three-fifths of the national total of about \$24 billion in 1991. Such growth reflects the Bush Administration's strong and continuing commitment to the long-established policy of investing in the creation of new knowledge through support of basic research.

Paradoxically, one measure of the success of basic research is whether or not a given line of inquiry generates more questions than it answers. In this respect, the Federal investment has been rewarded with unparalleled success. The number of significant new questions—and corresponding opportunities—that now confront scientists is greater than at any time in history.

Basic research aside, however, a somewhat different picture emerges. Increases in non-Federal support and investment in research and development has slackened in recent years. This is a worrisome trend since global economic competition takes place mostly in the private sector. During the 1980s, the average annual real rate of growth for non-Federal R&D funding fell from about 7.5 percent for 1980-1985 to about 2 percent.

An often-used indicator of technology output, the number of influential patents held, underscores the trend. Although an imperfect measure, high quality patents are seen by some as a potent predictor of future economic performance because they signal the emergence of important new technologies that will be under the patent holders' control for years to come. Due to the size of its industrial base, the United States is still the international leader in the number of patents held by its inventors. But this



position is being increasingly challenged by Japan. The rate of growth of Japanese patents in the United States nearly doubled from 1983 to 1988, by which time Japanese firms and individuals received 21 percent of all U.S. patents. In some key areas of technology, nearly half of the patents are being awarded to Japanese.

Another indicator of prowess in research and development is the number of citations in the scientific literature. Citation analysis clearly shows that the United States has an overwhelming lead in worldwide citations and that its average citation rate continues to grow. By this measure the Nation is maintaining its lead in basic research. In a few key areas of applied science and engineering, however, the relative rate of citations in the literature is declining.

POLICY RESPONSE

The Bush Administration has developed an array of policy responses that addresses the enhancement of U.S. economic performance as it relates to investment in research and development. These policies take account of major changes or trends in world affairs; of the expanded role of science and technology in meeting national needs; and of changes in the nature of science itself—as outlined above. Some highlights of these policy approaches can be briefly summarized as follows.

An overridingly important policy response in this and the preceding Administration has been to increase Federal investment in the creation of new knowledge. As noted above, research budgets have increased substantially since 1980. Such investments (discussed in more detail in Chapter IV.C. of the Budget of the United States Government, Fiscal Year 1992, "Enhancing Research and Expanding the Human Frontier"), reflect the Bush Administration's commitment to support significant advances in science and in technology. Because of the rapidly expanding opportunities for research, the Administration believes that such advances will be achievable in the future as they have in the past and that these advances will continue to create whole new industries and change the direction and composition of national economies.

Another policy response has been to reorganize and upgrade the Federal government's ability to deal with science and technology. This has included a revitalized Office of Science and Technology Policy, the establishment of the President's Council of Advisors on Science and Technology to provide a high-level

An overridingly important policy response in this and the preceding Administration has been to increase Federal investment in the creation of new knowledge.



advice on science and technology from the private sector, and a reorganized and upgraded Federal Coordinating Council for Science, Engineering, and Technology to provide a strengthened apparatus for coordinating R&D across the entire Federal government. A significant result of this reorganization has been the creation of a number of cross-cutting, multidisciplinary initiatives focused on critical national problems, such as global change, high performance computing, and mathematics and science education.

The Bush Administration has also developed a Technology Policy to achieve the national goals of an improved quality of life for all Americans, continued economic growth, and national security. Science and technology, while essential for robust economic growth in today's competitive global economy, are not in themselves sufficient. As discussed in the 1991 and 1992 Economic Reports of the President, other key factors include measures to improve capital formation such as reduced capital gains taxation, provision of a higher quality labor force through improved education, enhanced intellectual property rights protection, additional R&D investment in the private sector (e.g., enhanced research and investment tax credit), a less adversarial and more cooperative anti-trust environment, and a "level playing field" in the international trade area.

Recognizing unmet needs in the process of moving new knowledge into the marketplace, the Administration has identified and supported generic, pre-competitive technologies in cooperation with the private sector (Chapter 8). One example is the development, in cooperation with the Congress, of the multi-agency high performance computing initiative (Chapter 4).

The Bush Administration is committed to removing barriers to competitiveness, for example through the use of risk-based regulation of biotechnology products (Chapter 5), and the accelerated transfer of Federally-supported new knowledge from universities and government laboratories to the private sector.

As part of the President's commitment to education, the Administration has established a coordinated, government-wide program to improve science and mathematics education in order to maintain the country's science base and to train a more competitive work force (Chapter 3).

The Administration is also seeking increased international collaboration in science (Chapter 7) in, for example, such projects as Space Station Freedom and in strengthening multilateral and bilateral relationships, including those with developing nations.

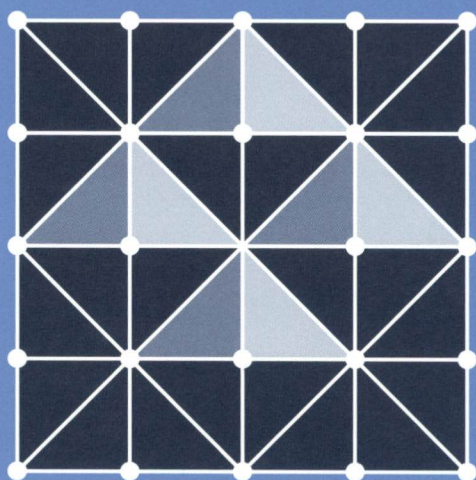


These examples and many others discussed in the balance of this report illustrate some of the high priority issues in science and technology being addressed by the Bush Administration.

CONCLUSION

Science, as Vannevar Bush pointed out nearly half a century ago, is an endless frontier. Exploiting the opportunities of that frontier has helped to strengthen this Nation and the entire world in the past and can continue to do so in the future at an accelerating rate. The Bush Administration believes that seizing these opportunities and securing their benefits for the United States require policies that are forward-looking and reflect a rapidly evolving world. The Bush Administration also believes that these objectives require vigorous initiatives in the private sector, continued excellence in academic research, and sustained progress in education.

In many ways, investment in science and technology reflects a deep-seated American belief in the possibility of a better future. With concerted action, that future—that endless frontier—lies within our grasp.



Investing in the Future



JEAN-CLAUDE LEJEUNE/BLACK STAR

Basic Research Foundations



BASIC RESEARCH is the foundation of the nation's research and development enterprise. It generates the new ideas, concepts, techniques, and tools upon which both science and technology endeavors are based. As such, basic research is the fuel for the new products and processes that stoke the engine of economic growth and improve the quality of life. Equally important is the role that basic research plays in satisfying our curiosity about the world in which we live; it contributes immeasurably to the cultural and intellectual vitality of the modern world.

Basic research also plays an educational role that is critical to the Nation's future. About half of the basic research done in this country takes place in colleges and universities. In addition to the new knowledge it creates, this research provides the advanced training experience for future researchers and enriches and contributes to the vitality of the educational environment in which future scientists, engineers, and humanists alike receive their undergraduate training. Thus academic basic research not only produces new knowledge but synergistically trains young minds to use that knowledge in innovative and creative ways.

In coupling research with advanced scientific training, the U.S. basic research system is unique among the major industrialized nations. It is also uniquely productive, whether measured by the number of Nobel Prizes won by U.S. researchers or by the degree to which U.S. research literature is cited by scientists throughout the world.

THE DOMAIN OF BASIC RESEARCH

Vannevar Bush, in his path-breaking 1945 report "Science: The Endless Frontier," noted that basic research is performed without thought of practical ends. It results in general knowledge and an understanding of nature and its laws. Such general knowledge provides the means for answering important practical questions, although it may not—at any given time—supply specific solutions for current problems.

When the 1945 report was written, most scientific disciplines



were broadly defined, with reasonably clear boundaries. In this context, equating basic research with research designed to push back the frontiers of one particular discipline made sense in terms of both the scope of each discipline and the state of fundamental knowledge in that field.

As the scientific knowledge base expanded and sub-disciplines grew to become disciplines in their own right, the earlier emphasis on research in a single discipline became too narrow an approach and one that could inhibit the growth of fundamental knowledge. To understand many aspects of "nature and its laws" now requires the involvement of many disciplines in cross-cutting research. Accordingly, basic research is now more properly defined to include both disciplinary and thematic approaches.

Disciplinary research consists primarily of research to develop and improve theories, methods, and techniques and to measure basic phenomena within a single discipline. Simply stated, this type of basic research advances a discipline, such as physics, economics, or neurology, by answering purely disciplinary questions and by responding to the curiosity of individual researchers or small groups of researchers. Thematic or multi-disciplinary research involves situations where researchers in several disciplines focus on a single subject. For example, understanding the fundamental physical processes and human activities affecting global climate change requires basic research in fields as diverse as climatology, oceanography, biology, sociology, and earth sciences.

The practical strength of thematic basic research focused on a specific subject is that it provides a body of information that is useful in dealing with a large number of problems of national significance. For example, basic research into the design of computer architecture, advanced software algorithms, and man-machine interfaces is all needed for high performance computing and communication systems. These systems are, in turn, needed to solve complex problems in modeling climate change, mapping the human genome, or developing more efficient combustion systems to save energy and reduce pollution.

In funding basic research, the Federal government assists disciplines to push back frontiers within their own fields of interest and create the broad base of knowledge needed to solve complex problems and address national needs. Equally important, basic research increases our understanding of the physical and social universe in which we live. It produces findings that can be of great value whether or not they can be immediately linked



to any particular product, industry, or to a major national problem.

Moreover, important as all these benefits are, perhaps the most fundamental aspect of basic research is that it constitutes one of the greatest intellectual adventures available to Mankind. In a very real sense, it is one of the activities that distinguish human beings from all other species on our planet.

THE RETURNS FROM BASIC RESEARCH

It has long been known that spending on research and development has a very high rate of return. Economists estimate that more than one third of the growth of the U.S. economy since the Great Depression has been based on "new knowledge," primarily the results of R&D. Evidence from the past four decades suggests that industry-financed R&D alone accounts for about one-third of the annual average increase in the nation's productivity over that period.

Calculating the returns from research, particularly basic research, is not a simple or easy task. The inputs to research—dollars and scientist-hours—are routinely measured, but there are few ways to measure accurately the corresponding outputs. For basic research, such difficulties are compounded because there is almost always a considerable lag between the time when new knowledge is discovered and its appearance in the form of new products or processes. Moreover, the path that a particular basic research discovery takes to its ultimate application is frequently circuitous and often difficult to trace.

Despite these inherent difficulties, some preliminary assessments have been made. Edwin Mansfield of the University of Pennsylvania is among the economists who have measured returns from research. In a recent study, specifically looking at research conducted at colleges and universities, he estimated that the average social rate of return on all academic research investments in a 15 year period before its results were commercially exploited was about 28 percent. This social rate of return includes direct benefits captured by the firms that directly use the results of the research as well as subsequent benefits derived by other members of society. In comparison, the return on equity (not including investment financed by debt) for all U.S. manufacturing through the last decade averaged less than 20 percent.

The high social rate of return from academic research provides a strong rationale for continued investment. It is estimated, moreover, that about two-thirds of the benefits of academic research measured by the social rate of return accrue to those

It has long been known that spending on research and development has a very high rate of return.



outside the firm that first uses the results. Thus it is appropriate that the Federal government, acting as a representative of society, take the lead in funding basic research. This rationale for a strong Federal role is further supported by the economic risk inherent in academic research, i.e., in the fundamental search for new knowledge. The average rate of social return cited above is about 28 percent, but for specific academic research projects the return is widely variable: zero return for some projects; much larger than 28 percent for others. An individual firm, especially one supporting only a few projects, may not be economically able to take the risk that none will generate a return to the firm in a given time, even though several may eventually lead to a successful new process or product. More importantly, 28 percent is the return to society as a whole; on average, firms supporting academic research are able to capture only a portion, even over a long period of time.

Further economic risk inherent in basic research derives from the delay between costs and benefits. For example, in 1968 Thomas Brock, a microbiologist at the University of Wisconsin, discovered in the thermal vents of Yellowstone National Park a form of bacteria that can survive only at very high temperatures. From these bacteria, an extractable enzyme was found that is stable at near-boiling temperatures. Not until two decades later was this enzyme shown to be vital to a process known as the polymerase chain reaction (PCR), now used to duplicate specific pieces of DNA. Today, PCR is the basis of a rapidly growing multi-million dollar business with applications ranging from the rapid diagnosis of disease to forensic medicine. Federal government support was essential to much of the research which led, over a twenty-year time span, to this now dramatic business success.

Such a lag between the efforts that lead to a basic research discovery and the social return from application of its results underscores the investment character of research. Clearly, failure to invest now may result in diminished economic returns in the future, a decline that cannot be quickly reversed. Thus continued investment in basic research is an essential requirement for future technological growth.

FUNDING BASIC RESEARCH AND RESEARCHERS

In 1991 an estimated \$23.5 billion from all sources was invested in basic research in the United States. The Federal government is the major source of basic research funds; in 1991, \$14.5 billion, or 61 percent, of expenditures for the conduct of basic research were supported by Federal funding. Industry provided 21 per-



cent, and other sectors, including academic institutions and non-profit organizations, provided 18 percent. Expenditures of Federal funds for basic research grew in real terms over 350 percent since 1960, and about 51 percent since 1980 alone. (Figure 1)

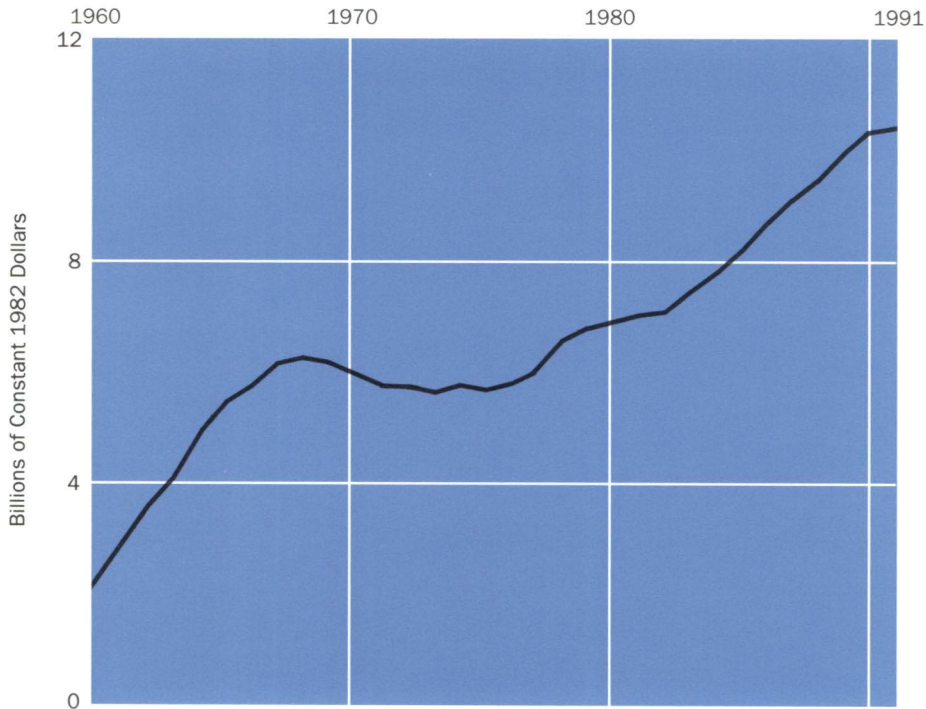


Figure 2.1 Federal Support for Basic Research

Source: National Science Foundation

Although the Federal government provides over three-fifths of the funds expended on the conduct of basic research, it performed only 12 percent of that research in its own laboratories. Forty-nine percent of Federal basic research funds were expended through grants and contracts to universities and colleges. When measured in terms of expenditures, the academic sector performs 47 percent of the basic research in the United States. The Federal government provides 60 percent of the funds that universities and colleges spend on the conduct of this research. (Figure 2)

The decision that Federal agencies could—and should—support research, particularly in academic institutions, was largely

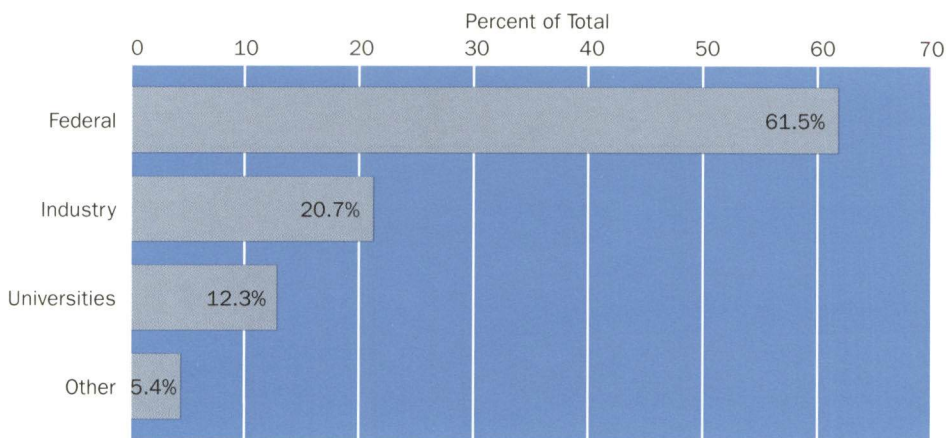


Figure 2.2 Basic Research by Source of Funds: 1991 (estimated)

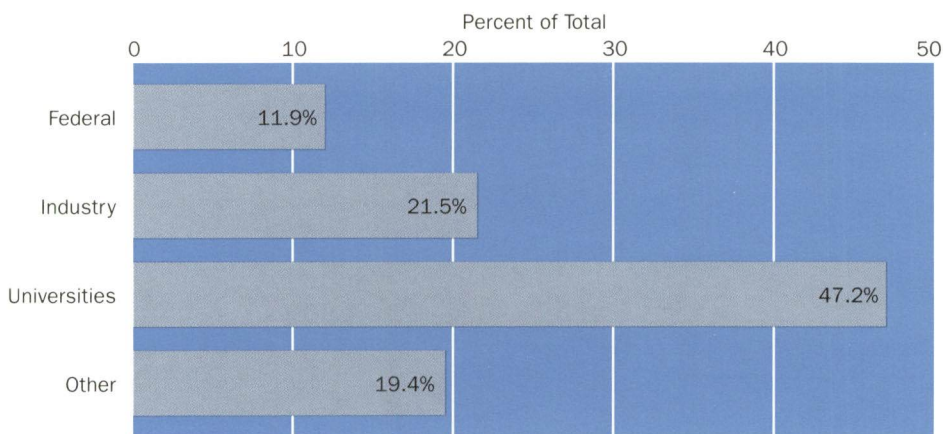


Figure 2.3 Basic Research by Performer: 1991 (estimated)

Source: National Science Foundation

responsible for the development and emergence of the major American research universities after World War II. Funding of basic research at universities and colleges also has been directly responsible for the creation of the expanding community of scientists and engineers that carry the U.S. science and technology enterprises forward. Basic research performance by universities and colleges, as measured by real expenditures, has increased almost five times since 1960. It increased an estimated 69 percent from 1980 to 1991, with a 44 percent increase in Federal funds supporting the bulk of this expansion.

Of the Federal funds obligated for basic research in 1991, the National Institutes of Health was responsible for 37 percent, followed by the National Science Foundation with 14 percent, the



National Aeronautics and Space Administration with 14 percent, the Department of Energy with 14 percent, the Department of Defense with 8 percent, and the Department of Agriculture with 5 percent. These six agencies accounted for 92 percent of the Federal funds obligated for basic research in 1991.

Over one-half of all Ph.D. scientists and engineers in the U.S. were employed at universities and colleges in 1989. Growth of Federally funded R&D facilitated the growth in the numbers of senior scientists and students through proliferation of research assistantships and post-doctoral positions supported by grants. For the National Science Foundation alone, funding increases between 1986 and 1991 provided an estimated increase of 45 percent in the number of post-baccalaureate science and technology personnel supported by Foundation funds. The number of undergraduate students supported by NSF funds increased 200 percent in the same period.

Federally funded R&D also plays an important role in training many non-Ph.D. scientists and engineers by creating an environment of discovery and exposing students to cutting-edge problems that develop their skills and foster creative thought.

The number of significant new questions—and corresponding opportunities—that now challenge scientists is greater than at any time in history.

OPPORTUNITIES AND CHALLENGES

Paradoxically, one measure of the success of scientific research is whether or not a given line of inquiry generates more questions than answers. In that respect, the Federal government's strong support of basic research for the past five decades has been an unparalleled success. The number of significant new questions—and corresponding opportunities—that now challenge scientists is greater than at any time in history.

A prime example can be found in the field of molecular biology. The ability to manipulate genetic material on the molecular level has created tremendous new knowledge and new insights into the functioning of living things. This ability has also made it possible to address a wealth of questions that once were considered largely unanswerable: Which genes are turned on and off during development? What are the genetic bases of disease? How does evolution operate at the molecular level? In addition, advances in molecular biology have created major new commercial opportunities in the rapidly growing field of biotechnology.

SETTING PRIORITIES

The Bush Administration is committed to investing in the future of both current citizens and future generations. Since there will never be sufficient resources to support all the excellent research



that could be done or to follow up on all the new opportunities revealed by current research, it is essential that available funds be used in the most effective fashion.

Basic research projects span a wide range of disciplines, types of research activities, and investments. All contribute to important national objectives: exploring intellectual, social, and physical frontiers; building on the fundamentally international character of science and technology; and strengthening mathematics and science education. Nowhere is the task of setting priorities more challenging than in basic research, where both the possible results of the research and their ultimate role in new products or processes are unknowable. The Administration and Congress, each year, face the difficult problem of establishing the best balance of activities and projects to include in the overall Federal R&D portfolio.

Establishing priorities is a complex process, far more complex than any simple exercise that ranks all possible projects in linear order and funds them until the available resources are exhausted. In research, as in most other endeavors, the whole is much greater than the sum of its parts; maximizing this whole depends on the overall balance of the R&D portfolio.

The priority setting and balancing take place through a unique interactive effort. Out of the extensive discussion and debate following World War II, a collaboration has arisen among the executive agencies, the Congress, and the science and engineering community in which, working together, they strive to develop the optimum portfolio of projects for Federal support. This collaboration is shaped by an informal social contract between government and the scientific community. Government provides support and delegates to representatives of the scientific community a major role in advising on the allocation of funds for research activities and facilities. In return, researchers have the obligation to produce and share knowledge freely to benefit the public good.

It bears emphasis that the United States is unique in the developed world in that its scientific and engineering enterprise to a substantial degree is built from the bottom up as the agencies receive and respond to proposals from individual researchers or groups of researchers. A much more common arrangement elsewhere involves the establishment, by the central government, of a specific R&D budget, approved in total and subsequently divided up from the top by officials in the federal agency responsible for R&D.

The most common way in which options and proposals are



evaluated by researchers is through their participation in peer review processes. Working researchers respond to agency requests to review funding proposals, using their technical knowledge to comment on the proposals' technical merit—as well as that of the proposers—and on contributions to the national science and technology effort that successful completion of the proposed project might be expected to provide. At this level, researchers provide, in essence, an analysis of options within their field of specialization. At a more aggregate level, groups of scientists and engineers, often represented by the professional organizations of their disciplines or under the aegis of the National Academies of Science and Engineering, articulate priorities for their fields.

At the same time, Federal agencies decide upon the proper balance between various projects and sub-disciplines under their purview. Various advisors to the President, (including the Office of Science and Technology Policy and the Office of Management and Budget) work with the agencies, the Congress, and other interested parties to determine what combination of projects will best move the Nation toward its objectives. In presenting the annual budget, the Administration sets forth its vision of the balanced portfolio of R&D projects required to meet national goals involving science and technology.

TRADEOFFS IN FUNDING

The Federal government now supports more principal investigators at universities and colleges than ever before, reflecting real increases in the level of Federal support for academic research. Nevertheless, because of an even more rapid increase in the number of applicants, the competition for available research funds is a matter of serious concern to the research community.

From 1980 to 1988 alone, the full time equivalent (FTE) scientists and engineers employed in research and development at universities and colleges increased 40 percent. During this same period, the number of science and engineering graduate students increased by 16 percent.

In addition, the cost of doing research is increasing. One factor in this increase is a general inflation in the price of standard research equipment and personnel. The National Institutes of Health publishes a biomedical R&D price index that measures the cost of doing biomedical research in different years using similar personnel, equipment, and facilities. The index shows that the cost of biomedical research increased 64 percent between 1980 and 1988, with salaries representing the major



component. By comparison, inflation in the cost of all goods and services, measured using the GNP implicit price deflator, increased only 41.5 percent during the same period.

