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Introduction and Summary

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American society is becoming increasingly reliant on the use of electronic information technology, principally computer and communication systems. Economists and social scientists point out that information is a basic resource for society and an important factor of production for the economy. Information technology provides business, governments, and citizens with the basic tools necessary to communicate and use information. Furthermore, the information industry, itself, including both those that produce electronic hardware and those that offer information services, is an increasingly important part of U.S. industrial strength.

Because of this reliance on information technology, public attention has been drawn to the process of innovation in that field, developing new technological products and bringing them to the marketplace. Since research and development (R&D) is generally considered to be a key element driving innovation (although not the only one), Congress is concerned with the general health of R&D in information technologies. Concerns include the effects that changes in the structure of the U.S. telecommunications industry are having on industrial R&D, and the implications of new foreign programs intended to challenge traditional U.S. market leadership in some areas of computers and communications. OTA examined these and related questions at the request of the House Committee on Science and Technology, the House Committee on Energy and Commerce, and its Subcommittee on Telecommunications, Consumer Protection, and Finance.

Goals for Federal R&D Policy

Currently, public concern with information technology is focused on its role in promoting economic competitiveness. However, Federal interest in promoting R&D and technological innovation, dating back to the writing of the Constitution, has always been motivated by several distinct goals, only one of which has been economic growth. These goals, which may for any specific technology or program either complement or compete with one another, are applicable to information technology.

- *Support National Defense:* A modem military force is dependent on communications and computer technologies for many purposes, including intelligence, missile guidance, command and control, and logistics. Projected future applications include battlefield management, fully automated weapons, and computer-based artificial intelligence advisors for pilots. The military importance of information technology is demonstrated by the predominant role the Department of Defense plays in support of R&D in that field (nearly 80 percent of direct government funding in this area is supplied by DOD).
- *Provide for Social Needs:* Government has always treated the telecommunications system as a basic social infrastructure. One major goal of communication policymakers is "universal service. " New services such as cable television and information services delivered over telecommunication channels can potentially improve the quality of life for American citizens. For example, OTA, in a recent report, pointed out the role information technology could play in improving the quality of and access to education and also stressed the need for additional R&D focused on educational technology. Another recent OTA report has described the po-

tential benefits of information technology to handicapped individuals.

- *Promote Economic Growth:* The information technology industry (those who make and sell or provide access to communications media) and the information industry (those who use the new technologies to produce and sell new information services and products) are a growing part of the U.S. economy. Their economic importance is felt both domestically and internationally. These industries also have an important indirect effect, in that the technologies and services they produce contribute materially to the economy in such forms as productivity growth, better quality of products, and improved managerial decisionmaking. The health of the information industries depends in part on their ability to bring forth new products and develop new applications; this ability, in turn, depends on R&D.
- *Advance Basic Understanding of the World:* Research in computer and communication science has contributed to basic understanding in fields that transcend pure information technology. For example, research in artificial intelligence has led to insights into brain functions and human thinking and problem solving. Communications researchers have made a Nobel Prize-winning contribution to our understanding of the origins of the universe. The study of computer languages has both benefited from and contributed to theories of the evolution and structure of natural human languages. Similarly, information technology researchers have contributed to knowledge in such other fields as fundamental mathematics, logic, and the theory of genetic coding.

  Moreover, computers have become indispensable research tools in many areas of science ranging from physics and astronomy to biology and social science. Some scientists now speak of "computational research" as a new, wholly different form as important to the progress of knowledge as is experimental and theoretical research.
- *Enhance National Prestige:* The United States has always been a world leader in computer and communication technologies, both in the discovery of new basic knowledge and in its development into commercial products. In certain areas of marketable technology, such as supercomputers (very powerful computers, the largest and fastest available on the market) or communication satellites, U.S. firms have in the past held an undisputed technological lead. Although such technological dominance has nearly disappeared in most cases and could not have been expected to continue as other nations developed research capability and industrial strength in information technology, preserving U.S. technological competitiveness and leadership is still an important public policy goal with implications that extend beyond purely economic advantage.
- *Support Civilian Agency Missions:* Many civilian Federal agencies need to use advanced information systems to perform their missions more efficiently or effectively. For example, computers and communication systems underlie the space exploration programs of the National Aeronautics and Space Administration (NASA). Weather researchers working for the National Oceanic and Atmospheric Administration (NOAA) and fusion researchers for the Department of Energy need access to the most advanced supercomputers. Although the support of mission agencies for basic research is limited, they have funded development and, often, applied research directed to meeting their specific needs.

Over the years, these Federal interests have led to a wide array of policies, programs, and agencies designed to promote the conduct of research and development in the United States and to appropriate its benefits to American society. Many of them have helped stimulate the development of computers and communication technologies.

The principal issue examined in this study is whether those policies, programs, and agencies are **now** adequate and appropriate for advancing information technologies in light of the emerging needs of society for these technologies, their particular characteristics, and the rapidly escalating world competition in producing and selling products and services based on them.

Principal Findings

In summary, OTA's study of information technology research and development reached the following conclusions:

- *Information technology is an area in which the United States has historically shown great strength, both in basic science and marketed technology; and this strength has benefited the Nation in several ways.* It has contributed to the growth of a strong economic sector, the information industry. It has contributed to national security. It has stimulated the evolution of basic science.
- *Most areas of information technology examined in this study, including microelectronics, fiber optics, artificial intelligence, computer design, and software engineering, are still in the early stages as technologies.* Much improvement in technological capability remains to be developed, and that improvement will depend on both fundamental research and technological development. Hence, R&D will be an important factor in stimulating continuing innovation.
- *By most measures, U.S. research and development in information technology is strong and viable; however, those traditional measures may not be realistic guides to the future needs of the United States for R&D in these areas.* In particular, increasing competition from foreign nations (in particular, Japan) as well as the growing intrinsic importance of information technology to the United States, suggest that more attention should be paid by policymakers to the needs for R&D in information technology. Many of these nations, motivated both by economic concerns and broader social goals, have developed national programs designed to foster information technology.
- *In response to these new pressures, industry support is growing rapidly for short-term applied research and developmental work, both within industrial labs and through support of university work.* Industry has generally looked, and still looks, to the academic community to perform and the Federal Government to fund the long-term basic research that will underlie future technological advances.
- *Universities, traditionally viewed as centers for basic research, are reexamining their roles with respect to applied research and are forming new types of relationships with industry and government.* State governments, in particular, looking for stimuli to economic development see new high-technology industry, including the information industry, as interested in being located near strong university basic research programs. Many states have formed new organizations within their universities in order to strengthen research, focus it toward problems of interest to industry, and facilitate the transfer of technology from the research laboratory to industrial application. With most of these experiments, it is too early to tell whether they will be successful in stimulating industrial development and whether they will have beneficial or negative effects on the universities.
- *The Department of Defense is the predominant source of Federal support of information technology research and development, providing nearly 80 percent of the funding.* Although some spillover to the civilian sector from DOD research can

