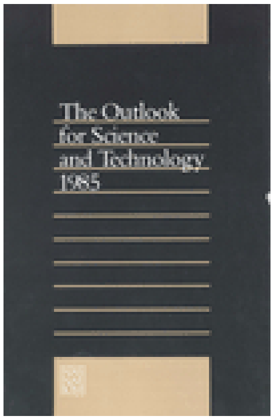


**The Outlook for Science and Technology 1985**

Committee on Science, Engineering, and Public Policy,
National Research Council

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# The Outlook for Science and Technology 1985

Committee on Science, Engineering, and Public Policy

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The Committee on Science, Engineering, and Public Policy is a joint committee of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. It includes members of the councils of all three bodies.

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# Preface

The 1985 Outlook for Science and Technology is the fourth report in a series originally mandated by the National Science and Technology Policy, Organization, and Priorities Act of 1976. Subsequent to the passage of that Act, a reorganization of the Executive Office of the President gave the National Science Foundation responsibility for preparing the Outlooks. In turn, the Foundation asked the National Academy of Sciences to assist. Since 1982, the Outlooks have been prepared by the Committee on Science, Engineering, and Public Policy (COSEPUP), a joint unit of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The purposes of these reports are to describe and discuss:

- current and emerging problems of national significance that are identified through scientific research or in which scientific or technical considerations are of major importance; and
- opportunities for the use of new and existing scientific and

technological capabilities that can help to resolve these problems and impediments to the effective use of these capabilities.

Issues presented in this Outlook were obtained from several sources, including discussion within COSEPUP and from research briefings prepared for the President's Office of Science and Technology Policy (OSTP), the National Science Foundation, and other federal agencies. These briefings summarized research opportunities with the potential for high scientific returns in a number of fields, identified by OSTP after consultation with COSEPUP. Twenty-one briefings have been presented in the last three years on subjects as diverse as agriculture, astronomy, atherosclerosis, catalysis and other topics in chemistry, computer-aided manufacturing, information technology in precollege education, neuroscience, immunology, and cognitive science and artificial intelligence.

In this report, we summarize the nine subjects that formed the bases of the 1984 research briefings. Subjects of comparable scientific merit could have been selected. However, as with past briefings, the topics selected were those for which near-term federal actions were considered likely.

Other suggestions for this Outlook came from the major units of the National Research Council and from Councilors of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The committee is grateful to all of these contributors and especially to the members of its subcommittee responsible for preparation of the 1985 Outlook: Jacob Bigeleisen, of the State University of New York at Stony Brook (chairman); Floyd E. Bloom, of the Scripps Clinic and Research Foundation; Emilio Q. Daddario, of Wilkes, Artis, Hedrick, and Lane; and Edward A. Mason, of the Standard Oil Company (Indiana). The substantial contributions by Norman Metzger in preparing this report are acknowledged.

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# The Outlook for Science and Technology 1985

# Overview

That basic research is vital to the nation's future is now an axiom of national policy. In their statements and in their budget proposals, both the Administration and the Congress agree that progress in fundamental science and engineering is essential to the economy of a modern technological society. This position is taken by other industrialized nations and is reflected in their rising investments in research.

Granting this acceptance of the value of an aggressive national program in basic research, there are limits to the resources available and hard choices to be made in budget priorities. As in other federal endeavors, those concerned with the levels of support for science and technology face difficult decisions:

- Of current and potential endeavors in science and engineering, what criteria should be used in selecting projects to be funded? What determines appropriate funding levels?
- How can the needs for large facilities—whether refurbishing those that have become outdated or constructing new ones—long evident in many fields of science and engineering be satisfied

without sharp perturbations in the federal budget for research and development?

- Are mechanisms and support available to fuel shifting research patterns, such as the heightened interactions among disciplines and between academic and industrial researchers?

To state these questions is not to assert that they are readily answerable. Progress toward answering them must come by exposing the problems and the opportunities.

The Outlook begins with brief glimpses of nine vibrant fields of science and technology. The status of each field was analyzed intensively in a series of research briefings prepared in 1984 by the Committee on Science, Engineering, and Public Policy and was presented to the President's Office of Science and Technology Policy, the National Science Foundation, and other federal agencies. In actuality, the menu of the particular fields chosen is not crucial; any other roster of significant topics would yield the same generalizations:

- *American science and technology continue to be amazingly fertile.* Whatever the particular field, the outcome is the same: new, sometimes startling, discoveries and unexpected progress in dealing with wider problems emerge, from the understanding of cancer and atherosclerosis to creating a new generation of electronic and optical devices. The same story applies to fields at the interface of science and technology—computer architecture, advanced composites, and engineering involving biotechnology; in these latter fields, the enormous interdependence of basic science and engineering knowledge is even more evident.
- *Research advances depend increasingly on the combined efforts of many disciplines.* Progress on oncogenes, for example, came not only from work on the cancer problem itself, but also from other fields: virology, molecular and cellular biology, pharmacology, and biochemistry.
- *Progress in basic science and technology is happening at an incredibly fast pace.* Ten years ago, Part I of this Outlook could not have been written: oncogenes were speculations at best; atherosclerosis remained a deeply puzzling affliction. The laser and integrated circuit chips were recent arrivals, while such contemporary techniques as molecular beam epitaxy and a host of

new spectroscopies such as femtosecond spectroscopy did not seem realizable. And, new technologies have arrived, from biotechnology to the imminent debut of computer architectures embodying the synchronous operation of several hundred processors.

- *The gap between new knowledge and its application has narrowed.* This report points out two examples of prompt application: the enormous industry upwelling from fundamental discoveries in gene manipulation and a totally new class of semiconductors arising from basic and quite recent advances in surface science.

The linked themes then are that: science and technology are being deeply refreshed by a torrent of new discoveries; in many fields, these discoveries are coming at an ever faster pace, and they are being translated rapidly into wider use.

In short, the American public is reaping the rewards for its continuing support of fundamental research. And it is reaping the rewards of having made the university the home of basic research, an achievement virtually unique among nations. In doing so, it has created a rich atmosphere of learning and discovery, of teaching and research, of unrelenting questioning as teachers and their students combine to attack the puzzles of nature.

The issues discussed in this Outlook deal with the present and future health of the research system and its principal components—the universities, industry, and government, and their relationships. These issues arise from several directions and include the following:

- *The international competitive strength of the United States.* That issue is a tangled one, although one certain thread is the standing of various fields of science and technology, especially those currently acknowledged as economically vital. This Outlook considers that issue, by examining the competitive status of several fields and suggesting some responses fitted to the U.S. system.
- *Scientific and engineering personnel.* The Outlook addresses several facets, among them counterincentives for promising students to enter research careers, illustrated by the difficulties faced by young investigators, and the role of foreign students in U.S. advanced education.

- *Facilities and instrumentation.* The almost desperate need of research universities to rejuvenate existing technical facilities and to build new ones, as well as the paucity of state-of-the-art instrumentation in many academic laboratories, is recognized increasingly—in the Congress and the Administration. This Outlook attempts to sort out the various needs. Recent episodes in which universities have obtained funding for facilities using the direct appropriation mode are also discussed.
- *Open scientific and technological communication and national security.* While the tensions inherent in this issue are now quite public, they continue to be unresolved. Considerable uncertainty burdens a number of research fields with military import, while restrictions, existing or prospective, on the flow of technical data have hindered or may hinder industrial progress, especially in the application of advanced technologies.

Other matters also are treated in this report, from human biology to research on the uncertainties embedded in the nuclear winter concept. Whether new or continuing, these are some of the issues that come to the fore in considering systematically the status and outlook for American science and technology.

This Outlook has two major parts.

Part I is a precis of recent progress in certain fields of science and technology, taken from nine research briefings prepared in 1984 by the Committee on Science, Engineering, and Public Policy.*

Part II summarizes several national issues that can be inferred from the fields covered in these briefings and from other areas of science and technology.

*The full text of the briefings summarized here has been published, as *Research Briefings 1984* and is available from the National Academy Press, 2101 Constitution Avenue, NW, Washington, DC 20418.

# PART I

# Recent Progress in Science and Technology

## ONCOGENES

How is a normal cell transformed into a cancer cell? How can diverse agents, from chemicals to radiation to viruses, cause that transformation? The answers to these questions require an understanding of the molecular changes that propel a normal cell into malignancy.

This understanding has been emerging in the last 10 years from intersecting work in several subfields of biology, among them cellular and molecular biology, pharmacology, and biochemistry. As a result, key aspects of cancer can now be described in molecular terms: normal genes that control cell growth become slightly modified. These modified genes then encode proteins capable of changing a normal cell into a cancer cell; hence, those genes are called oncogenes.

Oncogenes were first discovered through studies of animal cells infected by viruses, including the Rous sarcoma virus that causes cancers in chickens. The virus converts certain normal animal genes into potent oncogenes.

Human oncogenes were discovered by inserting DNA segments from human cancer cells into normal cells in culture. The specific DNA sequences responsible for transforming these recipient cells into cancerous cells—human oncogenes—are closely related both to normal human genes and to viral oncogenes. Active oncogenes have been demonstrated in a variety of human cancers.