Another major factor contributing to increased research cost is the sophistication of equipment and facilities needed to do frontier research. In 1980, for example, a scientist doing advanced research in medicine may have used a CAT scanner (computerized axial tomography) to produce images of internal body tissues. The equipment cost (in 1990 dollars) ranged from \$0.4-1.2 million. In the mid-1980's more advanced imaging equipment, MRI (magnetic resonance imaging) became available, but at a cost per machine of \$1.2-1.5 million. By the late 1980's, selected researchers gained access to PET (positron emission tomography) scanners at a cost per machine of \$3.6-4.2 million. Each of these tools allowed researchers to gain new insights at rapidly advancing frontiers of research, but the increase in sophistication was matched by an increase in costs.

There is no generally used "sophistication index" for research and development but most disciplines, like biomedicine, have experienced rapid increases in the complexity of techniques and the sophistication of equipment needed to stay on the cutting-edge. Another dramatic example comes from high energy physics, where larger and larger accelerators operating at higher and higher energy levels are needed to remain at the research frontier.

These increased costs have created pressure to increase the size of research grants. There have also been calls to increase the duration of grants, both to promote stability of support and to reduce the time and effort devoted to paperwork rather than research. Such changes, however, mean that fewer grants can be awarded for a given funding level and that, as more long-term grants are awarded, a higher proportion of the research money available in a given year is precommitted. While advantageous for those who receive grants, such policies can adversely affect scientists applying for new grant monies, especially those further down the peer-reviewed quality scale.

At the National Institutes of Health in recent years, the number of continuing grants has been growing while the number of new grants has also increased, so that the total number of grants rose by 6% between 1989 and 1991. At the National Science Foundation, the success rate for new grant applicants improved from 18 to 20 percent between 1989 and 1991. But the success rate for all grant applications has dropped about 15% over the past 10 years.

Choosing how to structure funding for different research activ-



ities involves balances and tradeoffs. Funds expended on personnel costs necessarily reduce the funding available for equipment and facilities. Yet cutting-edge research cannot be conducted without the proper tools. Providing some researchers with larger amounts of long-term grant monies ensures that they have the personnel and equipment needed to do their work and fosters continuity. But this necessarily means that other investigators with lower peer-reviewed priority scores may not be funded in a given grant application cycle. There are no easy answers to these dilemmas; both those requesting the resources and policymakers who determine their distribution must carefully weigh the tradeoffs.

It is also the case that in any given year the Federal government must balance the claims of researchers for support of their current activities against investment in the facilities that will be necessary to take these same researchers to the new frontiers of their fields five and ten years into the future. This balance is a delicate and difficult one to achieve.

THE RESEARCH/EDUCATION LINKAGE

Concern over the distribution of Federal research support for R&D also extends to its effect on mathematics, science, and engineering education. One of the criteria applied to prospective programs in science and technology is whether they act to strengthen such education. A large portion of the funds spent to support research and development in fact have an important ancillary benefit of either directly or indirectly supporting education in these fields.

Direct support of mathematics, science, and engineering education at the post-graduate level comes in the form of research assistantships and traineeships and through research grant support and characteristically does not appear in any of the formal accounting of Federal support of education. Indirect support comes from the active participation by faculty members in research, which enriches the learning environment both for graduate and undergraduate students. Training is enhanced when students confront cutting-edge problems in basic research, learning how to go about solving a problem no one has solved before, designing and building a piece of equipment that has not heretofore existed, and drawing the correct conclusions from myriad observations. By coupling research with education, each new generation of scientists and engineers learns what constitutes good work, thus setting the standards for research and technical performance in all sectors of the economy. Perhaps

The Federal government now supports more principal investigators at universities and colleges than ever before, reflecting real increases in the level of Federal support.



most important, they develop the self-confidence that allows them to attack the broad unstructured problems that are typical of those of greatest national importance.

Nourishing and strengthening the ties between research and education within colleges and universities is therefore a crucial part of any effort to improve national capabilities in science and technology. It is a task that grows more critical as the demand for scientists and engineers expands worldwide.

All students benefit from some exposure to high quality research. Since about half of the undergraduate students in the U.S. receive their college education within fifty miles of their home, all institutions of higher learning ideally would have first-rate research programs. Such a goal would require that research resources, now concentrated in the top research universities where cutting-edge R&D is performed, also be provided to a substantial number of other institutions. Such a trade-off again requires decision makers to balance competing opportunities, and emerging institutions must carefully select areas where they have the potential of achieving world-class excellence.

INTERNATIONALIZATION OF SCIENCE

International cooperation in science always has existed at the researcher level. This cooperation has led to the development of one of the most efficiently functioning of international markets, the market of ideas.

As the tools needed for advancing the frontiers in areas such as high energy physics and astronomy have become more and more expensive, the world is increasingly aware of the importance of cooperating more formally on related research projects. In high energy physics, for example, it is a more efficient use of resources for nations to join together to build one extremely high energy collider, at which scientists from all nations can work, than it is for each nation to attempt to replicate the effort on its own. By joining together to fund projects such as the Superconducting Super Collider (SSC), nations can, with the same resources, obtain the tools needed to advance the frontiers in a number of fields of science rather than in only one. Unlike some other forms of international exchange, genuine cooperation in science and technology benefits all participants. As has been said, "Science is the rising tide that raises all ships."

The United States continues to enjoy a preeminent role as the overall world leader in basic research. However, by focusing their resources and efforts, other countries have moved up to equal—and in some cases surpass this country—in narrow



areas. This is neither surprising nor necessarily bad. What is essential is that in those areas where U.S. activities do not define the frontiers, U.S. researchers must be close enough to those frontiers to exploit new discoveries rapidly and effectively wherever they are made.

In recent years, the United States has not been as effective as other nations in capturing the economic benefits from new knowledge in the form of new products or processes. Other countries have built on U.S. basic research, because the results of this research are, by their very nature, public knowledge, and progress in basic research requires an open system. The answer to current problems is not to attempt to protect or sequester new knowledge; rather, it is to strengthen the U.S. ability to apply new knowledge rapidly.

While the U.S. must invest to continue as the dominant provider of fundamental new knowledge in science and engineering, it should also continue to urge other countries to contribute to the growth of new knowledge to the extent of their capabilities. Openness has long been a characteristic of U.S. science, both basic and applied. Clearly, it has served the nation well and should continue. As other nations begin to contribute more extensively to the common pool of fundamental knowledge from which all draw, however, it is important that the United States take steps to insure a reciprocal openness, with maximum opportunities for mutual exploitation of new results as the overarching goal.

All countries that benefit from basic research have a responsibility to invest in the production of that research. Louis Pasteur once said, "Science knows no country because knowledge belongs to humanity and is the torch which illuminates the world." By continuing to invest in basic research, nations carry forward that torch to the benefit of their own citizens and of all peoples.



ROGER WALL

Science, Mathematics and Technology Education



AMERICA IS FACING a crisis in science and mathematics education, a crisis that extends throughout the U.S. educational system but is most serious in elementary and secondary education. Scholastic performance of American students lags behind considerably in school-age children in other industrialized countries. In addition, too many elementary and secondary school teachers have inadequate preparation for, and lack of, current knowledge of the subjects they are assigned to teach.

Quality of education is not the only concern. Too few American students are learning the skills necessary to qualify them to fill critical scientific and technical jobs. Student interest in science and mathematics is declining. In particular, the number of women and minorities seeking science courses and careers is relatively low, despite the fact that these groups comprise the largest share of new entrants to the work force.

As one indication of the declines in science and mathematics participation of large segments of our student population, consider the prospect that the United States may increasingly depend on foreign nationals to staff its university science and engineering departments and its industrial laboratories. Foreign students already constitute a large fraction—over 50 percent in some disciplines—of the enrollment in graduate degree programs in science and engineering in U.S. universities.

The crisis in elementary and secondary education extends beyond the question of who will become the next generation of scientists and engineers. Corporate leaders have expressed concern about the poor educational preparation of the technicians and semi-technical workers on whom the Nation depends to keep its airplanes flying, its computers on line, and its production machinery humming. In high-tech workplaces, including the service industries and automated factories of the future, more and more jobs require the ability to use computers and other sophisticated equipment.

The education crisis is compounded by the fact that the American public is not well informed about science and is uncomfortable with quantitative reasoning. Such widespread



scientific illiteracy and innumeracy make it difficult for many people to function effectively as citizens in a society marked by growing complexity and technical sophistication or even to grasp issues that affect their lives, from AIDS to the environment.

POLICY RELEVANCE

The Nation's concern about the performance of our schools, acknowledged in scores of reports, extends beyond science and mathematics and more than just the future supply of scientists and engineers is at risk. Declines in the performance of students in elementary and secondary schools directly affects the ability of the United States to compete economically and hence to provide jobs and a rising standard of living for its citizens. As the National Commission on Excellence in Education stated in its 1983 report on all aspects of American elementary and secondary education, *A Nation At Risk*, "If an unfriendly foreign power had attempted to impose on America the mediocre educational performance that exists today, we might well have viewed it as an act of war. As it stands, we have allowed this to happen to ourselves."

NATIONAL EDUCATION GOALS

- GOAL 1** By the year 2000, all children in America will start school ready to learn.
 - GOAL 2** By the year 2000, the high school graduation rate will increase to at least 90 percent.
 - GOAL 3** By the year 2000, American students will leave grades four, eight, and twelve having demonstrated competency in challenging subject matter including English, mathematics, science, history, and geography; and every school in America will ensure that all students learn to use their minds well, so they may be prepared for responsible citizenship, further learning, and productive employment in our modern economy.
 - GOAL 4** By the year 2000, U.S. students will be first in the world in science and mathematics achievement.
 - GOAL 5** By the year 2000, every adult American will be literate and will possess the knowledge and skills necessary to compete in a global economy and exercise the rights and responsibilities of citizenship.
 - GOAL 6** By the year 2000, every school in America will be free of drugs and violence and will offer a disciplined environment conducive to learning.
-

The Nation has begun to respond with a sense of urgency appropriate to a problem of this severity. President Bush, in



September, 1989, convened the Nation's first Education Summit with the Nation's Governors. The Summit led to the development of National Education Goals, which establish targets for American educational achievement by the year 2000 and serve as the framework for the national movement to improve education. Three of the six Goals are directly related to mathematics and science education (see Box).

The ongoing efforts to strengthen education received a further major impetus in April of 1991 when President Bush and Education Secretary Lamar Alexander announced AMERICA 2000, a long-term national strategy to move the United States toward the six National Education Goals. The strategy is not a Federal program but rather is a collaborative program focused on State, regional and local school participation. The Federal role in the overall strategy will include providing national leadership, the development of standards, highlighting and disseminating effective products and practices, providing Federal support for research and development as well as Federal seed money for a variety of activities, and providing flexibility in the use of federal resources in exchange for improved educational performance.

AMERICA 2000 EDUCATION STRATEGY

This strategy has four parts to be pursued simultaneously:

1. For today's students—we must radically improve today's schools, all 110,000 of them—make them better and more accountable for results. (Serves all six of the National Education Goals, but especially #2, #3, and #4.)
 2. For tomorrow's students—we must invent new schools to meet the demands of a new century—a New Generation of American Schools, bringing at least 535 of them into existence by 1996, and thousands by decade's end. (Serves all six Goals.)
 3. For those of us already out of school and in the work force—we must keep learning if we are to live and work successfully in today's world. A "Nation at Risk" must become a "Nation of Students." (Serves all six Goals, but especially #5.)
 4. For schools to succeed—we must look beyond their classrooms to our communities and families. Schools will never be much better than the commitment of their communities. Each of our communities must become a place where learning can happen. (Serves all six Goals.)
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Reform of mathematics and science education is a major task within the AMERICA 2000 education strategy (See Box). The task will not be easy. It involves turning around the quality of



mathematics and science education in a decentralized system that involves 46.8 million students and 2.8 million teachers in over 100,000 public schools in more than 15,000 school districts and over 25,000 private and religiously affiliated schools. However, if the Nation does not educate its children adequately, it cannot address long-term economic and social needs and may even find itself unable to compete in the emerging global economy of the 21st century.

Improving science and mathematics education will require greater efforts from all participants, including Federal, State and local governments, teachers, parents, students, professional associations, business and industry, community-based organizations, and individuals engaged in work relating to mathematics and science. Each has a stake in the quality and success of science and mathematics education, and each has a unique and critical role to play.

THE STATE OF EDUCATION

Leading the national effort to instill excellence in science and mathematics education is an important mission of the Federal government. The Bush Administration is giving priority to elementary and secondary mathematics and science education, focusing increased resources and attention on the crucial elementary and secondary years, while maintaining funding for other education levels. Specifically, Federal Agencies are emphasizing the following areas: student performance, teacher training, and curriculum materials; a scientifically and technically trained work force and enhanced science literacy.

Student Performance—Over the past decade many reports have called for the reform of American mathematics and science education, citing alarming evidence that U.S. student achievement in these areas is behind other nations. An international achievement survey that compared students in the United States to 15 other nations, revealed that American high school seniors scored among the bottom fourth on calculus and algebra achievement tests. Even the best American mathematics students—the top 13 percent—generally placed in the bottom 25 percent internationally. In a comparison with students in 12 other countries, U.S. high school students finished ninth in physics, eleventh in chemistry, and last in “advanced placement” biology. Overall, American high school students performed below their counterparts in Japan, China, Mexico, Canada, and Thailand.



In many of our high schools, upper level science and mathematics courses are frequently ignored electives or, too often, are simply unavailable. Nearly 30 percent of the U.S. high schools offer no courses in physics, 17 percent offer no chemistry, and 70 percent offer no earth or space science. Textbooks for the courses that do exist are sometimes outdated or inadequate. Elementary science materials are often unavailable or unused because of a lack of teacher training and inadequate classroom time spent on science.

To promote interest in the study of mathematics and science, States and schools are being encouraged to adopt curricula linked with the real world of science by increasing student exposure to the latest scientific and technical developments, using hands-on activities and contact with working scientists and advanced facilities. Efforts will be made to capture the interest of elementary school-age students in science, so they will be motivated to continue their study in high school. Targeted Federal programs will continue to help States develop programs in which students complete high school with competency in mathematics and science and are encouraged to enter college to receive further education in these subjects. The Administration's AMERICA 2000 education strategy includes legislation to provide special incentive awards to schools whose students show significant achievement gains over a 3 year period.

Teacher Training—Teaching is a profession in crisis. In spite of their tremendous responsibilities, many teachers suffer low salaries and low status. Recruiting qualified science and mathematics teachers is becoming a great national challenge. In the United States today, there are 2.3 million public school teachers in grades K-12. The Department of Education estimates that over the next decade, schools must hire 1.6 million new teachers, or an average of 160,000 a year. Yet the primary source of new teachers, college students majoring in education, has fallen 55 percent since 1972 and today this source supplies only about half the teachers that will probably be needed in the future. If it is particularly difficult to recruit teachers for certain urban and rural areas; it is even harder to retain them. Twenty percent of new science and mathematics teachers leave during their first year, and more than half leave before the sixth year.

The numbers of recent college graduates in new mathematics and science education do not in any case meet the need. Over 60 percent of junior high and high school principals say they have difficulty hiring qualified teachers for physics, chemistry,

The Bush Administration is focusing increased resources and attention on the crucial elementary and secondary years.



and computer science classes. With decreasing enrollments in mathematics and science at the undergraduate level, the problem is likely to get worse.

Serious concerns exist for maintaining and improving the quality of mathematics and science teaching. Few elementary school teachers have adequate preparation in science and mathematics before they begin to teach these subjects. Leading professional associations of mathematics and science educators have established standards for course work preparation for teachers. By their estimates, two-thirds or more of the nation's teachers do not meet these standards (Table 1):

Table 3.1 Percentage of Teachers Meeting Preparation Standards

	Science	Mathematics	Biology	Chemistry	Physics
Elementary School Teachers	33%	18%			
Middle School Teachers	22%	14%			
High School Teachers		15%	29%	31%	12%

To improve the quality of preparation and ability of teachers to teach math, the sciences, and other subjects, the President proposed Governors' teacher academies, to be funded in every State. More students taking science courses will form a larger pool of future teachers in critical scientific and technical fields.

Systemic Factors—A key element of AMERICA 2000 is the work of the New American Schools Development Corporation (NASDC). The NASDC is a private effort to raise \$200 million to help communities create schools that will reach the National Education Goals. The NASDC will fund R&D teams working with local communities to set aside traditional assumptions about schooling and loosen the constraints surrounding the operation of conventional schools. Time, space, staffing and other resources in these new schools may be used in new ways. Changing policies and practices within the formal settings of schools could have significant affects on the performance of students and on the ability of teachers to work with them.

There is growing recognition that teachers and students individually cannot solve all the difficulties encountered in mathematics and science education, and that resources beyond the formal settings of schools and campuses need to be exploited.



Many mathematicians, scientists, and educators have advocated more direct contacts between teachers and the science community and use of hands-on learning in elementary and secondary classrooms. Yet studies indicate that little hands-on science is taught at the elementary school level and that the amount of hands-on assignments and student experiments has actually declined in recent years. In secondary schools, instruction in 50 minute periods makes it impossible to do many kinds of science experiments or to explore complex mathematical problems in detail. Restructuring efforts, applications of interactive technologies, and alternative courses of instruction underway in many parts of the Nation are demonstrating more effective ways of engaging and motivating students. The Federal government has recognized and will continue to support these State and local reform efforts.

Competitive Work Force—If present trends in education continue, this country may not produce enough American scientists and engineers to meet its work force needs. Large numbers of those who entered the scientific work force after World War II are beginning to retire, with an insufficient number of science students progressing through the American educational system to take their places (Figure 1). There also appears to be a lack of technical competence among new entrants to the general work force, with many major industrial corporations reporting that the majority of employee applicants lack basic skills and abilities for today's computerized work place.

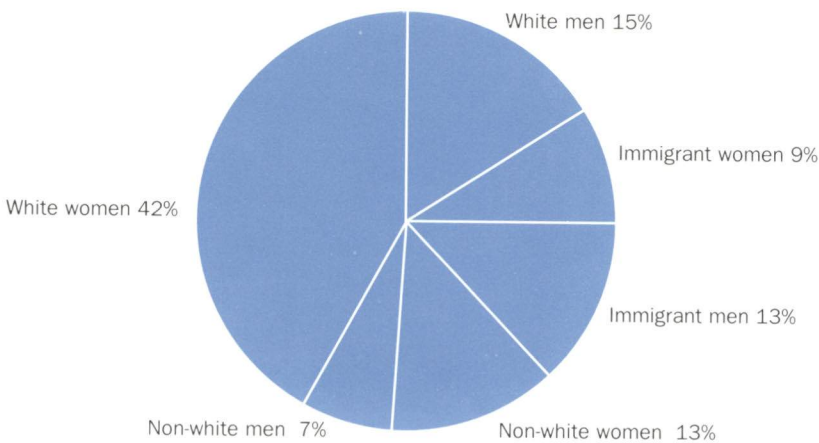


Figure 3.1 The Changing Labor Force
Net New Workers, 1985-2000

Source: U.S. Department of Labor



Low enrollments in upper level science courses are contributing to shortages of technical workers. Using 1989-90 State data, it is estimated that 95 percent of public high school students in the U.S. take biology by the time they graduate, but only 20 percent take physics and 45 percent take chemistry. Underlying these numbers is a growing disenchantment with science and technology as prospective careers. Among freshmen entering college, interest in science majors has declined by one-third over the past two decades; interest in engineering has fallen by a fourth since 1982; and interest in computer science has plunged by two-thirds in just four years.

Without growth in student interest and ability in science and technology, America's once-impressive lead in science and engineering talent may begin to falter. Japan, for example, has doubled its technical work force in the last two decades; with half the population size of the United States, Japan trains almost as many engineers each year as does the United States.

The problem of keeping students in science and mathematics courses as they progress through the educational system is even

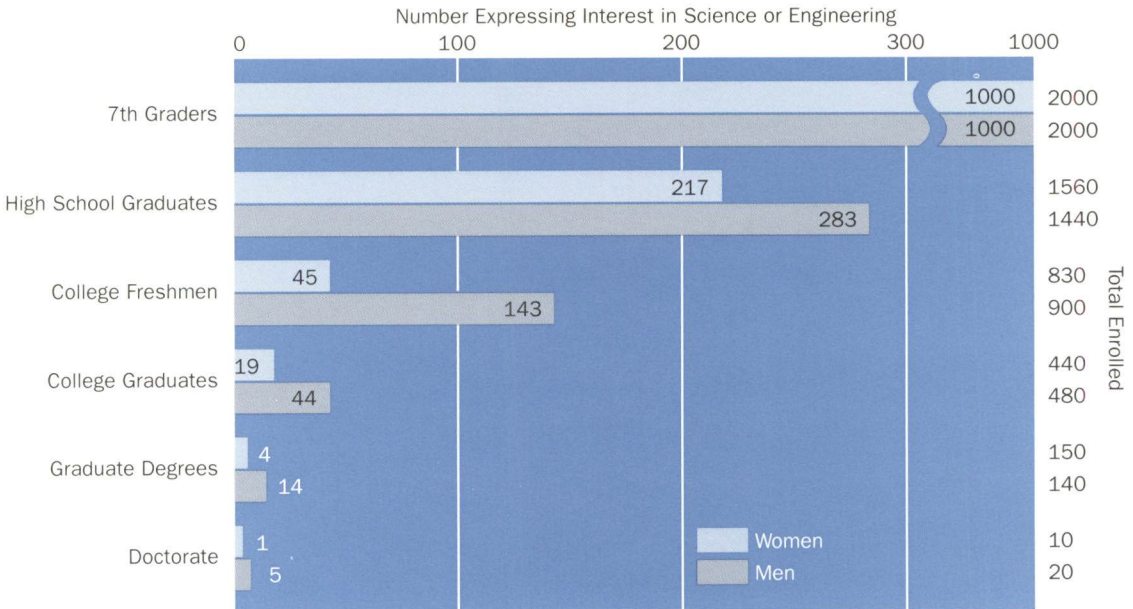


Figure 3.2 Pool of Potential Scientists and Engineers Among U.S. Students

Source: National Science Foundation



greater for women and minorities. This group, together with foreign nationals, will comprise 85 percent of the net new entrants into the American work force between now and the year 2000 (Figure 2) and will be called upon to replace the growing number of white male retirees. Yet these individuals have not traditionally comprised a major part of the technical work force. Today, only 8 percent of bachelor's degrees and 4 percent of all doctorate degrees in science and engineering are awarded to African and Hispanic Americans. By the turn of the century, minority students will account for more than 40 percent of the U.S. elementary and secondary school population. Thus, it is urgent that the Nation take steps to ensure greater participation by these groups in the scientific and technical work force.

The AMERICA 2000 strategy, its supporting legislation, the Administration's Job Training Partnership Act amendments and its workplace literacy and related skill training strategies all support the goal of developing a competitive work force. In addition, multiple Federal programs will continue to improve career awareness and educational opportunities for women, minorities, and individuals with disabilities who are integral to the future work force of the Nation.

Scientifically Literate Public—A high quality basic science and mathematics education is a prerequisite for those who eventually choose careers in science and engineering fields, but it is equally necessary for the balance of our population if our citizens are to understand the scientific and technical issues that affect their lives: space policy, nuclear energy, AIDS research, or human impact on the environment.

Although Americans have universal access to education and broad access to information, the level of scientific literacy in the public at large is distressing. In one recent study, half the adults questioned did not know that it took one year for the Earth to orbit the Sun. Science literacy will be critical to an increasingly wide range of jobs — from repairing heavy machinery to using a scanning electron microscope, from using computers in the office to operating an automated production line. In addition, science literacy is already an important job component in careers as diverse as food production, transportation, communication, forestry, water and environmental management, weather monitoring, national defense, and public health. It is increasingly likely that each individual will have several jobs during his or her lifetime, and must have the basic skills and flexibility necessary to change with the changing job market and to continue



the learning process throughout adulthood. In short, the quality of basic science and mathematics education is an issue for all Americans—citizens, workers, educators, and parents.

SCIENCE AND MATHEMATICS EDUCATION

A key dimension of educational reform, the need for national standards with local implementation, was strongly reinforced by the Education Summit of State Governors and the President and the subsequent adoption of the National Education Goals and the AMERICA 2000 education strategy. Standards for mathematics education have been developed under the auspices of the National Council of Teachers of Mathematics. This pioneering grass-roots effort can lead the development of mathematics curricula in the 50 states to ensure that students master the standards. The Association of State Supervisors of Mathematics is undertaking additional programs to translate the National Education Goals into state and local plans by training over 900 teachers who can then further spread the reform effort. The National Science Foundation and the Department of Education have funded the National Academy of Sciences, National Research Council to coordinate the development of world class Standards for K-12 science education.

Another initiative involves expanded and revitalized efforts to enhance the competence and status of science and mathematics teachers. By using Federal funds to leverage local funds for teacher enhancements, these efforts have the capability of reaching a substantial portion of the Nation's teachers. Efforts include programs administered by the Department of Education and the National Science Foundation that support teacher training and enhancement grants to State and local educational agencies, teacher workshops, research experiences, and plans for developing electronic networks which will enable teachers and school officials to communicate and share experiences with colleagues in distant locations.

