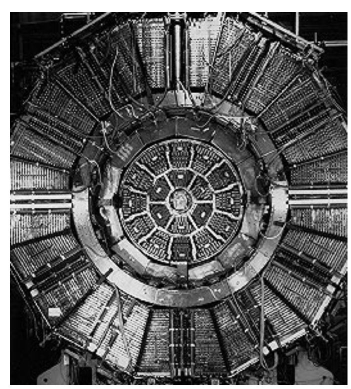
The Changing Nature of Science 2

This chapter provides an overview of the fundamental changes that are occurring in scientific research, including the rapid diffusion of information, new areas of scientific inquiry, and the role of large projects. These changes, the link between science and economic competitiveness, and growing budget constraints have spurred U.S. and other nations' interest in international collaboration.

DIFFUSION OF KNOWLEDGE

Over the past century, the pace of scientific and technical innovation has expanded at historically unprecedented rates. Currently, the scope and rate of human inquiry are leading to a doubling of scientific information roughly every 12 years.[1] It is estimated, for example, that nearly half of the roughly one million publications in the field of mathematics have been published in the past decade alone.[2] The sheer velocity of this scientific and technological change has transformed the very fabric of daily life, affecting the course of economic and social development as well as the relationship between human society and the natural world.

Yet, the modern scientific enterprise cannot be characterized simply by the speed at which information is generated or exchanged, but also by its breadth, creativity, and degree of sophistication. The very character of research and development (R&D) activities is experiencing fundamental change as greater interaction across disciplines is giving rise to new fields of investigation and new methods for defining, measuring, and understanding



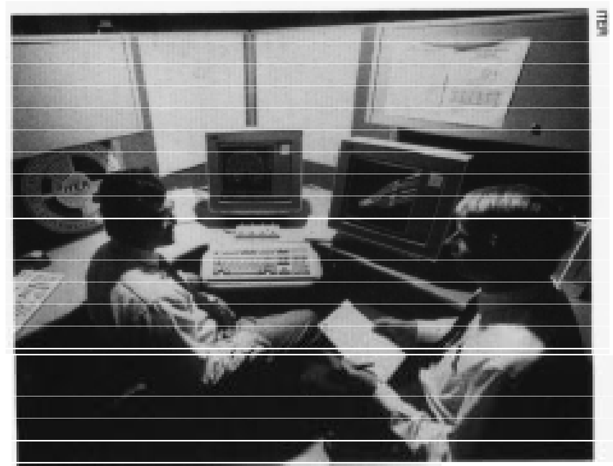
[1]Gary Stix, "The Speed of Write," *Scientific American*, December 1994, p. 107.

[2]Ibid.

physical, biological, and ecological phenomena. Increasingly, advances in one field are accelerating developments in others.[3] Successive advances in underlying scientific knowledge and technology have an enabling or multiplier effect in that they permit deeper examination of more complex scientific problems. From understanding and manipulating essential genetic processes, to discovering new classes of materials, to exploring the fundamental aspects of natural law, modem science is laying the foundation for even more profound discoveries and novel applications. On many fronts, new areas of study and innovation are emerging that will no doubt have important social and economic consequences.

With the rapid development and diffusion of information and communications technologies, the extraordinary pace of scientific discovery is undergoing further acceleration. By effectively removing barriers of time and distance, new electronic networks are fundamentally altering traditional patterns of R&D. These networks have greatly expedited the exchange of information among researchers and promoted new possibilities for international collaboration within and across disciplines.

The emergence of these new tools of communication is serving to reinforce the international dimension of basic scientific research.[4] Even if science projects and investigations have been essentially national in character, the resulting scientific knowledge has, in most disciplines,



High-performance computers and high-speed electronic communications networks are essential tools for ITER fusion collaborators located around the world.

spread globally. This diffusion of information has taken on a dramatically different character in recent years. Both formal and informal global research networks now exist in practically every major domain of science. Leading scientific journals increasingly publish the work of multinational research teams. With access to the Internet and other forms of communication, the manner in which scientists design experiments, analyze data, and interact with each other is undergoing major change. In virtually every scientific field, researchers throughout the globe have daily communications in which data are exchanged, preliminary experimental findings are discussed, and new concepts and theories are debated.[5] In addi-

[3] For example, the tremendous advances in the field of microelectronics have been a result of advances in such disparate fields as condensed matter physics, optics, metallurgy, plasma chemistry, accelerator physics, electronic circuit theory, and software architecture. These developments in microelectronics have, in turn, affected virtually every scientific and technical discipline from aeronautics to molecular biology.