Knowledge of the structures of oncogenes, their relation to chromosomal abnormalities seen in malignancies, the proteins they encode, and the intriguing relation of some oncogenes to growth factors observed in hormonal tissue repair has expanded enormously in recent years. However, exactly how oncogenes act, the functions of the proteins they encode, and the nature of their activation by chemical carcinogens, viruses, radiation, and other agents are still unclear.

Cancers are diverse; they have neither a single cause nor a single cure. Further, the transformation of normal cells into malignant ones includes many steps. Among them, the activation of oncogenes is an important, perhaps necessary step, but not the only one. While efforts to prevent cancers can be directed against any of these critical stages, the discovery of some 20 human oncogenes has expanded possibilities for the treatment and prevention of cancers. There could be drugs to block the action of oncogene proteins; or immunologic agents, including antibodies, that would recognize and destroy cells carrying oncogene proteins on their surfaces; or agents to block cellular receptors that enhance the growth of malignant cells. The diagnosis of cancers also may be improved by identifying oncogenes activated by an environmental or other agent.

## ATHEROSCLEROSIS

Atherosclerosis causes heart attacks and strokes and accounts for half of all of the deaths in the United States. In this disease, the flow of blood through the arteries is obstructed by plaques that have formed on the arterial walls. Eventually, a blood clot develops and obstructs the artery, blocking the flow of blood to the heart muscle or the brain.

This disease is the product of a complex interplay between components of the blood and the cells that line the interior walls of the blood vessels. Through interdisciplinary efforts drawing upon molecular and cellular biology, physics, chemistry, and genetics, that interplay has become better understood. The new understanding applies not only to atherosclerosis but also to other illnesses characterized by abnormal interactions between blood and vessel walls, such as blood-clotting disorders, adult respiratory distress syndromes, and high blood pressure.

Structures, molecular mechanisms, and controls involved in various components of blood-blood vessel interactions have been identified. For example, the inner lining of blood vessels is a single layer of cells: the endothelium. Research has transformed our view of the endothelium from an apparently simple material with simple tasks to one capable of performing an impressive array of complex functions, among them the regulation of blood pressure, blood clotting, and the growth of new capillaries. The structure of the endothelium has been probed, as have the mechanisms by which materials cross it when moving from blood to tissue.

At the same time, the structure and functions of the blood components that interact with the endothelium have been investigated. These include platelets, essential to blood clotting; leukocytes, or white blood cells, which help to defend the body against infectious agents; and plasma lipoproteins, from which the cholesterol in atherosclerotic plaques is derived.

The impetus for research into these interactions stems from new concepts and techniques. For instance, more factors affecting the very complex set of reactions involved in the formation and removal of blood clots have been found. Two hypotheses concerning the origins of atherosclerosis—both dealing with the deposition of fat, especially cholesterol, upon inner arterial layers—have stimulated a wide range of research. New approaches to slowing the onset of atherosclerosis, ones coupling modified diets with medication, are being pursued. And new instrumentation for sorting and isolating cells now makes it possible to obtain sufficient numbers of individual blood cells for study. Finally, receptors and channels, the modes by which materials pass in and out of cells and cellular organelles, can be examined using advanced techniques of cellular and molecular biology.

Important clinical advances likely to emerge from this work include improved prosthetic devices, such as heart valves, vascular replacements, dialyzing membranes, and artificial organs, and fresh insights into the prevention and treatment of atherosclerosis.

## PARASITISM

Research on infections caused by parasites is driven by interlocking humanitarian and scientific motives. Parasitic diseases such as malaria and schistosomiasis affect more than a billion people globally. In the United States, the parasite, *Giardia lamblia,* is a common cause of epidemic diarrhea. Immigration, increased international travel, and the stationing of U.S. military and civilian personnel in countries where parasitic diseases are common are increasing the incidence of these diseases in Americans.

Confounding an effective attack on parasitic diseases is the very complex life cycle of parasites, which makes them extremely difficult to control without harming the host. In addition, parasites have evolved novel mechanisms for eluding the usual immunological and other defenses. However, these same traits —adaptability and complex life cycles—make parasites attractive for the investigation of such basic biological events as cell growth and differentiation. Thus, work on parasitic diseases has led to advances in molecular biology, immunology, membrane and cellular biology, biochemistry, and pharmacology. In turn, parasitology has benefited from advances in these fields by exploiting new techniques such as monoclonal antibodies and the isolation and copying of specific genes.

A constant theme in this field is exploration of the unique traits of parasites. For example, the usual response to most infections is the appearance of antibodies that can react with the surface antigens of the infecting agent. However, one type of parasite can change its surface coating hundreds of times during an infection, so that the antibodies invariably attack the wrong antigen. Research on such antigen structures has influenced research on gene expression already and may be important to understanding how genes are regulated. Continuing studies of parasitic evasions of immunological defenses may clarify the nature of such defenses, or the reasons for their absence, in other diseases. Exploring how antigens and other substances traverse parasitic and cellular membranes will enhance our understanding of membrane biology.

Finally, a better understanding of the basic biology of parasitic diseases should yield ways to combat them more effectively. Thus, studying the genes that modulate the transformation of parasites through their different stages may reveal new ways to interrupt their life cycles. Already, the use of monoclonal antibodies is leading to the development of greatly improved diagnostic reagents. And there are new methods to generate antigens for use in vaccines against those diseases.

## CHEMICAL AND PROCESS ENGINEERING FOR BIOTECHNOLOGY

The phenomenal progress in molecular biology, genetics, and biochemistry in the last 20 years now makes it possible to have cells manufacture products ranging from simple molecules to complex proteins. The need today is for fundamental engineering knowledge—and people—to translate that capacity into commercial processes. That translation faces several difficulties:

- living organisms can mutate or change genetically, affecting process operations;
- biological processes must be completely aseptic; and
- these processes usually occur in very dilute, aqueous solutions, so the products have to be separated from large volumes of water; such separations are complicated by the fact that the products are often fragile, hard to purify, and structurally complex.

Surmounting these problems entails the design of suitable bioreactors for the large-scale culturing of plant and animal cells, the separation and purification of reaction mixtures in order to obtain products of sufficient purity at competitive costs, and the improvement of bioprocess instrumentation and control. Each area requires blending scientific with engineering knowledge. Bioreactor research, for example, involves the merger of such biological sciences as molecular and cellular biology, microbiology, and cell physiology with engineering skills, chemical kinetics, thermodynamics, fluid dynamics, heat and mass transport, and precise process control. Progress in separation and purification sciences necessitates in part adapting to large-scale processes such powerful techniques of the research laboratory as electrophoretic and affinity separations. The control of bioprocesses poses special demands, such as the on-line monitoring of complex products for which no sensors are available yet. Solutions to these problems may require the use of enzymes, monoclonal antibodies, and living cells as components of electrochemical and optical detectors.

Potential opportunities for applying biochemical technologies are diverse and provocative. In the area of human and animal health care, for example, a new family of products based on genetically engineered proteins may emerge that can detect quickly and accurately viral and bacterial diseases, susceptibility to autoimmune diseases, genetic defects, and neoplasms. Other proteins, such as those inhibiting the growth of tumors or those that dissolve blood clots, are being tested. In agriculture, the new technologies may yield fungicides and herbicides that are highly potent, specific, and environmentally safe. Other prospects lie in environmental protection, where biochemical engineering may provide methods of destroying or removing toxic products, and in the use of natural resources, such as the improved recovery of metals from low-grade ores.

## ADVANCED POLYMERIC COMPOSITES

Bone, wood, and clam shells are natural composites: their structures have properties matched to specific purposes. A grow ing array of manmade polymeric composites similarly matches properties to use, most commonly to provide materials that, on a per-weight basis, are stronger and stiffer than the best structural metals. Such advanced composites are being used already in the manufacture of aircraft and sporting equipment, and are on the verge of major applications in automobiles, heavy equipment, robotics, and other areas.

The rapid technological development of advanced composites in the last decade has outpaced the underlying science. For instance, the understanding of the relationships between structure and properties is still primitive, as is the knowledge of why and how composite structures fail. A science of the design and processing of polymeric composites, embodying extensive computer-based modeling in design, engineering, and manufacture, needs to be developed. Further, the toxicity of components, their long-term environmental effects, and their reuse need to be studied and this knowledge applied to the development of new composites.

Advances on these and related fronts will amplify the already substantial use of advanced composites. For example, the wider use of composites in the automobile industry will depend on attaining an acceptable balance between processing speed and product quality, a useful technology for joining and repairing composites, and their long-term dimensional stability. The resultant benefits may be considerable. The costs of tooling for composites are much lower than for steel and allow for greater manufacturing flexibility, quicker design turnover, and less capital investment. Composites also are less likely to corrode than metals; lower vehicle weights will save fuel.