Supplementing such programs are efforts to create closer ties between teachers and scientists. One aspect involves the participation of scientists and engineers, and partnerships with universities and research institutions of all kinds, in the education of young students. Scientists and engineers will come to the classroom to teach or serve as technical resources and mentors to teachers and students. Likewise, science and mathematics teachers will be brought closer to the mainstream of science and incorporate findings from science research into their instruction. Individual Federal agencies will play an important role in this



process, since many agencies conduct research and maintain laboratories or technical facilities located throughout the nation. This unparalleled collection of facilities will be utilized more fully to serve mathematics and science education, benefiting local communities and the nation as a whole. Already, Federal agencies such as the Department of Energy are developing formal partnerships between National Laboratories and local school systems. These partnerships provide technical assistance to the school systems, including short courses and institutes for teachers on energy-related topics, the loan of equipment, and help in developing classroom and out-of-classroom science experiments; they also provide summer research appointments for teachers and students and mentoring of students by laboratory scientists. Perhaps the most important aspect of such interactions is the potential for increasing the motivation of both students and teachers.

A third initiative involves innovations and experiments using new and advanced telecommunications technologies. It is expected that electronic network services and interactive video technologies will have a major impact on learning in and out of schools. These innovations, summarized in reports by the Congressional Office of Technology Assessment (OTA) and the National Telecommunications and Information Administration (NTIA), include satellite and fiber optic networks that have enormous potential for sharing master teachers and for teacher training at the school site. There are already several national consortia providing interactive video instruction on a regional or national scale. Increasing applications of the power of computers and high speed computer networks should give students broader access to information and learning tools, to share vast amounts of data and programs within a school or across school boundaries. New educational technologies are likely to intensify pressures for restructuring the schools and removing antiquated barriers.

New educational technologies are likely to intensify pressures for restructuring the schools and removing antiquated barriers.

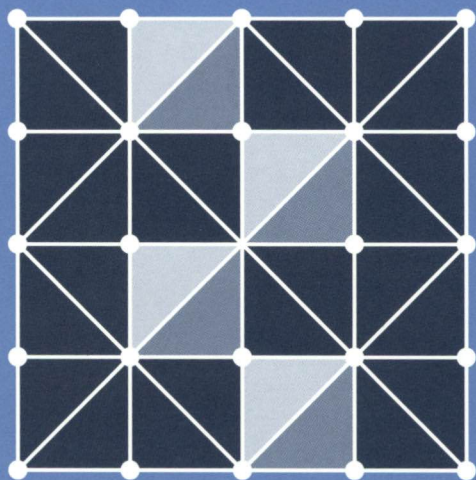
CONCLUSION

The United States is facing a crisis in science and mathematics education, centered on elementary and secondary school levels. The crisis relates to the Nation's ability to educate the next generation of scientists and engineers in adequate numbers, given the rapidly changing demographics of the American public. It also relates to the technical competence of the general work force in an increasingly computerized and high-tech work envi-

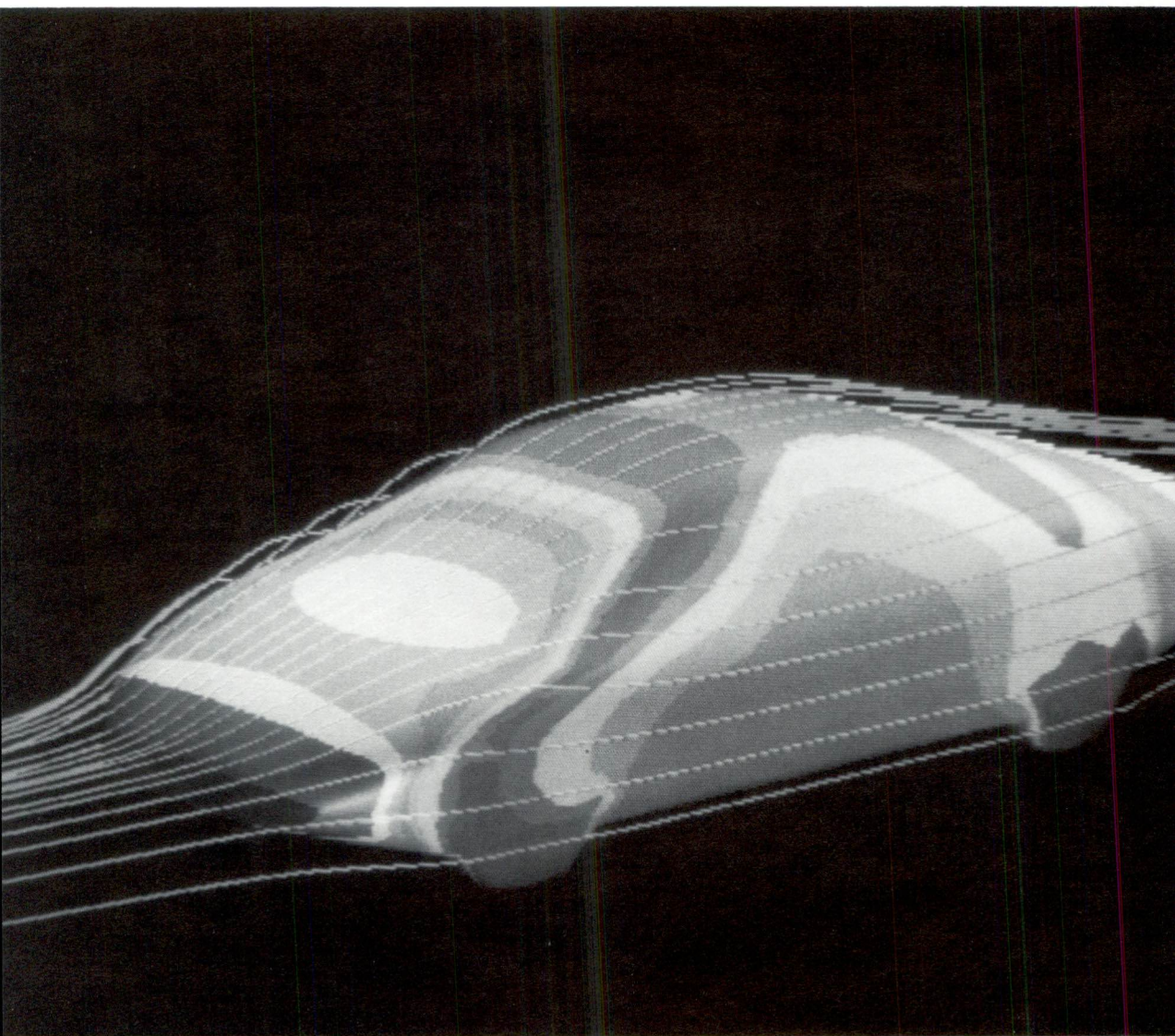


ronment and the ability of U.S. citizens to exercise the rights and responsibilities of citizenship in an ever more complex world. The concern is that, if the Nation does not educate its children adequately, it cannot address long-term goals and social needs and may find its ability to compete in the global economy impaired.

The Education Summit led to the National Education Goals and the AMERICA 2000 education strategy, and plans for the development of National Standards which serve as a framework for the national effort to improve education across the board. The Bush Administration, in translating the goals into programs to promote excellence in science and mathematics education, is giving priority to elementary and secondary education. The programs under way include efforts to motivate students to stay in science and mathematics courses, to enhance teacher skills, to increase the participation of underrepresented groups in the technical work force, to rethink and restructure the school system, and to improve public science literacy. New initiatives include the development of national frameworks for mathematics and science curricula, efforts to forge closer ties between teachers and working scientists, and the application of new technologies to improve education.



Meeting the Nation's Needs Through Science and Technology



HANK MORGAN/RAINBOW

High Performance Computing and Communication



HIGH PERFORMANCE COMPUTERS and the data networks that connect them are becoming increasingly important to scientific advancement, economic competition, and national security. The technology has the potential for extraordinarily rapid advances within the next five years—a 1000-fold improvement in computing speed and a 100-fold improvement in the transmission rate of data networks. As such, the technology is close to the point of having a transforming effect on industry, educational institutions at all levels, and society as a whole.

Such a transforming effect is already evident in scientific research and in engineering practice, where computational methods have joined, and in some areas displaced, the traditional methods of observation and experiment. In the design of commercial aircraft, for example, many engineering issues are resolved through computer simulation rather than through costly wind tunnel experiments. Access to high performance computers is already essential in many fields of research, from theoretical astrophysics to the study of complex biochemical molecules to climate prediction.

Despite remarkable advances over the past 30 years, however, computers have far to go to realize their full potential. Without unprecedented advances in computer technology, operating software, and computational techniques, many fundamental scientific problems whose solution is critical to national needs will remain beyond reach. Moreover, many information-processing applications of great economic and social importance will require unleashing the full power of which high performance computing systems are capable.

A 1000-fold increase in computer speed in half a decade would be a magnificent achievement, one which is likely to involve a radically different approach to computing known as “scalable parallel systems.” Unlike most of today’s computers that have a single processor, a scalable parallel computer can employ tens of thousands of processors and achieve a speed that is proportional to the number of processors. With increased



numbers of processors, however, comes increased complexity, particularly in the software needed for operating systems. Nonetheless, there is optimism that a concentrated effort can resolve such difficulties and accelerate the development of a new generation of high performance computers.

Such computers will enable a more efficient, integrated approach to the design and manufacturing of many kinds of products. They will also facilitate new, more powerful methods of managing or even creating information and the ability to display it in graphic forms that enable the human brain to grasp patterns and complexities heretofore unimagined. High performance computers also exert a strong leverage on the rest of the computer industry. Historically, just 15 years separated the appearance of a new supercomputer and the availability of the same computing power in desktop machines.

So far, high performance computers are located primarily in major research laboratories and large companies. But for high performance computing to realize its potential, this computing power must also be accessible to researchers in colleges and universities, to small and medium-sized businesses, and ultimately even to the classroom at both college and pre-college levels. A national computer network capable of communicating at speeds measured in billions of databits per second—100 times faster than present technology allows—would make such widespread access possible.

Many computer networks are already in place. In a growing number of science and engineering fields, progress and productivity in modern research are increasingly dependent on the close interaction of people located in distant places. Computer networks, by providing low cost communication and essentially instantaneous transfer of data and graphic information, makes such interaction possible. Use of existing networks is growing rapidly, doubling every six months. But for high performance computing much higher communication capacities and speeds are required to accommodate this growth, to handle the volume of data that high performance computers and new generations of space- and land-based remote sensors generate, and to expand and link existing networks into a major national communication infrastructure for research and education.

These high capacity networks will have the capability to "shrink the world", rendering physical distances less important, and at the same time expanding the world of information available to individuals. Access to the vast stores of information that



already exist—in laboratories, in government agencies, in museums and libraries—and the computing power to shape and present that information in forms appealing to the human mind could enormously enrich American society.

POLICY RELEVANCE

The national stakes in high performance computing include the enhancement of research itself, because advances in this revolutionary technology enable progress in almost every other science and engineering discipline. Achieving the prospective 1000-fold leap in computing power is essential to solve some of the Nation's critical problems such as climate prediction (important to the Nation's energy strategy), language translation, and cognition. A high speed network is equally essential to give the nation's scientists and engineers ready access to high performance computers and to facilitate the collaboration of physically distant research groups, thus making the most efficient use of the nation's scientific talent.

But very fast, very powerful computers and the high-speed networks to link them are tools of vital importance far beyond the university or the federal research laboratory. These technologies are economically important because they are pertinent to virtually every industrial field. High performance computing can speed the pace of innovation and spur gains in U.S. productivity and industrial competitiveness by transforming the process of product design and production throughout the U.S. economy.

High performance computing is already important in national security and national defense, in the analysis of intelligence and in the development of advanced military technology. Its importance has been proven through electronic battlefield management and missile defense which are central to today's military strategies.

Finally, high performance computing and communications also has the potential to transform and enrich education at all levels, making immense libraries of information and powerful learning aids universally available in every school in the nation. A high-speed, high-capacity network could link students to distant scholars or master teachers, could offer students at rural schools the same wealth of visual materials and advanced curricula that their urban counterparts have, and could make science courses available even in schools that lack modern facilities. Ultimately the network could facilitate the ability of schools at all levels to offer individualized instruction to every student.

Very fast, very powerful computers and the high-speed networks to link them are tools of vital importance far beyond the university or the Federal research laboratory.



THE HIGH PERFORMANCE COMPUTING AND COMMUNICATION INITIATIVE

To accelerate the commercial availability and utilization of the next generation of high performance computers and networks, the Bush Administration has proposed a strategic Federal investment in the frontiers of computing and computer communications technologies. The program has four components representing the key areas of high performance computing and communications:

High Performance Computing Systems: the development of the underlying technology required for computing systems capable of sustaining trillions of operations per second on large problems. One key challenge is the development of new computer designs or architectures that can operate thousands or tens of thousands of processors in parallel. Many future designs will involve "scalable" architectures, meaning that additional processors can be added without changing the design leading to performance increases nearly proportional with the number of processors. Thus, a single design could be used to build computers with a wide range of computing power.

Advanced Software Technology and Algorithms: the development of generic programs and calculational rules for applying high performance computer systems to critical scientific problems. A key challenge is to discover ways of splitting up major parts of a problem into many loosely coupled pieces in order to take advantage of parallelism and to integrate the outputs of the processors into a solution for the overall problem. The plan is to do this on a number of "grand challenge" problems that will tax the capability of the most powerful computer, whose solutions will represent major achievements in their own right.

National Research and Education Network: the development of a national high speed network to provide high performance computing capability to research and educational institutions and to further advanced research on such networks and their applications. To accommodate many types of users and link many different computers, for example, may require development of a hierarchy of communication paths—like high speed and low speed lanes on a turnpike—together with uniform "rules of the road" for navigating on the data highways. Another challenge will be to enable network users to find readily the information they seek among a vast and potentially confusing array of electronic libraries and data depositories.

Basic Research and Human Resources: support for fundamental research in computer and computational science and engi-



neering activities to significantly increase the pool of trained personnel, and support for efforts to accelerate technology transition. A predicted potential shortage of programmers and computer scientists, for example, would severely inhibit the nation's ability to exploit and commercialize the advances expected in high performance computing.

The program provides for development of these revolutionary technologies within the framework of a partnership among government, industry, and universities which allows for rapid translation of laboratory results into new products.

STATE OF THE TECHNOLOGY

The development of high performance computing poses significant technology challenges in both hardware and software. Use of these technologies and development of specific applications will engage the entire scientific and engineering community. Central to high performance computing is the new technology known as parallel processing, which emerged in the early 1980s from research that began two decades earlier. This innovative approach to high performance computing has the potential to achieve sustained speeds 1000-fold faster than current systems.

Hardware—The generation of supercomputers pioneered by Seymour Cray achieved their performance through the use of the fastest possible components and most advanced technologies. In current versions, these computers employ a single, very high speed processor or make use of a limited amount of parallelism—employing up to eight parallel processors—and reach speeds up to 3 billion operations per second. Computer architectures with higher levels of parallelism, in which the computational workload is shared among many simpler and less costly processors, promise significantly faster high performance computers. Not all computational problems lend themselves to parallel processing approaches, however, so that this new approach will complement rather than replace conventional supercomputers.

The recent development of massively parallel, scalable computers is based on sharing a single computational task among a very large number (up to 64,000 at present) of processors. These processors are each of moderate speed but connected in a sophisticated communication architecture so that the overall speed on a single task is proportional to the number of processors used. The increase in speed in proportion to the number of processors is known as scalability, and verifica-



tion of this ability over a range of meaningful problems was an important achievement of the 1980s.

An important benefit of the scalable architectures is that a single design, with its attendant components and software, may prove to be useful and efficient over a performance range of 10 to 100 or more. This would allow one design and one set of operating and applications software to be used for a family of work stations, mini-supercomputers, and very high performance computers.

The United States is currently the leader in developing scalable parallel processing computers and the component processors for these computers. The first generation of such systems is now commercially available. One example is the Touchstone-Delta system, built by Intel and recently installed at the California Institute of Technology, which has achieved speeds of 8.6 billion operations per second on "benchmark" problems. Comparable systems do not yet exist outside the United States.

Experience with these systems has shown that, even with existing software, they are effective for certain classes of problems. New approaches to software for these large scale parallel systems, now beginning to emerge, indicate that parallel computing can be applied to wide classes of scientific and engineering problems. However, exploiting parallel processing effectively presents significant challenges. To achieve high performance computers operating in the range of a trillion operations per second will require major improvement in many aspects: faster processors, faster inter-processor communication, and improved algorithms and software.

Software—Computer hardware, by itself, can do nothing until its power is tapped by the sets of instructions, or software, that guide computer operations. Historically, advances in software and in computational methods have proved just as important to advances in computing as hardware advances. In several classes of scientific computing problems, for example, hardware improvements yielded a 1000-fold speed-up over 20 years, while improvements in software and algorithms yielded a 3000-fold speed-up over the same period.

As high performance computing systems evolve, it is becoming clear that major advances in software are also essential to realize their full performance potential. Software development is difficult and costly for traditional computer architectures, and parallel systems pose even greater challenges. Too often, new high performance computers are released with weak system



software and inadequate programming tools, thus slowing the development of applications software. Current approaches to software development often do not yield portable and reusable programs. A lack of portability—the capability of moving software from one type of computer to another—significantly raises the cost of transition to newer architectures for many applications programs. Approaches that facilitate the reuse and portability of programs need strong support.

Parallel computers raise some specific software challenges, such as finding the efficient methods of problem solution with effective distribution of tasks among processors. Although it is not yet possible to define the optimum distribution, important progress has been made in the development of computational models and parallel algorithms for many key problem areas. Access to high performance parallel systems is an important element in such progress. Experience has shown that the quality of system and application software increases rapidly as computing systems are made more available.

Networks—Many educational institutions, government laboratories, and industrial research facilities in the United States are currently connected to a world-wide computer network called the Internet. However, the Internet falls short of what is required for a national computer communications infrastructure in both capacity and in the number of institutions connected to it. The proposed National Research and Education Network is intended to help remedy these limitations by serving as a testbed for advanced networking concepts that will ultimately lead to high-speed, high capacity private sector networks as ubiquitous as the telephone.

Such networks are needed not only to provide high performance computing access to research and educational institutions at all levels and locations, but also to deliver new capabilities. Just as scientists are learning to do experiments and collect data remotely from space platforms, they will in the future increasingly conduct experiments remotely at ground facilities. Investigators at the University of Wisconsin, for example, collect data from and control experimental apparatus located at the National Synchrotron Light Source on Long Island over an optical fiber network.

The new network is intended to stimulate the development of technologies that will enable a hundred-fold increase in capacity and speed and of a wide range of network applications. The Federal government does not own the optical fibers over which

The Bush Administration has proposed a strategic Federal investment in the frontiers of computing and computer communications technologies.



Internet travels, nor will it in the proposed National Research and Education Network.

Some of these applications, such as remote control of scientific experiments and distance learning in schools, may initially be extensions of current technology. However, networks capable of far higher speeds will be needed to support access to remote digital libraries and high performance computers. Other applications of interest include real time visualization of modeling and simulation results, rapid interrogation and retrieval of scientific data from specialized data bases, teleconferencing, and new forms of computer-supported cooperative work.

One example of the potential uses for a high speed computer network is provided by the field of radiology. Departments of some of the nation's leading medical centers plan to share and transmit digital radiological images on networks operating at speeds of 100 million to one billion data bits per second. Such applications will require significant advances in the areas of network protocols (the formal structure of inter-computer communications), high speed computer interfaces for computers, and network equipment such as switches. Another priority need is for advanced software that exploits the capabilities of the network to store computer files in a distributed manner and to serve as a national software library.

The development of more powerful computers feeds both the demand for, as well as the growth of, more powerful data communications capability. As computing technology progresses, greater demands are placed on network performance as researchers conceive of new tasks and modes of use that require even higher performance. Current developments in large scale scientific computing are leading to truly distributed computing, allowing a given job to be executed on several different machines communicating partial results among themselves, sharing in different facets of calculations, and jointly assembling a final result for output. Such inter-machine communication can in principle take place at speeds that are a hundred or more times faster than are possible on today's long distance networks.

Applications conducted over a computer network vary in their flow of information from steady, as in the transfer of files between two computers, to intermittent bursts, as in human-computer interaction via keyboard. Similarly, some applications can be carried out at relatively low communication rates, while others by their nature require high speeds (Figure 1). Traffic seen in the early days of networks appears near the bottom of the chart. More advanced applications are furthest from the origin. The



chart illustrates that a network operating at the rate of a billion bits per second (one gigabit) is needed not only to carry the aggregation of low speed traffic, but also to accommodate high speed uses.

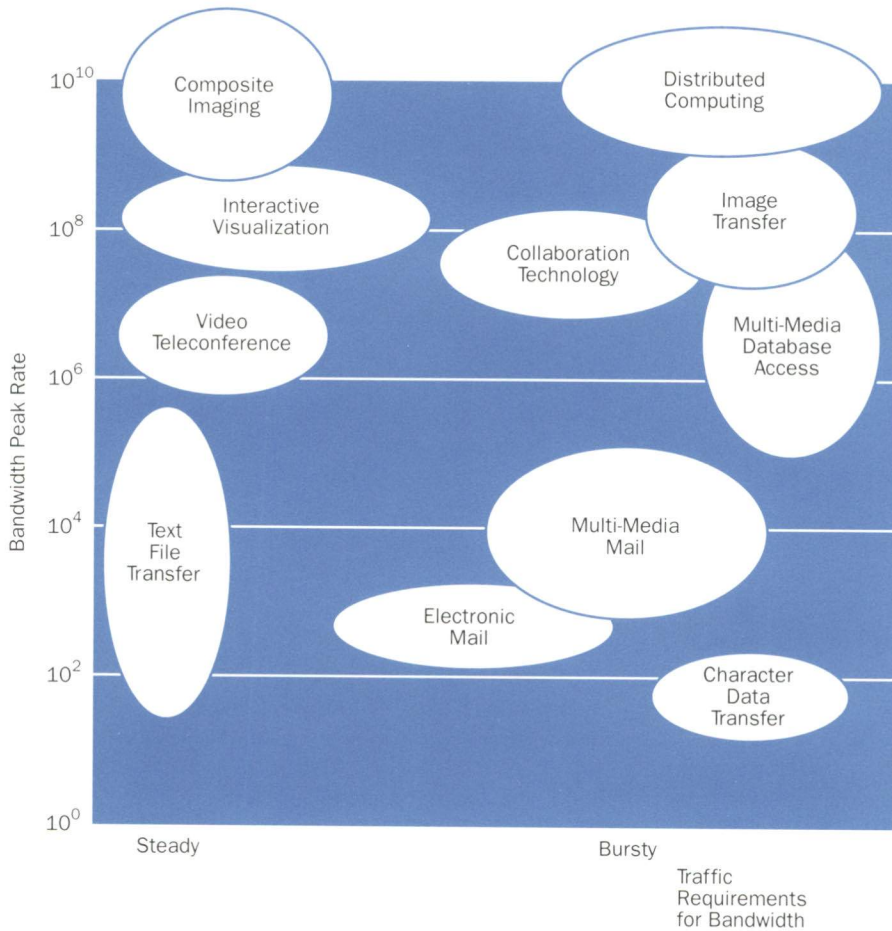


Figure 4.1 National Research and Education Network Applications

Source: Office of Science and Technology Policy

In addition to serving the needs of the scientific and research communities, the National Research and Education Network will provide valuable experience necessary for the successful development of a broader, privately-operated national information infrastructure. Such an infrastructure would allow consumers,



businesses, and schools and government at all levels to share quality information and entertainment when and where they want it at a reasonable cost.

Human Resources—A growing pool of scientific and engineering talent will be required if the potential of high performance computing and high speed networks is to be realized. The most recent analysis by the National Science Foundation, however, concludes that the greatest shortfalls of trained personnel in the United States will be in the areas of computer science and engineering, amounting to hundreds of thousands of people over the next decade. Additional efforts are needed to attract new talent into this field, and to retrain people to new skills. The rapid pace of knowledge creation and technical innovation in computing necessitates attention to infusing new skills throughout the entire human resource “pipeline”, of educational opportunity. Thus, the Basic Research and Human Resource components of the HPCC Initiative will create for students and their teachers new formal learning programs. It will involve them in research experiences for “hands-on” informal training. It will provide opportunities for researchers young and old to acquire new skills, to reach across traditional disciplinary boundaries to work with the new technologies on the “Grand Challenges”.