be expected, its work is predominately focused on military requirements and cannot be relied on to provide for all civilian needs. An important issue for consideration by Congress is whether increased funding by nondefense agencies of long-term research in information technology is needed to focus more work on civilian needs.

- *There is substantial concern that technical and scientific information flows between the United States and other countries are unbalanced outward.* Proposals to redress that balance focus both on increasing access to foreign information and on restricting outflows of U.S. information. Policies that would enhance the access of U.S. information scientists to the work of foreign researchers (through such vehicles as translation services, travel grants, and foreign science exchange programs) would help their own work. Such programs would also help science policy experts to evaluate the state of foreign technology more accurately.

  Steps have also been taken to tighten controls over the export of technical information on national security grounds. In considering such controls, Congress needs to balance national security considerations against both first amendment rights and the possible negative impacts on domestic R&D.
- *Instruments for scientific research are growing more sophisticated and are becoming obsolete at an increasingly rapid pace.* As a result, they are more expensive and yet must be replaced more frequently if researchers are to keep at the forefronts of knowledge. In particular, computer software researchers need access to sophisticated computational facilities and data communication networks, and those working on microelectronics need access to chip processing facilities and computer-aided-design tools.
- *Policies designed to stimulate information technology R&D need to be evaluated for possibly significant tradeoffs and external costs in other areas.* Some costs are clear. For example, R&D tax incentives are a short-term loss of Federal revenues. Policies designed to draw more highly trained people into information technology may create manpower shortages in other areas of research. Devoting educational resources to information technology education and training draws them away from other areas of need, at a time when overall resources are not growing.

The Nature of Information Technology R&D

For purposes of this study, OTA defines the term “information technology to refer to electronic hardware that is used to create, communicate, store, modify, or display information and to programming or “software” that is developed to control the operation of that hardware. Modern information technology is based on the microelectronic chip, the large-scale integrated circuit that over the last decade has transformed the computer and communications industries through steady and rapid increase of performance and decrease in price. This high rate of technological improve ‘merit in microelectronics will continue into the 1990s and probably beyond. Changes in the information technology products and services available in the marketplace will likely be as revolutionary in the next decade as they have been over the last one that has seen the appearance and growth of such technologies as the personal computer, fiber optics, satellite communications, the video cassette recorder, and two-way cable television. Industry will compete worldwide to bring these new prod-

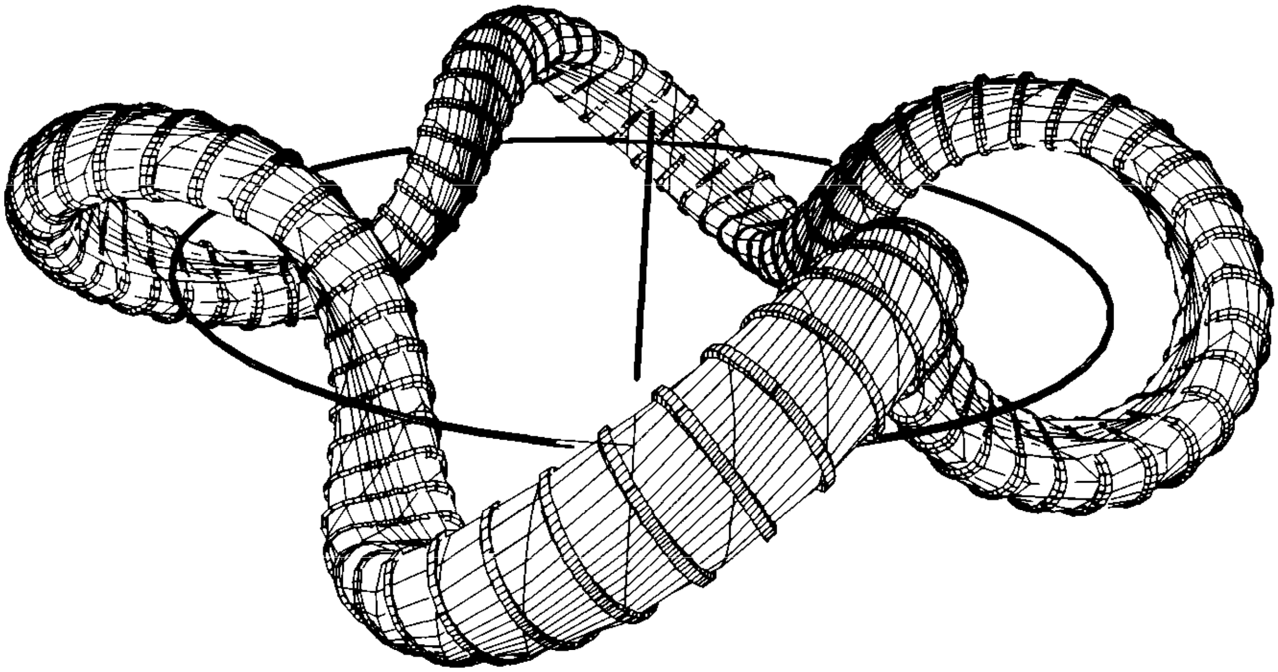

Photo credit: Arthur A. Merin, National Magnetic Fusion Energy Computer Center, Lawrence Livermore National *Laboratory*

The use of computer modeling and graphics to study fusion energy. Outer magnetic surface of four-period helical axis stellarator (HELIAC)

ucts and services to use, and an important element of that competition will be research and development.