[4] The globalization of business is also strengthening the international character of scientific research. Elaborate webs of production now span the globe. These production networks often includeR&D centers in many parts of the world. Multinational companies increasingly draw on the intellectual resources of a variety of different countries in both basic research and product development. In addition, corporations from different counties are increasingly forming strategic relationships to jointly carry out research and introduce new products.

[5] There is thus far limited empirical reserach on how communication technology is affecting the social or organizational aspects of collaboration. As communications capabilities advance, the need for face-to-face interaction could to a certain degree be supplanted by sophisticated interactive multimedia networking. However, such networking will obviously have limits, such as the need to oversee and operate complicated instrumentation. For a discussion of these issues see BruceV.Lewenstein, 'The Changing Culture of Research: Processes of Knowledge Transfer,"contractor report prepared for the Office of Technology Assessment, Sept. 21, 1992; and Lisa Heinz, Coates & Jarratt, Inc., "Consequences of New Electronic Communications Technologies for Knowledge Transfer in Science: Policy Implications," contractor report prepared for the Office of Technology Assessment, August 1992.

BOX 2-1: Earth Observing System Data and

As part of the U.S. Global Change Research Program to monitor global ecosystems, the National Aeronautics and Space Administration (NASA) is now constructing one of the most sophisticated and ambitious data storage and distribution systems ever developed. The Earth Observing System Data and Information System (EOSDIS), the centerpiece of NASA's Mission to Planet Earth, is designed to provide continuous, high-quality data to support better scientific understanding of the Earth's oceans, land, and atmosphere. When the multisatellite Earth Observing System (EOS) becomes fully operational, sensors aboard EOS instruments will generate immense quantities of data. EOS satellites could produce as much as 300 trillion bytes of information per year, an amount roughly comparable to 250 million, 1.2 megabyte floppy disks. In addition to gathering and processing data, EOSDIS will calibrate satellite instruments, control EOS spacecraft, and schedule the observation periods of remote sensors. EOSDIS will also integrate data from non-EOS spacecraft and non-NASA space systems, as well as key data from land-based and ocean-based sensors from around the planet. Moreover, the EOS data system is being designed to detect subtle changes in ecosystem behavior over long periods of time.

In order to facilitate interdisciplinary global change research, NASA plans to make these large quantities of experimental data easily available to a wide body of researchers at locations throughout the world. More than 10,000 physical scientists and as many as 200,000 other researchers could become regular users of the EOSDIS data repositories. This will create considerable data management and networking challenges. Having readily accessible, user-friendly data retrieval and management tools could be an important step for promoting online collaboration among researchers who are geographically dispersed. To meet these challenges, NASA is implementing a "distributed architecture" for EOSDIS rather than having a single central processing facility. Distributed Active Archive Centers, located at regional sites across the country, will each process, store, and distribute data related to specific scientific disciplines. For instance, the EROS Data Center in South Dakota will archive and distribute satellite and aircraft data, the Jet Propulsion Laboratory in California will store data on ocean circulation and atmospheric-oceanic interactions. However, researchers throughout the U.S. and the globe will have routine access to the EOSDIS data archives.

SOURCE: U.S. Congress, Office of Technology Assessment, *Remotely Sensed Data:* Technology, Management, and Markets, OTA-1SS-604 (Washington, DC: U.S. Government Printing Office, September 1994.)

tion, network-based scientific communications can broaden the base of research by opening up data sources and publications to researchers who previously did not have access to such information. Small institutions, in particular, can strengthen their R&D activities by accessing data provided by larger, well-established institutions.[6]

Scientists can now use sophisticated information search tools that effectively link databases in different countries to a single integrated data repository. For example, a number of biological databases are now linked together. This is particularly useful for researchers in the areas of biotechnology and molecular biology. Another illustration of sophisticated data management is the Earth Observing System Data and Information System now being developed by the National Aeronautics and Space Administration (NASA) (see box 2-l).

[6] There is some evidence that scientists who are geographically or institutionally isolated can improve their scientific productivity through the usage of electronic network resources and communications. See Heinz, ibid.

Other potentially important developments include the emergence of electronic publications, or so-called multimedia journals, that do not simply present experimental results and analysis, but may also contain interactive computer simulations that illustrate the behavior of physical phenomena.[7] "Virtual" experimental communities or "collaboratories" that permit real-time interaction among researchers have also begun to appear.[8] In some cases, experimental data are transmitted immediately from instruments to investigators throughout the world.[9] Yet, perhaps a more significant development is the ability of researchers in far-flung locations to actually witness and participate in experiments as they occur. For example, neuroscience investigators in Tennessee and Scotland recently controlled an electron microscope in California to study various tissue specimens.[10] In the future, remote access to telescopes, meteorological instrumentation, and other computer-controlled apparatus will likely be common.