ILLUSTRATING THE IMPACT: GRAND CHALLENGES

Computers already play a fundamental role in the process of scientific discovery in almost every field. Yet scientists and engineers have long been limited in their ability to deal with a group of fundamental problems whose solution is critical to national needs and to the missions of Federal agencies. These “grand challenge” problems include: prediction of weather and climate; determination of molecular, atomic, and nuclear structures; understanding turbulence, pollution dispersion, and combustion systems; mapping the human genome and understanding the structure of biological macromolecules; understanding the nature of new materials; real-time language translation; and understanding of the cognitive functions of the human brain.

Computer-based methods can, in principle, help to solve many grand challenge problems. At present, however, such solutions would require years of calculation with the fastest supercomputers now available (Figure 2). The implications of this “computation gap” for a number of grand challenge problems are discussed in this section.

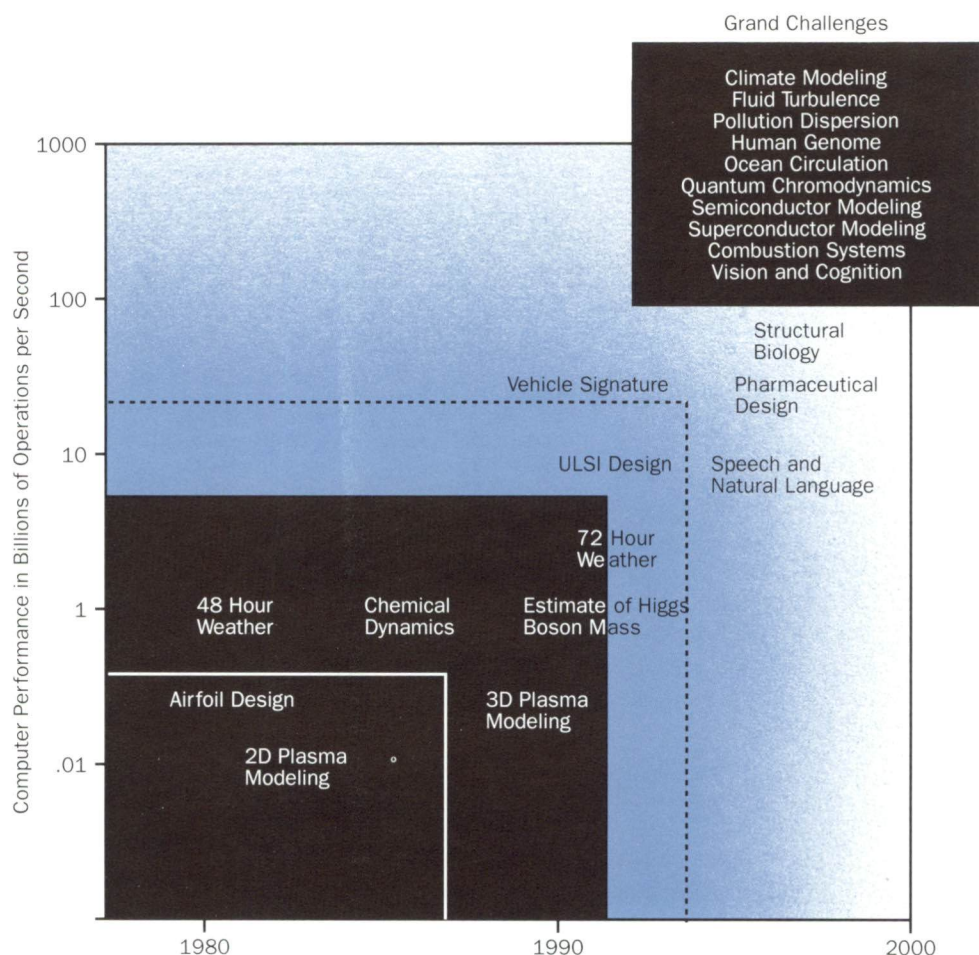


Figure 4.2 Performance Requirements for Grand Challenge Problems

Source: Office of Science and Technology Policy

In Science—One example of the growing role of high performance computing in science concerns the genetic basis of cancer and other diseases. The genes are contained in DNA, the molecular thread in the nucleus of each living cell which guides the assembly of molecules and complete living organisms. When the genetic code is altered by mutation, serious diseases can result, such as cancer. This phenomenon was known to scientists studying animal tumors in the 1970s. They isolated cancer-causing genes, called "oncogenes" from animal tumors, and later found that similar genes existed in normal human DNA. This was



a profound mystery. Why would people carry the seeds of their own destruction in their genetic inheritance?

In 1984, two separate research groups used a computerized searching algorithm to compare a newly discovered oncogene to the relatively few genes known at the time. To their astonishment, the cancer causing gene matched a normal gene involved in growth and development. Suddenly, it became clear that cancer might be caused by a normal growth gene being switched on at the wrong time. This fundamental and unexpected insight was an early example of a field that is now known as Computational Biology, the science of using computers to store and analyze data from complex molecules in living cells.

What is pertinent here is how rapidly the potential for—and the demands on—Computational Biology have expanded. The databases used in 1984 for the oncogene comparisons contained information about several thousand DNA building blocks, called nucleotides; now they contain over 30 million. Moreover, current research programs to map the entire human genome, as well as those of selected simpler organisms, will acquire data on tens of billions of nucleotides. The best computer algorithms for determining the similarity of genes require time proportional to the length of the DNA being compared; if the methods used to analyze oncogenes in 1984 were applied to the three billion base pairs of the human genome, they would require hundreds of years of computer time on today's fastest supercomputers.

At the same time, progress in medical genetics has made clear the large number of diseases that derive from a genetic defect or an inherited propensity, from cystic fibrosis to many forms of heart disease. Rational drug design based on the deliberate alteration of complex biological molecules is increasingly the focus of pharmaceutical research. New computer designs and software methods will be essential to cope with the explosive growth of genetic and molecular data and to exploit it fully to relieve human suffering and disease. Functioning as intellectual amplifiers to detect similarities and differences in molecules whose size and complexity are too vast for the unaided human mind, high performance computer systems will be a critical tool for the life sciences in the 1990s and the health care systems of the 21st Century.

A similar phenomenon is occurring in the Earth Science field. Remote sensing instruments on satellites provide a growing flow of data and images to characterize the planet, reporting on temperature and cloudiness, tracking severe storms, assessing crop yields and the extent of deforestation. Storing, processing, and



analyzing this data already requires substantial computing resources. To produce a global view of the Earth's ocean chlorophyll and land vegetation, for example, required the processing of over 2 trillion bytes of raw data, accumulated over several years. By the year 2000, advanced new satellite systems with higher resolution sensors are expected to increase the flow of data a thousand- fold, sending back to Earth many trillions of bytes of information every day. For example, as currently planned, the Earth Observing System spacecraft that are part of the National Aeronautics and Space Administration's Mission to Planet Earth will return data equivalent to the entire contents of the Library of Congress more than once a week. To fully utilize this information to describe and document changes in climate, in biological productivity, and in land use will require major improvements in the means for collecting, analyzing, distributing, and archiving data.

To answer critical questions about the future climate of the Earth and the impact of human activities on the environment requires the ability to predict, not just describe, global change. Current computerized models of the atmosphere must be extended to include the coupled behavior of the full Earth System, including land, air, sea, ice, and biosphere components and to do so with far greater geographical resolution. The computational requirements exceed the capacity of even the most powerful of present computers by a factor of a thousand in speed. Also needed are advanced software and algorithms for handling massive amounts of data and working with coupled models of the Earth System.

On a regional level, high performance computers will be needed to model air pollution and to predict the effectiveness of regulatory control strategies, as mandated in the new Clean Air Act. Since the "killer fogs" in London, England and Donora, Pennsylvania caused the deaths of hundreds of people in the 1950s, the ability of the atmosphere to absorb and to cleanse itself of pollutant contaminants is no longer taken for granted. Legislation has mandated emissions controls on automobiles, factories, and power plants. However, reduction strategies of individual pollutant types do not always produce the desired results. In fact, these simple solutions can even make air quality worse due to complex chemical interactions of the remaining airborne contaminants.

Unburned hydrocarbons from fuels and oxides of nitrogen produced in the combustion process can be transformed in the atmosphere to ozone, the main constituent of urban smog.

The databases used in 1984 contained information about several thousand DNA building blocks, called nucleotides; now they contain over 30 million.



Pollutants may travel long distances from urban or industrial centers, contributing to the haze that obscures some natural wonders or to the development of acid rain that endangers sensitive upland lakes and forests. Because these complexities of pollutant transport and transformation are costly and difficult to study experimentally, numerical models of the atmosphere have been developed to assess the effects of man-made emissions on air quality. But present computing limitations force simplifications in the scientific descriptions of chemical and physical processes, and slow examination of alternatives. Control strategies for each pollutant are often determined independently with little evaluation of pollutant interactions.

High performance computing will enable rapid numerical explorations of pollutant interactions and resulting pollution levels and distribution. Advanced computer designs and software methods will also help find the pollutant control regimes of lowest cost—an important consideration, since the potential cost to society of proposed controls is estimated to reach tens of billions of dollars. Improved visualization techniques will enhance the interpretation and evaluation of massive amounts of environmental measurement and computer simulation data. The result should be a better understanding of the actions needed to minimize pollutant damage to materials and environmental damage to crops while making our air safer to breathe for future generations.

On a local scale, high performance computing will make possible more accurate predictions of severe storms, hurricanes, floods, and other weather related phenomena. Current weather prediction models have been constrained both by inadequate data sets and by computer power. During the next five years, major progress will be made on the data using a combination of new ground-based and remote-observing systems. This leaves inadequate computer power as the primary stumbling block to operation of the advanced weather prediction models of the future.

Current weather prediction models have a resolution of about 40 kilometers, and hence must treat many small scale but physically significant events or processes, such as normal rain clouds, indirectly. Fine scale details that may affect the prediction for the surrounding area—in, for example, thunderstorm evolution—cannot even be addressed by the model. Improved models with a resolution of less than five kilometers have already shown significant advances in the accuracy of predicting a wide variety of weather events, from severe thunderstorms to lake effect snow-



falls. But to improve the resolution of the model by a factor of two requires an increase in computer power of almost a factor of ten, as well as comparable increases in supporting memory, mass storage and networks. For example, a model with five kilometer resolution could require a computer system capable of executing 20 trillion operations per second to produce forecasts on operational schedules. Hence high performance computing systems will be necessary to achieve the economic benefits of improved weather prediction.

In 1986, the world was excited by the discovery that a particular arium-copper-oxide compound is a superconductor at a temperature of 93° Kelvin, still very cold, (-287° F) but much warmer than any previous superconductor. This discovery sparked a worldwide effort to expand research to discover new superconducting materials. The economic benefit of a high-temperature superconductor is beyond calculation, portending the development of, for example, much more efficient power transmission and lightweight, powerful magnets to revolutionize the transportation business.

Advanced computing is a central part of the arsenal of research tools which will be necessary to reach that payoff. Despite these early successes, many questions remain before it is understood how some materials superconduct when very similar compounds do not. This understanding will be critical to predicting new superconductors, which might work at even higher temperatures, be less expensive, carry more current, or be more amenable to manufacturing processes. Increasing progress in all these areas is required before the impact of these new materials will be felt. The solution of physical models requires intensive calculations to understand the material structure. High performance computing can shorten the discovery process by allowing the development of accurate simulations to point experimenters in the most promising directions. For example, most of the groups looking for new superconductors are trying various copper-oxide combinations. Researchers are using high performance computers to explore the possibility of various combinations of elements that may lead to new superconducting materials.

In Industry—The development of high performance computing will impact not only industries that contribute to making computers, but also companies that use computers. The electronics industry is one that both makes and uses computers. The electronics industry is one that both makes and uses computers.



Since the invention of the integrated circuit in 1958, the number of transistors fabricated on a microchip has doubled every two years. The result is an ever-increasing complexity in the electronic design of chips, components, and packages. At present, for example, the complexity of detail incorporated in a single integrated circuit one centimeter square is equivalent to representing the map features, at a city block level, of the entire Eastern United States. The complexity of a five centimeter square module densely packed with a collection of chips would be the equivalent of a map of North and South America. Computers are already an essential part of the design process, which involves determining the interconnecting paths, selecting the right modules, testing the interfaces, and choosing the mix of technologies.

The complexity is rapidly increasing. The chips containing a few million transistors of today will evolve in the mid 1990s to chips containing tens of millions of transistors and more. The diversity of microchip technologies combined in a single module will allow unprecedented flexibility for designers. Managing this explosion in complexity would be overwhelming without the use of computational based approaches that reduce the time to develop such systems while optimizing the design itself. Thus, high performance computing applied to the microelectronic design process is itself an important tool in the evolution of high performance computing.

Similar examples abound in a wide variety of engineering and technological fields. Supercomputers are already used to predict the flow of air around a wing and other aerodynamic characteristics of aircraft and spacecraft prior to testing in wind tunnels or actual flight, because computational simulations of a particular design are faster and less costly. For advanced supersonic and hypersonic craft, wind tunnels tests will not be able to reach their designed speeds, making computer simulations even more important. Modelling the flow of fluids is also important in the design of automobiles and ships.

Improving the design and efficiency of internal combustion engines is important for both energy conservation and pollution control. Indeed, these goals appear to conflict, because automobile engines are most efficient when run at high temperatures, but increased temperatures also lead to increased nitrogen oxide emissions. What is required to optimize the design of an engine is a far better understanding of the combustion process, which involves over 400 chemical reactions of hydrocarbon and nitrogen. In present numerical models, however, only ten or



fewer of the most significant reactions are used, and even so the calculations require several hours on today's large supercomputers. To simulate the full 400 reactions would require better algorithms running on a machine 10,000 times more powerful.

In Education—Computers increasingly fill important niches in all phases of the learning process, providing flexible instruments for interactive instruction and student-based learning experiences. Their use in education both provides the skills needed to function in our increasingly technology-intensive world and aids teaching and learning of all science and engineering topics. The development of the National Research and Education Network will accelerate and transfer the technology of computer communications to the needs of educators and students. The result will be to empower them to share resources and ideas on a national scale.

A recent project provides an illustration of educational collaboration on a national scale that the network would facilitate. Secondary school classes in many locations chose a day to measure the length of the sun's shadow from a vertical measuring stick on the school grounds at 12 noon. Each class consulted maps and geography books to find its school's latitude, and sent the results to a shared database located in the U.S. and Canada. All schools then received the database of measurements from around the world, and each class used the complete database to calculate the curvature of the earth, and from that, the earth's diameter. A normally dry recitation of facts became an engaging problem-solving exercise because the students themselves derived the answer from their shared measurements. Along the way they learned geography, geometry, statistics, and how to collect and share data over computer networks, which became a learning laboratory without walls.

This project is similar to the way research scientists take advantage of high speed digital networks to conduct shared research that is "distance independent." What is needed is to scale up today's networks and make them not only faster, but also easier to use, with improved services so that the National Research and Education Network is readily accessible to all U.S. educational institutions.

The chips containing a few million transistors of today will evolve in the mid 1990s to chips containing tens of millions of transistors and more.

CONCLUSION

The field of high performance computing is making extraordinary advances. These gains have the potential of achieving a



1,000-fold increase in speed within the next five years through the development of the technology known as massively parallel processing. The resulting computers—harnessing tens of thousands of processors or more to attack a single computational task—may have extraordinary effects on the practice of science itself, making possible computational solutions to critical problems that are now beyond reach.

High performance computers may have a transforming effect on society, especially when coupled with high speed, high capacity computer networks. Such networks, capable of transferring huge quantities of information and graphics as easily as current communication networks complete a phone call, promise to provide broad access to high performance computers and to digital libraries and databanks. Very fast computers and the networks to link them have the potential to radically alter product design and production and thus speed the pace of innovation and increase U.S. industrial competitiveness. The same technologies can enrich education at all levels. For these reasons, among others, the Bush Administration has proposed a strategic Federal investment to advance the frontiers of high performance computing.



KAY CHERNUSH

Life Sciences and Biotechnology



PRIMITIVE BIOTECHNOLOGY dates back thousands of years, to the time when human beings unwittingly began using microorganisms to ferment beer or cause bread to rise. Traditional breeding techniques to improve livestock or crop cultivars are also a form of biotechnology. But beginning about 20 years ago, scientists learned to alter precisely the genetic constitution of living organisms, initiating a scientific and industrial revolution based on what we now call the new biotechnology.

This new biotechnology is a rapidly expanding collection of tools and technologies that allow unprecedented control over and manipulation of the genetic material of organisms. Collectively, these technological advances may well bring about momentous changes comparable to those during the Iron Age when man began to make effective tools for specific purposes, rather than relying upon crudely shaped stones. We now have in our grasp the means to produce large quantities of rare, medically-valuable proteins, to modify plants and animals to carry specific hereditary traits, and novel means to detect disease, produce useful chemicals, and clean up and restore the environment.

Biotechnology holds the promise of additional breakthroughs and a profound industrial transformation in the fields of health, food processing, agriculture, energy, and the environment. It has the potential to provide a wide array of benefits to humanity, including treatments for previously incurable genetic diseases; healthier meats, dairy products, fruits and vegetables; hardier, more productive crop plants; and additional production of renewable sources of energy.

The applications of biotechnology create many new beneficial opportunities while raising issues for public education and discussion. The use of powerful new medical tools such as genetic screening may eventually enable physicians to prevent certain inherited diseases or permit early therapeutic interventions in patients. Microbial organisms have the potential to reduce or eliminate adverse side-effects of current chemical-intensive agricultural practices as well as improve methods for



cleaning up oil spills and the environmental damage. These biotechnology methods operate at the molecular level; they are amenable to highly precise monitoring and control procedures. Indicative of this precision of biotechnology is the fact that, to date, they have had no resultant untoward effects on human health or the environment. Fermentation and most other biotechnology synthesis and production processes take place at relatively low temperatures and consequently use less energy than many traditional chemical operations. Public acceptance of the important methods and products of biotechnology will be accelerated by a scientifically literate population that can appreciate its benefits and understand its limits.

Biotechnology offers potential benefits to every nation. In fact, biotechnology is one key to enriching the earth's productivity and to gaining full use for human benefit of its vast genetic heritage without depleting precious resources.

In spite of the rapid growth of biotechnology and of the knowledge base on which it rests, many opportunities remain unrealized because of fundamental gaps in scientific knowledge. To date most biotechnology research has focused on biomedical problems and relatively little is yet known about the molecular genetics of plants, compared to the understanding of microbes or animals. Remedying this deficit will greatly stimulate agricultural applications of biotechnology. The rules that govern the shapes of proteins, which in turn play a critical role in determining their biological properties, remain largely a mystery; progress on this front will greatly aid in the rational design of new drugs with greater efficacy and safety.

Although researchers still have a long way to go before the hundreds of thousands of genetic sequences that comprise the human genome are ordered and identified, the resulting "dictionary" of human genes will be a very important aid at the expanding frontier of molecular medicine. Additional scientists and other skilled workers will be needed to exploit research opportunities fully and to build the biotechnology knowledge base.

Translating laboratory discoveries into practical applications is often difficult. Funds have proved more difficult to obtain for "proof of concept" research—as opposed to discovery—or for scaling up biotechnology processes from the test tube to a size large enough to attract industrial interest and support. Transferring new technology from a university or Federal laboratory to the private sector may pose additional problems. Additional challenges on the road to product development



include the costs of testing to meet regulatory requirements and the uncertainties and delays in obtaining approvals from regulatory agencies, patents, and cautious public attitudes towards biotechnology products. For example, certain applications of biotechnology raise difficult choices for society, which may take time and informed public debate to resolve.

The potential of biotechnology to improve the quality of life and economic health of the Nation are ample reasons to overcome these difficulties and to find ways to accelerate the full development of this diverse and powerful new technology.

POLICY RELEVANCE

U.S. industrial sectors employing the latest biotechnologies now include more than 500 start-up firms, and more than 200 established companies that have diversified into biotechnology—including many major chemical and pharmaceutical firms—and more than 200 biotechnology supplier firms in the United States alone. In just a decade and a half, this nascent industry has grown to produce U.S. products worth close to \$3 billion annually. A growing proportion of new drugs approved for the prevention and treatment of life-threatening diseases are biotechnology related products. Enzymes made in cell culture systems promise to change the way specialty chemicals are synthesized, making them cheaper and cleaner. Plants engineered to resist insect damage can reduce dependence on environmentally hazardous chemical pesticides. Researchers are harnessing some bacteria to produce silk and employing others to mine ore. In fact, biotechnology already has such an extraordinary range of applications that it is misleading to refer to a single “biotechnology industry.”

Because of the pervasive role of biologically produced products in everyday life, the value of new biotechnologies and products has the potential to expand at least 10-fold by the end of the century and to match or surpass even the computer industry in size, importance, and rate of growth. In the long run, no industrial country concerned with its economic well-being can afford to ignore biotechnology.

American researchers developed much of the basic science of the new biotechnology, and the United States continues to lead the world in the commercialization of most emerging biotechnology products. But other countries have recognized the fundamental importance of biotechnology; their governments have focused on this area as critical to future economic growth; and their companies are beginning to challenge the U.S. lead in par-

In the long run, no industrial country concerned with its economic well-being can afford to ignore biotechnology.



ticular areas. Japan, for example, is targeting pharmaceutical applications of biotechnology in the same way that it earlier targeted the semiconductor and consumer electronic areas. Building on Japan's traditional strengths and strong lead in fermentation technology, its government is focusing on pre-competitive and applied research and product development. Investment by European governments in the new biotechnology is close to that of the United States government, and European companies lead in the production of some types of biotechnology products, such as monoclonal antibodies.

The Bush Administration intends to maintain and improve U.S. competitiveness in biotechnology as an essential element in a growing and vigorous economy. To this end, it is giving priority attention to actions that can facilitate new discoveries and bring them to the market place.

Securing the Science and Technology Base—The Bush Administration believes that adequate support for basic research and research training is the key to continued national competitiveness in biotechnology. As part of the FY 1993 Budget, the President has announced the establishment of the National Biotechnology Research Initiative, a coordinated, interagency effort to maintain the momentum of U.S. leadership in biotechnology and to expand research in such promising areas as environmental bioremediation, energy production and conservation, and manufacturing and bioprocessing. Of particular interest is the Human Genome Project, which has the goal of mapping the location, and eventually identifying the chemical structure, of all the genes in the human genome and those of several model organisms. The expanded knowledge base gained in such research is expected to lead to many new applications in medicine, agriculture, energy and the environment.

Among other fundamental problems that drive basic research is the puzzle of development and differentiation—the process that guides one cell of a developing fetus to become a neuron and another to become a muscle cell. A full understanding of the process—one of biology's deepest and most enduring mysteries—will shed light on the mechanisms that turn individual genes on and off. The ability to switch genes on and off is critical to the manipulation of cells to produce particular proteins of medical or nutritional interest and for interventions in abnormal disease states. For example, improved understanding of the process may help combat cancer, which appears often to involve the switching on of certain normally beneficial genes,



known as oncogenes, at the wrong time, or the switching off of so-called cancer-suppressor genes.

A frontier area of high interest is research on the human brain; indeed, the 1990's have been designated the "Decade of the Brain." Neuroscientists are intensifying their efforts to understand the complex interplay of electrical and chemical processes by which the brain analyzes sensory input, stores memories, and gives instructions to the rest of the body. Others are focusing on the brain's interactions with hormonal systems that influence mood and emotions and with the immune system that combats infection. Still others are trying to understand the nature of cognition and exploring whether computers patterned after the brain can have decisive advantages in tasks such as pattern recognition.

Fundamental basic research needs to be coupled with thematic research leading to the solution of problems which are inherently multidisciplinary and require a broad base of research capabilities. The solutions to these problems are likely to come in tandem with the development of generic enabling technologies, tools which have application over the entire spectrum of U.S. industries. This strategically focused research and generic enabling technology development frequently reflects initiatives at the biology-engineering interface rather than the traditional research disciplines that contribute to fundamental biotechnology. For example, metabolic engineering joins molecular biology and chemical engineering approaches to redesign reactors for purposes such as enhanced metabolite production. Tissues engineering combines modern genetic techniques with the insights gained from material sciences to produce synthetic organs.

All of these interdisciplinary research efforts require a cadre of trained investigators capable of understanding both the biological and the chemical and engineering problems which are characteristic of this research. At the current time, such individuals are in very short supply in the U.S.

In addition to the support of basic research, the President's Council on Competitiveness recommends vigorous efforts to transfer technology from Federal or Federally-supported laboratories to the marketplace and to train a multidisciplinary pool of biotechnology scientists and engineers.

Risk-Based Regulation—It is important to avoid overly restrictive regulation by matching regulatory restraints to the degree of risk posed by specific products. In biotechnology, Federal reg-



ulation is a critical determinant of the time and cost of bringing a new product to market. To remove uncertainties in the regulatory environment, the President's Council of Competitiveness has recommended that Federal regulation should focus on the characteristics and risks of the biotechnology product, not on process by which it is created. This recommendation is based on the finding that products developed through biotechnology are not per se inherently more risky than those created through the more traditional methods such as selective breeding, varietal graph, etc. Risk-based regulation will allow products of low or negligible risk to be developed and brought to market with relatively less administrative burden thus freeing regulatory agencies to focus their resources on those products with greater potential hazards.