## SUPERCOMPUTER ARCHITECTURES

Supercomputers, able to respond to about 100 million instructions per second, will soon be capable of executing 1,000 million instructions per second, rising to 20,000 million in the next decade. Such extreme speeds derive from the rapidly developing technology for raising the densities—and hence the speed —of integrated circuit chips; they also derive from new architectures which often embody, in a limited way, parallel or concurrent computations.

While further improvements in the underlying componentry are vital, attaining even faster speeds in the future will depend on implementing new computer architectures—specifically, the effective use of large-scale parallelism. This entails the development of computers that can execute many hundreds, thousands, or tens of thousands of instructions simultaneously, and of software that can orchestrate these simultaneous streams of computation effectively.

Faster computers, accompanied by refinements in software, will expand dramatically the applications of computers to ever more complex scientific and technological problems. To illustrate, computer simulation will affect aircraft design, the development of new pharmaceuticals, the design of energy storage systems and industrial products, and the testing of new generations of integrated circuit chips. In science, faster computers will be applied to simulating intricate phenomena lying beyond observation and experimentation. Examples include the path taken by an electron traversing a neutron star; a chemical reaction under extreme temperatures and pressures; the forces that give protons and neutrons their structure; the optimal conditions for a fusion reactor; the neural pattern triggered when, say, a finger touches an object; and climate, weather, and other atmospheric phenomena, such as tornadoes and wind shears. Finally, faster computers are vital to national security goals, weapons design, and to assessing phenomena such as "nuclear winter."

## INFORMATION TECHNOLOGY IN PRECOLLEGE EDUCATION

The cognitive sciences—combining cognitive psychology, linguistics, philosophy, and biology—examine how humans process information. Artificial intelligence reflects a concern with how computers process information and their emulation of intelligent action and human perception. Recent progress in the cognitive sciences and in artificial intelligence, combined with more powerful, versatile, and accessible computers, provides a basis for new technologies to improve education. Problem-solving, hearing, and the organization of semantic memory are all areas to which the cognitive sciences have contributed substantially. Similarly, expert systems have provided both an original method for organizing the knowledge of a human expert and a window into the nature of human knowledge, skilled problem-solving, and reasoning.

These recent advances have occurred through a linking of the cognitive sciences, artificial intelligence, and educational research. This progress offers a major opportunity to create learning systems that can help students to acquire the knowledge and cognitive skills necessary for effective work and citizenship. Experimental learning systems such as DEBUGGY, an expert system for diagnosing a student's procedural errors in subtraction, are being tested already.

Analogous efforts certainly will not solve all—or even most—of the problems of education. However, they will provide a coherent and scientific basis for designing instructional systems and for training teachers and restructuring curricula. They also may create valuable new resources in the form of model electronic learning environments, while attracting a new cadre of professionals to education and to educational research.

## OPPORTUNITIES IN PHYSICS

Discoveries in physics have influenced virtually all of the sciences and have spawned industries. Observations of electrical and magnetic phenomena, starting in the eighteenth century, led to concepts that, in the nineteenth century, spurred a crescendo of experimental and theoretical knowledge of electromagnetism. This rich body of knowledge is the basis of electric power, telephony, radio, radar, and television. The emergence of quantum mechanics in the twentieth century underlies much of physics and chemistry and is the foundation of such technological discoveries as transistors, lasers, and solar cells.

Fundamental advances in physics continue to enrich all of science, and virtually all technologies. Cosmology and astrophysics are intertwined with the subnuclear physics of elementary particles. New discoveries in quantum mechanics have changed our knowledge of atoms and molecules dramatically and have revolutionized our understanding of solids. Semiconductors are not only the results of these discoveries, in the invention of the transistor and the solar cell, but also have led, in turn, to striking progress in many technologies.

Two contemporary examples convey the influences of physics. One is the deliberate structural design of materials through the arrangement of atoms in one or two dimensions. The resulting materials have remarkable properties quite different from those of natural materials, thus presenting scientific puzzles and technological opportunities. The physics of these layered materials is fundamentally interesting and their properties are technologically important to the computer and energy industries.

Another example is the contribution of physicists to biological problems, including recent work on transmembrane signaling—the transmission of information in brain, nerve, and muscle tissue. The molecular basis of such signaling is now accessible, and the perspectives of physicists joining with those of biologists are expanding upon a vast array of research questions, such as how nerves conduct information and execute commands.

These few examples illustrate continuing traits of physics: enormous diversity, the search for fundamental laws, strong connections to other sciences, and technological and industrial applications.

## SOLAR-TERRESTRIAL PLASMA PHYSICS

Plasma physics studies the interactions of charged particles with each other and with electrical and magnetic fields. Its research areas comprise, in addition to the effort to attain fusion power, the interactions of the sun and the earth: the chain of physical processes that starts with the generation of the sun's magnetic field in the solar interior and links it to activity at the sun's surface and, ultimately, to the earth's ionosphere and atmosphere.

Fundamental questions continue to drive solar-terrestrial physics. Why does the appearance of sunspots on the sun presage magnetic storms and auroras? What roles do magnetic fields play in stars and galaxies? Rapid progress toward answering such questions has occurred in the last decade, made possible by the increasing precision of measurements, numerical modeling, and the further development of theories applied to solar-terrestrial plasma problems.

Plasma phenomena in the solar system are mirrored in other stars, in the neighborhood of neutron stars and black holes, and in galaxies. The sun and the solar system have become, therefore, a laboratory in which astrophysical plasma processes can be studied *in situ* and with a precision attainable nowhere else. As a result, space and astrophysical plasma physicists have begun to work closely together and a new and broad research field is developing.

The power of the solar-terrestrial system as an astrophysical laboratory will be enhanced by the proposed multispacecraft International Solar-Terrestrial Physics Program. Together with the Solar Optical Telescope, this program can be expected to provide the fundamental underpinning of solar-terrestrial plasma research for the next 10 years.

The overall research goal is to synthesize growing knowledge to create a unified and quantitative model of events affecting the sun and the earth: solar wind, or the plasma connection between the sun and the earth; sources of coronal heating and solar flares; and links between solar activity and magnetic storms on earth.

# PART II

# An Outline of Selected Issues

This second part of the 1985 Outlook highlights several issues, abstracted either from the fields discussed in Part I or from reports and discussions within the National Research Council or the Committee on Science, Engineering, and Public Policy. The intent is to articulate national concerns involving science and technology. Within that broad purpose, two caveats apply to the issues discussed: (1) they constitute a selected rather than a comprehensive listing, and (2) they are described in outline rather than in detail, to keep this report brief.

Within these limits, the issues are:

- *international competition in science and technology;*
- *scientific and engineering personnel;*
- *cooperative work across disciplines;*
- *research and transportation;*
- *facilities and instrumentation;*
- *issues in genetic engineering;*
- *issues in human biology;*

- *scientific communication, technology transfer, and national security;* and
- *global atmospheric effects of nuclear explosions.*

## INTERNATIONAL COMPETITION IN SCIENCE AND TECHNOLOGY

As emphasized most recently in the report by the President's Commission on Industrial Competitiveness, the nation's ability to compete in global markets depends on several interlocking elements, among them the ability to create, apply, and protect new technology; an adequate supply of productive capital; a well-educated and flexible work force; and increased policy emphasis on international trade.

These multiple elements represent difficult tasks for legislators and policymakers. This section concentrates on one aspect of them: improving the nation's competitive strength in science and technology. It does this by using three examples taken from Part I of this report, all of them economically important: supercomputers, biochemical engineering, and advanced polymeric composites.

### Supercomputers

Rapidly developing microelectronic technology and computer architectures have created the bases for major advances in computational speeds. Such revolutionary changes are crucial to maintaining U.S. leadership in many scientific and technological areas. However, they also will expose the U.S. computer industry to new international challenges as rapid fluctuations in product price and performance undermine the predictable customer preferences that have characterized the industry.

Given this context, it is essential that the United States look to the solidity of its technological position. That position needs to be measured continually against developments abroad and strengthened judiciously where weaknesses are found. Major supercomputer technology initiatives are under way in three agencies—the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), and the

Department of Energy (DOE). These activities need to be accelerated and coordinated carefully to ensure both a systematic exploration of significant design alternatives and a rapid translation of successful designs into commercial production. Also vital is the early involvement of the major user communities—especially the research universities—in the development of software and utilization expertise for the new machines.

Although DARPA has the leading role in funding major development projects in computing, the DOE role in the development of scientific supercomputing will be crucial also, especially in view of the latter's traditionally strong ties to the research community. In addition, the basic research programs of the NSF, which contribute to the conceptual and algorithmic bases for new styles of supercomputing, and the NSF computer access program, which will put the new machines into the hands of the broad scientific communities that must pioneer their use, are very important and need to be kept strong. Access to supercomputers is becoming indispensable to frontier research in a growing number of scientific and engineering fields, among them fusion research, quantum chemistry, particle physics, materials science, petroleum exploration, and process technology.