These trends have a number of implications for big science projects. With the advent of new communications and data transfer tools, design and engineering activities can be decentralized more readily. For example, the development of engineering parameters and specifications for the International Thermonuclear Experimental Reactor (ITER) has been divided among teams working in the United States, Europe, and Japan. These teams frequently exchange detailed engineering analyses and documentation. In addition, distributed science activities such as the Human Genome Project and global change research, which involve the coordination of thousands of individual investigators, can be managed more effectively. Whether working in conjunction with a large group of investigators, or independently, scientists at particular geographic sites can now draw on the expertise of a much wider technical community. Thus, the existence of new information networks and technologies can serve to reduce some of the practical obstacles associated with large collaborative undertakings (see chapter 4).

NEW AREAS OF SCIENTIFIC INQUIRY

The Environment

Although the scientific and technological progress of the past century undoubtedly represents a new phase in human creativity and intellectual accomplishment, these advances have given rise to a new set of challenges. In particular, the large-scale expansion of economic and industrial activities over the past several decades has raised concerns about the impact of such activities on local and global ecosystems.[11] For the first time in history, humankind can potentially alter the basic biophysical cycles of the Earth. Human activities are now resulting in materials flows commensurate with those of nature. Human releases of elements such as mercury, nickel, arsenic, and vanadium are now several times those of nature, and the amount of lead released is nearly 300 times as great as natural processes.[12] Concentrations of carbon dioxide in the atmosphere are increasing 30 to 100 times faster than the rate observed in the climatic record; methane con-

[7] A recent paper placed on the Internet by IBM researchers included a computer simulation of how cracks propagate in materials. Stix, see footnote 1.

[8] See "Scientists Predict Internet Will Revolutionize Research," *The Scientist*, May 2, 1994, pp. 1, 8-9.

[9] For example, data from high-energy physics and fusion laboratories are routinely disseminated to researchers in different parts of the world either during or immediately following experiments.

[10] See "New Internet Capabilities Fueling Innovative Science," *The Scientist*, May 16, 1994, p. 9.

[11] The world economy is consuming resources and generating wastes at unprecedented rates. In the past 100 years, the world's industrial production increased more than fiftyfold. See W.W. Rostow, *The World Economy: History and Prospects* (Austin, TX: University of Texas Press, 1978), pp. 48-49.

[12] See James Galloway et al., *Atmospheric Environment*, vol. 16, No. 7, 1982, p. 1678. Also see Robert U. Ayres, "Toxic Heavy Metals: Materials Cycle Optimization," *Proceedings of the National Academy of Sciences*, vol. 89, No. 3, Feb. 1, 1992, pp. 815-820.

centrations are increasing 400 times faster than previously recorded.[13]

Understanding and addressing the impacts of global climate change are likely to require unprecedented levels of global coordination and cooperation across a broad spectrum of disciplines. Gaining a predictive understanding of the Earth's physical, chemical, and biological processes will require collaboration among ecologists, microbiologists, atmospheric chemists and physicists, oceanographers, botanists, space scientists, geologists, economists, and researchers from many other fields. The challenges are indeed formidable. For example, decoupling the effects of natural change from human-induced change is an extremely difficult task. Decades of continuous monitoring of the Earth's oceans, land, and atmosphere will be necessary to document possible climate and ecosystem changes.

The United States is spending billions of dollars in a multidisciplinary, multiyear effort to measure, understand, and ultimately predict the extent and underlying mechanisms of global environmental change.[14] However, given that these environmental questions are inherently transnational in character, the efforts of the United States or a few other countries will likely not be sufficient. Any credible global environmental monitoring program will require thousands of strategically located, ground-based instruments around the planet, as well as satellite and aircraft-based instruments.[15] Systematic and carefully calibrated measurements over many decades will be necessary to develop even a limited predictive understanding of climatological and ecosystem processes. The involvement of many if not all nations will be necessary to design and implement an effective monitoring effort. Moreover, developing the appropriate tools—whether technical, behavioral, or institutional—for adaptation to widespread ecological change will also require considerable global coordination. Thus, in the environmental area, international collaborative undertakings will likely increase in both number and complexity.[16]

Biotechology

Another significant revolution in scientific inquiry is in the field of biological sciences.[17] Since the early 1970s, considerable progress has been made in research in genetics, cellular and molecular biology, virology, and biochemistry. This progress has led to the creation of biotechnologies, which are defined as tools or techniques used in research and product development, and to the growth of related industries. Biotechnologies have enabled the diagnosis of human genetic disorders that would not have been detected by conventional methods; they have led to increases in food production and to the discovery of new drugs and vaccines. Biotechnologies also have several potential environmental applications, such as pollution remediation and pest control. The potential to improve human health and environmental

[13]See U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps To Reduce Greenhouse Gases*, OTA-O-482 (Washington, DC: U.S. Government Printing Office, February 1991), p. 45.