In developing regulations, the Council on Competitiveness also recommended the use of performance criteria—specifying the ends or goals, not the specific design or methods required to achieve a health or environmental goal. This approach provides researchers and firms flexibility in choosing the best means of compliance and reduces the need for lengthy revisions of regulations as the technology advances.

Risk-based regulation will help to keep the United States at the forefront of biotechnology and make its benefits available to Americans while ensuring their safety and that of their environment. In Europe, for example, a more restrictive approach to regulation has already caused some biotechnology companies to move their research laboratories and production facilities to the United States or elsewhere. It is therefore apparent that a rational, predictable, risk-based regulatory environment provides a competitive advantage to the U.S. vis a vis other nations.

STATE OF THE SCIENCE

Fundamental research often leads to the development of unforeseen techniques or products of immense social and economic value. Past U.S. investment in biological research is in fact the basis for the present flowering of the biotechnology industry. One example is the group of biological compounds known as growth factors which stimulate cell growth. In 1959, Dr. Levi-Montalcini received a \$53,000 federal grant to study the first of these compounds to be identified, nerve growth factor. Subsequently, a large array of growth factors has been identified, purified, cloned, and brought to commercial use. By 1989, just 30 years after Levi-Montalcini's pioneering work, sales of



growth hormones by two U.S. biotechnology companies amounted to \$430 million annually.

Health Applications—An important use of biotechnology is the development of new, more potent medicines and vaccines, and the production of purer, more effective versions of existing drugs and vaccines. As of January, 1991, 500 novel biotechnology products had been approved by the Food and Drug Administration for medical use in the U.S. More than 1,000 trials of additional new drugs, vaccines, and devices are under way.

Revolutionary new medical approaches to treatments based on biotechnology, such as the use of gene therapy to correct inherited genetic defects, have begun clinical trials. Children who suffer from the rare and devastating immune disorder known as Severe Combined Immune Deficiency Syndrome, for example, are receiving infusions of genetically-corrected lymphocytes in an experimental attempt to restore their ability to fight systems infections. Similar gene therapy approaches appear to be imminent for other diseases, including some forms of cancer and familial hypercholesterolemia. The recent localization of the genetic defect responsible for cystic fibrosis suggests potential means for treating this disease.

Biotechnology has also made it easier to detect and diagnose diseases. With remarkable simplicity and precision, these methods can now detect a wide variety of conditions. They vary from user-friendly and inexpensive home diagnostic kits for pregnancy, to hospital or office-based tests that simplify formerly complex laboratory procedures. More than 500 diagnostic devices based on biotechnology are used in clinical practice today. Of these, the most important have been the screening tests for blood products that have safeguarded the blood supply from contamination by the AIDS and the hepatitis B and C viruses.

Agricultural Applications—No single industry is more vital to the well-being of the Nation and, indeed, that of the world's population, than agriculture. Moreover, as the largest commercial component of the U.S. economy, the health of the domestic agriculture industry has enormous implications for U.S. financial stability and competitiveness abroad. Assuring a rich science base can support the development of agricultural biotechnologies essential to U.S. agriculture in the next century.

Potential applications of biotechnology in agriculture include better management of agro-ecosystems through decreased use

**Risk-based
regulation will
help to keep the
United States at
the forefront of
biotechnology.**



of chemicals; new methods of maintaining soil productivity; better water management; and new and improved agricultural products. They promise the development of crops and animals with higher tolerances for biological and environmental stress and better quality foodstuffs with higher contents with desired nutrients.

The need for more basic information is particularly acute for plant systems in which important traits have complex genetics and few parallels among microbial or animal systems. Recent advances have provided the opportunity to obtain this information and thus to apply genetic engineering technologies to benefit agriculture. The production of fertilizer is a major consumer of energy in the United States. Biotechnology approaches to nitrogen fixation enabling crop plants to produce their own fertilizer would save energy and reduce damage to the environment caused by excess applications of artificial fertilizer, as well as helping to alleviate hunger in many parts of the world.

The new biotechnology can produce many of the same benefits as traditional breeding techniques, only more quickly and with greater precision and predictability. Enhancements of certain characteristics of tomatoes, for example, are expected to provide increased resistance to pests, thus reducing the need for chemical pesticides. Other enhancements could improve the texture and produce tomatoes with less spoilage between the farm and the consumer. Companies are field testing a variety of crops with enhanced resistance to specific viruses, insect pests, and herbicides. Under development are improved staple crops such as soybean or corn with higher levels of specific nutrients and vegetable oils with lower levels of saturated fats.

Many manufactured foods such as cheese and yogurt require the use of bacteria or enzymes in their production. Scientists are modifying existing enzymes, isolating new varieties, and cloning genes for other enzymes into microorganisms for easier isolation and purification. For example, chymosin, an enzyme used in the manufacture of cheese, has traditionally been extracted from the stomach of calves, but can now be produced by specially developed microorganisms. Likewise, using the new techniques, scientists are genetically improving the microorganisms used to ferment many food stuffs and beverages.

In the area of animal husbandry, biotechnology has enabled development of hormone applications that increase the ratio of protein to fat in pigs and the milk yield from cows. Additionally, veterinary diagnostic techniques and new animal drugs similar to those for humans are under development with several having reached the marketplace. One vaccine now being tested holds



great promise for controlling rabies in wild and domestic animal populations effectively and inexpensively.

Environmental Applications—A healthy environment depends on the interaction of many different living organisms, from plants and animals to the communities of soil microorganisms that degrade biological matter and recycle nutrients. Biotechnology can protect these organisms and their interactions by introducing biological methods to replace toxic chemicals. Biological pesticides such as the toxins produced by the bacterium, *Bacillus thuringiensis* (BT), are used to control gypsy moths and have been found to break down quickly, leaving no harmful residues; genes from BT, inserted into crop seeds, can confer pest resistance.

When toxic chemicals or waste materials do enter the environment, biotechnology offers efficient means of dealing with the problem. The use of biological processes to clean up wastes from human activities is well established; bacterial degradation of sewage forms the basis of a substantial portion of the waste treatment industry. Recombinant DNA techniques will enhance methods for gathering, screening, and breeding oil-eating bacteria from around the world, and to create more efficient microorganisms using genetic engineering techniques. Biotechnology also has potential applications in breaking down toxic wastes and rendering them harmless through the action of specially designed microorganisms, enzymes, or catalytic antibodies. Another possible use of biotechnology is in the rehabilitation of areas fouled by pollutants, such as the removal of chlorinated hydrocarbons from contaminated groundwater by bacterial attack. Recent experiments in Prince William Sound and the Gulf of Mexico suggests the value of selected microorganisms for clean-up of oil spills in the sea, on the shore and in wetlands.

Early detection of small quantities of environmental pollutants could decrease markedly the costs of clean-up and more rapidly return habitats to acceptable norms. Biotechnology may be able to provide "indicator" organisms, sensitive enzyme assays, monoclonal antibodies, and other biosensors able to detect minuscule levels of potentially toxic agents and to provide early detection of ecosystems under stress. Although the vast majority of microorganisms in soil, fresh water, and oceans cannot yet be isolated or identified by traditional microbiological methods, biotechnology techniques of DNA fingerprinting and gene amplification now are making it possible to detect many of these microorganisms, even when present in low numbers, and to



identify their essential role in the complex cycling of nutrients and gases in the biosphere. Changes in gene frequencies in near-shore populations of microorganisms, for example, may provide one of the most sensitive indicators of ocean environmental degradation.

To fulfill biotechnology's full potential in environmental applications, however, further research is needed. Scientific understanding of the physiology and interactions of different kinds of organisms and the contributions their activities make to the functions of different ecosystems is rudimentary at best. This is particularly true of microorganisms whose presence and activities are crucial for the continued viability of the larger, more visible organisms. Successful bioremediation of polluted areas will require improved processes for getting microorganisms into direct contact with contaminants, for effecting degradation of contaminants present in very low concentrations, and for manipulating the ecology of the treatment environment. In addition to the lack of basic information, there is a significant shortage of scientists and engineers with training in the disciplines related both to biotechnology and environmental science.

Energy and Chemical Process Applications—Environmental and energy security concerns with fossil fuels such as oil are prompting a new look at renewable energy resources. Scientists are studying the use of microorganisms, modified plants, plant material, municipal and animal wastes, and other renewable materials as sources of fuels such as gasoline, alcohol, and natural gas. Examples include the use of wood to produce gasoline substitutes, and wood waste products such as bark and sawdust to yield ethanol. Biotechnology promises to accelerate such efforts by developing genetically-altered organisms and improved bioconversion processes.

Other energy-related research is focused on the potential of biological systems to enhance oil recovery, to clean and desulfurize coal before combustion, and to convert coal to gaseous and liquid fuels. For example, oil that otherwise would remain in the ground may be recovered through the introduction of certain microorganisms to oil wells. Biotechnology research aimed at reducing wastes from energy-generating processes and cleaning up energy-related waste is also underway.

Energy applications are special instances of the larger area of bioprocessing and bioconversion, in which biological means are used to accomplish chemical transformations. Examples include production of commercially valuable molecules, such as specialty chemicals and pharmaceuticals, that are often present only in



low concentration in the starting materials or are expensive and difficult to synthesize. Thus, certain microorganisms are used to refine copper ores, recovering the metal without the environmental and energy costs of smelting and making economical the recovery of copper from even low-grade ores.

Bacteria have been recently discovered in the oceans oxidizing and precipitating iron, manganese, cobalt, nickel, and other valuable and strategic metals. Harnessing the genes and enzymes of these bacteria may make it possible to produce these metals catalytically from low-grade sources, bypassing other more expensive industrial approaches presently used. Other bacteria reverse this processes for a variety of different metals, both strategic and toxic, thus presenting further economic opportunities for exploitation, as well as the possibility of using engineered organisms for remediating heavy metal pollution.

Another class of applications includes the use of quite diverse biological systems and bioreactors to recover, produce, or modify novel molecules for commercial application. An extremely challenging problem in the synthesis of high value molecules such as pharmaceuticals is that of maintaining the proper stereochemistry in each step. In some cases the active molecule is only one of several dozen possible products of a chemical reaction that have the same connections between atoms, but different shapes. Enzymes can be used to produce a desired molecule with a specific shape or stereochemical properties with almost perfect fidelity, so that biotechnological approaches to chemical synthesis have the potential for both minimizing the use of valuable starting materials and minimizing chemical waste. Chemzymes, artificial molecules designed to mimic enzymes, are expected to play important roles in biotechnological approaches to chemical syntheses.

In addition to greater specificity and lower wastes, bioprocessing typically takes place at lower temperatures than traditional chemical processing, resulting in energy savings, and can accommodate a wide range of non-petroleum starting materials. Thus the importance of biotechnology in the chemical and energy industries seems likely to increase over time.

To achieve these goals, however, a broader base of fundamental science and engineering knowledge is needed. Improvements must be sought in the biochemical pathways by which animal, microbial, or plant materials are converted into single-cell proteins, lipids, feedstocks, surfactants, specific pesticides, or other chemical products. More experience is needed

The importance of biotechnology in the chemical and energy industries seems likely to increase over time.



with commercial-scale processes for transforming organic raw materials into useful products, including the design of novel bioreactors that can maintain the viability of living organisms in sometimes harsh environments. The biology of organisms that not only survive, but thrive and multiply at temperatures near that of boiling water, is still a mystery, but one whose solution is likely to lead to useful enzymes of commercial catalytic value.

A deeper understanding of how enzymes function on a molecular level is needed to broaden the usefulness of isolated enzymes for chemical synthesis. For example, such an understanding should allow the production of chemically, or genetically, altered enzymes capable of carrying out a specific chemical step on a whole family of related molecules. In order to understand the biological and chemical action of proteins such as enzymes and receptors, scientists need to be able to predict their three-dimensional structure and to simulate their interaction with other molecules using powerful computers.

A fundamental limitation is and will be the supply of scientific and engineering talent. The nation has an inadequate supply of well-trained microbial physiologists, biochemists, and geneticists to study and develop uses for presently recognized bacteria, let alone the isolation and characterization of the large number of microorganisms that exist in nature and that await study.

Enabling Technologies—Much has been said about the loss of technology from the United States to other countries and the nation's lag in translating basic science into commercial products. Biotechnology is no exception, and appears to be at a critical juncture. The U.S. lead in basic biotechnology related sciences is still intact, albeit threatened; means exist to facilitate the "scale-up" process from the laboratory to industrial-scale production; but there may be a bottleneck at the first step outside of the laboratory.

In biotechnology, each of the progressive steps of scale-up from test tube to flask to small fermentation vessel to pilot plant and ultimately to large scale production facilities involves new scientific questions. These arise because living cells are vulnerable to shear forces, temperature and oxygen fluctuations, and the inhibiting effects of waste products. They generally have special nutritional requirements and carefully maintain conditions for growth. Methods for efficiently separating and purifying the desired product, which may be present at very low concentrations, from the cellular and other materials in the fermentation vessel also pose formidable problems. The answers to such



questions are attainable from biotechnology process research and the results can often applied generically to the development of numerous products.

Research of this nature has been relatively neglected. In awarding competitive federal research grants, peer review committees tend to favor basic research in contrast to more applied investigation. Smaller companies sometimes do not have the capital to invest in high-risk research. The larger companies may conduct such research but maintain the results as proprietary information, thus withholding its use from others.

The methods and techniques employed to move from laboratory to industrial scale production are known collectively as enabling technologies. Although they may vary from field to field, many are common in areas such as the production of proteins. In this case, much of the technology employed today is more than 30 years old. For example, human and animal cells are cultured in cumbersome and inefficient systems unsuitable for large scale operations, and progress in the development of superior bioreactor systems would achieve rapid increases in cost-efficiency. Another example of enabling technology is improved understanding of model organism systems most likely to be employed for scale-up production of biotechnology products. These can now include mammalian, insect, and plant cells, as well as bacteria, viruses, yeasts and other microorganisms. Further progress in enabling technologies could accelerate the translation of such fundamental knowledge into new products and hence accelerate the benefits of biotechnology for humankind.

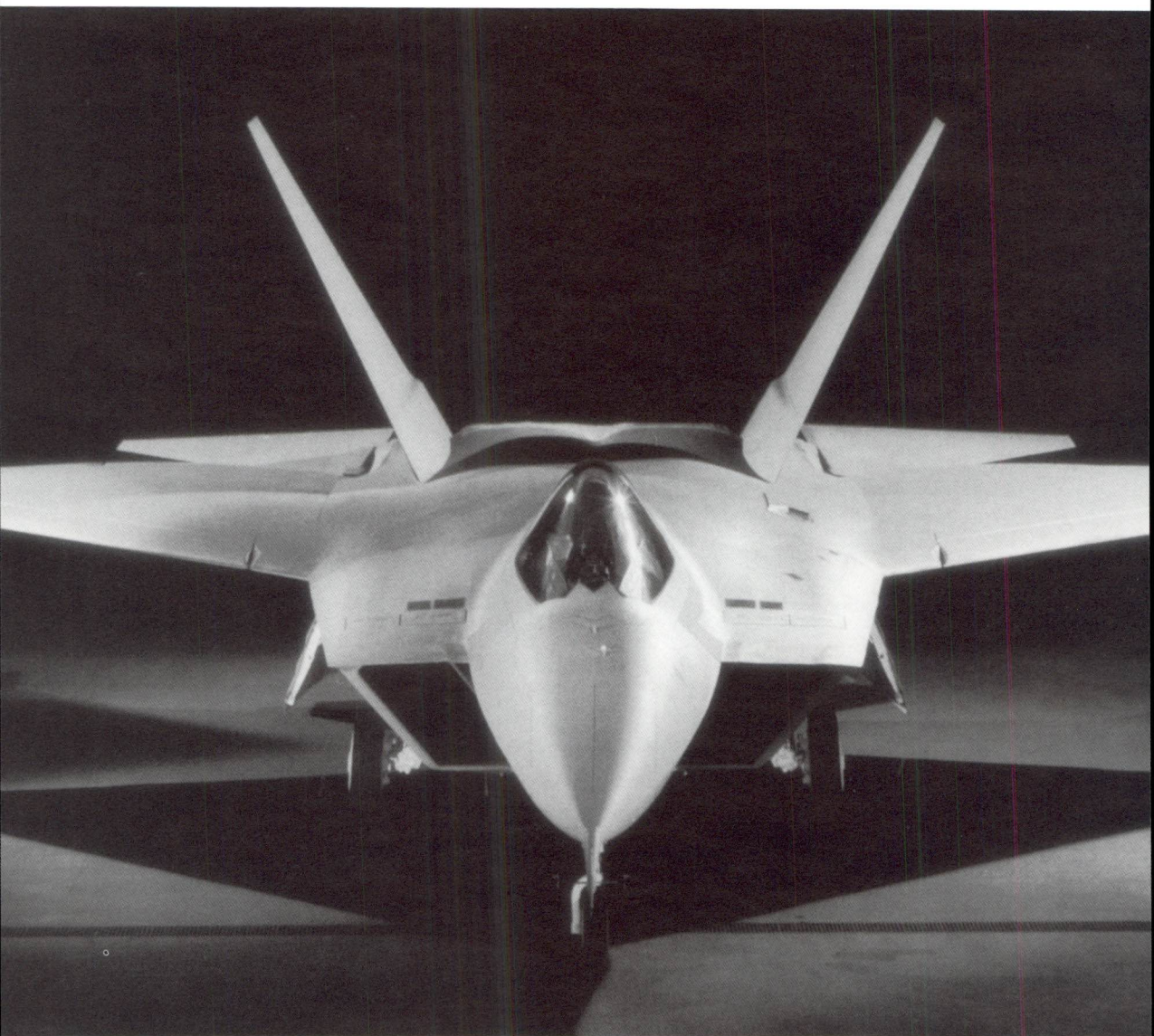
CONCLUSION

Biotechnology represents an unprecedented development in our ability to alter the genetic material of living organisms and thus is giving rise to a new industrial revolution. The rapidly expanding biotechnology industries promise significant new benefits in human health, in agriculture, in environmental protection, and in the production of energy and chemicals.

The United States leads the world in developing new biotechnology products, but competition is increasing and the economic stakes are high. Maintaining U. S. leadership will require continued efforts to expand the knowledge base and to solve fundamental problems through basic research. It will require increased efforts to translate new knowledge into products by improving the ability to "scale up" laboratory processes into industrial application. Finally, it will require the encouragement



of a flourishing free market and a "risk-based", scientifically sound regulatory approach that can protect health and the environment while removing unnecessary barriers to innovation. The potential of biotechnology gives ample human, national, and economic incentives to hasten the full application of this diverse group of technologies for human benefits.



DEPARTMENT OF DEFENSE

Science and Technology and National Security



THE CONFLICT IN THE GULF, and the dramatic developments underway in Eastern Europe and the former Soviet Union, presage far-reaching changes in the international environment and in the security needs of the West. The development and application of technology to support changing defense, foreign policy, and intelligence requirements present dynamic and diverse challenges to those entrusted with ensuring our nation's security. *

THE FUTURE NATIONAL SECURITY ENVIRONMENT

The past 2 years have seen historic changes in many parts of the world. With the fall of the Berlin Wall, the face of Europe has been altered dramatically, bringing a new spirit of hope and opportunity to the peoples of Central and Eastern Europe. Many of the changes we are witnessing have made the United States safer, reaffirming the wisdom of the West's postwar strategy of containment, deterrence, and support for democracy around the world.

Yet with the end of the Cold War comes a set of new national security problems and strategic challenges for the future. While the threat of war in Europe has receded sharply, we still face regional threats. Moreover, vast quantities of modern nuclear and conventional forces, previously held by the Soviet Union, still exist in the Commonwealth of Independent States and its constituent republics.

Arms control agreements, such as the Strategic Arms Reductions Treaty (pending Senate approval) and the agreement on Conventional Forces in Europe, as well as any new agreements being discussed with the new Commonwealth of Independent States or Republics, offer opportunities for enhancing stability and peace. But the key to arms control is effective verification, and it presents continuing challenges to our tech-

* This chapter does not fully address the S&T implications of the break-up of the Soviet Union and formation of the Commonwealth of Independent States which post-date the period covered by this report.



nical capabilities and creativity. In addition, Soviet intelligence activities, especially their efforts to acquire Western technology, remain aggressive. As a consequence, military technology competition continues with muffled intensity.

Throughout the world, there is a premium for high technology, particularly weapons technology, that can turn a small nation into a threat to its neighbors, its region, or, indeed, to the United States itself, and to the Western nations. In particular, proliferation of the technologies for weapons of mass destruction and their delivery systems is an increasing problem for the United States and the whole world.

Although we would wish for a peaceful post-cold war world, the invasion of Kuwait shows that militarism and aggression are still very much with us. As the threat of global conventional conflict recedes, the potential for major regional threats to U.S. interests remains. Such conflicts can arise suddenly, unpredictably, and from unexpected sources. And, as was evident during Operation Desert Storm, some of these regional threats are seeking to arm themselves with weapons of mass destruction.

Although it is impossible to predict precisely which countries will come to possess weapons of mass destruction, unless ballistic missile sales and existing development programs are halted, a number will have the capability to deploy short-range ballistic missiles with chemical and, perhaps in some cases, biological warheads by the year 2000. In addition, several countries probably will have nuclear weapons and a few medium range ballistic missiles. Chemical and biological agents are also likely to be available for use by insurgency forces and possibly terrorists. While the Bush Administration is committed to combating the worldwide proliferation of weapons of mass destruction and the missiles that deliver them, foreign indigenous programs and determined diverters of controlled technology make the challenge very difficult.

Another challenge lies in the need to reconcile the inherent tensions between wanting to facilitate new business opportunities for American concerns abroad, while at the same time controlling the spread of goods and technologies that may have military application. We have made substantial progress with other potential supplier countries to promote agreement on further strengthening export controls but much remains to be done.

These are but a few of the many national security science and technology challenges facing the United States in the 1990s.



CHALLENGES FOR SCIENCE AND TECHNOLOGY

As Desert Storm reminded us, America's tremendous scientific and technological strength provides the qualitative edge that has long ensured the nation's deterrent and helped preserve the peace. The superiority of the current generation of U.S. weapons is a direct result of decisions made in years past to harness American technical ingenuity to develop military systems of unparalleled performance and quality. Costly though some were, these systems have saved the lives of many U.S. servicemen and women, as well as countless civilians. As the U.S. enters the 1990s, the strength of our basic and applied research in defense and intelligence technologies must be sustained.

At a time of declining defense budgets and heightened international instabilities, it is especially critical that we not lose sight of our future security needs. They will require a stable, long-term investment in science and technology. By its nature, long lead time R&D work is especially vulnerable to disruptions in funding: time lost and teams disbanded due to discontinuances and delays cannot be recovered by future budget add-ons. Accordingly, current defense planning guidance stresses the need to ensure adequate research funding, to provide future technology options, and to exploit U.S. technological advantages.

In providing for the nation's security, we need a defense research base that will guard against technological surprises, one which will keep the United States in lead in the technology breakthroughs to define tomorrow's military advantages. Derivatives of stealth technologies, military night vision technologies, and new generations of smart weapons are among the leading examples that proved their worth during the Gulf War. These were all based on technology breakthroughs that are now 10 or more years old.

The defense community also needs effective means for sustaining and exploiting evolutionary improvements in military technologies. For instance, Desert Storm has shown the importance of developing real time command, control, communications, and intelligence, under all conditions of weather, night or day. In these areas, improvements are important both for the national leadership, as well as for commanders in the field.

We also need to focus attention on cutting edge technologies that lend themselves to wide application, because potential adversaries are certain to be doing the same. In the laboratory we are learning how to build structures at the molecular and atomic level, which indicates that the rapid progress in sensor

In providing for the nation's security, we need a defense research base that will guard against technological surprises.



and computer materials of the last 10 years is very likely to continue for the next 10 and beyond. In other areas such as materials science and technology, stronger and lighter materials are becoming available, as well as materials with other tailored properties. And in the computer sciences, new computer architectures, faster machines, larger memories, more robust and "intelligent" software have all opened new possibilities, ranging from the design of new weapon systems, through high performance aircraft and intelligence collection and analysis.

To meet these requirements, the Bush Administration is increasing the magnitude and improving the direction of investments in defense science and technology. While defense spending overall has declined in real terms over the period covered by this report, defense-related research has continued to grow. DOD funds obligated for research in FY 1991 increased approximately 4 percent over the FY 1990 level.

In these endeavors, the national laboratories represent unique resources. Their long experience in defense, their pool of dedicated and highly motivated scientists and engineers, and their unparalleled R&D facilities, continue to help provide the technological superiority upon which our security and freedom depend. As DOD laboratories undergo reorganization and consolidation, we will need to ensure that the unique capabilities they represent are not lost.