Early industrial participation in these developments is imperative. Means of increasing cooperation between the computer industry and university and national laboratory research groups should be explored vigorously by the federal agencies that fund major supercomputer development. To allow time for familiarization and formation of strong technology-transfer links, cooperation among the different sectors should be encouraged in the early stages of computer design. Administrative obstacles to research collaboration between companies and to the commercialization of experimental products need to be reexamined.

Extremely high computation rates often can be attained efficiently by tailoring electronic hardware to the requirements of particular computer-intensive applications. Such special design efforts have become a significant component of computer research that needs to be recognized explicitly and cultivated systematically. In this area, the breadth and many-sided in genuity of the U.S. academic and commercial communities can be exploited to gain competitive advantage. To do this, high-quality design tools and fabrication systems need to be widely available. A component of the DARPA Strategic Computing Program will address this issue, but a supplementary NSF program aimed at making the resulting design facilities available to the entire U.S. computer science community also may be appropriate.

Increased attempts by the United States to learn from foreign developments, especially in Japan, are prudent in view of Japanese strength in certain lines of integrated circuit fabrication and current reports of rapidly growing capabilities in software. Much more systematic collection and translation of Japanese technical literature are called for.

Of course, there are other elements in the international competition in supercomputers that are not included in this brief discussion. These include:

- the appropriate role of government and industry in implementing the new computer architectures designed in the universities; for example, what would be the respective roles of government and industry in what is usually considered applied research and development?;
- problems arising from limited industrial access to supercomputers;
- assuring continuity for recent attempts by the federal government to increase access to supercomputers by academic scientists;
- financial and other incentives for U.S. companies to develop a new generation of supercomputers; and
- the level of software development needed to ensure optimal application of parallel architectures.

## Biochemical Engineering

Several countries are trying to develop strong biochemical engineering industries. West Germany, Japan, and Great Britain have national institutes for biotechnology. Such investments are driven by the economic potential of biochemical engineering.

For example, it is estimated that global markets for biological products will run from $40 to $100 billion annually by the year 2000, or about 15 percent of the total annual market for chemicals.

The United States has a strong capacity for leadership in biochemical engineering, owing largely to the basic research conducted in American laboratories. Achieving that leadership requires a wider knowledge base than is now available, greater numbers of trained personnel, support for pilot studies of biochemical engineering processes, and working connections between basic biological research and engineering practice.

The knowledge needed has been summarized in Part I. Engineering personnel needs can be expressed as a shortage of both competent biochemical engineers and the faculty to train them. These personnel problems are worsening as biochemical engineering companies absorb both faculty members and recent graduates who have research and teaching talents. A second difficulty derives from the fact that many biotechnology companies tend to be small and oriented toward research and development, so that they do not have a sufficient variety of large-volume products to support the development of new pilot processes and large-scale production facilities. Further, the government, not currently a major buyer of biochemical engineering products, may see no reason for supporting pilot studies. The result may be a lack of both corporate resources and governmental rationale to initiate new production processes.

Overall, an issue for congressional consideration is strengthening the links between life scientists and biochemical engineers. Mechanisms might include:

- support for cooperative cross-disciplinary research;
- institutional grants to train graduate students;
- funds to enable academic units to purchase the equipment essential for contemporary research in biochemical engineering; and
- incentives for quality faculty to dedicate their careers to launching innovative university instructional and research programs.

## Advanced Polymeric Composites

While the United States has a sound position in advanced polymeric composites, vigorous programs also are proceeding in Japan and West Germany. The United States is strong in the chemistry of these materials, in their materials engineering, and in their application; Japan dominates in many aspects of carbon fiber technology.

As with computers and biochemical engineering, the best response of the United States is not necessarily to mimic international competitors. Rather, the effective transfer of information among basic, applied, and developmental activities is needed, as are mechanisms to enable different disciplines to work cooperatively on materials problems. Such disciplines include chemistry, physics, mechanical and chemical engineering, materials science, computer science, and toxicology. Only about 30 universities have research programs in advanced composites; of these, only two have multidisciplinary groups in the area. There are only 40 full-time equivalent faculty members in this field nationally.

In terms of national policy, a major issue is the creation of several research centers devoted to basic research on advanced composites. The goals of such centers could be to:

- carry out high-quality scientific and engineering research;
- perform toxicologic assessments;
- provide scientists and engineers trained in specific disciplines for research on advanced composites; and
- infuse engineering curricula with new knowledge.

## Issues for the Congress

*These three fields—computers, biochemical engineering, and advanced composites—illustrate both special needs and general guidelines for maintaining their strengths. The general lessons for effective progress, which are applicable to other fields, include the need for:*

- *complementary competence both in the basic science and in the developmental engineering, including personnel trained in both the fundamental science and the engineering principles underlying new technologies; and*

- *mechanisms to link different disciplines with each other, universities with industry, and basic scientists with technologists.*

*An additional issue for the Congress to consider is:*

- *the extent to which the expansion of technological programs for defense is creating shortages of trained personnel in areas critical to our international competitiveness.*

## SCIENTIFIC AND ENGINEERING PERSONNEL

Only a few issues are discussed under this broad topic. These issues include the real difficulties of a young investigator trying to begin a career in research; the paucity of clinician-researchers; possible shortages of trained research personnel some five years from now; and the role of foreign nationals in U.S. advanced education in science and engineering.

### Starting a Research Career

There is, typically, a cyclical pattern to surpluses and shortages of trained research personnel relative to job opportunities. The system tends to adjust to small oscillations; on occasion, the swings become quite large and require national attention. Thus, we now face severe shortages of computer science and engineering faculties as a result of insufficient numbers of doctorates in these fields and the large competition from industry.

In contrast, upon completing their training in biomedical research, many young people cannot find suitable openings and support to continue their research careers. Specifically, the concern is with research trainees in their mid-20's to mid-30's; that is, those who are doing much of the experimental work in fast-moving research fields, such as those described in Part I—oncogenes, atherosclerosis, and parasitology. Similar difficulties were seen in physics in the early 1970's and in mathematics in the late 1970's. The NSF postdoctoral program in mathematics, instituted to prevent the loss of a generation of gifted young mathematicians, may be applicable to other fields of science.

Several consequences follow. Promising students may turn away from biomedical research in favor of more secure and remunerative careers. Some of the best academic departments admit and train far fewer individuals than their pool of qualified applicants, faculties, and facilities permits. The overall impact—as in other fields of science—eventually may be an insufficient flow of young people into research careers and slower progress in exploiting research advances.

The Institute of Medicine's Committee on National Needs for Biomedical and Behavioral Research Personnel observed that this problem cannot be solved solely at the training level and that it is addressed more effectively in terms of funds available to support faculty members and their research programs.

The cost of equipment to set up a new investigator in many branches of science and engineering now runs into hundreds of thousands of dollars. These funds must come from institutional resources. This precludes many universities from making appointments. Even those research universities with the greatest financial resources are finding it difficult to meet these costs. The result is a pattern of shifting away from bringing young investigators into the system in favor of attracting established investigators who are better able to bring external resources with them.

## Clinicians in Research

A related concern is the declining number of clinicians entering research. Yet, clinician-researchers are indispensable for progress in areas such as the biology of atherosclerosis, discussed earlier. Current clinical training programs in universities offer both inadequate salaries to trainees and uncertainty of continued support. The fact that fewer clinicians are entering research undermines the transfer of basic research to clinical practice and lessens the contributions of physicians in directing research into the proper channels for understanding and managing human diseases.

## Possible Shortages

Beyond these immediate problems affecting the sufficiency of research personnel, several more may be in the offing. Student enrollments reflect job opportunities. Thus, the numbers of bachelors' degrees awarded in computer sciences rose from 5,600 in 1976 to 15,000 in 1982, while in engineering the figures were 45,000 and 74,000, respectively. In contrast, the numbers of recipients of bachelors' degrees in mathematics dropped from 15,800 to 10,900 between 1976 and 1983; the corresponding figures in the biological sciences were 54,000 and 43,000, respectively. The diminishing pool of students from which candidates for doctorates and postdoctoral work in various fields will be drawn five years from now could lead to shortages of trained personnel for universities and industry in the 1990's.

### Doctorates for Non-U.S. Citizens

Five percent more doctorates in science and engineering were awarded in the United States in 1983 than in 1978. Virtually all of this increase is accounted for by degrees given to non-U.S. citizens on temporary visas. Overall, about 20 percent of all doctoral degrees in science and engineering in 1983 were earned by those holding temporary visas. In the same year, more engineering doctorates were awarded to foreign citizens than to U.S. citizens; 38 percent of the doctoral degrees in mathematics and 35 percent in the agricultural sciences went to foreign students.

Overall, the proportion of master's and doctoral degrees awarded to foreign students relative to American students has increased substantially in engineering, but has plateaued or fallen slightly in the physical and biological sciences. In actual numbers, graduate enrollments in engineering increased from 36,000 in 1976 to 53,000 in 1983. Of these, there were 24,000 and 31,000 U.S. citizens, respectively. That reflects a 30 percent increase, compared to an 80 percent increase in foreign graduate students in engineering.