[14]This effort, designated the U.S. Global Change Research Program (USGCRP), consists of a number of existing and new programs. The largest element of USGCRP is the National Aeronautic and Space Administration's (NASA) Mission to Planet Earth, a program that uses space- and ground-based instruments to observe changes in Earth's ecosystems. NASA's Earth Observing System is the principal component of the Mission to Planet Earth effort. See U.S. Congress, Office of Technology Assessment, *Global Change Research and NASA's Earth Observing System*, OTA-BP-ISC-122 (Washington, DC: U.S. Government Printing Office, November 1993).

[15]Ibid.

[16]For a detailed discussion of how natural and human systems may be affected by climate change and what tools are available to adjust to such change, see U.S. Congress, Office of Technology Assessment, *Preparing for an Uncertain Climate*, OTA-O-563 (Washington, DC: U.S. Government Printing Office, September 1993).

[17]For an indepth discussion of biotechnologies, see U.S. Congress, Office of Technology Assessment, *Biotechnology in a Global Economy*, OTA-BA-494 (Washington DC: U.S. Government Printing Office, October 1991).

quality is truly global in nature and requires that the best ideas be sought out, regardless of the nation in which they originated.

Because of the strong biological science research base and entrepreneurial spirit that exist in this country, commercial development of biotechnologies has been strongest in the United States. A multiyear, research initiative is now under way to maintain and extend U.S. leadership in biotechnology and to spur economic growth. The Biotechnology Research Initiative is supported by 12 federal agencies. Another initiative, the Human Genome Project, is a 15-year, $3-billion, distributed effort to locate and characterize human genes for biomedical research in the 21st century.

In recent years, many nations have focused increasing attention on developing and/or expanding biotechnology research programs and the capacity to convert research into new products. The link between biotechnology R&D and future economic competitiveness is a primary motivation for funding these programs. This link is likely to continue to grow in the future. However, the increasing internationalization of scientific research may be a challenge to the pursuit of strictly national biotechnology programs.

Other Trends in Science

In recent years, there has been a marked increase in the level of interaction among researchers from different disciplines. The availability of satellite imagery of the Earth's oceans and land masses, for example, has led to research initiatives that explore the linkages among agriculture, meteorology, geology, and ecology. Materials scientists and molecular biologists are collaborating in the synthesis of new classes of high-performance materials that are biocompatible and biodegradable; chemists, physicists, and electrical engineers have joined forces to create innovative optical and computational devices. Psychologists, mathematicians, and linguists are developing software concepts that emulate natural language structures. Social and physical scientists are exploring the applications of complexity and chaos theory to human behavior. As the barriers between disciplines become more porous, previous trends toward specialization may be supplanted by a broader movement toward interdisciplinary research. The ease with which researchers from far-flung locations around the globe can now exchange and debate ideas is likely to reinforce this trend toward cross-disciplinary interaction.

Finally, with the end of the Cold War, a fundamental shift in the focus of R&D activities is occurring in the United States and abroad. Public and private expenditures on R&D now reflect a greater emphasis on civilian applications. Yet, comparable levels of spending for civilian and defense R&D activities will probably come about only over the long term, and will be subject to changing national security requirements. In fiscal year 1993, spending on defense R&D still represented about 60 percent of total federal support for R&D activities. In contrast, the national expenditure on civilian basic research amounted to about 25 percent of total government R&D spending.[18]

SCIENCE AND COMPETITIVENESS

Scientific and technological innovation have been closely linked to economic growth since the Middle Ages.[19] In the 20th century, efforts to harness the benefits of science have resulted in a highly structured and institutionalized approach to both basic and applied research. The essential premise underlying public support of fundamen-

[18]William J. Clinton and Albert Gore, Jr., *Science in the National Interest* (Washington, DC: Executive Office of the President, Office of Science and Technology Policy, August 1994).