We also require a defense industrial base that is prepared respond to a broad range of military contingencies that may emerge in the future. It is no longer sufficient to rely upon individual weapon system programs to develop needed defense production capabilities. Rather, we will need to rely increasingly on technological leadership available in the commercial sector, and to take account of growing international markets in emerging technologies.

The Bush Administration is committed to ensuring healthy and wise levels of investment in critical and cutting edge technologies central to tomorrow's defense, and to the support of a defense establishment that is ready for the challenges of a changing world. These challenges will be many and diverse. Below is a small sampling of the national security issues which will require focused science and technology policy and planning.

Protection of the Nation's Strategic Information and Technology—Technology has brought us unprecedented growth in the supply of telecommunications and information processing



services within the Federal government and throughout the private sector. With the advent and extension of high performance computing capabilities, those services will continue to expand at an unprecedented rate, as discussed in Chapter 4. And, to ensure the security of the United States, a vast array of different types of information must be collected, structured, analyzed, and evaluated. In this endeavor, science and technology are making increasingly significant contributions.

But this technology revolution is proving a double-edged sword. Just as technology has made more information available to us, thereby enhancing its value, so too has the technology to exploit information systems become ever cheaper and easier to acquire. As a result, government national security information systems as well as private sector information systems are increasingly at risk.

As computer and communications systems continue to converge and become embedded in many other strategic technologies security and protection of information systems become more complicated. Simultaneously, the dependence of government, private sector and National Security is becoming increasingly dependent on information systems. So, at a time when we are most dependent, we are also most exposed.

At the same time, the technological wealth of the United States is today, and has long been, a target for foreign adversaries who seek access to that technology both openly and legally as well as through other means. The identification and protection of the critical technologies upon which we will depend for our future security is a key challenge for both government and the private sector.

Over the past 10 years, the United States has come of age in recognizing the strategic importance of the security of our information, our technology, and the communications and computer systems which enable us to use them productively. The next 10 years will challenge us to act on that knowledge. And our success will be measured by how well the government and the private sector work together to secure vital strategic information and technologies against an increasingly sophisticated, aggressive and diverse threat.

Technologies to Defend Against Ballistic Missiles—The proliferation of ballistic missile technology worldwide, and concerns over the potential for accidental or unauthorized strikes, underscore the pressing need for a capability to defend against ballistic missile attack, whatever its source. No responsible leader can



afford to leave Americans undefended against ballistic attack. Accordingly, the Bush Administration has assigned high priority to developing and deploying a system to address this growing danger.

The war in the Persian Gulf conclusively demonstrated that we need defense against ballistic missiles, and that such defense is technically feasible. The ballistic missile threats we will face in the future will be more sophisticated than the Scud, and we will require more advanced and capable defenses to counter them. The success achieved with the Patriot, which is a "point" defense system, suggests that advanced systems capable of defending larger areas would be even more effective in extending protection to deployed U.S. forces and to our allies. Moreover, such defenses would help ensure regional stability and our non-proliferation goals by reducing the potential advantages for would be aggressors from the acquisition or use of ballistic missiles.

Because of these threats, the Strategic Defense Initiative has been redirected to develop capabilities to protect U.S. forward deployed forces, and allies, as well as the United States itself, against limited ballistic missile attacks, whatever their source. That system, called GPALS (Global Protection Against Limited Strikes), would ensure continuous global detection, tracking, and interception of ballistic and theater missiles and their associated warheads.

In order to find solutions to the multi-faceted demands of ballistic missile defense, SDI has challenged the science and technology community to push the edges of creativity and innovation, and the program has witnessed several important technological accomplishments since inception in the mid-1980s. Breakthroughs have been made in research on interceptors, computers and signal processors, propulsion and navigation systems, and in future defensive technologies, such as laser beam propagation, and neutral particle beam operations in space. There is every indication that we can expect additional scientific and technical advances in the years to come.

The SDI technology research strategy is to preserve a strong technology base to support four broad categories of research: (1) projects to support or upgrade the GPALS system, (2) projects that support candidate elements of possible follow-on systems, (3) projects to resolve key technology issues applicable to several ballistic missile defense elements, and (4) projects that encompass generic, long-term research that promises high payoff, albeit at high technical risk.



SDI is also funding an innovative science and technology project to encourage prompt exploration of new initiatives. It will explore innovative technologies seeking "breakthroughs or quantum leaps" in six areas: (1) advanced high-speed computing, (2) materials and structures for space applications, (3) sensing and discrimination, (4) advanced space power, (5) advanced propellants and propulsion, and (6) directed, kinetic energy concepts.

In addition to its direct contribution to national security, the Strategic Defense Initiative is an excellent example of the high and largely unanticipated returns we as a nation derive from funding defense research and technology initiatives. SDI-sponsored research is serving as a catalyst for spin-offs in many scientific and technical fields, including medicine, computer technology, electronics, aerospace innovations, optics, automotive engine components, and industrial and manufacturing processes.

Arms Control Verification Technologies—As several new treaties have recently been signed, the coordination of federal R&D efforts in support of arms control verification technologies is growing increasingly complex. Verification has always been a difficult process, and numerous factors will make the verification of future agreements even more complicated. The most important of these include: (1) the scope of current and future agreements in which strategic and space systems, conventional forces, and chemical weapons must be considered, and (2) advances in and proliferation of technologies that are leading to smaller, more mobile, easily hidden weapon systems that are difficult to detect. A related problem is the cost and potential risk to U.S. industry presented by intrusive Soviet inspection and verification activities here.

Over the past two decades, greater demands have been placed on arms control verification. The early arms control agreements were generally well-matched to our intelligence technology. The primary focus of such agreements was on counting large, stationary objects, such as ICBM silos. Increasingly arms agreements have come to focus on smaller, mobile units of account (such as mobile missiles and cruise missiles), and also on qualitative weapons features, such as throwweight and size of reentry vehicles. To meet these new challenges, we are adopting technologies for use by on-site inspectors, as well as continuing to develop and incorporate technologies for national technical means (NTM) of verification (including reconnaissance satellites and radars). In applying these technologies

Verification has always been a difficult process, and numerous factors will make the verification of future agreements even more complicated.



to arms control verification, we must not lose sight of the potential for determined attempts at data denial and deception. For the foreseeable future, effective arms control verification will be of great importance to U.S. national security, and will continue to present challenges to our technical capabilities and energies.

Finally, it is critical that other vital intelligence missions are not shortchanged as scarce intelligence resources are dedicated to verification and compliance monitoring. Meeting all of the priority needs of policy makers for quality intelligence is a key national security technology policy concern.

Science and Technology to Support Intelligence—In the past, the U.S. intelligence community has enjoyed a preeminent position in its scientific and technological abilities. But today's commercial world has caught up, and we are seeing the spread of the kinds of technologies (such as specialty electronics) that were once the exclusive province of the intelligence community.

As a result, other nations, actors and individuals can have access to collection and other devices which heretofore only the intelligence community possessed. Cryptographic encoders and decoders, sensors, communications suites, signals intercept capabilities, and increasingly overhead surveillance assets are now widely available. The proliferation of these technologies will pose significant challenges to U.S. collection and security in the future.

In the past, the vast majority of our intelligence S&T dollars have been invested in technology to support collection; relatively little effort has been devoted to technologies to improve collation and analysis. But effectiveness in intelligence production is measured by meaning, not just volume. For the future, we will need to exploit technology to support analysis and production of this information, just as we have developed technology for its collection. We also need to be more aggressive in exploiting innovative technologies as force multipliers to support counter-intelligence, security, and counter-measures to protect national strategic assets.

For the past 30 years, we have relied on unsurpassed science and technology capabilities to support the vital intelligence needs of the country. We will need to find ways to ensure that the coming decade will be as creative and productive a period for science and technology applied to intelligence collection and analysis.

**Intelligence Support to Science and Technology Policy Making**

The use of intelligence to support science and technology policy making is increasingly of interest, as intelligence priorities are reexamined in light of changes in the world. The consumers (policy makers) and the producers (the intelligence community) will need to work together to ensure that requirements are carefully established and that the usefulness of the products is maximized.

Increasingly, people are coming to understand what has always been true: that the well-being of the United States depends as much on our economic strength as upon our military might. While traditional national security requirements for intelligence remain paramount, the resources of the intelligence community have been and can be of great use to economic and S&T policy makers in making decisions that affect the health of our economy.

While the intelligence community has turned out economic intelligence for many years, the process by which requirements are set and analysis and estimates performed is far from mature when measured against the more traditional national security activities. If our intelligence resources are to be used wisely and well, we will need to effect greater coordination between the Intelligence and S&T communities, as well as a better understanding of the functions of intelligence in the policy community.

CONCLUSION

The evolving world security environment presents the United States with a new set of national security problems that differ strikingly from those of the past. Bush Administration investments in defense research and development, and our defense and intelligence S&T policies and programs, are designed to help preserve for future generations the margin of technological superiority the United States enjoys today.



NATIONAL SCIENCE FOUNDATION

Science, Technology and Foreign Policy



THE INSTITUTIONAL AND POLICY FRAMEWORK of American science and technology, which has been in place for nearly a half century, emerged from the critical national needs of World War II. Our science and technology policies in the post-War decades were further influenced significantly by the international backdrop of the Cold War and our competition with the Soviet Union in weapons and space. Profound world political changes in recent years will necessarily redefine our national security needs. It remains clear, however, that national security is dependent on steady scientific and technological advances and that the future course of our science and technology enterprise will continue to be influenced by worldwide political developments.

In more recent decades, the economic dimensions of international relations have grown sharply in importance. The key role of science and technology in economic growth has become widely recognized around the world. As other nations expand their R&D activities and capabilities, the U.S. science and technology enterprise has to adopt a more global outlook and adjust its international scientific and technical relations.

Another set of issues which has gained worldwide attention over the past decade pertains to the environment. Those global concerns involve both economic issues and scientific and technological ones. As an increasing number of governments becomes concerned with policies for mitigating environmental degradation and ensuring sustainable development, the need increases for a reliable scientific and economic understanding of the relevant physical and human phenomena and the impact of technologies on the environment. Much of that understanding requires large scale and long-term internationally coordinated research programs.

THE GROWING INTERNATIONALIZATION OF SCIENCE AND TECHNOLOGY

Despite the importance of the international context for the development of American science and technology following World War II, the emergence of the United States as the preeminent



world performer of research and development resulted in an initial tendency toward self-sufficiency and insularity. In the first two post-War decades, international interactions were not insignificant, but tended to be initiated from outside the United States. This was because of the attractiveness of America's system of higher education in science and engineering and of its research laboratories to the scientific communities of other nations. Although the shift away from that situation is still in its early stages, all evidence suggests that change is occurring at a very rapid rate, as more and more of our research and educational institutions turn outward and international ties are recognized to be more important to their activities.

As reliance on science and technology for economic development and competitiveness becomes more widespread and as more nations invest greater resources in research, development, and science and engineering education, the number and size of technical communities within which U.S. research institutions might establish productive partnerships increases. Furthermore, as important scientific and technological accomplishments occur more widely throughout the world, the interest of the United States scientists and engineers in tracking the technical activities of other countries and in becoming involved in them is also bound to increase.

At the same time, the United States, with its large, diverse and open research and educational systems, continues to be the world's most attractive partner for technical cooperation. As the level of science and technology activities in other countries increases, an ever expanding number of researchers and students seeks scientific and technological cooperation and education in the United States. Because of this, our national scientific and technological resources constitute an important aspect of international diplomacy.

There is, in fact, a clear trend toward a growing scientific and technological interaction between the United States and other countries. The dynamics of that interaction are largely driven by industry, the university sector and individual scientists and engineers from all sectors, private and public.

The greatest interaction takes place in the industrial sector, a reflection of industry's dominant role in national R&D activities. For example, in the United States, the Federal Republic of Germany, the United Kingdom, Sweden, and Japan, about 70 percent of all R&D is performed in the industrial sector. Multinational firms by their nature have a global perspective and are increasingly making technical alliances on an inter-



national basis. Much of this is done through direct investment, transfers of technical know-how to their subsidiaries, and trade in high technology goods and services. Joint ventures are also becoming increasingly common.

Foreign investment in U.S. high technology firms and universities within the United States is growing and U.S. manufacturing firms are also increasing their investments abroad. In 1989, the U.S. overseas investment in R&D was equivalent to 9 percent of industry's own domestic R&D investments—up from 6 percent in 1985. Foreign company R&D investments in the United States have also grown since 1985; in the late eighties they accounted for 11 percent of all industries' self-financed R&D performance in the United States. Illustrative of such international industrial activity, IBM's wholly-owned subsidiary in Japan has expanded its Japanese R&D operations and added a new science center in Tokyo. Dupont has built a new technical research institute near Yokohama. Eastman Kodak, W.R. Grace, Hewlett-Packard, Motorola, Texas Instruments and Upjohn are among the many corporations which have recently invested, or have plans to invest, in R&D facilities in Japan.

Universities also occupy a very important place in international scientific relations. Since World War II, the United States has hosted the largest number of foreign students of any country—over 366,000 in 1989. Although this represents only 2.7 percent of total U.S. enrollment, the impact on our scientific system is significant for a number of reasons. First, about half of those foreign students are enrolled in science and engineering fields. Second, the presence of foreign students and graduates is quite marked at the graduate levels in science and engineering fields.

For example, by the mid 1980s, one-quarter of the full-time faculty in mechanical and civil engineering and one-fifth of those in chemical engineering had foreign bachelor's degrees. In 1989, more than half of all engineering, and almost half of all computer sciences, doctoral degrees granted by U.S. universities went to foreign students. Many of these doctorate students remain in the United States and become part of the U.S. work force. Many of those who return to their own countries maintain collaborative ties with U.S. researchers and are effective "ambassadors" on behalf of the United States.

Thousands of Federal or federally-supported scientists and engineers in both the civilian and the defense sectors are also involved in international cooperation, much of it facilitated by about six hundred bilateral agreements between Federal agencies and their foreign counterparts. Although statistics are not

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maintained in this area, available evidence suggests that there is a long-term trend toward increasing numbers of personnel and projects. Interaction with personnel and institutions overseas reflect the full scope of technical activities of the Federal government, from basic science and health to energy and agriculture. The interests of Federal scientists and engineers in international cooperation are similar to those in other sectors, especially the universities: access to technical data and information from other countries and about foreign locales (such as geological, climate or epidemiological data); economies resulting from shared facilities and instrumentation; and intellectual interaction with foreign scientific talent made possible by mutual exchange visits between research laboratories.

IN PURSUIT OF THE NATIONAL INTEREST: THE FEDERAL ROLE

Industry and academe as well as individual scientists and engineers in all sectors (including government laboratories) provide the fabric of international scientific and technological relations by their own transnational activities. The role of the Federal Government is that of shaping or directing those relations in ways that advance the national interest.

Economic and National Security Interests—Among the many dimensions of the national interest are economic well-being and national security. The international flows of technological knowledge and information and of technology itself have a complex but direct impact on those dimensions of the national interest. Accordingly, the Federal Government plays an active role in managing those flows—using a combination of inhibitive or facilitative mechanisms, and working bilaterally or multilaterally as appropriate.

For example, the U.S. Trade Representative, with the Departments of Commerce, State, and other agencies, acts to enforce U.S. trade laws and to promote the international competitiveness of the U.S. economy. Enforcement of intellectual property rights protection helps to ensure that the fruits of innovation are rewarded and that incentives remain to undertake economically risky research. The Trade Representative's office also negotiates and enforces bilateral trade agreements affecting sectors of the economy dominated by technology, including semiconductors, aerospace, automobiles, and machine tools. In addition, there are numerous programs that the Department of Commerce and other agencies run to assist the competitiveness of U.S. firms abroad, especially in high technology sectors which constitute about one fifth of U.S. manufactures.



The U.S. government also acts to protect the national security interests of the United States by exercising control over the proliferation of militarily significant technologies. Through an interagency export control process—and with the help of our allies and like-minded third countries—the United States administers a licensing regime which requires exporters to obtain government approved export licenses for a range of sensitive goods.

These goods include weapons and defense technologies (including chemical and biological weapons), nuclear and nuclear-related technologies, missile technologies, and high technology commercial goods that have a “dual use” in both civilian and military applications. Quite aside from the regulation of international technology transfer, the Federal government’s annual support of approximately \$40 billion in defense R&D is directly related to U.S. national security interests. Both bilaterally and multilaterally, the United States is working to advance our interest in protecting the global environment. Through technical assistance from U.S.AID and other U.S. agencies as well as through U.S. involvement with organizations such as the World Bank, the UN Environmental Program, the UN Development Program, and the Global Environmental Facility, we hope to show developing countries that environmental protection need not come at the expense of economic development. Under the Brady plan, we are promoting debt-for-nature swaps. These permit forgiveness of a portion of a developing country’s bilateral debt to the United States in return for a commitment to invest a like amount of money in domestic environmental projects.

Foreign Policy Interests—It has long been recognized that international cooperation in science and technology has the potential of serving the foreign policy interests of the United States. The growing internationalization of science and technology noted in the previous section has tended to raise that potential. Because an expanding number of countries has a growing interest in technical interaction with the United States, the potential for mutually beneficial cooperation in science and technology can also be used in the diplomatic process to advance U.S. foreign policy interests.

On the other hand, it is important to recognize that international science and technology cooperation has a dynamic of its own and is not a process which the Federal government can or should try to control. For a number of reasons, the mechanism that links international scientific and technological cooperation



to foreign policy is a loose one at best. Our political system is not prone to applying stringent controls to the activities of our academic or industrial sectors, beyond the immediate needs of national security. Secondly, the United States has historically supported free and open scientific communication (again, within the constraints of national security) and has sought to encourage other countries to emulate the openness of American society. Thirdly, international technical cooperation tends to be very much in the scientific (and, somewhat less consistently, technological) interests of the United States as well as that of partner countries. This is increasingly true as other countries increase their R&D investments and gain leadership in technical areas. Thus, if we inhibit cooperation for reasons of foreign policy (or trade policy or national security), we may be doing so at the expense of our scientific interests. Consequently, international technical cooperation is generally more useful as a foreign policy "carrot" than as a foreign policy "stick".

SCIENCE, TECHNOLOGY AND FOREIGN POLICY: INTEGRATIVE MECHANISMS

Federal involvement in international science and technology affairs involves close interplay among three Executive Branch elements: the Department of State, a cluster of about 20 Federal scientific and technical agencies and organizations, and the Executive Office of the President.

The Department of State carries out numerous functions with respect to international scientific affairs. The Department has statutory responsibility for concluding and managing international agreements, thereby providing the formal legal framework for cooperation. It is, at present, responsible for the approximately 600 bilateral agreements for science and technology cooperation alone between the United States and 120 foreign countries. The Department also participates actively in the negotiation of technology-related trade issues. Internally, the Department ensures coordination of science and technology issues worldwide primarily through its Bureau of Oceans, and International Environmental and Scientific Affairs and coordination between technical cooperation and other bilateral or regional issues through its regional bureaus. Of special importance to the implementation of international science and technology affairs is the Department of State's overseas representation and, in particular, its network of over two dozen full-time science and technology officers posted in over 20 missions around the world. The Department's overseas posts provide important



liaison, communication and information functions, all of which support the management and further development of technical cooperation. The Department's overseas representation and reporting function in science and technology is, in some cases, usefully augmented by personnel from technical agencies.

The Federal government's technical agencies provide substance to the international agreements by planning and managing cooperative programs. These programs cover a diversity of fields and types of projects, as benefits the mutual interests of the United States and the partner country. In many cases, especially in basic research, the cooperation provides reciprocal access to locale-specific technical data in such areas as geology, seismology, climate and oceans research, epidemiology, or demography. In other cases, cooperation emphasizes joint efforts to resolve common problems such as new energy sources, clean coal technology, energy conservation, natural hazard mitigation, disease prevention, or waste management. Cost-sharing of existing research facilities and instrumentation such as land-based observatories and particle accelerators as well as joint planning and financing of the megaprojects of the future are also critical elements of government-to-government cooperation.

Most elements of the Executive Office of the President are involved in some aspect of international scientific and technological affairs, participating in a complex policy development process which ultimately integrates the various components of the national interest affected by science and technology. The National Security Council utilizes science and technology as one instrument in the broad policy process. The office of the U.S. Trade Representative is most centrally involved in technology-related trade issues. The Council of Economic Advisors and the Cabinet Councils and the Competitiveness Council have an overall responsibility for economic competitiveness, in which technology plays a key role. The National Space Council addresses space policy with its myriad technological components. And, since policy and budgets are inseparable, the Office of Management and Budget also plays a key role in the process.

When it comes to integrating the specifics of those science, technology and foreign policy issues, the White House Office of Science and Technology Policy plays a strategic role. Scientific and technological issues can have strong international and foreign policy implications. This encompasses, for example, such challenges as integrating global change research internationally and addressing international cooperation in big science projects such as those in high energy physics.

International technical cooperation tends to be very much in the scientific interests of the United States.



It is, of course, sometimes difficult to neatly divide issues into two simple categories and there are in fact many policy levels at which science, technology and foreign policy are closely integrated. The challenge within the Administration is to focus collectively and effectively on policy areas where the foreign policy and national security issues are of exceptional importance (e.g., cooperation with specific nations), or where the financial stakes are high (e.g. international cooperation in large scale projects) as well as those in between.

International science issues which have been coordinated across the Federal government by the White House recently include global change, the protection of intellectual property rights under science and technology agreements, big science projects, and cooperative opportunities with the European Community, Central Europe, Japan, and developing countries.

SCIENCE, TECHNOLOGY AND FOREIGN POLICY: MAJOR DEVELOPMENTS

This section highlights some of the major international scientific and technological activities of the Administration during the past two years. The examples serve to illustrate the integration of science and technology with foreign policy and broad national interests.

Reorienting Our Strategic Relationships: The Former Soviet Union—The renewal and blossoming of government-to-government technical cooperation between the United States and the Soviet Union was a key element in the reshaping of the strategic relationship between the two countries. For example, the 1989 Agreement for Cooperation in the Field of Basic Scientific Research not only provided the framework for U.S. and Soviet scientists and engineers to conduct activities of mutual scientific benefit, but also served as a symbol of the U.S. commitment to support the process of profound political and economic reform occurring in the Soviet Union and its republics. High level meetings in the past two years served to underscore U.S. interest in the cooperation, as did renewed Soviet participation in the Ocean Drilling Program and discussions on solar system exploration.

Balancing Our Interests: China—Cooperation in science and technology between the United States and China at the governmental level began in 1979 and was keyed to political and economic changes which were underway in China at that time. The



U.S.-China agreement constituted both tangible and symbolic involvement of the United States with some of the most progressive elements of Chinese society. Despite the setback of the 1989 massacre at Tiananmen, and a wave of political repression since that time, China's scientific and technological community remains professionally active and committed to China's modernization. On the premise that the United States should remain involved with and supportive of China's progressive elements, and following more than two years of negotiations to ensure the protection of U.S. intellectual property generated under the cooperative program, the U.S.-China Agreement for Scientific and Technological Cooperation was renewed in 1991.

Fostering Democracy and Capitalism: Central Europe—The breakup of the Warsaw Pact and the internal political upheavals in Central and Eastern Europe of the past two years are among the most profound and dramatic changes in the world in the latter half of the Twentieth Century. The consolidation of these changes and the rebuilding of political and economic systems are a major challenge for those nations. The United States and its West European allies have a strong interest in, and commitment to, ensuring that the transitional process occurring in Central Europe results in political democratization and a shift to market economies. Here, too, cooperation in science and technology, can have strong implications for the growth of Central European economies and their integration into the world economy. Scientific cooperation will also support the revitalization of Eastern European universities and research institutions. Those institutions are likely to play an important role in building pluralistic and democratic societies.

Dealing with the Competition: Japan and the Other Asian Economies—The economic success of Japan and its Asian neighbors which has derived largely from technology manufacture, has prompted those countries to further advance and refine national R&D strategies. Not only are Japan, South Korea, Taiwan and others committed to increased investments in R&D, but they are paying increased attention to building up their basic research capability. It is essential that the United States be well informed about scientific and technological developments in the dynamic nations of East Asia and maintain a framework for productive partnerships in pre-competitive research.

Because of the commercially competitive context in which our technical cooperation takes place, the science and technology



agreement with Japan, which was re-negotiated in the late 1980s, emphasizes strongly the importance of equitable access and adequate protection of intellectual property rights. By providing a framework which makes mutually beneficial cooperation possible in a competitive environment, the U.S.-Japan agreement and further refinements developed by the Administration in 1990 have served as a model for technical cooperation between the U.S. and other countries around the world.