Much of the increase in numbers of foreign graduate students enrolled in science and engineering is a direct consequence of the normalization of relations with the People's Republic of China in 1979. Improvement of higher education in the People's Republic was adopted at the Fourth National People's Congress held in January 1975 as a part of Premier Chou En-Lai's doctrine of "four modernizations." In 1984, China (including Taiwan) led all other foreign countries in the number of doctorates awarded to non-U.S. citizens in engineering and science, with the exception of the social sciences. The number of doctorates awarded to Chinese nationals in electrical engineering in that year is particularly impressive.

How good are these foreign students? One measure is their scores on Graduate Record Examinations (GRE). On average, foreign students enter U.S. doctoral institutions with quantitative skills, as measured by the GRE, exceeding those of U.S. students. The differential is smallest for students in the mathematical and physical sciences and greatest for students in the social sciences. The higher performance of foreign students on the GRE quantitative examination may reflect the higher selectivity in the application and admission of foreign graduate students compared with U.S. students. Understandably, foreign students, for whom English is a second language, perform less well than do U.S. students on the GRE verbal examination.

There are benefits and possible costs to this major participation by foreigners in U.S. graduate education in science and engineering. The benefits to the United States are substantial; they include the exposure of a new generation of foreign scientists and engineers to American society and culture, the opportunity for American faculties and students to gain foreign perspectives on current research, and the improvement of international scientific and engineering communication. In some instances, the presence of foreign students has made up for low enrollments of American students and faculty shortages, and helped to meet industrial needs. Thus, a substantial proportion—56 percent in 1983—of foreign doctoral recipients are remaining in the United States, in academia, or industry.

There are also some possible costs. Foreign students who do not return home after being educated in the United States are a “brain drain,” particularly for less developed countries. While the opportunity to remain in the United States usually presents greater opportunities for research, the home country is denied the benefit of science and technology transfer for development.

Further, a higher proportion of graduate teaching and research assistants for whom English is a second language reduces the effectiveness of teaching at American universities and may even deter promising American students from taking advanced degrees. The greater availability of foreign students, often with financial support in hand, may decrease the incentive to recruit promising American students. Finally, and more subtly, foreign students and faculty members often have a theoretical rather than an experimental bent, a difference that may affect both the directions of future research and the efficacy of programs intended to accelerate the use of knowledge.

Overall, it is in the U.S. interest to serve as “schoolhouse to the world,” to provide graduate education in science and engineering to the brightest students, no matter where they come from. The real issue is *not* the number of foreign students training in U.S. graduate schools, but rather the reduced proportion of U.S. students taking advanced training, especially in engineering. Incentives are needed to make advanced training in several fields of science and engineering more attractive to U.S. students.

### Issues for the Congress

*Even this brief summary of several personnel issues in national science and technology makes it clear that public policy is only one factor in dealing with them. Others include market forces of supply and demand, economic cycles, individual perceptions of promising careers, and the policies of foreign governments with regard to their brightest students. Further, there are other issues of comparable importance, such as providing the fullest opportunities for women and minorities to contribute to the health and vigor of the research enterprise. Within these limits, there are a number of issues in this area for the Congress to consider:*

- *federal programs and policies that would help to minimize the impact of and reduce the cyclical fluctuations in the mismatch between the supply and demand for young investigators;*
- *additional programs, complementing the Presidential Young Investigators Awards, to help young researchers begin their careers; and,*

- *in its review of immigration legislation, policies regarding the ability of promising foreign students to study in American schools, of U.S. industries and universities to employ them, and the impact of such policies upon U.S. institutions, corporations, and other nations.*

## COOPERATIVE WORK ACROSS DISCIPLINES

Consideration of new funding modes, research structures, and agency organization may become a major legislative issue, driven by a growing need for multidisciplinary research. Thus, many of the fields discussed in Part I of this Outlook benefit from different disciplines working on common problems. This situation is not new, but its breadth is and its importance may be. Multidisciplinary work now ranges from neuroscience, requiring the effective collaboration of biologists, anatomists, physicists, physicians, chemists, cognitive scientists, and computer scientists, to deliberately structured materials, requiring atomic and condensed-state physicists, materials scientists and engineers, chemists, toxicologists, and process designers.

Such cooperative work is clearly in the national interest, scientifically and technologically. To be effective, it demands continuing disciplinary strength and flexible mechanisms. Although research involving the collaboration of chemists, biologists, engineers, and others is common in industry, such collaboration across traditional disciplinary boundaries needs nurturing to function optimally in academia. Universities are, understandably, conservative in creating new organizational structures and in starting new programs. An issue certainly will be how to encourage the creation of such mechanisms without sapping disciplinary excellence. The NSF program for Engineering Research Centers is one example whose effectiveness will be tested. Undoubtedly, others will emerge.

The creation by NSF of a program on the chemistry of life processes responds to a particular need in multidisciplinary research: funding work not falling into the established programs of support agencies. Another example is biophysical research of the sort discussed in the section on “Opportunities in Physics” in Part I.

## The Special Case of Agriculture

One aspect of cooperative work is moving the techniques and insights of one field into another. This is well illustrated by the efforts of the scientific community since the early 1970's to apply the spectacular advances in molecular biology and the techniques of genetic engineering to agricultural research. In time, such research will offer major improvements in crops and cropping practices. Promising research areas include: understanding the genetic information system governing plant growth and function; the genetic and biochemical systems controlling the virulence of plant pathogens; biological nitrogen fixation; biological controls of insect pests; and photosynthetic energy conversion and carbon metabolism.

Such research opportunities are constrained in several ways, such as insufficient numbers of scientists trained in both molecular biology and genetics as well as in agronomy and the basic plant sciences. Inadequate methods for stimulating cooperative research among these and related disciplines and for exchanging ideas are another obstacle.

The competitive grants program for agricultural research, established by Congress in 1977, is one important device for overcoming such constraints. However, it continues to be underfunded when compared to other programs supported by the Department of Agriculture. The latter are either intramural or operate under a formula funding structure. The current scale of competitive grants is too small to support a competitive molecular biology laboratory focused on agriculture.

In summary, Congress can usefully continue to consider mechanisms, such as the competitive grants program, that will reduce disciplinary barriers among the agricultural sciences and between them and the biological sciences. Such barriers are especially unfortunate when compared with the way in which technologies such as gene cloning and recombinant DNA are able to unify other biological disciplines. These barriers continue to retard what is still an inadequate national effort in the development of the molecular biology of plants.

The Administration has supported strengthening the basic research capabilities of the Department of Agriculture. However, further opportunities exist, and the Department is encouraged to continue to enhance its capabilities in molecular biology and related areas. Attention must also be paid to the process by which work supported by the Department and other federal agencies enters agricultural development and practice.

### Issues for the Congress

*The impetus toward multidisciplinary research, including the particular needs of agriculture, suggests several issues:*

- *articulating an appropriate federal role for encouraging multidisciplinary research;*
- *providing incentives for universities to undertake multidisciplinary research, whether within their campuses, with other universities, or with industry; and*
- *encouraging the infusion of basic biology into agricultural research.*

## RESEARCH AND TRANSPORTATION

A chronic issue for Congress is maintaining and improving the national transportation system. There are difficulties in bringing the benefits of sound research and effective technological improvements to this vast system. It is neither easily nor quickly nor cheaply changed. Further, transportation systems must be considered both in terms of their components—such as changes in the speed limit on highways or in the vehicles using them—and also as a network of highly interdependent parts; for example, rail and marine systems or highways and air transport. These systems are also affected by issues involving the environment, the economy, and public safety. Finally, a host of uncertainties —regulatory and economic policies, antitrust, and so on—often tends to depress private-sector spending on research and development in transportation.

Nevertheless, various transportation modes have benefited from the introduction of new technologies. For example, improved fuel economy, better safety, and lower pollution levels have been achieved for cars and other vehicles. Improved container technology has helped to integrate freight transportation.

Transportation systems undoubtedly can use to advantage much of the research done in other sectors. Thus, the development of advanced composites, discussed in Part I, as well as progress in combustion and heat transfer technology, in computer-aided design and manufacturing, and in optical scanning techniques have improved, and will continue to improve, transportation systems. Mechanisms for effective information and technological transfer across transportation modes will benefit the nation.

## Highways

A comprehensive examination of research opportunities for these transportation modes, both individually and in terms of the interactions among them, is clearly needed. The advantages of such research to the nation are likely to be considerable. That can be illustrated by examining, briefly, research opportunities for just one facet of transportation: the highway system.

Over the years, some $1 trillion has been invested in about 4 million miles of highway, about a quarter of which represents federal investments. The costs of repairing this road network have increased, but the chief source of revenue that finances these repairs—the tax on motor fuels—has been increased only once in real terms in the last two decades. With increasing efficiencies in fuel economy, the greater use of alcohol and other fuels usually exempted from tax, and other factors, future revenues are likely to decrease.