Information technology has characteristics that distinguish it from many other areas of R&D and that affect policies designed to stimulate and direct it.

Software as Technology

"Software," or programs, are sets of instructions that direct a computer in its tasks. The term can also refer to information; for example, computer data bases, the information content transmitted over communication lines, or that contained on a video disk. Because software often can be the most complex part of an information system, research and development on software is considered to be of equal importance to research on hardware technology. Yet, to some people, software does not "look" like technology. The concepts and techniques that underlie programs are intangible, and their embodiment is usually in a form such as a list of instructions on paper or a sequence of images on a video screen. Research in information technology includes research on both hardware and software technology, and on the boundaries between them, for many computational techniques may appear in either hardware or software.

Software as an area of research presents Federal R&D support with some unusual problems. For example, intellectual property as expressed in software is difficult to protect. It can also be hard to distinguish between R&D in computer programming, work which advances the state of software technology, and using existing techniques to write new programs and maintain old ones—a distinction that drew particular attention in the debate over R&D tax credits, for example.

Multidisciplinary Nature

R&D in information technology spans a wide variety of disparate fields of work. For example:

- Solid-state physicists work to improve the performance of the semiconductor devices that form the heart of modern computer and communication systems.

- Mathematicians study abstract theories of computation, looking for methods of faster calculations, for ways to write error-free software, and to transmit the maximum amount of information reliably over communication lines.
- Psychologists and brain physiologists find clues for writing "smarter" programs that can solve more complex problems.
- Linguistic theorists contribute to the design of new languages for programming computers and build the foundations for computer programs that can understand and automatically translate human languages.
- Users of computer systems, ranging from physical scientists to graphic artists, develop new types of software for their applications. In this development process, they make fundamental contributions to software technology.
- Sociologists, psychologists, and the management scientists search for the most effective ways to design office automation and decision support systems. Their research ranges from human factors, which examines direct human-machine interaction, to investigations of organizational decisionmaking.
- A few computer scientists, sociologists, historians of science, and experts in other fields, examine the broader questions of the interactions of information technology with society.

As a result of this breadth of subject area, relevant Federal programs of R&D support are distributed among many Government agencies and among many organizational parts of those agencies. The National Science Foundation (NSF), for example, has at least four divisions, each in a different directorate, that support research directly related to computers and communications systems. Another important implication is that manpower programs must be concerned not just with the supply of "core" computer scientists and engineers, but with a much broader base of researchers and users in many disciplines.

Close Boundary Between Theory and Application

Both the rapid pace of commercialization and the intrinsic nature of the technology result in a short time lag between basic research results and commercialization. Because information systems are so flexible and because manufacturers are using powerful new design tools to create new types of computers, less time is required to implement a new concept. It may take only a few months for the results of a basic research project in pure mathematics to be realized in a commercial software package.

This close relationship between basic research and commercial application, possibly most closely paralleled by biotechnology, creates unusual and difficult issues for institutions, such as universities, that are traditionally concerned only with basic research published in the public domain. These issues include publication policies, intellectual property rights, faculty conflicts of interest, competition with the private sector, and research priorities. Federal agencies that fund basic research, such as NSF, also find themselves dealing with these issues more frequently.

Complexity

Modem computer/communications systems are among the most complex technologies ever assembled by human beings. Computers consist of millions of logical subunits. Computer programs can contain millions of instructions. These complex machines, running complex programs, are then interlinked through communications networks. To be able to understand, predict, and control the behavior of these technologies requires a powerful theory of complex processes. No such theory yet exists, although it remains a major goal of computer science.

It is because of this complexity that, even though computers and communication systerns are artificial devices—technologies created and built by human beings-there is basic science devoted to understanding their behavior. This science has a strong experimental component to it. Many computer scientists and engineers need access to large-scale computers. Writing large, complex programs to do unusual tasks is a common research methodology aimed at understanding basic principals underlying the structure of problems and software.

Case Studies

Information technology is a broad subject area. To better understand and describe R&D issues, four specific areas of technology were examined in more detail. These case studies covered both software and hardware and both computer and communications technologies. In addition, all four technologies have raised policy issues in the last few years.

Advanced Computer Architecture

Although computers have increased in sophistication over the years, and individual models differ from one another in detail, the higher level logical design, called the "architecture, " of most commercially available computers is based on concepts that date back a few decades.

New concepts of computer architecture now being explored in the laboratory will underlie two types of innovation: 1) the development of highly specialized, low-cost computer modules that do specific types of tasks at extremely high speeds; and 2) the future generations of supercomputers.

Low-cost specialized computers are designed to perform specific types of computational tasks very efficiently. When hardware is expensive, as computer hardware has been in the past, users usually try to allocate its cost over a variety of applications. Hence, the so-called *general-purpose computer,* which performs a wide variety of computations relatively well, has been and continues to be the mainstay of the computer industry. However, most types of computational tasks have unique characteristics. Since hardware costs have dropped significantly, new market possibilities have appeared for inexpensive special purpose hardware that takes advantage of these characteristics. The general purpose computer system of the future may serve mainly as a routing switch, sending a computing task to the appropriate one of several different specialized processors attached to it.

Supercomputers, the label given to the most powerful machines on the market at any time, have received significant press attention lately. Until recently, U.S. firms have been the only significant marketers of supercomputers. However, Japanese firms have now brought out supercomputers that, by some measures, seem to perform comparably to U.S. machines. In addition, Japan has embarked on two major supercomputer projects. One is designed to develop the next generation of high-speed numerical calculating machines; the other, the Fifth-Generation Computer Project based on artificial intelligence theories, is intended to produce a machine that performs reasoning functions similar to human thinking processes.