Adjusting to Regional Integration: the European Community—

Throughout history, the opposing forces of integration and fragmentation have tugged and pulled the international community. Today this is doubly true. Science and technology are forces that integrate the community of nations, and have always been highly internationalized activities. The countries of Western Europe are well into an experiment to create a unified economic market among members of the European Community. The 1992 target date for market unification actually represents the culmination of a several-decade long process that may ultimately fully integrate the economies, societies, and politics of Europe together. Science and technology are important elements in this process.

European integration, which may ultimately come to include Central Europe (as it already has in the case of Germany) presents a challenge to the United States in terms of the need to redefine relationships while maintaining the historically strong and complex fabric of bilateral European relationships with the United States. The United States is faced with new opportunities in the growing technical programs of the European community during this critical transitional period. In order to facilitate cooperation and better communication, the United States and the European Community established a Joint Consultative Group on Science and Technology in 1991. That group has begun discussions on a variety of topics including cooperation in large projects and the transnational mobility of scientists and engineers.

North-South Relations: Global Environmental Issues—

A scientific and technical understanding of our physical and human environment is indispensable to sustainable economic development. It is well understood that science and technology are key to the solution of many of the environmental problems faced by developing countries and countries in economic transition. These countries look to the United States for technical cooperation to address problems such as the food and energy sources,



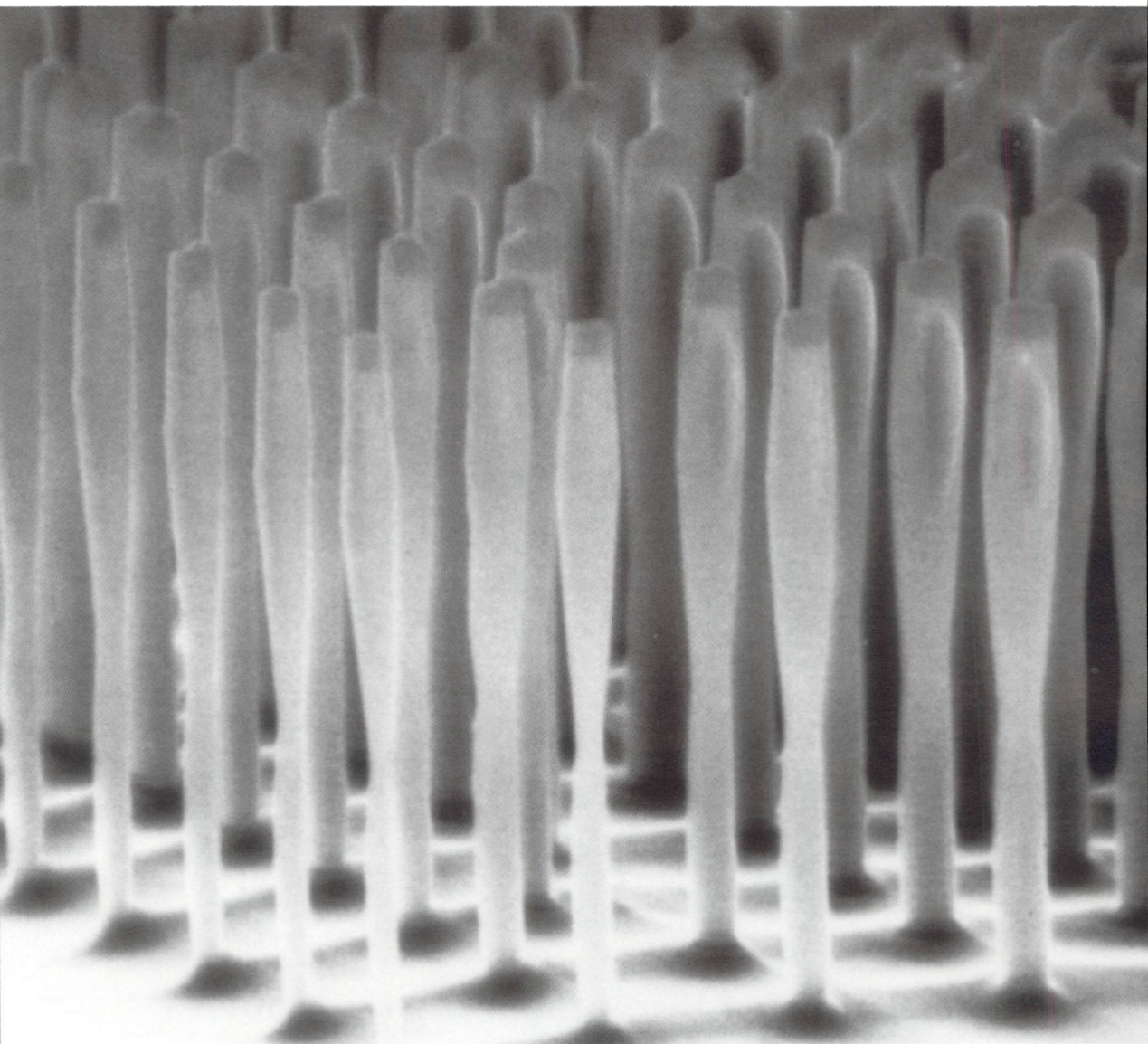
environmental degradation, population, nutrition and health concerns.

The Bush Administration supports cooperation in science and technology with Latin American countries and is encouraging new efforts and the maintenance of ongoing collaboration. These efforts involve a wide range of developing countries including Brazil, Chile, Mexico, Uruguay, and Venezuela, as well as increasing regional cooperation on important topics.

During the White House Conference on the Science and Economics of Global Change in April 1990, President Bush endorsed the concept of establishing a network of regional research institutes for collaborative research on the science and economics of global change which would include a Western Hemisphere research institute based on cooperation between the countries of North and South America.

LOOKING TOWARD THE FUTURE

As we look toward the next century, two fundamental trends are likely to continue. The first is that humankind will be faced with problems of ever increasing complexity posed by the growing world population, the finite supply of certain resources, the physical changes in our environment and the need for economic growth and military security. Those challenges are international in nature, not just national or regional. The second trend follows from the first: in response to problems and challenges, a growing number of national communities around the world will substantially increase their efforts in science and technology. Those efforts will not only mobilize the intellectual resources necessary to unlock the secrets of nature, but they also fuel both the incremental advances and the dramatic breakthroughs that will ensure the long-term well-being of humankind. A vigorous policy toward international cooperation in science and technology is essential as we move into the Twenty First Century.



AT&T/BELL LABORATORIES

Science, Technology and Competitiveness



IN A SPEECH to the recipients of the National Medals of Science and National Medals of Technology in the fall of 1990, President Bush said, "Today our government must help carry research forward and contribute to the development of generic technologies that build on basic discoveries. If America is to maintain and strengthen our competitive position, we must continue not only to create new technologies, but learn to more effectively translate those technologies into commercial products. In this way, we can help leverage the R&D of the private sector, helping whole industries advance in an increasingly competitive global market."

The 1991 and 1992 Economic Reports of the President to the Congress emphasized the role of economic growth in bringing new jobs, raising living standards, and increasing national wealth. In an era of increased international competition, economic growth is enhanced by comparative advantage. In some countries, that advantage is cheap labor; in others, it is access to markets. In industrialized countries, such as the United States, superior technology is a principal source of comparative advantage in the manufacture of products and the delivery of services. More fundamentally, it is the integration of new technologies into products, services, and the production system itself that is a key to enhanced productivity and expanded productive capacity—a process that is widely acknowledged to be a critical strategic element in the economy of virtually all modern industrial nations.

The private sector has the principal role in identifying, developing, and applying technology for commercial products and processes. As described in a report on U.S. Technology Policy, the Federal government also has a role in establishing an economic environment to encourage innovation, providing a stable regulatory regime, helping to create a more educated work force, seeking better international protection of intellectual property, and similar actions. More specifically, the Federal government can support technological innovation by investing in basic research, by contributing to the development of generic, pre-



competitive technologies, by improving the transfer of Federally funded technology to the private sector, and by catalyzing cooperation among industry, academia, and government.

The Bush Administration has taken a number of actions to help advance America's competitive position through improvements in technology. These include significant increases in basic research funding, the establishment of the Council on Competitiveness headed by the Vice-President, and the creation of a coordinated, multi-agency R&D program and budget on the generic, pre-competitive technology of high performance computing. Additional evidence of concern with technology at the highest level comes from the appointment of the President's Council of Advisors on Science and Technology (PCAST), and the publication of a U.S. Technology Policy.

It must be emphasized that advances in technology alone cannot ensure economic prosperity and national security. There are, moreover, very real limits on what the Federal government should do to promote technological success: the private sector must carry the responsibility for developing commercial products. The government role is to foster a stable economic environment that is conducive to investment. A recent poll conducted by the Industrial Research Institute of its membership, consisting of the top-ranking R&D officials in many of America's leading companies, underscored this division of responsibility. The members were asked to rank five major factors contributing to the erosion of U.S. industrial technology: "general management practices" and "external financial pressures" were deemed most important, according to those polled, while "federal technology policy" was ranked fifth.

TECHNOLOGY, PRODUCTIVITY, AND ECONOMIC GROWTH

Economic growth occurs with the production and consumption of more goods and services in an economy. But simply producing or consuming more goods and services does not lead to a competitive economy. To be more competitive in today's international markets, a nation must learn to produce higher quality and greater variety of goods and services using fewer resources. The degree to which more can be produced with less reflects increases in productivity in the economy. Technology is one of the fundamental forces driving increases in productivity and a growing and competitive economy.

A basic input into the process of technological innovation is research and development. Economists estimate that more than one-third of the growth in the US economy since 1930 has been



due to advances in knowledge. Evidence from economic studies of the past four decades suggests that industry-financed R&D alone accounts for about one-third of the annual average growth of productivity over that period.

Currently, there is widespread concern that productivity growth in the U.S. is not keeping pace with that of our industrial trading partners and that as a result the Nation will lose its competitive edge. As specifically documented in other reports, U.S. productivity growth, on average, is not as high in recent years as it was in the 1960s. During the 1960s, the productivity of labor (output per unit of labor) in the private sector increased on average by 2.7 percent per year. This tremendous growth rate was due, in large part, to the widespread incorporation of technological and managerial advances into production systems; with more advanced equipment and machinery, one worker's output could be expanded dramatically. From 1973 through 1979, however, the average rate of growth of labor productivity was only 0.6 percent, increasing to 1.4 percent per year during the period 1979 through 1986.

The use of labor productivity alone gives an incomplete picture of the economy's productivity; the effects of capital must also be included. An advanced computer workstation may make an engineer's labor more productive by multiple factors. But the workstation is also an input into production. When returns to the engineer (labor) and the workstation (capital) are calculated together, this "multifactor productivity" is likely to be lower than the productivity growth for labor alone. In fact, from 1960 through 1986, multifactor productivity has grown significantly less than labor productivity. For the period 1960-73, the average annual rate of growth of multifactor productivity was 1.8 percent, for the period 1973 through 1979, the average annual rate of growth fell to 0.1 percent. From 1979 through 1986 it increased to 0.5 percent, still far below the rates of growth experienced in the 1960s.

By any measure, however, the decline in productivity growth of the economy as a whole is cause for concern. There is also a marked differential in the productivity growth of different sectors of the economy. The manufacturing sector, for example, experienced the same slump in productivity growth as the aggregate economy in the 1970s but rebounded sharply in the 1980s: labor productivity in manufacturing grew on average by 3.2 percent per year from 1960 to 1973, 1.4 percent from 1973 to 1979, and 3.5 percent from 1979 to 1986. In contrast, four service sectors—retail trade, finance, insurance, and real estate—appear to have con-

The Bush Administration has taken a number of actions to help advance America's competitive position through improvements in technology.



tinued as "slow growth" productivity areas during the 1980s. A major problem in interpreting overall productivity growth is that productivity is difficult to measure for the service sector, which accounts for over two-thirds of U.S. gross national product.

New capital investment and technological innovation are expected to have their greatest effect on those industries that are already of sufficient scale, degree of investment of capital relative to labor, and technological sophistication to be able to apply technology effectively. Industries that meet these requirements can be found in both the manufacturing and service sectors. Technology, labor, and investment of capital are not independent forces on innovation but are closely intertwined in the process of economic growth. As suggested in the 1991 Economic Report of the President, it is widely accepted that raising the rate of capital investment can have multiple effects on the rate of economic growth. New technologies can spur capital investment as well as investment in improving the quality of labor through education and training.

TECHNOLOGY POLICY

The goal of technology policy is to make the best use of technology in achieving the national goals of improved quality of life for all Americans, continued economic growth, and national security. This policy explicitly recognizes that industry, academia, state and local governments, and the Federal Government all have roles to play.

The Private Sector and Industrial Innovation—America remains the undisputed world leader in basic research. Yet basic research clearly cannot be the only component of a nation's R&D enterprise. Other nations have R&D enterprises that bring great benefits to society yet include very little basic research. Their firms are able to effectively exploit the results of basic research, no matter where it is done. This is the stage of the innovation process—between the generation of knowledge and its application in the marketplace—that poses the greatest challenges to the United States.

In a comparative study of industrial innovation in the United States and Japan, Edwin Mansfield showed that, on average, the Japanese develop and commercially introduce new products and processes faster and at less cost than the Americans, although their advantage in this respect is not as great as is sometimes claimed. Mansfield found that Japanese firms' cost and time involved in bringing products based on internal R&D to



the market is the same as for American firms, on average. But he concluded that it takes a Japanese firm about 25 percent less time and 50 percent less money to commercialize innovations based on externally generated rather than internally developed technology. Finally, according to Mansfield, the percentage of innovation cost during product commercialization devoted in Japan to tooling and manufacturing equipment is almost double that in the U.S., which reflects Japan's emphasis on process engineering and efficient manufacturing facilities. On the other hand, according to Mansfield, the percentage of innovation cost during product commercialization devoted to marketing start-up is significantly higher in the U.S. than in Japan.

Comparison of the expenditures for R&D on product and process technologies in Japan and the U.S. may help explain some of the difference in overall performance. In the U.S., two-thirds of industrial R&D expenditures are going to product technology and one-third to process technology. In Japan, the pattern is reversed, with two-thirds of industrial R&D expenditure directed to process technology. These results shed new light on a major issue concerning industrial R&D in the U.S. Many observers have criticized U.S. industry for neglecting process innovation. The President's Commission on Industrial Competitiveness in a 1985 report summed up the situation succinctly: "It does us little good to design state-of-the-art products if, within a short time, our foreign competitors can manufacture them more cheaply."

Advanced process and manufacturing technologies are increasingly essential to more rapid product introduction, increased flexibility, and the integration of product design, production, and quality control. Integration of these advanced technologies and techniques can contribute to remaining competitive in the world marketplace.

Advanced manufacturing involves far more than simple factory automation, as the findings of a five-year study of the global automotive industry by the Massachusetts Institute of Technology confirm. Instead, both new technologies and changes in management and engineering practices are necessary. Computer integrated manufacturing, for example, encompasses the operation of virtually the entire enterprise by integrating company-wide information systems, plant-wide planning and control systems, and individual work stations or computer-controlled machinery. Combined with advanced systems management technologies including advanced software tools and extensive databases, and properly developed standards, computer inte-



grated manufacturing allows flexible manufacturing in which production can be switched rapidly from one product to another.

In considering innovation broadly throughout the economy, it is apparent that the returns on expensive investments in generic enabling technologies can seldom be maximized—and in some cases even recouped—unless the results are used in several applications, often in different industries. There is thus an increasing need for cross-industry cooperation in creating and deploying these technologies.

These new technologies—process and product—implemented effectively, can improve efficiency and the ability to adjust rapidly to changing market conditions. Advanced product, process and manufacturing technologies, when combined with effective management, can provide the basis for industry to bring a stream of innovative, cost competitive, quality products and services into the marketplace.

The Federal Government and Technological Innovation—

Federal support for technological innovation begins with support for basic sciences, which provide the underpinnings of new technology. Since scientific discoveries that spark technological development are inherently unpredictable in both timing and content, research support for basic sciences that is broadly based is most likely to yield useful advances that can ultimately be translated into new technologies.

Federal support for technological innovation requires a greater selectivity and concentration of resources on activities that offer the potential of large benefits to the economy as a whole but do not offer the prospect of adequate profit to any private firm that might undertake the research. This is the rationale for focusing Federal support on a group of generic, pre-competitive technologies that are important in both public and private sectors and that are widely perceived to be critical for competitiveness in the marketplace of the future. In this context, generic technologies mean those that have the potential to be applied to a wide variety of products and processes in many industries. A "pre-competitive technology" is one where the commercial potential can be clearly assessed without further development. Operationally, a pre-competitive technology is one on which a company is willing to spend money in cooperative joint ventures including potential competitors. Results from pre-competitive technology can be shared by a group of companies without reducing the incentives for any of them to further develop proprietary products based on the work.



One example of an important pre-competitive technology meriting focused Federal support is the area of Materials, a field that is experiencing what only can be described as a revolution. At the center of this revolution is the development of new materials with vastly superior properties and completely new ways of producing them. Together, these changes are beginning to make available materials that would have been unthinkable a decade ago. Increasingly, engineers can tailor the composition of certain materials atom by atom, creating so-called "designer materials" which have precisely the desired combination of strength, weight, corrosion resistance or other properties. The potential impact of advanced materials includes lighter, more agile, or more "stealthy" airplanes, higher performance engines, novel medical applications, corrosion-proof auto bodies, and more energy-efficient construction materials. Advanced materials promise significant improvement in the performance of items produced and used by virtually every sector of the economy.

Still other pre-competitive enabling technology areas, where R&D investments can have a very high leverage effect on industrial competitiveness, include: information and communication technologies (critical to the functioning of our increasingly "electronic" society); air and transportation systems (which provide the basic infrastructure for the whole economy); manufacturing methods and processes (the ultimate means by which other technologies are incorporated into products); and the life sciences (where increased understanding and control over life processes has already had major positive impacts in health care and agriculture). Energy technologies are still another critical set of inputs to our economic system, particularly since the uses, by-products and sources of energy can all have substantial and long lasting effects on both the local and world wide environment.

Federal R&D responsibilities under technology policy thus include increased investment in basic research, appropriately limited participation with the private sector in precompetitive research on generic, enabling technologies, continued development of defense technologies for which the Federal government is the sole or major consumer, and encouragement of mutually beneficial international cooperation in science and technology.

Cooperation among Industry, Academia, and Government—

Technology policy calls for close cooperation among the Federal research system, private firms, and academic researchers.

After World War II, there was a separation of science and

Federal support for technological innovation requires a greater selectivity and concentration of resources, focusing on a group of generic, pre-competitive technologies.



technology accompanied by a de facto division of responsibility between the Federal government (science) and industry (technology). The separation seemed logical in light of the then prevalent view of innovation as a linear track along which developments moved. Technology was viewed as a separate, downstream process from research and development. But the process of technological innovation is not akin to a pipeline. Instead, all parts of the complicated process may take place simultaneously with complex feedback loops, including the initial perception of a need that leads to innovation.

This is not to say that the private sector has not benefitted from Federal investment in research. Historically, the Federal government has supported generic technology work for two reasons: to meet its own needs in such areas as defense and space, and to meet broader national needs that can be seen as benefitting all of society, such as better health care, the clean-up of pollution, or a stronger transportation or communications infrastructure. However, this R&D also has resulted, over time, in major advances in the private sector. Particular examples are the development of commercial aircraft, the creation and growth of the computer industry, and the strength of American agriculture. But the impact is much more pervasive because Federal R&D has helped to establish the science and technology base from which industry has been able to draw in developing commercial products and processes.

It has become apparent that many of the reasons for government funding of basic research apply equally to certain types of applied research. One motivating factor for the government to assume major responsibility for the funding of basic research is that the activities entail high costs and high risk and because no one firm can capture a return sufficient to justify their investment. It is now known that at an early, or pre-competitive, stage, many technologies share these same characteristics. Many of these technologies also share the characteristic of basic research that their "results" can be applied to a wide variety of problem areas. In this sense, the technologies are generic or enabling and have the potential to be applied in a wide variety of products or processes in many industries.

Pre-competitive technologies are ripe for collaboration among firms within an industry, between firms in different industries and among industry, government, and academia in their further development. One such program now under way is the Advanced Technology Program, administered by the National Institute of Standards and Technology within the Department of



Commerce. The program is aimed at assisting businesses in developing pre-competitive generic technologies that will widely benefit the nation. It is designed to help support joint ventures and other research arrangements that have been developed by industry, including industry-academia cooperation, for which industry will pay at least half of the cost. Among the eleven R&D programs selected in 1991 for funding under the Advanced Technology Program are research on high temperature superconductivity, improved manufacturing techniques for electronics, and methods for improving the accuracy of machine tools.

The National Science Foundation's Engineering Research Centers bring engineering and scientific disciplines together to address fundamental issues crucial to the next generation of technological advances. The program is a partnership between the Federal Government, State governments, academic institutions, and over 400 industrial firms. Industry-University Cooperative Research Centers, also sponsored by the National Science Foundation, encourage interaction between industry and universities by developing research programs defined by the industries supporting each center. On average, Federal funds have been matched 10 to one by industries. There currently are 45 centers operating. One example of the potential of such cooperative efforts is the development, in response to industry's needs, of a technique for the measurement of very small quantities of impurities in gases by the Cooperative Research Center at the University of Arizona. The technique has wide potential application in pollution monitoring and process control in the semiconductor industry.

Another type of cooperation in research is exemplified by SEMATECH, a private sector consortium formed to conduct R&D on improved semiconductor manufacturing processes. SEMATECH has received half of its funding from the Department of Defense and the other half from participating companies. SEMATECH has given top priority to improving relations between chipmakers and equipment producers to facilitate the development of a range of high-quality, affordable equipment and materials for American producers.

Transferring Federal Technology to Industry—The development of working relationships between scientists, engineers, and managers in industry, academia, and government has the added advantage of fostering technology transfer, an important component of U.S. Technology Policy. The term "technology transfer" implies to many people that technology can be neatly



identified, wrapped up, and transported cleanly to another organization where it can be unwrapped and applied without significant change. This is, of course, an oversimplification. In fact, one of the most effective ways that technology can be transferred is by being carried in the minds of people as they move from one organization to another. Short of the wholesale transfer of scientists and engineers, however, there are many steps that can be taken to foster the transfer of appropriate technology from laboratories in all sectors to the economic agents that can best put them to use in competitively producing products and services.

Concerted Federal activity in technology transfer was reinvigorated during the 1980's, starting with the Stevenson-Wydler Technology Innovation Act of 1980. Among the stated purposes of the act was to promote technology development through the establishment of organizations within the executive branch to study and stimulate technology, and stimulate improved utilization of federally funded technology developments by State and local governments and the private sector.

The passage of the Federal Technology Transfer Act of 1986 amended the Stevenson-Wydler Act to encourage further the transfer of Federal technology to industry. Among its provisions are those that encourage Federal laboratories to perform cooperative research with outside parties, as long as the research is consistent with the mission of the laboratory, and permit private companies to obtain advance rights to patent technology developed under the cooperative agreements. The Act also allows laboratory directors to negotiate other types of intellectual property right assignment agreements and the sharing of royalties. Thus, the key principles of decentralization of technology management, interaction with private industry throughout the R&D process, and suitable incentives for the federal laboratory worker as well as private industry were all addressed in the 1986 Act. Since inception of the Act, Cooperative Research and Development Agreements (CRADA's) at federal agencies have increased from 33 in FY 1987 to 460 in FY 1990.

Particular attention has been paid to reducing the barriers faced by small and medium sized manufacturers in adopting new technology. The U.S. is home to more than 350,000 manufacturing companies with 500 or fewer people on the payroll; these firms produce over half of the value added by all U.S. manufacturing. The National Institute of Standards and Technology has established five Regional Manufacturing Technology Centers which provide small businesses with up-to-date practical information and expertise on manufacturing technologies and prac-



tices, from quality control to computer-aided design and manufacturing, to "just-in-time" production systems. The centers do not conduct research; they provide assistance through factory service visits, technical training, and direct help with the introduction of modern manufacturing equipment. Whether these centers are an effective and efficient means of addressing the problems of small manufacturers awaits evaluation.

Any consideration of how best to exploit Federal development of technologies must include an extremely valuable but often overlooked asset. In addition to the nation's researchers in academia and industry, there exists an enormous national resource in the professional personnel, expertise, and infrastructure resident in over 700 Federally-owned laboratories. The federal government invests over \$21 billion a year in these laboratories—almost a third of the total federal R&D budget. A continuing challenge is to involve these laboratories in joint R&D projects with universities and industry so that they can play a more effective role in transferring technology to the private sector.

In addition to targeted programs for technology transfer, the Federal government helps to sustain the pool of technically trained manpower through the support of graduate students on fellowships and traineeships or receiving research assistantships as part of Federal grants. In 1986, there were already over two-and-one-half million scientists and engineers employed in U.S. industry. One reason for industry interest in cost sharing for activities such as the National Science Foundation's Engineering Research Centers may be to develop contacts with students who, after matriculation, can be hired into the firm.