However, the point is not solely one of additional construction funding; indeed, Congress voted $58 billion in federal aid for highways in the Surface Transportation Assistance Act of 1982. The point is the emplacement of a serious and concerted research program to find better ways to build, maintain, and operate the highway system. The gap between costs and revenues can be closed in part by research to identify more durable highway materials than those used now and the factors that lead to their deterioration. About $70 to $75 million is spent annually on highway research, but most of it is parceled out in "problem-specific" contracts of $30,000 to $300,000, resulting in research applications that are highly local and often not applicable to the generic problems of highways. Responsibility for conducting such research tends to be distributed, and therefore diffused, among private and governmental groups at the local, state, and national levels. In addition, the research tends to be parochial: virtually no work is done on asphaltic materials, even though almost all roads and streets are surfaced or resurfaced with such materials.

## Issues for the Congress

*Summarizing a recent congressional review of the nation's transportation research activities, then Representative (now Senator) Albert Gore, Jr., observed that "considering both the importance of the nation's highways to commerce, industry, and recreational activities and the staggering estimates of repair and replacement costs—placed by some at a major part of the total cost of trillions of dollars—the need for and importance of a well directed and targeted research effort becomes clear." Representatives of industry have voiced similar sentiments, pointing to the large dollar paybacks expected from accelerated research in highway and bridge materials and construction. A recent report of the Transportation Research Board of the National Research Council supports these assertions and estimates that an annual investment of $30 million over 5 years in an interdisciplinary research program would translate into a saving of about $600 million each year from improvements in highway performance.*

*Among the immediate issues, then, are:*

- *the creation of a research program on highway transportation that is coherent, durable, adequately funded, and of a quality commensurate with the level of national investment; and*
- *the need for systems studies to attain optimal utilization of the various components of the transportation system—air, marine, motor vehicle, and rail.*

## FACILITIES AND INSTRUMENTATION

The inadequacy of facilities and instrumentation in research universities is recognized by the Administration and the Congress. As the Congress prepares to deal with particulars of this issue in the next several years, some comments on the research infrastructure may be useful. These comments focus on three aspects: large-scale facilities; the intensifying need for medium-scale instrumentation; and the problems raised by recent and partly successful efforts to bypass normal agency procedures, including scientific and technical reviews, used to ensure merit.

### Large-Scale Facilities

Experimental science increasingly entails large financial commitments for the acquisition and maintenance of instrumentation and specialized facilities. To undertake frontier research, some disciplines now require facilities with capital costs of several hundred million to several billion dollars. Recent high-cost proposals envisage new facilities for materials research comprising synchrotron radiation and neutron-scattering facilities, earthquake engineering facilities, major new astronomy facilities, and the superconducting supercollider.

The immediate issue is the scale of costs; more subtly, it is the effect of such large funding commitments on less costly instrumentation and facilities or on other research programs. Specifically, the latter concern is that attention to large facilities may overshadow the need for smaller-scale instrumentation and limit grant support. In budget terms, the belief is that, while large facilities may be nontransferable additions to the budget, medium-scale instrumentation must compete for marginal increases in existing budgets.

With intensifying pressures for both large-scale and medium-scale instrumentation, Congress will face several questions in the next several years: What approaches are optimal in the decision-making required for initiating and funding large facilities? Is it in the interest of the United States to encourage international fund ing for major facilities? If so, for which research areas? And in which areas should the funding be exclusively national? How is funding sustained over time, despite yearly appropriations cycles? Are the typical funding patterns the most effective; for instance, support scattered among several agencies? Is the concern that "big" science impoverishes "small" science valid? That is, does support for large-scale facilities, such as sources of synchrotron radiation, reduce funding for laboratory-scale materials research or support for individual university researchers? If so, what remedies are applicable? How can the individual university researcher be assured of the funds, including travel costs, required to use major facilities productively?

## Medium-Scale Instrumentation

New directions in a number of fields are increasing the need for medium-scale instrumentation. Medium-scale instrumentation refers to tools that, in costing from $100,000 to $1,000,000, fall between the major facilities discussed above and the relatively lower-cost instruments accessible to most researchers. Purchases of medium-scale instruments inevitably entail special budgetary procedures, in many cases involving pooling mechanisms such as institutional and regional facilities. Further, most federal grants for medium-scale instrumentation require significant cost-sharing by institutions. Realistically, however, institutional resources, even those of the major research universities, are unable to meet all of the requests from their faculties for cost-sharing.

Grants to buy instruments need to be accompanied by funds for operation and maintenance throughout their expected life-times. That is not always the case today. Funds to purchase instruments often do not include money to operate them or to hire and train technical personnel to help investigators use state-of-the-art technology. Sometimes, it is easier for academic institutions to obtain financing for new equipment than for operating and upgrading existing equipment, even though the latter may be only a year old. Therefore, it would seem prudent for granting agencies to consider policies for funding capital equip ment that allow money for maintenance, operation, upgrading, and training or hiring technical personnel.

In any case, concern for the inadequacy of advanced instrumentation for academic research is likely to increase in the next few years. There is a significant gap in access to medium-scale, technologically advanced instrumentation between academic and industrial researchers working in the same area. While several federal agencies—such as the National Science Foundation, the Department of Defense, and the Department of Energy—have initiated instrumentation programs to bring state-of-the-art equipment into university laboratories, these programs tend to be small compared to the magnitude of the problem. Also, they must be stable over several years.

To give the issue greater concreteness, instances of four fields offering rich research opportunities but constrained by inadequate, medium-scale instrumentation are discussed below. These examples are: chemistry, materials science, neuroscience, and biochemical engineering.

*Chemistry.* These are propitious times in such chemical fields as reactivity, catalysis, and the chemistry of life processes. But favorable opportunities can be exploited fully only with highly sophisticated instrumentation to create molecular beams, to follow the energy and compositional changes of a catalyst during a reaction, to watch reactions occurring more rapidly than a beam of light can cross a strand of hair, and to provide a host of techniques for separating and then identifying incredibly minute amounts of complex molecules.

The difficulty is that, historically, funding for basic research in chemistry did not allow for access to such sophisticated equipment. The resultant lag in instrumentation in universities threatens the dynamism and opportunities for chemistry in the United States and, ultimately, the international competitiveness of several of our major industries.

*Deliberately Structured Materials.* As mentioned in Part I, this field has advanced rapidly in the last 10 years because of unprecedented innovations in atom-by-atom control of both the syn thesis and the characterization of materials. The potential applications are immense; communications and computers are the most obvious.

It is impossible to do research in this field without medium-scale instruments: X-ray apparatus, electron microscopes, special laser systems, ultrahigh vacuum systems, and so forth. A specific example is molecular beam epitaxy, a technique for atom-by-atom layering of a crystalline surface, creating a sort of molecular pousse-cafe. The technique enables exacting controls of the electronic and optical properties of a semiconductor or a catalyst. The paucity of molecular beam epitaxy equipment in university laboratories impoverishes both academic research in this field and interactions between academic and industrial researchers.

*Neuroscience.* Neuroscience is one of the most active and dynamic fields in science, yet it also faces serious equipment obstacles. For example, there is a major need to assess the active human brain noninvasively by methods that include radiological and nonradiological imaging, electrical and magnetic mapping of brain activity, and techniques in which brain function and response are assayed by chemical measurements of blood and spinal fluid. Funds for improving and developing equipment are needed to accomplish this work. Further, advances in solid-state measuring devices now available commercially have not been applied to research as fully as possible because of insufficient money to modernize laboratory equipment.

*Biochemical Engineering.* As indicated earlier, this field requires critical research elements in order to translate basic biology into large-scale processes. Advanced research demands, among other things, fermentation equipment and tissue culture laboratories, the latter costing approximately $250,000 each. That amount of money is not available in standard research grants. As in the case of materials research, the effect is to limit both academic research in bioengineering and dialogue between university and industry.

## Planning New Facilities

Decisions by federal agencies and Congress on large expenditures of public funds for scientific facilities are necessarily tempered by costs and policies. Within these constraints, scientific evaluations have provided objective assistance in decisions to initiate major scientific facilities and instruments and in their selection, siting, and operation. This process has served the country well.

However, in the past several years, there have been—and continue to be—efforts to circumvent these important elements of consultation and open competition. Attrition of accepted and successful mechanisms threatens to: (1) eliminate scientific justification as an element in spending large amounts of federal funds, (2) disenchant the many able scientists who voluntarily and carefully review proposals for federal funding, (3) discourage other institutions already frustrated by the limited amount of federal money available for research facilities, and (4) erode the process for judicious allocation of funds among facilities, institutions, programs, and projects.

In thinking about the funding of facilities, it is useful to keep in mind that there are several classes of facilities and that the review and approval processes for different classes of facilities are hardly homogeneous, differing from class to class and from agency to agency.

Granting that the divisions are arbitrary, one can distinguish at least four classes of research facilities:

(1) national facilities, intended to serve a national, often international, research community—for example, the Fermi National Accelerator Laboratory;
(2) university-based research facilities—a new chemistry building, for instance;
(3) regional research facilities, usually based at a university—for example, the Triangle Universities Nuclear Laboratory in Durham, North Carolina; and
(4) technology centers, tied to local and regional economies

and located at or affiliated with universities—for example, the Basic Industry Research Institute at Northwestern University.