The Federal Government is considering several responses to maintain leadership in this technology. For example, the Defense Advanced Research Projects Agency (DARPA) is beginning a "Strategic Computing Program" to develop artificial intelligence capabilities for the needs of the Department of Defense. The National Science Foundation has embarked on a program intended both to increase their support of computer architecture research and to put more supercomputer capability in the hands of scientific users. Both

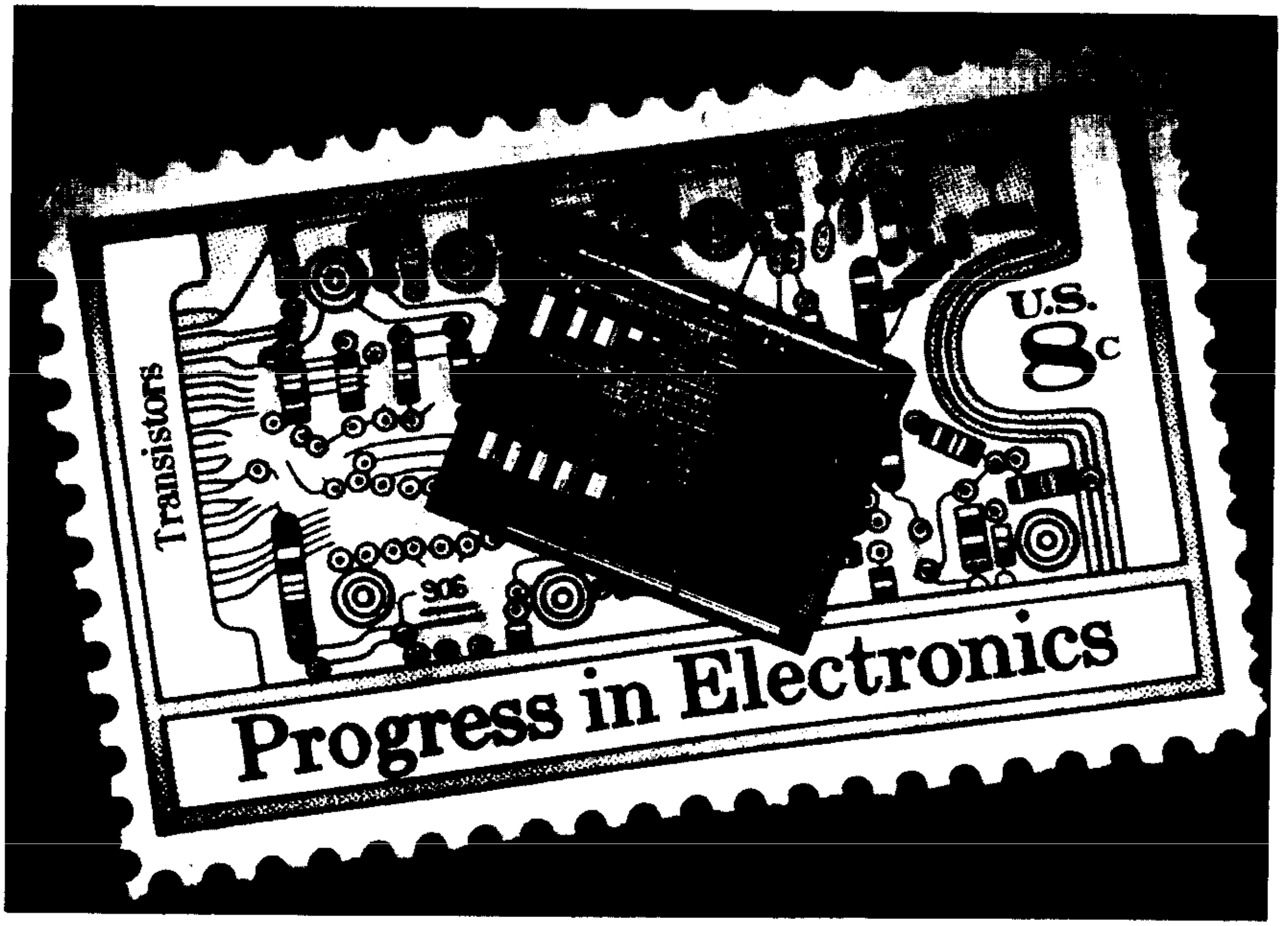

Photo credit: AT&T

A microprocessor on a chip. This chip contains a entire computer, as powerful as some minicomputers

NASA and the Department of Energy have developed similar plans to increase the advanced supercomputing capability available to their researchers.

If they were fully implemented, these Federal plans would constitute an important response to the growing need for access to advanced computing resources. Over the last decade, computing resources available to basic researchers, particularly in universities, have steadily fallen behind the state of the art. Although the U.S. computer industry has traditionally led the market in the supercomputer field, basic researchers in other countries such as West Germany and Japan may have more and easier access to supercomputers from the United States than their counterparts at American universities.

In addition to providing access to supercomputers for agency supported researchers, such Federal procurements would also stimulate the market for the next generation machine, a market that has traditionally been small and, hence, unattractive to computer manufacturers. As the principal user of them, the Federal Government has always had a major influence on the supercomputer market. This Federal stimulus may be particularly important for experimental machines that are based on new architectural concepts. Markets and applications for these machines are particularly unpredictable.

Should Congress decide that additional Federal emphasis on computer design is in the national interest, support of basic research should also be expanded to provide the scientific base for succeeding generations of advanced architecture computers, large and small. Although R&D on the next generation supercomputers and other specialized architectures is underway in a few industrial laboratories, firms participating in this specialized market tend to be small. Longer term basic research is usually left to be performed in academic laboratories and receives little industrial support. Hence, Federal support of basic research can have significant effect.

In the past, responding to funding limitations as well as the complexity of implementing computer hardware in a laboratory, agencies have usually kept basic research in machine architecture at the theoretical, or "paper and pencil" stage. This restriction has not allowed new concepts to be tested as hardware. To allow such testing, some of these conceptual level basic research projects need to be funded at a level that allows them to be carried to experimental and even prototype stages. Microelectronics allows such hardware experimentation to be done more easily and cheaply than in the past, because prototypes can now be assembled from chips that form large logical modules containing thousands of functions.

Software has also been and continues to be a major problem area. Taking full advantage of a supercomputer's speed and power requires the design of specialized programs. Significantly more research needs to be done on numerical computational techniques and programming theory for new computer architectures.