[19]See N. Rosenberg and L.E. Birdzell, *How the West Grew Rich: The Economic Transformation of the Industrial World* (New York, NY: Basic Books, 1986).

tal scientific research is that it expands the base of human knowledge and thereby opens new possibilities for improving societal well-being.[20]

Although it is often difficult to assess the near-term impact of basic scientific research, its benefits to society over the long term, can be substantial.[21] For example, fundamental research in solid-state physics in the early decades of this century ultimately laid the groundwork for the modern electronics and computer industries. The emerging biotechnology industry can trace its origin directly to discoveries in the fields of molecular biology and biochemistry. Frequently, discoveries or insights from disparate fields of research can lead to fundamental advances. For instance, magnetic resonance imaging, a noninvasive medical diagnostic tool now in wide use, resulted from nuclear physics research dealing with the magnetic behavior of atomic nuclei. Even with a more structured approach to basic research, many significant technological developments have originated from research that was driven principally by curiosity. As an illustration, the study of bacteria that live in hot springs led to a new technique for rapidly cloning DNA (deoxyribonucleic acid), a discovery of potentially great scientific and commercial importance.[22] The process of understanding and harnessing natural phenomena has often been a serendipitous affair.

Although basic research can provide the essential inputs for commercial innovation, it alone is not sufficient to bring about improvements in national economic well-being. This is illustrated in one way by the lack of correlation between the number of Nobel prizes awarded to a particular nation and its overall economic and technological prowess.[23] Basic scientific discoveries in and of themselves usually possess little intrinsic value without further investments.[24] These investments might include more focused applications of research, the development of organizational and educational capabilities,[25] or greater awareness of how discoveries in different disciplines can improve existing manufacturing processes and products.

With the diffusion of knowledge throughout the world, many countries have developed comparable technical capabilities in a variety of industries. This has given rise to a highly competitive global arena that, in turn, has created an underlying tension between basic and applied research. Increasingly, policymakers are calling for national research efforts that are tied more directly to

[20]For some categories of R&D, particularly those that explore the frontiers of scientific understanding or entail significant risk, government support may be required if socially optimal levels of investment are to be realized. Government involvement may be particularly crucial when fundamental scientific or technological barriers need to be overcome in a short time. The challenge for policymakers is to determine where government can best use its R&D resources to complement, rather than replicate, the activities of the private sector. Government support of R&D activities can take many forms, including tax credits; direct financing of R&D through government labs, university research grants, or private contracts; or joint public-private partnerships.

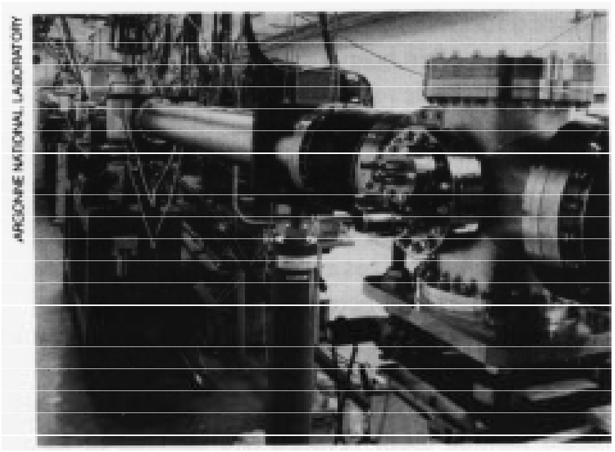
[21]One study concluded that rates of return for R&D in particular industries and from university research can be 30 percent or more. See Edwin Mansfield, "Estimates of the Social Returns from Research and Development," *AAAS Science and Technology Policy Yearbook, 1991*, Margaret O. Meredith et al., (eds.) (Washington, DC: American Association for the Advancement of Science, 1991). Also see Edwin Mansfield, "Academic Research and Industrial Innovation," *Research Policy*, vol. 20, 1991, pp. 1-12.

[22]The polymerase chain reaction method for cloning DNA is now being used in a number of applications ranging from "DNA fingerprinting" to the production of genetically engineered drugs.

[23]For example, from 1960 to 1992, the Japanese received only four Nobel Prizes in science but had over 22,000 patents issued by the U.S. Patent Office. See Center for Science, Trade and Technology Policy, George Mason University, "Large Science Priorities of Selected Countries," contractor report prepared for the Office of Technology Assessment, Jan. 23, 1995.

[24]See Paul David et al., Center for Economic Policy Research, Stanford University "The Economic Analysis of Payoffs from Basic Research—An Examination of the Case of Particle Physics Research," CEPR Publication No. 122, January 1988.

[25]The world's fastest growing economies have placed an extraordinary emphasis on primary and secondary education. This investment in education has often been complemented by investments in science and technology.