By and large, the review procedures for class (1), national facilities, are well established and have worked satisfactorily. That is true for Fermilab and for recent planning, such as for the new synchrotron radiation facilities now under consideration.

Recent and successful efforts by universities to circumvent normal comprehensive review mechanisms for deciding on facilities have involved the other three classes. A committee of the National Science Board estimates that, through the direct appropriation process (rarely used in funding academic research facilities), 15 universities have succeeded in obtaining over $100 million for facilities without going through the usual processes of open competition and review of scientific merit—two important elements in decision-making.

Many groups and individuals—in and out of government—have decried these circumventions. The potential for vital damage to the U.S. research system and to the apolitical role of the universities has been well articulated. The point is the nature of the pressures prompting such actions and what can be done about them. Certainly, a major source of such actions lies in two intersecting trends: (1) the decline, for over a decade, of federal support for new facilities and the renovation of existing ones, and (2) the explosive growth of science and, with that, the corollary need for facilities—with ancillary operating funds and personnel—to provide the complex instrumentation required at the frontiers of research. As the president of Stanford University recently observed in *Science*: “The political spasms we are now seeing result from the struggles of the scientific venture to escape from the prison of its own undercapitalization. . . . We now find ourselves caught in a mismatch between the needs and expectations of scientific research and the willingness of the public sector to support it.”

## Issues for the Congress

*Given the large deficit in the U.S. budget and other constraints, it is unrealistic to expect the government to provide all of the large* *shortfalls in capital and operating funds for academic research facilities. In any case, it is rare—national facilities of the Fermilab type again excepted—that the federal government covers all of the costs of an academic facility. The issue is how can federal funds for facilities be leveraged most effectively and equitably? What responses will improve the overall health of the U.S. research system?*

*First, the universities must be imaginative in obtaining funding for facilities, especially in leveraging private-sector, state, and federal investments. Illustrative mechanisms might include:*

- *the use of federal funds to pay the interest on money borrowed by universities;*
- *the use of local bonding authorities;*
- *sharing costs with other universities and research centers; and*
- *establishing different overhead rates for different sections of the university.*

*Second, on a national scale, the contending pressures of rapid scientific and technological advances, a decade of reduced federal expenditures on facilities, and limited national resources present an extremely prickly set of policy issues. Among them are:*

- *enhancing systems for comprehensive merit review which include judgments from the scientific community on the quality of science likely to be conducted at a facility to be built with federal funds;*
- *anticipating and planning for future needs for large scientific facilities;*
- *seeking optimal ways to leverage federal investments in such facilities;*
- *considering criteria to test whether international cost-sharing is appropriate for a large facility;*
- *ensuring that support for large new facilities is not offset by inadequate support for qualified individual investigators;*
- *reviewing current federal fiscal and accounting policies with respect to the capital and operating costs of facilities; and*
- *evaluating alternative mechanisms for funding instrumenta*

*tion, including capital cost recovery as a part of the operating budget of a federal grant or contract.*

## ISSUES IN GENETIC ENGINEERING

In a short time, recombinant DNA and the related techniques of molecular biology have generated remarkable advances in basic biological research. These efforts are on the verge of yielding promising applications in clinical medicine, veterinary medicine, agriculture, energy, and pollution control.

Several federal agencies are assessing the impacts of applications that require the use of genetically altered organisms in environments less well controlled than those in research laboratories. For example, the Environmental Protection Agency is trying to develop its own capabilities for assessing potential ecological and health effects, for monitoring organisms and genomes in various environmental media, and for devising effective control technologies. These efforts are overseen by the Federal Interagency Recombinant DNA Committee. The Recombinant DNA Advisory Committee of the National Institutes of Health still exercises the main responsibility for supervision of research protocols.

The need to coordinate the policies of the federal agencies whose responsibilities encompass various applications was recognized in the recent publication for comment in the December 31, 1984, *Federal Register* of a "Proposal for a Coordinated Framework for Regulation of Biotechnology," prepared by the Cabinet Council Working Group in Biotechnology. This proposal describes the policies of the major regulatory agencies that review biotechnology research and products. It also provides a regulatory matrix, outlining the applicable laws, regulations, and guidelines.

The pattern established in the late 1970's—federal guidelines for research and specific risk assessment experiments for determining potential ecological hazards—remains useful. Altered microorganisms can be tested in the laboratory first and then in well-controlled field sites, before release into the general environment. Using such test environments, scientists can de vise effective means of monitoring the fate of the organism and its specific genes.

### Issues for the Congress

*Two major related issues continue to be:*

- *maintaining oversight of what have been remarkably effective mechanisms for monitoring the use of recombinant DNA and related technologies; and*
- *assuring full and balanced consideration of requirements for public safety and the needs and opportunities of an emerging industry.*

## ISSUES IN HUMAN BIOLOGY

Many discussions of new biological techniques involving reproduction and human genes have been subject to misinterpretation. A description of a potential application sometimes devolves, incorrectly, into an assumption that the application actually is possible or indeed is on the verge of being put into practice. Also, it is difficult to emphasize sufficiently that the spectacular successes achieved in isolating and copying certain human genes leave unsolved the much more difficult tasks of inserting these genes into the right cell and the right DNA position, and then having them function properly. Further, the differences between the genetic content of germline and somatic cells—the first transmissible from parent to offspring and the second not—are often lost in the discussion. Yet, such differences are vast in terms of the technical difficulties of gaining access to and engineering genes, the possible risks, and the accompanying social and ethical considerations.

There are two areas in which new biological techniques do or may have roles. First, the fertilization of human eggs outside the body and their subsequent implantation is a technology that is in use but that suffers from a *de facto* ban in the United States on research to understand it better. Second, consideration needs to be given to potential techniques, typically classed as genetic engineering, involving human somatic and germline cells.

## In Vitro Fertilization and Implantation of Human Eggs

Based on data reported informally at a recent international conference, this technology is in substantial use already as a treatment for infertility. There are now about 200 centers worldwide. Of these 200 centers, 50 are in the United States and about 70 have been in existence over one year. About 500 children have been born through these techniques. Many more embryo transfers have been carried out—about 7,500—but pregnancy does not always ensue. About 24,000 human eggs have been collected at these centers. This has been possible, in part, because hormone treatments allow women to produce more than one egg cell per ovulation.

Against this reality of a robust technology is the fact that there are substantial gaps in knowledge of the underlying science, especially of the embryo. For example, a fairly new technique is to remove a few cells from a very early embryo, one that is still a solid sphere of cells, freeze the embryo, and check the separated cells for chromosomal abnormalities. Assuming no problems, the embryo can then be implanted. Several children have been born through this technique, and three clinics in the United States are using it. Yet, we have little basic knowledge of the effects of freezing and thawing on the embryo or of the removal of a few cells.

Part of the problem is a *de facto* ban on federally funded fetal research. All such research must be approved by a board of the Public Health Service. But the board does not exist; no members have been appointed.

## Genetic Therapy of Human Cells*

Engineering of somatic cells—such as bone marrow cells—is similar to that of germline cells—eggs and sperm. In each case, a gene being transferred must (1) be put inside the appropriate cell,

*Useful background on this issue, especially on therapy involving somatic cells, is provided in the recent report by the congressional Office of Technology Assessment entitled *Human Gene Therapy.*

and (2) be positioned properly into the cell's DNA. Beyond these generalities, there are major and important differences.

*Somatic Cells.* Genetic therapy with somatic cells is likely to begin with bone marrow cells. These cells are accessible, can be grown in the laboratory, and can be transferred successfully into a patient's bone marrow. Further, there are very serious genetic diseases in which the genetic defect is both relatively simple (for example, a single defect involving a single gene) and may be treatable through bone marrow cells. In contrast, genetic defects involving multiple genes, brain and nerve cells, or several different kinds of cells are much more difficult to treat and are not likely candidates for initial therapies.

A spectrum of techniques exists for transferring genes into a cell. Each has its limits, with the use of certain types of viruses being the most promising at the moment. However, no methods exist yet to deliver a donated gene with certainty to the targeted region of the recipient cell's DNA; nor are there methods to regulate precisely the expression of a properly inserted gene.

These and other factors in genetic therapy with human somatic cells are articulated in a recent statement, entitled “Points to Consider in the Design and Submission of Somatic-Cell Gene Therapy Protocols,” by the National Institutes of Health Working Group on Human Gene Therapy.

*Germline Cells.* Several laboratories have been able to transfer genes into fertilized mouse eggs, which then develop in *utero* into living animals. The transferred genes are expressed in different tissues of these “transgenic” animals and are inherited by subsequent generations. Such experiments are providing new insights in developmental biology and tumorigenesis. These procedures are now being extended to farm animals.

In the case of humans, no experiments of this kind have been attempted nor, in contrast to gene transfer in somatic cells, is there consensus on the potential usefulness of germline therapy in human genetic disorders. Aside from the critical ethical questions raised by heritable modification of the human germline, there are also severe technical limitations. For example, it is not possible yet to target genes into their correct position in recipient cells; therefore, gene expression is unpredictable and possible deleterious effects of the random insertion of genes cannot be excluded.