Software Engineering

The computer industry has transformed over the few decades of its existence from being hardware dominant to being software dominant. In the early years, hardware was the most expensive component of a computer system. Software was often given away free by computer manufacturers, and the costs of developing custom programs were much less than the costs of purchasing and maintaining the machines. The situation is now reversed. In most cases, costs of developing and maintaining software are now the dominant costs of creating and operating large computer applications. Although developments in microelectronics have steadily and rapidly reduced the cost and increased the performance of computer hardware, improvements in the productivity of programmers has come much more slowly.

Since the limits of cost, reliability, and time required to create new applications are increasingly dictated by software instead of hardware considerations, research directed toward improving the productivity of programmers and designers will have high leverage. "Software engineering" is the term used to describe this area of research.

Research in software engineering ranges widely in content and approach. At one extreme is highly theoretical work directed at de veloping a fundamental understanding of the nature of programs and "proving" in some mathematical sense that they act as intended. At the other end of the spectrum are behavioral and management scientists concerned with understanding how people interact with computer systems and how to manage programming projects. Not all research related to understanding programming and program behavior is called "software engineering"; many fields of computer science and *engineering* contribute.

The Department of Defense, faced with an annual software expense estimated at $4-$8 billion, supports a large effort in software engineering. DOD has funded the design of a new programming language, *ADA*, and a "programming environment" called *STARS* that provides a set of automated tools for use by the program designer. These tools are intended to be standards, required to be used in the development of DOD software.

Because the economic stakes are so high, researchers at industry centers such as the Bell

Laboratories and IBM's T. J. Watson Research Laboratories have also been active in software engineering research. University researchers in software engineering, supported by Federal agencies, have concentrated on understanding better the theoretical underpinnings of computer programs.

Other countries have also recognized the importance of software engineering. It has been made an explicit part of the British information technology research program. The Japanese, realizing that software has been a major weakness in their attempts to be competitive in the worldwide computer market, are experimenting with what they call "software factories. " The French have always had strength in the area of programming, particularly the theory of programming languages. The Department of Defense language, ADA, was developed in a French laboratory.

Although the potential benefits to the Nation of advances in software engineering are high, the implications for Federal support are less clear. Some experts arguing that lack of fundamental research is not the key bottleneck, point to the failure of designers to apply existing basic theories and research methodologies to the development of large-scale systems. To do so would require closer industry-university researcher interaction and might be helped by the establishment of some large laboratory facilities to study design problems on a realistic scale.

Other experts, pointing out that we still lack the fundamental theoretical breakthrough necessary to develop a true discipline of software engineering, argue that the problems will persist until such a theory is established. Expanded long-term Federal support of a broad range of fundamental research on software is necessary to develop a sound theoretical basis to programming.

Fiber Optics

The last decade has seen the rapid development of a new communications medium, information transmitted by pulses of laser light through thin glass fibers. These optical fibers can transmit far more information than can copper wires or coaxial cables of the same size. Since information is transmitted as light, fiber optics are resistant to both electrical interference and eavesdropping. The potential capacity and economy of optical fiber is such that it not only will help keep communications costs down, but, over the long term, it will relieve the growing congestion of the radio spectrum and may ease some of the demands for satellite communications.

Optical fiber is already used for communication lines between some major cities in the United States, and a transatlantic cable using optical transmission will be laid in the late 1980s. By the end of the 1980s optical fiber will be used heavily in nearly every stage of the telecommunication systems, from local intraoffice networks to long-distance lines.

Although European firms are also developing capability in fiber optics, the principal foreign competition has been from the Japanese, whose technology is roughly at a par with that available from U.S. firms. Since a large world market for fiber optical hardware is growing, innovation in this technology is critical to U.S. competitiveness in telecommunications.

The technology of the fibers, themselves, is still advancing rapidly along three general lines: 1) techniques to increase the information capacity of the fibers; 2) improvements to the transparency of the glass, which allow longer distances between "repeaters," devices that detect the signals and retransmit them on down the line; and 3) improved process technologies for manufacturing fibers. Hence, even though fiber optics is now in the commercial marketplace, the need for basic research continues and the current state-of-the-art is a long way from any fundamental limits to this technology.

Applied research and development on fiber optics, because it is expensive and capital-intensive, is concentrated in a few large laboratories; and, since the economic reward for technological advance is clear, it is done primarily by industry. However, long-term development of fiber optics will depend on funda-

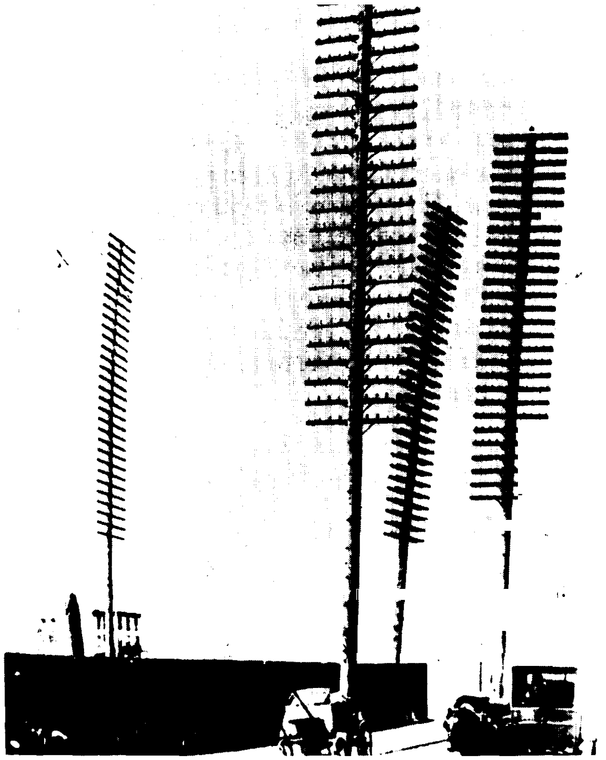

Photo credit: AT& T

Telephone lines circa 1887. Fiber optics is only the most recent of many technological developments that have increased the capacity and shrunk the physical size of communication lines

mental research in materials and solid-state electronics. Increased Federal funding of research in universities would achieve the dual objectives of stimulating fundamental research and training people at the Ph.D. level in fiber optics technology. A current lack of trained research personnel has been pointed out to be a handicap to progress in this field.