X-ray beams originating from the Advanced Photon Source storage ring are directed through a beamline (as shown) to an experimental station.

meeting the needs of society.[26] In both government and the private sector, there has been an inclination to shift funding priorities to the applied research area, where returns on investment can be more immediately realized. What is not clear, however, is whether there is an ideal mix of basic and applied research programs, or whether a major shift to applied programs will limit the range of new discoveries and innovations.[27] Regardless of the way in which national science priorities are set, it is important to recognize that there is not necessarily a linear relationship between basic and applied research. Rather, a complex interaction exists that cannot easily be characterized. Although additional funding for both basic and applied research would permit the pursuit of a broader range of scientific opportunities and possible commercial applications, enlarging the U.S. research system could lead to additional problems in the future. As the Office of Technology Assessment report ***Federally Funded Research: Decisions for a Decade*** concluded:

> Given the extraordinary strength of the U.S. research system and the character of scientific research, there will always be more opportunities than can be funded, more researchers competing than can be sustained, and more institutions seeking to expand than the prime sponsor-the Federal Government-can fund. The objective, then, is to ensure that the best research continues to be funded, that a full portfolio of research is maintained, and that there is a sufficient research work force of the highest caliber to do the job.[28]

At a time when all governments are sensitive to the strategic economic advantages that can accrue from knowledge-based or technologically based industries, participation in large-scale international science projects is carefully scrutinized. Whereas some countries may see distinct benefits associated with multinational collaboration, others may deem participation in particular projects as militating against the national interest. This can be especially true if a nation is attempting to develop its expertise in a particular scientific or technological field.

Yet, building up national scientific capabilities and joining international collaborations are not necessarily mutually exclusive strategies. In many cases, having access to scientific facilities in other countries or participating in the planning and operation of particular projects may strengthen and diversify a nation's science base. Over the past several decades, the diffusion of scientific and technological knowledge has, in fact, accelerated progress in many fields (e.g., biotechnology,

[26] See, for example, George E. Brown, "New Ways of Looking at U.S. Science and Technology," *Physics Today,* September 1994. Also see Chancellor of Duchy of Lancaster, *Realising Our Potential, A Strategy for Science, Engineering and Technology,* presented to Parliament by Command of Her Majesty (London, England: Her Majesty's Science Office, May 1993).

[27] Currently, total nondefense U.S. support of R&D is about 1.9 percent of the gross domestic product (GDP). The major portion of that funding is industrially sponsored appliedR&D. The portion of funding directed toward basic research is 0.42 percent of the GDP, two-thirds of which comes from the federal government. See footnote 18.

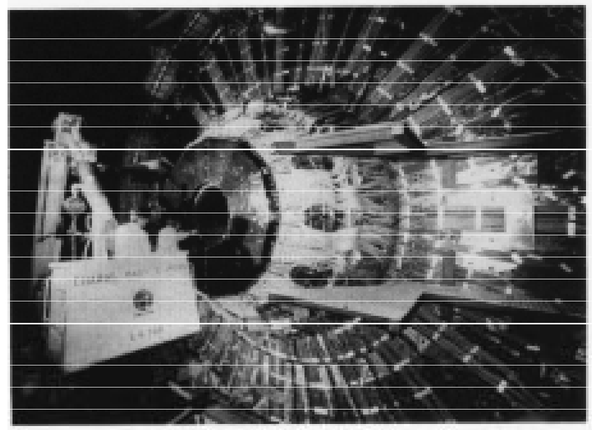
[28] U.S. Congress, Office of Technology Assessment, *Federally Funded Research: Decisions for a Decade,* OTA-SET-490 (Washington, DC: U.S. Government printing Office, May 1991).

computer and communications technology). Also, as many Asian nations have demonstrated, long-term investments in education or science and technology can be particularly productive when linked to international networks of research. Increased global cooperation in science will no doubt provide economic and social benefits for many nations. The challenge for policymakers is to ensure that the costs and benefits of collaborative activities are shared more or less equitably.

ROLE OF LARGE PROJECTS

Large projects have been a key component of our nation's science portfolio for several decades. Although small science is the backbone of the modem scientific enterprise, big science has steadily encroached onto the scene. Unlike small science projects, almost no knowledge can be generated from a megaproject in the area of direct inquiry until some large-scale investment has occurred. However, significant indirect benefits can be realized throughout the course of a project. For example, ITER research may produce major indirect benefits in the areas of materials science and magnet design even if the ITER project is not brought to completion.