CONCLUSION

The private sector has the principal role in innovation and in identifying and utilizing technologies for commercial products and processes. Even in meeting its own needs, the government relies on the private sector to undertake the development process, and the government's role is to provide an economic and legal environment conducive to commercialization of R&D. In certain circumstances, however, the Federal government and the private sector share responsibility for supporting appropriate pre-competitive research on generic enabling technologies.

However, it is not an appropriate role for the Government to develop commercial products, whether they are based on technologies developed with Federal R&D support or not. Moreover, where appropriate, the private sector must take an active role in guiding the innovation process from the outset to ensure that

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R&D fits market needs. In providing a cooperative framework for the private sector and government, the Department of Commerce has announced a Strategic Partnership Initiative through which it will provide a cross-industry forum for industry to discuss the formation of partnerships of noncompeting firms to develop and apply large-scale enabling technologies.

Thus, the Federal government, because of both its interest in maintaining a competitive economy and the resources it commits to R&D for non-commercial purposes, can be a partner in the innovation process. In addition, the Government is in a unique position to encourage improvements in private sector competitive performance. An example of this is the Malcolm Baldrige National Quality Award established by the Congress and President Reagan in 1987. This award, which recognizes U.S. companies that excel in quality achievements and total quality management, has had a tremendous effect on those companies that have prepared to compete for it: some companies have experienced productivity gains of 20 to 30 percent just in the process of competing. One company was so impressed with the gains to be made in the process of qualifying for the competition that it required all of its suppliers to compete for the award as well.

Additional Federal responsibilities include creation of an environment conducive to technological competitiveness through such measures as reducing the capital gains tax and creating a permanent tax credit for research and experimentation, removing obstacles to innovation such as anti-trust uncertainties about joint research and production ventures, and negotiating international protection of intellectual property. The Federal government also seeks to revitalize education at all levels and to encourage States, localities, and universities as they improve science and technology education.



PETER SIMON/PETER ARNOLD, INC.

Global Change



THE ENVIRONMENT OF THE EARTH has been changing continually due to interactions of natural forces over the millions of years of its lifetime. Ice ages have come and gone and climatic regimes have fluctuated between dry and wet and between hot and cold. However, during the past century, human activities have also begun to significantly alter the environment of the planet. People have begun to change the surface of the Earth by clearing forests, building cities, and converting wild lands for agricultural and industrial uses. Humans have also altered the composition of the Earth's atmosphere through such activities as the burning of fossil fuels, the production and release of industrial compounds, and the expansion of agriculture.

Already some of these anthropogenic factors have resulted in a significant impact on the Earth's environment. For example, human activities have led to the partial degradation of the atmosphere's protective ozone shield, exposing both humans and other forms of life to higher levels of ultraviolet radiation. The degradation has been most severe in a polar region remote from population or industrial centers, where airborne industrial compounds combine with unique meteorological conditions to form the "ozone hole" above Antarctica, demonstrating the global reach of human activities. The speed with which the "ozone hole" has developed provides dramatic evidence that human activities can change the global environment within just a few decades. New results from the International Ozone Scientific Assessment of 1991 also show, for the first time, evidence of decreases of ozone in spring and summer in both the northern and southern hemispheres at middle and high latitudes, as well as in the southern winter.

A far more complex potential threat to the global environment is the possibility, that human actions will lead to an intensification of the "greenhouse effect" and thus to a significant warming of the Earth's climate. Such changes in the Earth's environment involve the entire Earth system—including the land surface, its vegetative cover, the oceans and their currents, the polar ice caps, as well as the atmosphere and now, human activity.



Reliable predictions of the magnitude and rate of climate change as well as the impacts—global or regional—of these changes are not yet possible.

Nonetheless, these fundamental changes in the environment of the Earth transcend national boundaries, and scientists and governments around the world are working together to build a solid scientific understanding of both natural and human induced climate change in order to have a sound information base for policy-making.

POLICY RELEVANCE

To create prudent environmental policies will require a much improved scientific understanding of the Earth system, how it changes naturally, how human activities change it, and how it might respond to future changes in environmental conditions.

The Bush Administration has been giving priority attention to research on global change through a special Presidential Initiative called the United States Global Change Research Program (US/GCRP). This effort was designed to provide strategic input to the domestic and international policy-making needs and to provide the decision-making process with the strongest scientific information base possible. In addition, the US/GCRP also specifically addresses the requirements of the US Global Change Research Act of 1990 (PL 101-606). This Presidential Initiative represents a substantial contribution to the international activities in this area, represented by the rapidly emerging Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change (IPCC) process, both of which will form the basis for international policy making related to the global environment through the programs to be discussed at the United Nations Conference on Environment and Development (UNCED).

The US/Global Change Research Program (USGCRP) is comprised of a coordinated interagency research effort and a substantial portion of a significantly increased budget in the context of the cooperative international effort. The research program was developed under the auspices of the Office of Science and Technology Policy and the Office of Management and Budget through the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET).

STATE OF THE SCIENCE

An international team of scientists concluded in their IPCC-sponsored report released in 1990, that there is a natural greenhouse



effect which keeps the Earth warmer, by about 33 degrees centigrade, than it otherwise would be. Furthermore, it is also known that emissions resulting from human activities are increasing atmospheric concentrations of greenhouse gases such as carbon dioxide, methane, chlorofluorocarbons and nitrous oxide. For example, atmospheric levels of carbon dioxide have gone up about 25 percent since pre-industrial times due to human combustion of fossil fuels and other organic matter; levels of other principal greenhouse gases, methane and industrial chemicals, especially chlorofluorocarbons, have gone up even faster. The geological record contains clear evidence of natural variations of climate, over the past 160,000 years, indicating that changes in Earth's surface temperature have been closely correlated with changes in atmospheric concentrations of greenhouse gases such as carbon dioxide and methane.

The Intergovernmental Panel on Climate Change (IPCC) also concluded that the global mean surface temperature has increased by 0.3 degrees to 0.6 degrees Centigrade during the past 100 years. This warming is broadly consistent with climate model projections based on increased greenhouse effects of 0.6 degrees Centigrade over the past 100 years. The models predict a global mean surface temperature increase of between 1.5 degrees and 4.5 degrees Centigrade due to a doubling of atmospheric carbon dioxide or its equivalent in other greenhouse gases. However, these predictions must be regarded as uncertain, according to the IPCC, particularly with regard to the timing, magnitude, and regional patterns of climate change because of inadequate representation in climate models of the various Earth system processes that are at present not well understood or quantifiable. Regional patterns are especially important, since it is the rainfall, soil moisture, and temperature in a particular region that are critical to those who live in any given area.

A recent study suggests that only minimum temperatures have changed over the past four decades. This further compounds the uncertainty surrounding this issue since it is unclear if the models are wrong or human generated greenhouse gases are having less of an impact on warming.

The risks associated with global change and the scientific uncertainties surrounding it are both substantial. So, too, are the economic costs associated with addressing global change. Only a better understanding of the many components of the Earth system and their interactions can lead to an improved ability to predict global change. Research to reduce scientific and economic uncertainties of global changes thus provides the best means of

To create prudent environmental policies will require a much improved scientific understanding of the Earth system.



assessing the societal impacts and provides a firmer basis for national and international policy actions.

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

The central goal of the US/GCRP is to establish the scientific basis for national and international policy making relating to natural and human-induced changes in the global Earth system. To meet this goal, the following objectives for the US/GCRP have been established:

- To achieve an integrated, comprehensive, long-term program of documenting the Earth system on a global scale;
- To conduct a program of focused studies to enhance our understanding of key physical, geological, chemical, biological, and socio-economic processes and their impacts on regional and global scales; and
- To develop integrated conceptual and predictive Earth system models to predict regional and global change.

While the US/GCRP is thus designed to be comprehensive in scope, overall constraints on Federal funding have led the U.S. to pursue a program more focused on the near-term, highest priority scientific, economics research and policy issues identified by the IPCC and at the 1990 White House Conference on Science and Economics Research Related to Global Change. In particular, the highest priority scientific and policy-related issue for the US/GCRP in the current decade is the ways in which human activities are changing or will change the global climate system.

Using the information needs identified by the IPCC as a guide, the GCRP has adopted four integrating research themes to help focus the collective efforts of government, academic, and industry scientists involved in global change, as follows:

1. Climate Modeling and Prediction: research to develop an improved predictive capability of the Earth's many coupled systems with enhanced regional resolution.
2. Global Water and Energy Cycles: research to improve the understanding of water related phenomena (precipitation, evaporation, evapotranspiration, soil moisture, ice quantity, type and movement) and energy cycles (warming/cooling, radiative balance, solar variability, latent heat) including the roles of clouds, of the oceans, of terrestrial ecosystems, and changes in sea levels.
3. Global Carbon Cycle: research to improve the understanding of the carbon cycle by quantifying the natural and anthropogenic terrestrial and oceanic sources and sinks of key carbon compounds including their chemical reactions in the atmos-



phere and ocean; the chemical, biological and physical processes that control their fluxes; how these fluxes may be influenced by changes in climate; and how changes in greenhouse gas concentrations may affect all these processes.

4. Ecological Systems and Population Dynamics: research to improve the capacity to assess the effects of global change at regional scales. Specifically, to improve the understanding of the responses of intensively managed and natural oceanic and terrestrial ecosystems to global change by focusing scientific research on species composition of ecosystems, distribution and extent of ecosystems, and the productivity of ecosystems.

In these four areas, the GCRP will support and expand research to reduce uncertainties identified by the IPCC, by investigations into:

- the sources and sinks of greenhouse gases, which affect predictions of future concentration;
- clouds and radiative balance, which strongly influence the magnitude of climate change at global and regional scales;
- oceans, which influence the timing and patterns of climate change;
- land-surface hydrology, which affects regional climate change and water availability;
- polar ice sheets, which affect predictions of global sea level changes;
- ecological dynamics, which are impacted by and respond to climate change; and special attention will also be directed toward research on socio-economic issues associated with global change, especially impacts on and adaptation of economic systems to potential changes.

In all of these investigations, special attention will be directed to the data collection, storage, and analysis systems required to adequately support the research efforts and carefully document the new knowledge about the Earth and its many complex and closely interrelated systems.

CLIMATE MODELING AND PREDICTION AND ASSESSMENT

Understanding and predicting changes in the Earth system require that many distinct components be successfully linked. Currently global models, such as those used in the first IPCC assessment, consist of coupled atmosphere-ocean models which contain rather crude representations of oceanic circulation and relatively poor representations of terrestrial ecological processes. One reason for the relative crude representations is that the



processes that govern the interaction of the Earth system's components are insufficiently understood. Improving the knowledge base and integrating the predictions from these various models is thus a central goal of research. A second reason is that the capacity and speed of computers required to simulate the coupled ocean/atmosphere/land Earth system are presently inadequate (Chapter 4).

Given the complexity of the Earth system and its many feedbacks, prediction of climate and environmental changes is not straightforward. For example, the human-generated increases in atmospheric carbon dioxide concentration are a major factor potentially causing climate change. However, because carbon dioxide is the primary raw material for photosynthesis, increased carbon dioxide concentrations are also likely to stimulate plant growth and thus change the extent and distribution of the Earth's vegetative cover. This, in turn, affects the water cycle of the Earth and the degree to which the surface reflects or absorbs sunlight—and thus could affect climate. Such complex Earth system processes and interactive feedbacks can only be understood through model simulations.

Today's global models can simulate some of the important processes of global change, including the direct response of the climate system to increased atmospheric concentrations of greenhouse gases, the warming of the troposphere, and the cooling of the stratosphere. Many important processes, however, are treated only in a rudimentary fashion by the models. These include the interaction between clouds and radiation, the circulation of the oceans, changes in the distribution and abundance of living things, the role of plants and other organisms in recycling carbon, and exchanges of heat, water, carbon dioxide and other gases between the oceans, the land, and the atmosphere.

Today, scientists model individual components or limited subsystems of climate, such as the atmosphere; the atmosphere and ocean; or the atmosphere, ocean and prescribed land-surface, rather than the entire coupled system. More reliable climate change predictions, especially at the regional scale, will require modeling the integrated behavior of the entire system.

The primary climate models, called general circulation models, predict a variety of climatic variables, such as temperature, precipitation, winds, snow accumulation, and soil moisture. Integrating these largely atmospheric models with those for the ocean, the land surface, and the biotic changes in those regimes will be necessary for improved prediction.

Observations of a wide variety of past and present physical,



geological, chemical, and biological parameters associated with the atmosphere, land, and ocean will be required to improve scientific understanding of how the Earth functions as a single coupled system. Good data and information management are essential to accomplish this. Data sets must be organized and assimilated so the model simulations of present and past environments can be compared to nature as a test of model accuracy.

Model development requires greater understanding of processes within each component of the Earth system, such as cloud-radiation interactions, and of processes that involve interactions between two or more of the components, such as the role of the oceans and terrestrial vegetation as sinks for atmospheric carbon dioxide, together with the changes that may occur in these processes under different climatic regimes.

Global Water and Energy Cycles—Water plays a central role in the Earth system, and not only because of its essential role for all forms of life. Water's physical properties give it a role as a climatic thermostat and as a carrier of heat. The global hydrologic cycle plays a pivotal role in the Earth's radiation and heat budgets. The distribution of clouds and water vapor, for example, are a major factor in controlling the amount of solar energy absorbed by the Earth system as well as the infrared radiation emitted to space, and they strongly influence the redistribution of heat throughout the Earth system.

The research projects accorded a high priority by the USGCRP include the study of atmospheric water vapor (the most important greenhouse gas in the atmosphere), clouds and their role in climate system feedbacks, precipitation and its distribution over land and sea, changes in sea ice extent and amount, the role of the oceanic circulation in absorbing greenhouse gases and redistributing heat, and the interaction of land-based biota with the atmosphere.

The flow of energy in the atmosphere is strongly influenced by the presence of all three phases of water (as water vapor, as condensed water in clouds, and as ice or snow). Clouds play a major role in the exchange of energy and moisture, yet are not well understood. For example, small changes in the distribution of relative humidity can alter the characteristics of clouds and hence alter the amount of solar heat retained by the atmosphere. Scientific understanding of these processes is currently limited by inadequate understanding of how water in the atmosphere condenses to form clouds of varying type and spatial distribution.

Given the complexity of the Earth system and its many feedbacks, prediction of climate and environmental changes is not straightforward.



The oceans are by far the dominant reservoir on the planet for both water and heat. Evaporation and precipitation over the ocean result in the exchange of heat, as well as water, with the atmosphere. In turn, precipitation and evaporation exert a strong control on the salinity and the deep circulation of the ocean. A prominent example of the interaction between the ocean and the atmosphere is provided by the phenomenon known as El Nino/Southern Oscillation, in which major shifts in upper ocean and atmospheric circulation in the tropical Pacific result in changes in the distribution of rainfall over an area stretching from India and Australia to North and South America. Changes in the deep circulation of the ocean can also cause global changes in the distribution of rainfall on time scales of decades to centuries, according to evidence from studies of past climates and experiments with coupled ocean-atmosphere models.

Recent research has shown the importance of land surface processes in regulating the supply of heat and moisture available in air masses as they move across continents. Although the basic processes that govern the movement of water are reasonably well understood over small areas, they are poorly understood over larger regions and continental-sized areas. It is well known that soil moisture provides a source of atmospheric water vapor that can then produce precipitation. Thus a large area of wet soils can enhance precipitation, while a drought (and the associated dry soils) can become self sustaining. However, researchers need better understanding of the role of vegetation, because plants also regulate the rate at which the land surface returns water vapor to the atmosphere. Better understanding is also needed regarding the growth or shrinkage of glaciers, of changes in the permafrost found in polar regions, and the effects of human activities such as deforestation, irrigation, urbanization, and the construction of dams.

During the past century, scientists estimate that the sea level has risen about 10–20 centimeters due to the observed worldwide retreat and melting of temperate glaciers, especially those in southeastern Alaska, and from thermal expansion of the oceans. Sea level would be expected to rise further in response to potential global warming, but there are enormous uncertainties in both measurement and in the understanding of the underlying science. For example, the relationship between atmospheric levels of carbon dioxide, temperature, and global ice volume remains uncertain.

Characterization and representation of the hydrologic cycle is one of the major acknowledged weaknesses in general circula-



tion models of climate. Quantitative understanding of the global water and energy cycles would significantly enhance the development of an advanced climate modelling capability.

Global Carbon Cycle—Carbon plays the central role in the chemistry of life. As fossil fuels, carbon compounds continue to provide the primary source of energy for industry, as they have throughout this century. Carbon compounds are also central to the operation of the greenhouse mechanism that has maintained the Earth system at a habitable temperature.

Human activities are altering the global carbon cycle, increasing the atmospheric concentrations of carbon-based gases such as carbon dioxide, methane, and chlorofluorocarbons that absorb infrared radiation and thus increase the radiative heating of the atmosphere. The concentrations of other trace gases, such as carbon monoxide and the oxides of nitrogen, are also increasing, with subsequent effects on the formation or lifetimes of greenhouse gases.

Many of the key processes in the carbon cycle that control the sources and sinks of these gases are still poorly understood. Of the carbon dioxide emitted from the burning of fossil fuels, for example, only about half reaches the upper atmosphere: about half of the rest is apparently absorbed by the oceans, and the remainder—fully a quarter of the anthropogenetically produced carbon dioxide—vanishes into a still unknown sink.

The atmospheric concentration of carbon dioxide is now about 350 parts per million (ppm), and is increasing about 1.8 ppm per year. About 6–8 billion metric tons of carbon is released to the atmosphere annually as carbon dioxide from human activities. This amount is less than one twentieth the amount from natural sources, but it has been large enough to increase atmospheric carbon dioxide concentrations by 25 percent since pre-industrial times.

The research challenge is to understand the fate of the carbon released from human activities—to determine the sinks that remove carbon from the atmosphere. The rate at which carbon dioxide is removed by the oceans depends both on the immediate exchange between air and sea and the subsequent transfer of carbon to the deep ocean and to seafloor sediments. The chemical, biological, and physical processes that control carbon transfer need to be better understood and the movement of carbon dioxide into and within the oceans more accurately measured. The challenge is also to understand the amount of carbon stored in different terrestrial ecosystems and their compo-



nents—including living biomass, detritus, soil, permafrost, and sediments—and the cycling and transformation of carbon within these ecosystems.

The atmospheric concentration of methane is 1.72 ppm, now more than double the pre-industrial value, is increasing at a rate of 0.9 percent per year. Methane is produced by a wide variety of human activities and natural sources, including natural wetlands, rice cultivation, domestic animals, burning of biomass, and venting or leaks of natural gas from wells and pipelines. The research challenge is to improve the quantitative knowledge of these sources of methane and the process that control its release. Investigating the processes that affect the atmospheric retention of methane is an important research need.

Ecological Systems and Population Dynamics—The living organisms of the Earth both play a part in and are affected by climate change. Plants are a major reservoir of carbon dioxide. Microbial activity is a major source of methane. Human activities such as the burning of fossil fuel, deforestation, and agriculture are increasing the levels of greenhouse gases. It is of great importance to understand these roles and the consequences of changes in climate on living organisms and their ecosystems. The growth of human populations, in particular, plays an increasingly critical role in global ecological problems. What is at stake is both the carrying capacity of the planet and the wealth and diversity of Earth's biological resources.

At present, the net effects of warming on biological processes cannot be reliably predicted. Higher temperatures, for example, tend to increase both photosynthesis—which removes carbon dioxide from the atmosphere—and respiration in plants and microbial decomposition of biomass—which release carbon dioxide. Increased soil moisture, on the other hand, could increase plant growth and carbon storage. Higher levels of carbon dioxide also may increase plant growth in a number of ways, from stimulating photosynthesis to improving plant's resistance to water and nutrient stress to prolonging the growing season. There is considerable uncertainty about the operation and interrelation of such processes in natural ecosystems.

Because species respond differently to climatic change, ecosystems are likely to change in structure and composition under conditions of global warming. Temperature changes comparable in magnitude to those predicted by today's climate models have in the past been associated with significant shifts in the geographical distribution of terrestrial plants and animals.



During the Medieval Warm Epoch from 800 to 1200 AD, the boreal forests of Canada extended well north of their present boundaries and Scandinavian farmers grew grain as far north as 65° latitude.

Deforestation in tropical regions and forest harvesting and regrowth in temperate zones alter the flux of carbon dioxide between the land and the atmosphere. The net effect of these human activities are quite uncertain, however. The issue is further complicated by the over-fertilization of surface waters in the Northern Hemisphere attributable to runoff of nitrogen fertilizers, which may be promoting carbon storage in biomass. Proposed reforestation efforts will also increase carbon storage.

The research need is to quantify both the effects of global change on biological systems and their contributions to such change. The study of population dynamics provides links among these interacting social, economic, biological and ecological variables, from small-scale experiments on how competing plants may grow in high carbon dioxide atmospheres to larger-scale considerations of how global food availability may be affected under global change.

Sampling biological populations and building ecological databases is one important research focus. Crop yields, fishery and forestry resources, and the abundances of game and some non-game species are measured directly in many nations. Remote sensing from satellites can indicate the distribution of major plant life-forms. The application of sampling and monitoring methods needs to be extended over longer periods of time, in order to detect projected changes due to global change over a naturally variable background. The empirical climate records have made obvious the lack of detailed ecological databases with comparable data.

A second research focus is the exploration of factors that govern the response of populations to global change. Key unknowns include the extent to which climate and carbon dioxide levels control species composition and abundances, the importance of interactions in determining the composition of an ecological community, and how species interactions are likely to be altered under global change. In environments, which have been affected by human activity, more understanding is needed of the consequences that global change will have on human health and on the vulnerabilities of economic institutions nationally, regionally, and worldwide. The consequences of global change for geographic distributions, dispersal and migration of populations, both human and otherwise, are poorly understood.

What is at stake is both the carrying capacity of the planet and the wealth and diversity of Earth's biological resources.



A more realistic accounting of the true environmental and economic costs of resource exploitation and management is necessary for wise stewardship of resources now and in the future. Better descriptions and models of the links between energy use, agricultural and forest management practices, land-use, human migration and gas emissions will be especially important for predicting both direct and indirect human contributions to global change.

The scientific community has many well-developed tools for simulating the dynamics of single and, in some cases two or more, interacting populations of plants and animals. Models of larger numbers of interacting populations must be improved, coupled to the physical environment, and scaled up to larger geographic regions. Human population and economic models should be integrated with resource and biological models, in order to provide a more complete description of the interaction of resource management and the distribution and abundance of species.

Economics Research—Economic activities play a central role in determining the level of energy, land use, and industrial activity that contribute to global change. Thus economic research and methods provide an important tool for evaluating the interactions between society and global changes. Economic considerations are also important in evaluating the costs and human consequences of actions that might possibly be taken to alter the timing or magnitude of global change, and thus are essential to the choice of policy response options. Many of these issues were identified at the 1990 White House Conference on Science and Economics Research Related to Global Change.

The key needs for research are to document economic trends that determine human inputs to global change throughout the world, to study the economic consequences of responses to global change, and to develop means of assessing issues that cross-cut the physical, biological, and economic sciences. This includes, for example, a better understanding of the economic forces driving technological change and productivity growth; of the underlying adaptive capability of economic sectors faced with climate changes; and of the nature of economic growth, especially in developing countries. An ability to represent this improved understanding in economic models is also needed in order to evaluate international market and trade effects and to develop consistent scenarios and predictions of trace gas emissions and global change effects.



Global environmental changes could have profound impacts on the resources and systems which determine the health, abundance, distribution, and well-being of human beings and other species. Irreversibility of species loss and other potential consequences of global change and the need to consider a time frame of 50 to 100 years or more pose special problems for economics and decision science research. Researchers must re-examine research and decision making under uncertainty and the general topic of valuing future outcomes and costs, drawing on approaches from both the social and physical sciences.

Economics research can make several important contributions to establishing a foundation for policy analysis. First, economics research can address issues in strategy, negotiation, compliance and enforcement that are relevant to the global change policy process. Second, research can examine the strengths and weaknesses of the types of generic policy instruments that are potentially applicable in the global change context. Finally, research can contribute to the development and refinement of tools, such as internationally linked macroeconomic models, that will play an important role in policy analysis.

CONCLUSION

For the first time in history, the human species has the capability of changing the global environment. Already, human activities have led to a partial degradation of the atmosphere's protective ozone shield and have raised the possibility of intensifying the greenhouse effect and so changing Earth's climate. The great challenge is to anticipate future global change and to develop a rational program for protecting the environment. That will require a far better understanding of the many components of the Earth system— air, water, land, and living organisms—and their interactions.

The Bush Administration is giving priority attention to research on global change through the US/GCRP, which is designed to increase the knowledge base concerning the entire Earth system and to improve the ability to model and predict global change, both natural and that caused by human activities.



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