Artificial Intelligence

"Artificial Intelligence (AI)" is a term that has historically been applied to a wide variety of research areas that, roughly speaking, are concerned with extending the ability of the computer to do tasks that resemble those performed by human beings. These capabilities include the ability to recognize and translate human speech, to prove the truth of mathematical statements, and to win at chess.

For two reasons public attention has recently focused on an area of AI called *expert systems*. First, expert systems are seen to be the first significant commercialization of 25 years of research in artificial intelligence; and, secondly, they form the basis of the Japanese Fifth Generation Computer Project.

An expert system is an "intelligent" computer information retrieval system designed for use in a specific decisionmaking task, say medical diagnosis. It stores not only data, itself, but the rules of inference that describe how an expert uses the data to make decisions. By asking questions and suggesting courses of action, the expert system interacts with a decisionmaker to help solve a problem. AI researchers now understand this process well enough to be able to build profitable commercial systems for applications in very narrow areas of specialization, for example, advising on repair of telephone cable or diagnosing pulmonary disease.

Although few computer scientists doubt that sometime in the next century, people will interact with computers differently than they do now and that computers will show behavior that we would now call "intelligent," they differ over the nearer term significance of expert systems. Some maintain that expert systems represent an interesting and profitable, yet small, application area. In their view, AI continues to move slowly and is a long way from realizing the potential predicted for it. Others argue that expert systems are a model of how most computing will be done within a decade; and, hence, that future U.S. leadership in computer science will depend on an aggressive program of research in this field.

The Department of Defense has always been a dominant supporter of AI research, including work on expert systems. It has funded this work by establishing and funding large-scale laboratories at a few academic and nonprofit research centers. Civilian support is limited.

NSF has steadily supported basic research in AI, but has done so at a relatively low funding level, and NASA has funded work supporting applications to autonomous spacecraft. DOD experience suggests that AI research is best performed in large laboratories with access to largc-scale computing facilities and collections of specialized software. Some areas of research will begin to require access to specialized hardware and the facilities to design and build new systems.

This field in particular is experiencing an acute faculty shortage. The new commercial excitement in A/I comes after a long period of relative disinterest by funding agencies. As a result, there are few researchers and research centers working in the field, and competition for limited human resources is sharp. In particular, experienced faculty are being drawn off campus just as demand for newly trained graduates is growing rapidly.

The increased public attention and excitement about the promise of AI holds some dangers to the field. If Federal and private support is contingent on high expectations for significant short-term advances, failure to meet those expectations could result in an abrupt withdrawal of funding. Yet AI is a very difficult field of research, just in its infancy. Much basic science remains to be learned in AI, and steady long-term support is required for that learning.

Issues and Strategies

The level and nature of R&Din all fields, including information technology, is influenced by many social, economic, and political factors beyond those specifically related to science and technology. For example, the overall cost of capital and the general health of the national economy will affect management's ability and incentives to invest in R&D. Trade and export policies that affect the access of domestic firms to foreign markets or vice versa will influence the willingness of U.S. firms to invest in innovation.

Some observers have suggested that senior corporate managers in many firms have downplayed investment in R&D, which promises risky and long-term payoffs, in favor of short-term gains. According to this view, although these managers may have been reacting rationally in terms of immediate economic incentives and the desires of stockholders, the result of their decisions has been a low rate of innovation and a long-term loss of competitiveness.

Although these broad factors set an overall environment for R&D decisions, Congress also deals with several specific policy issues that directly relate to science and technology. In this study, OTA concentrated on those direct issues, particularly as they relate to information technology.

Impacts of Telecommunications Deregulation

During the last few years, the fundamental structure of the telecommunications industry has changed. AT&T has been subdivided into several smaller (although still very large) independent firms. Many telecommunication products and services traditionally provided by regulated monopolies are now provided through a competitive marketplace. Improved innovation and international competitiveness in the telecommunications industry is one of the benefits intended by proponents of deregulation, and OTA expects such increased innovation will occur over the next decade. The open question is whether that burst of innovation will be at the expense of basic research that would lay the foundation for future innovation.

However, although technological development should increase, many science policy experts have worried about the impact of deregulation on basic research. In particular, they view Bell Laboratories as a national scientific resource and have expressed concern that a new, competitive AT&T will have decreased

Photo credit: AT&T

Alexander Graham Bell opening the first telephone line to Chicago commitment to the basic research that has traditionally marked at least part of the Laboratories' activities.

OTA found that, although laboratory management will be admittedly more interested in the contribution of research programs to AT&T business, short-term effects on basic research will likely be small. In the first place, most large firms in historically competitive information technology areas, such as computers, have a history of supporting long-term research. Furthermore, AT&T senior management has a strong appreciation for the contribution that research at the Laboratories has made to the growth of the telephone system. They are unlikely to make a sudden shift in policy in the foreseeable future. Finally, most of the areas in which AT&T Bell Laboratories has particular scientific strength are those that, although fundamental, are clearly related to information technology-e. g., solid-state physics and computer science. Since the line between basic and applied research in these fields tends to be particularly hazy, fundamental work is likely to continue to be supported even were management to adopt a short time horizon for results.

Long-term prospects for basic research at. AT&T Bell Laboratories will depend, in part, on AT&T's success as a competitor in the computer and telecommunications industry. This long-term success will depend on many factors including the regulatory environment, the economic climate, the skill of AT&T management in operating under new rules, and the contributions made by the Laboratories to innovation.

The divestiture has also introduced a new and potentially important organization, Bell Communication Research (Bellcore), to the information technology R&D arena. Bellcore serves the seven Bell operating companies, which hold it jointly. It commands the resources of a significant number of researchers from the pre-divestiture Bell Laboratories. Bellcore's relationships with the operating companies and its research activities are in the genesis stage at present; thus, some time will be required to determine its overall contribution to the national R&D effort.

At the same time, the former Bell Laboratories was a major performer of information technology research in the United States, and the divestiture in the telecommunications industry is a structural and regulatory change unprecedented in scale. The impact of this change on industrywide research including that done at AT&T Bell Laboratories and Bellcore should be closely monitored by Congress.