Over the past few years, expenditures on large projects and facilities have essentially leveled off at about 10 percent of the total federal (defense and nondefense) R&D budget, but this situation could change as several big science projects are brought up for congressional approval.[29] Although some large undertakings such as the National High Magnetic Field Laboratory and the Advanced Photon Source (an advanced x-ray synchrotrons facility) provide platforms for small science, and thus reinforce the research support given to individual investigators across many disciplines, many other projects do not complement small science programs.


CERN

Scientists making adjustments to DELPHI particle detector.

In recent years, the role of large, costly projects has stimulated considerable debate in Congress and the science community. Priority setting is becoming much more of an issue because all proposed megaprojects may not be supportable without eroding the underlying national science base. The Superconducting Super Collider (SSC), the International Space Station, the Earth Observing System (EOS), and ITER are just a few examples of recent megaprojects.

There are several reasons for engaging in large scientific ventures. In some fields of inquiry, scientific projects must be large in scale in order to advance and demonstrate the underlying science or to achieve specific technical goals. For example, probing the energy domains that will provide new insights into the fundamental characteristics of matter, or demonstrating the feasibility of controlled nuclear fusion, will require apparatus (accelerators, detectors, reactors) of unusual size and sophistication. The International Space Station project-an effort to build and operate a permanently inhabited Earth-orbiting facility—is by its very nature, a complicated, immense undertaking. Other classes of problems, such as climate change, are truly global in nature and require

[29] This figure is based on a "basket"of large projects tracked by the Congressional Research Service. See Genevieve J. Knezo, *Major Science and Technology Programs: Megaprojects and Presidential Initiatives, Trends Through FY 1996 Requested,* CRS Report for Congress (Washington, DC: Congressional Research Service, Mar. 27, 1995).

broad-based multinational, multidisciplinary initiatives to develop a better scientific understanding of fundamental physical processes and to ensure the international credibility of scientific results.

Although large science projects are often symbols of national prestige, their principal justification is that they serve as a means for strengthening essential national capabilities in different scientific fields. For example, the U.S. high-energy physics program has, over the course of several decades, led to the development of leading-edge capabilities in the areas of accelerator design and detector methods. Other examples are Japan's Subaru telescope project, which is being used to strengthen the Japanese research base in astronomy, and strategic programs such as the various national efforts to develop sophisticated capabilities in launching and deploying satellites. Admittedly, some projects have strong scientific rationales, whereas others are being pursued less for science and more for broad social, economic, and technological reasons.

In addition, there is sometimes a strong political rationale for pursuing large collaborative undertakings. For instance, European governments support a number of extensive research programs through the European Union Research Commissariat. In addition, separate facilities and institutions have been created including the European Laboratory for Particle Physics (CERN), the European Synchrotron Radiation Facility (ESRF), and the European Space Agency (ESA). The governments involved believe that promoting scientific cooperation among scientists throughout Europe will strengthen the political processes associated with the unification of Europe. Coordinated small science projects have had a unifying effect as well.

Finally, if pursued in a multidisciplinary or multilateral fashion, large science projects permit, to differing degrees, the opportunity to leverage intellectual resources and technical capabilities. Synergies can often be achieved simply by bringing individual investigators or research groups together. Depending on the nature of the undertaking, large projects may also provide opportunities for addressing scientific questions that will benefit humankind (e.g., human genome research).

INDUSTRIAL IMPLICATIONS OF LARGE PROJECTS

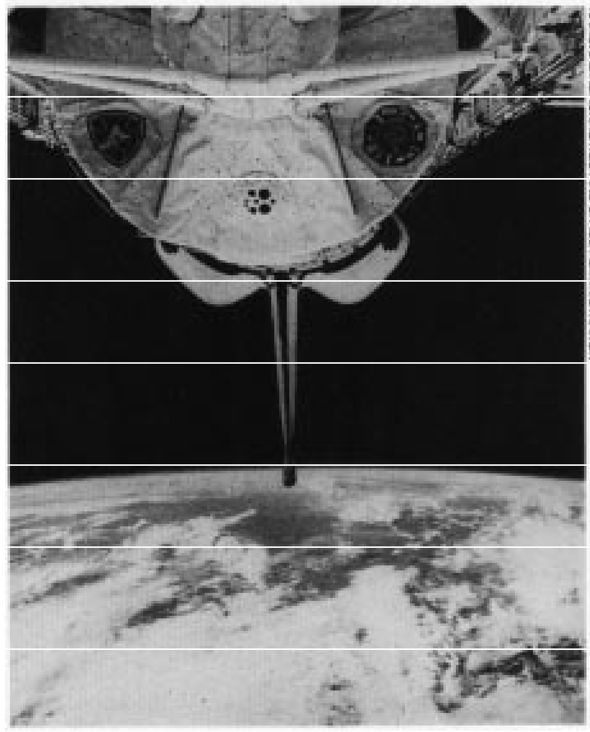
Although the principal purpose underlying large scientific endeavors centers on the pursuit of basic research and engineering goals, some megascience activities have been used to varying degrees as a means for developing industrial capabilities in certain spheres of technology (e.g., rocket-launching capabilities, satellite design, superconducting magnets, advanced materials). As a consequence, some programs and projects, particularly those that are capital-intensive, have developed strong industrial constituencies. In the United States, Europe, and Japan, for example, major industrial enterprises perform key system and component development work for national space agencies. ESA has, in fact, evolved a contracting system that is designed to return a significant proportion of member-state contributions to national companies. Thus, in certain cases, large science undertakings have been used by governments as an instrument of industrial policy.