### Issues for the Congress

*Overall, the immediate prospects for germline therapy are nonexistent, and the long-term prospects are highly problematical. The outlook for somatic therapy is brighter, but it still faces major technical difficulties.*

*The issues in the area of human biology include:*

- *maintaining oversight through the National Institutes of Health of plans for human gene therapy; and*
- *encouraging programs to enlarge fundamental understanding of fetal biology.*

## SCIENTIFIC COMMUNICATION, TECHNOLOGY TRANSFER, AND NATIONAL SECURITY

The scientific and technological strengths of the United States depend in part on the rapid and free exchange of information. There is concern in the defense and intelligence communities, however, that this openness may be of military benefit to the Warsaw Pact countries. Part of that concern, focused on academic research supported by the government, was addressed in September 1982, in a report of the Committee on Science, Engineering, and Public Policy (COSEPUP), entitled *Scientific Communication and National Security* (also known as the Corson report, after its chairman, Dale R. Corson).

The Corson Panel limited itself to questions involving academic science, leaving unresolved the complementary issue of the communication and transfer of industrial science and technology. It drew two major conclusions: first, a national strategy of “security by secrecy” is flawed because there is no practical way to restrict international scientific communication without disrupting domestic scientific communication, which inevitably weakens American capabilities in military and civilian technolo gies; and, second, that a national strategy of "security by accomplishment"—i.e., one that emphasizes protecting the U.S. technological lead by aggressively promoting scientific and technical productivity—is a far better alternative. The panel also outlined "gray areas,"—categories of technologies that, by their nature, could not be either completely open or totally classified.

Much discussion followed upon the release of the report, both within and outside the government. But implementation has not followed and the problem has remained unresolved.

## The Department of Defense

In the spring of 1984, the Department of Defense (DOD) proposed an alternative policy that, in lieu of "gray areas," returned to a basic "black and white" approach whereby DOD research contracts would stipulate whether a particular project was open or classified. Many in the scientific community welcomed this as a positive development, although most have reserved judgment until the new policy is formally adopted and implemented.

In view of the prevailing federal policy on classification (that information must be restricted whenever there is reasonable doubt about the need for its protection), the government may be inclined to adopt a more conservative approach when deciding whether to classify militarily sensitive research—for example, on microelectronics or composite materials—that heretofore has been completely or partially unrestricted. Moreover, most research universities have standing policies against classified research projects on campus, except during national emergencies. Since most universities do not maintain secure off-campus facilities, there is the possibility that these institutions might withdraw from certain types of research sponsored by the Department of Defense.

## The Department of Commerce

While the Department of Defense has been developing policies for the control of information resulting from federally fund ed research, the Department of Commerce has been working on a revision of the Export Administration Regulations, particularly the portion dealing with the export of technical data. This effort has been undertaken in parallel with congressional debate on new statutory language for the Export Control Act. These two initiatives may have a far greater impact on international technology transfer than the new DOD policy. Whereas the DOD policy affects only work done directly under contract to the department, changes in the export regulations affect everything involved in or related to any movement of products, processes, data, or expertise outside the borders of the United States. The Department of Commerce has acquiesced recently to DOD's insistence that the latter has the rights of review and timely refusal of export licenses.

From the narrow standpoint of scientific communication, the proposed revision of the Export Control Act creates the possibility that individual researchers would be required to obtain validated export licenses each time they planned to give a lecture, participate in a symposium, or work in a laboratory where foreigners were to be present and where so-called “militarily critical technical data” were to be presented or discussed. Any of these activities would constitute an “export.” A similar obligation would exist whenever the research deals with critical technical data and the researchers plan to travel, to publish abroad, or, using this logic, to publish in U.S. journals read by foreign scientists. The net effect would be the regulation of scientific communication by the Export Control Act.

The implications of these new restrictions on the private sector may be equally profound. For example, the communication of technical data to and from the foreign offices, subsidiaries, affiliates, and suppliers of integrated, transnational corporations is central to their global nature. If these data flows were restricted, corporate research, development, and sales efforts would be inhibited. Similarly, the ability of a company to compete in world markets is based, in part, on its capacity to deliver a product, service (and related knowledge), or technical data in timely and unrestricted fashion. Particularly for the so-called “dual use” technologies (those that have both military and com mercial applications), the new regulations may restrict severely the freedom of companies to reveal technical data or specifications at sales meetings or, in some cases, even to market a product. Many in industry have expressed their concern about these proposed changes in the export regulations. They have urged officials at the Department of Commerce and other agencies to engage in broader consultation and public debate before implementing them.

Another aspect of the problem pertains to the multilateral control of technology transfer by and/or between free-world, industrialized countries. Some in private industry argue that, because the policies of other industrialized countries toward their own companies are generally more liberal, current U.S. national security export controls succeed only in damaging the ability of American companies to compete for their share of the market for high-technology international trade and there is no gain from the security standpoint. This brings into question the effectiveness of CoCom, the International Coordinating Committee on Multilateral Export Controls, which has evolved over the years in a largely *ad hoc,* incremental manner.

### Issues for the Congress

*The sometimes contending and equally legitimate aims of protecting the nation's security, enhancing the U.S. competitive position in international markets, and protecting freedom of scientific communication raise difficult and durable issues. As a result, COSEPUP has initiated a new study to address those issues, entitled* The Impact of National Security Controls on International Technology Transfer. *The panel, to be chaired by Dr. Lew Allen, Director of the California Institute of Technology's Jet Propulsion Laboratory, and former Air Force Chief of Staff and Director of the National Security Agency, will complete its work within the time frame of the 99th Congress. Hopefully, this study will assist the Congress in its efforts to develope clear policies to:*

- *protect the interests of national security;*
- *promote freedom of exchange of basic scientific information; and*

- *reconcile corporate needs to transmit technical data and sell products and processes internationally with the requirements of national security.*

## GLOBAL ATMOSPHERIC EFFECTS OF NUCLEAR EXPLOSIONS

Several studies of the global atmospheric effects of nuclear explosions have appeared, among the most recent being the December 1984 report of the National Research Council (NRC) entitled *The Effects on the Atmosphere of a Major Nuclear Exchange.* These reports agree that a major nuclear exchange could alter the atmosphere seriously, at least for the short term. The precise effects depend on such variables as the season, the sites and yields of detonations, the altitudes at which explosions occur, the amount and nature of the smoke produced, and the ways in which soot particles are scavenged and rain out, especially from the upper atmosphere.

Such uncertainties make it difficult to state firm conclusions. As the NRC report pointed out:

All calculations of the atmospheric effects of a major nuclear war require quantitative assumptions about uncertain physical parameters. In many areas, wide ranges of values are scientifically credible, and the overall results depend materially on the values chosen. Some of these uncertainties may be reduced by further empirical or theoretical research, but others will be difficult to reduce.

Why do these studies? One answer is that strategic thinking—and world opinion—may be affected already by the prospects of a “nuclear winter” and other possible climatic changes. As Herbert Simon writing in *Science* and others have pointed out, the strategic implications of the nuclear winter hypothesis have not yet been examined to the depth required. Whatever the implications, it is imperative that they rest on adequate information and well-based estimates. As the NRC report stated:

Long-term atmospheric consequences imply additional problems that are not easily mitigated by prior preparedness and that are not in harmony with any notion of rapid postwar restoration of social struc ture. They also create an entirely new threat to populations far removed from target areas, and suggest the possibility of additional major risks for any nation that itself initiates use of nuclear weapons, even if nuclear retaliation should somehow be limited.

Some have argued recently that the nuclear winter hypothesis has implications for strategic defense, arms control, first-strike effects, target selection, and techniques of battle management. Given that the nuclear winter hypothesis has been overlooked for decades, are there other consequences of nuclear detonations not yet considered?

The need then is to identify all possible consequences, to narrow uncertainties, and to obtain credible, quantitative, and reasonably accurate estimates of what might happen to the atmosphere in a nuclear exchange. That research has begun; it needs continuing support.

### Issues for the Congress

*The immediate issues concerning research on the prospects of a "nuclear winter" are straightforward:*

- *adequate support must be provided to conduct the research program called for in recent reports;*
- *all research findings should be public, within the legitimate constraints of national security; and*
- *the scientific community should be engaged fully, not only in planning and conducting the research program but also in appraising its quality and implications.*

## FINAL COMMENT

This Outlook has highlighted important progress in some selected fields of science and technology. It has defined a number of issues and opportunities that relate to this progress and to national goals. The Outlook records new contributions to several problems once seemingly insurmountable, from cancer to the global devastation wrought by parasitic disease. American science and technology continue to display strength and leadership.

These essential qualities will be sustained only if timely attention is given to the basic resources needed, from instrumentation and facilities to the research climate and training for young investigators. In sum, the course of the nation's research system, and the magnitude of its contributions to meeting national goals, continues to depend on the wisdom, support, and guidance of the federal government.