Scientific and Technological Manpower

The Federal Government has historically assumed a role in stimulating the production of technical manpower in areas of national interest. Policy has focused on increasing both the quantity and quality of technical graduates, but it has also played an important role in equity. Federal scholarship and fellowship programs are vital mechanisms to eliminate financial barriers to entry into technological careers.

Information technology is a fast-growing field of national importance, and Federal policies for developing R&D manpower in information technology may be deemed warranted by Congress. However, those policies should be broadly focused rather than aimed at narrow fields of specialization, and they should be consistent and steady over the long term.

Any policy designed to increase technical manpower will not take full effect for several years. The delays are inherent in the education system. They represent both the time it takes educational institutions to respond by developing new instructional programs and hiring staff, and the time it takes for a student to pass through the system. Hence, these policies should be directed, not to short-term, but to long-term needs. If addressed to current shortages, Federal programs run the risk of overproduction by the time they take effect, for needs may have changed or labor market forces such as high wages may have already encouraged adequate new entrants in the field.

Detailed long-term needs for technical manpower are hard to assess in a field changing as rapidly as information technology. Hence, projections of future requirements differ significantly from one to another. They do not account well for the appearance of new fields of specialization, such as the recent emerging area of fiber optics, nor the sudden growth in importance of older fields of research such as artificial intelligence. Thus, policies that deal broadly with science and engineering manpower in all fields are most likely to be successful.

OTA found that, although some shortages exist in specific fields, the long-term outlook is promising. Enrollments at university programs, both at the undergraduate and graduate level have been increasing rapidly, and educators from some institutions have expressed concern that in a few years there may be an overabundance of computer scientists and engineers, at least at the bachelor's degree level. Similarly, as competition for admission to undergraduate and graduate programs grows, so should the quality of the graduates.

Science education policy also addresses equity issues. Undergraduate and graduate technological education is increasingly expensive. Access barriers to high-paying careers in information technology could become formidable for some parts of society, due both to cost and poor preparation at the precollege level. To help offset these barriers, Federal policy may need to address scholarships, fellowships, traineeships, and other forms of direct assistance to students, as well as the improvement of precollege science education.

Changing Roles of Universities

The United States has traditionally looked to its university system whenever national needs called for improved technological innovation and the development of new expertise. This dependence on the education system, probably unparalleled in the world, has often resulted in experiments in institutional structures associated with higher education. The Morrow Act established the land grant colleges to develop a scientific basis for agriculture and to train farmers in modern techniques. During World War II and after, major federally funded research laboratories were established in association with universities. Examples include the Lincoln laboratories at the Massachusetts Institute of Technology, the Lawrence Radiation Laboratory at the University of California, Berkeley, and the Jet Propulsion Laboratory at the California Institute of Technology.

Once again, in response to some of the concerns raised earlier in this chapter, many universities are experimenting with new structures designed with the dual objectives of improving the quality of technical education on campus and improving the flow of research results into industrial innovation. In contrast to many past experiments, these new structures are, by and large, not in response to Federal programs. Rather, many of them respond to initiatives both from industry looking for closer ties with academic programs and from States who see strong academic technical programs as attracting high-technology industry and, thus, serving as stimuli for economic development.

Some potential issues have arisen, but to date problems appear to have been or are being resolved to mutual satisfaction by negotiation between the academic institutions and the industrial sponsors. They include the following:

- How intellectual property rights are distributed among researchers, their institutions, and the industrial sponsors.
- When and under what circumstances research results may be published.
- Who establishes research priorities and standards of scientific quality.

Over the longer term, other issues will also become important, such as the overall influence on the directions of academic basic research. Another long term concern is the potential imbalance of campus resources and attention between science and technology on the one hand and other important scholarly fields such as foreign studies, social science, the arts, or the humanities.

Another question of equity concerns the balance between institutions, themselves. In the first place, are these programs "zero-sum games" in which the gains of a few institutions are mainly at the expense of all the others? Secondly, although the top research institutions have been able to negotiate arrangements that, in their view, do not threaten their other academic roles, less influential schools will have far less bargaining power.

Since many of these institutional experiments are new, it is too early to tell whether they will be successful in meeting their sponsor's expectations or whether the negotiated solutions to the major issues will work. However, it is important that Federal science agencies watch these developments carefully for two reasons:

- Many of these new research institutions will be performers of federally funded research or will be cosponsors of federally funded research.
- Many of the issues under negotiation between universities and industry, such as ownership of intellectual property rights and restrictions on publication are currently echoed as problems in government/university relationships.

Foreign Programs

Programs in other countries designed to promote innovation in information technology have received attention in the United States. These programs have raised both concern about increased competition in technologies in which the United States has traditionally been a world leader, and they have provided models to those who suggest that the United States also needs to develop more coherent programs to foster innovation by domestic industries. Some examples of such programs are the following:

- The Japanese *Fifth Generation Computer Project* is an attempt to move beyond current concepts of computer design to develop an entirely different type of machine based on artificial intelligence concepts.
- The French *La Filiere Electronique Program* is a five-year national information technology R&D program with long-term goals of strengthening the French electronics industry and developing technology for social applications.
- *ESPRIT*, is a pan-European program intended to draw together the technical resources of Europe to focus on R&D in information technology.
- The British *Alvey* program, constituted in part as a British response to the Japanese Fifth Generation Computer Project, is a program of government support for research and development in semiconductors and computer software.

Regardless of assessments of the specific prospects for any one program or its implications for U.S. policy, they demonstrate in total the new competitive world that is developing in information technology. No longer can the United States expect to maintain unquestioned technological leadership and unchallenged domination of world markets in information technology. Other nations now see it in their own interests to build scientific and industrial strength in these areas and are taking steps to do so. U.S. science and technology policy will need to adapt to take this new reality into account.

However, the foreign programs being established do not necessarily constitute useful models for U.S. policies, for several reasons. In the first place, many of them are too new to determine success. Secondly, each is tailored to the unique patterns of government/industry/academic relationships as they exist in country of origin and may not be workable in the country. Finally, many of these programs are designed to address particular bottlenecks to innovation that may exist in the specific country. U.S. science and technology has a different balance of strengths and weaknesses. For example, some countries have a lack of venture capital, others a shortage of scientific manpower, and still others have strong cultural barriers between business and academic institutions that impede technology transfer.