Whether large scientific projects can be effectively used to facilitate the development and deployment of new commercial technologies is an open question. As a general proposition, though, it is difficult to demonstrate that large projects or specific aspects of large projects can be efficiently utilized for this purpose. There have been varying results in different fields.

Although over the course of many decades there has been considerable transferability of advances in high-energy and nuclear physics to the commercial sector, such spin-off technologies have developed in a rather unpredictable and discontinuous fashion. These spin-offs include ion implantation in the semiconductor industry, accelerator-based cancer therapy, CAT (computerized axial tomography) scanner systems, positron emission tomography, free electron lasers, and synchrotron generated x-ray beams. None of these technologies were conceived in a deliberate or direct manner; rather they were unanticipated offshoots of basic experimental research. Moreover, these transfers from high-energy and nuclear physics research to the marketplace have taken place over a considerably long time.

In contrast, the development of rocket-launching systems, satellites, and space platforms has been a direct and integral objective of different national space programs. Unlike the basic research focus of high-energy physics projects, some space activities have an explicit technological orientation and can be more naturally geared to achieving the specific engineering or performance goals necessary for commercial applications.

Other programs have objectives that require progress both in basic scientific understanding and in certain underlying technologies. In pursuing nuclear fusion as a commercial power source, which is primarily a basic research undertaking, there are certain technological imperatives that must be met before further fusion advances can occur. The attainment of these technical goals could also provide opportunities for spin-offs to other fields. In particular, the goals of demonstrating the technical and economic feasibility of fusion power using magnetic confinement schemes envision the development of advanced materials and greater use of superconducting magnet technologies. Proposed advanced tokamak fusion reactor designs, for example, call for extremely powerful superconducting magnets. Research on high-performance, low-activation materials and on the design and fabrication of superconducting magnetic coils for fusion reactors have become critical elements of all major fusion programs, and major industrial companies in Japan, Europe, and the United States have emerged as key project participants.[30] These companies could be well positioned to apply their expertise with magnets to areas outside fusion, such as magnetic resonance imaging, free electron lasers, electric motors, advanced materials separation processing, and energy storage.[31]


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

The European Spacelab module in the cargo bay of the orbiting space shuttle Columbia.

Apart from the development of technological systems or components for projects, large scientific facilities themselves can also provide benefits to national economies. One study found that between 40 and 70 percent of the funds used to operate large international facilities are spent in the

[30] For example, in Japan, Toshiba, Hitachi, and Mitsubishi have contracts to advance superconducting magnet technology. In the United States, Westinghouse and Lockheed-Martin are active in fusion-relevant superconducting magnet technology development.

[31] See U.S. Congress, Office of Technology Assessment, *High Temperature Superconductivity in Perspective,* OTA-E-440 (Washington, DC: U.S. Government Printing Office, April 1990). See also U.S. Department of Energy, Office of Energy Research, *The U.S. Fusion Program as a Source of Technology Transfer* (Washington, DC: September 1993).

host nation.[32] Although substantial portions of these funds are used to provide basic services such as construction, materials, chemicals, or food, local companies that provide technical support or equipment can enhance their underlying scientific or engineering expertise. A large facility can also attract new companies and thereby raise the skill base of a region's population. However, contracts for the most knowledge-intensive components of large projects are typically assigned to companies in many different countries. Thus, in most cases, the particular location of a facility is generally not of strategic economic importance.

[32]This analysis was based on the spending patterns of CERN, located on the Swiss-French border; the Joint European Torus fusion experiment in England; and the ESRF and the Institute Laue-Langevin for neutron research, both in France. See "International Facilities Said To Boost National Economy," *Nature*, vol. 363, May 6, 1993.