Information technology R&D is, in many respects, an international activity. For example, some domestic firms are owned or partially owned by foreign firms (and vice versa). Many large computer and communications companies are multinationals that operate laboratories in several nations; and many companies have agreements to exchange and cross-license technology with foreign counterparts. Scientists have always viewed basic research as an international activity. Thus, international conferences, scientific journals, and exchange of researchers are common.

Programs designed to strengthen and protect technology as a purely domestic resource need to balance this goal against the natural limitations posed by this international character. For example, the managers of ESPRIT, a program designed to stimulate European technology, must decide whether and on what basis to admit or deny the participation of multinationals based, at least partly, outside of Europe. Companies concerned about what they may view as stringent controls over technology in one country can simply move their R&D efforts to their laboratories in other countries.

Science Policy

Federal programs designed to stimulate information technology R&D exist in the much broader context of Federal science and technology policy.

Congress needs to ask whether existing science and technology policy serves the needs of information technology R&D both in terms of its unique characteristics and the potential importance of the technology to the nation. Similarly, it is important to ask whether policies designed specifically to support information technology R&D are consonant with the broader scope of science and technology policy.

OTA identified three major sets of policy issues that, although applicable to a broad range of science and technology, seem particularly important in the context of information technology.

Institutional Focus.—The Federal Government has traditionally and purposefully supported research and development through several programs administered by different agencies. Despite occasional calls for centralizing R&D support within a single science and technology agency, this historical approach was accepted for two basic reasons. In the first place, agencies with specific technological needs were considered to be best suited to support R&D focused on their needs. Secondly, multiple sources have been considered healthy for the support of science, since diversity and redundancy are both important attributes of scientific research.

The issue of government organization is being reexamined, in the case of information technology. Arguments in favor of a more centralized and/or coordinated approach are based both on the changing nature of R&D and on the challenges posed by new foreign programs stressing R&D in fields such as microelectronics, computer systems, and communications technology.

Research is becoming increasingly expensive. Research equipment such as a microelectronic fabrication facility or a supercomputer can cost several million dollars in capital costs, plus several hundred thousands of dollars a year to maintain and operate. Salaries of research-level technologists are escalating, and much research in information technology now requires large teams of different specialists and technicians. This cost and complexity of R&D not only may make redundancy and duplication of effort a luxury, but may even make some types of research impossible to initiate without coordination of Federal programs.

Some foreign research programs targeted at specific technologies have claimed successes in the sense of capturing a world market-the most notable being the Japanese program for the so-called “64k” computer memory chip for computers that stores about 64,000 characters of information on a microchip. While Japanese success in this market may be attributed to many factors, the existence of a specific government program may have been a major influence. Seeing such programs targeted at selected technologies in Japan and Europe has led some experts to call for the United States to respond with a similar approach to domestic R&D.

Photo credit: NASA

A communication satellite being launched from a space shuttle. Satellite communication technology was stimulated by both Federal military and civilian R&D programs

Such programs, if initiated, would not likely be restricted to information technology alone, but would be focused on a wide range of technologies deemed critical. It would be a significant departure from the past approach that featured multiple government programs of support for basic research, agency-by-agency support of applied research based on mission needs, and, with a few exceptions, private sector support for innovation and product development.

Military and Domestic R&D.–Military funding tends to dominate the Federal R&D budget, particularly in the case of information technology. Such a high level of DOD involvement is not surprising considering the importance of information technology to its mission. The policy issue is whether the high level of defense support provides adequate underpinnings for the broad development of civilian technology or whether a case exists for strong civilian agency support of R&D.

There is no doubt that past DOD and Department of Energy support of R&D in such areas as microelectronics and computer design has been a spur to the entire information technology industry. However, there is evidence that, as the technology becomes more mature, military requirements have begun to diverge from civilian interests. For example, in the area of supercomputers and very high speed integrated circuits, there is a significant doubt that the DOD Strategic Computing and very high speed integrated circuit programs, although responsive to DOD needs, will also serve civilian needs. Hence, there may be a need to boost civilian support in information R&D.

*Influence of International Competitive*ness.—The growing concern over economic issues, in particular, international competitive ness has led to issues in which attempts to treat technology as a national resource that can be held and protected conflict with traditional approaches to science policy.

For example, concern about the international flow of scientific and technical information conflict with the historical science policy goal of establishing international cooperation in science and technology. Open publication of some scientific material has been challenged on the grounds that the information should be restricted to the United States. Some have suggested that the practice of admitting foreign science students, who comprise a significant percentage of degree candidates in information technology, conflicts with U.S. economic interests. Restrictions have been imposed on foreign scholars attempting to attend U.S. conferences and seminars.

Other policies assume that the United States does not need to draw on foreign science. Hence, research project support typically gives little attention to the potential benefits of travel by U.S. scientists to foreign research laboratories and conferences. Unlike the practices of other countries, little support is provided to provide translations and analyses of foreign research papers and monographs. Yet U.S. scientists, in general, do not have facility in some of the significant scientific languages of today, particularly Japanese. Due to the weakening of foreign language requirements in some graduate programs, many U.S. information scientists do not even have facility with traditional scientific languages like French and German.

Summary

During the past decade, information technology has grown to major economic and social importance in the United States and abroad. The desire to maintain a competitive posture in worldwide markets as well as the urge to realize potential social benefits of new computer and communications systems has focused public attention on the process of innovation, in particular, on R&D. OTA has found that, in response to these pressures, the system has been remarkably adaptable. Federal programs are changing rapidly in response to new perceived needs; science and engineering enrollments are increasing in response to an anticipated need for more technological manpower; and universities and industry are changing their traditional patterns of research and relationships. The policy problem will be to monitor and manage this change. In particular, Congress will need to:

- determine and maintain an appropriate level and balance of R&D support for information technology (including research on the social impacts of these technologies),
- remove unintended barriers to government and private sector R&D efforts,
- assure that these changes in the R&D system do not have unintentional side effects on other sectors or goals of the U.S. system of science and technology, and
- assure access by researchers in all disciplines to powerful new computational and data communication technologies.