



Innovation in Information Technology

National Research Council

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Innovation

in INFORMATION TECHNOLOGY

Computer Science and Telecommunications Board

Division on Engineering and Physical Sciences

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Preface

The health of the computer science field and related disciplines has been an enduring concern of the National Research Council's Computer Science and Telecommunications Board (CSTB). From its first reports in the late 1980s, CSTB has examined the nature, conduct, scope, and directions of the research that drives innovation in information technology.

Ironically, the success of the industries that produce information technology (IT) has caused confusion about the roles of government and academia in IT research. And it does not help that research in computer science—especially research relating to software—is hard for many people outside the field to understand. This synthesis report draws on several CSTB reports, published over the course of the past decade, to explain the what and why of IT research. It was developed by members of the board, drawing on CSTB's body of work and on insights and experience from their own careers.

This synthesis is kept brief in order to highlight key points. It is paired with a set of excerpts from previous reports, chosen either for their explanation of relevant history or for their compelling development of core arguments and principles.

David D. Clark, *Chair*
Computer Science and
Telecommunications Board

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Frederick P. Brooks, Jr., University of North Carolina at Chapel Hill,
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Juris Hartmanis, Cornell University,
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Joseph F. Traub, Columbia University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John

Hopcroft, Cornell University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring board and the institution.

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Summary and Recommendations

Progress in information technology (IT) has been remarkable, but the best truly is yet to come: the power of IT as a *human enabler* is just beginning to be realized. Whether the nation builds on this momentum or plateaus prematurely depends on today's decisions about fundamental research in computer science (CS) and the related fields behind IT.

The Computer Science and Telecommunications Board (CSTB) has often been asked to examine how innovation occurs in IT, what the most promising research directions are, and what impacts such innovation might have on society. Consistent themes emerge from CSTB studies, notwithstanding changes in information technology itself, in the IT-producing sector, and in the U.S. university system, a key player in IT research.

In this synthesis report, based largely on the eight CSTB reports enumerated below, CSTB highlights these themes and updates some of the data that support them. Much of the material is drawn from (1) the 1999 CSTB report *Funding a Revolution: Government Support for Computing Research*,¹ written by both professional historians and computer scientists to ensure its objectivity, and (2) *Making IT Better: Expanding Information Tech-*

¹Computer Science and Telecommunications Board, National Research Council. 1999. *Funding a Revolution: Government Support for Computing Research*. National Academy Press, Washington, D.C.

nology Research to Meet Society's Needs,² the 2000 CSTB report that focuses on long-term goals for maintaining the vitality of IT research. Many of the themes achieved prominence in (3) the 1995 CSTB report *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*,³ known informally as the Brooks-Sutherland report. Other reports contributing to this synthesis include (4) *Computing the Future: A Broader Agenda for Computer Science and Engineering* (1992),⁴ (5) *Building a Workforce for the Information Economy* (2001),⁵ (6) *Academic Careers in Experimental Computer Science and Engineering* (1994),⁶ (7) *Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers* (2001),⁷ and (8) *More Than Screen Deep: Toward Every-Citizen Interfaces to the Nation's Information Infrastructure* (1997).⁸ In the text that follows, these reports are cited by number as listed, for easy reference, in Box 1.

Here are the most important themes from CSTB's studies of innovation in IT:

- *The results of research*
 - America's international leadership in IT—leadership that is vital to the nation—springs from a deep tradition of research (1,3,4).
 - The unanticipated results of research are often as important as the anticipated results—for example, electronic mail and instant messaging were by-products of research in the 1960s that was aimed at making it

²Computer Science and Telecommunications Board, National Research Council. 2000. *Making IT Better: Expanding Information Technology Research to Meet Society's Needs*. National Academy Press, Washington, D.C.

³Computer Science and Telecommunications Board, National Research Council. 1995. *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*. National Academy Press, Washington, D.C.

⁴Computer Science and Telecommunications Board, National Research Council. 1992. *Computing the Future: A Broader Agenda for Computer Science and Engineering*. National Academy Press, Washington, D.C.

⁵Computer Science and Telecommunications Board, National Research Council. 2001. *Building a Workforce for the Information Economy*. National Academy Press, Washington, D.C.

⁶Computer Science and Telecommunications Board., National Research Council. 1994. *Academic Careers in Experimental Computer Science and Engineering*. National Academy Press, Washington, D.C.

⁷Computer Science and Telecommunications Board, National Research Council. 2001. *Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers*. National Academy Press, Washington, D.C.

⁸Computer Science and Telecommunications Board, National Research Council. 1997. *More Than Screen Deep: Toward Every-Citizen Interfaces to the Nation's Information Infrastructure*. National Academy Press, Washington, D.C.

BOX 1
Reference Numbers for Key CSTB Titles Cited in This Report

<i>Reference Number</i>	<i>Title</i>
(1)	<i>Funding a Revolution: Government Support for Computing Research (1999)</i>
(2)	<i>Making IT Better: Expanding Information Technology Research to Meet Society's Needs (2000)</i>
(3)	<i>Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure (1995)</i>
(4)	<i>Computing the Future: A Broader Agenda for Computer Science and Engineering (1992)</i>
(5)	<i>Building a Workforce for the Information Economy (2001)</i>
(6)	<i>Academic Careers in Experimental Computer Science and Engineering (1994)</i>
(7)	<i>Embedded, Everywhere: A Research Agenda for Networked Systems of Embedded Computers (2001)</i>
(8)	<i>More Than Screen Deep: Toward Every-Citizen Interfaces to the Nation's Information Infrastructure (1997)</i>

NOTE: Complete citations for these reports appear in footnotes 1 through 8 in this "Summary and Recommendations" section.

possible to share expensive computing resources among multiple simultaneous interactive users (1,3).

- The interaction of research ideas multiplies their impact—for example, concurrent research programs targeted at integrated circuit design, computer graphics, networking, and workstation-based computing strongly reinforced and amplified one another (1-4).

- *Research as a partnership*

- The success of the IT research enterprise reflects a complex partnership among government, industry, and universities (1-8).

- The federal government has had and will continue to have an essential role in sponsoring fundamental research in IT—largely university-based—because it does what industry does not and cannot do (1-8). Industrial and governmental investments in research reflect different

motivations, resulting in differences in style, focus, and time horizon (1-3,7,8).

- Companies have little incentive to invest significantly in activities whose benefits will spread quickly to their rivals (1,3,7). Fundamental research often falls into this category. By contrast, the vast majority of corporate research and development (R&D) addresses product and process development (1,2,4).

- Government funding for research has leveraged the effective decision making of visionary program managers and program office directors from the research community, empowering them to take risks in designing programs and selecting grantees (1,3). Government sponsorship of research especially in universities also helps to develop the IT talent used by industry, universities, and other parts of the economy (1-5).

- *The economic payoff of research*

- Past returns on federal investments in IT research have been extraordinary for both U.S. society and the U.S. economy (1,3). The transformative effects of IT grow as innovations build on one another and as user know-how compounds. Priming that pump for tomorrow is today's challenge.

- When companies create products using the ideas and workforce that result from federally sponsored research, they repay the nation in jobs, tax revenues, productivity increases, and world leadership (1,3,5).

The themes highlighted above underlie two recurring and overarching recommendations evident in the eight CSTB reports cited:

Recommendation 1 The federal government should continue to boost funding levels for fundamental information technology research, commensurate with the growing scope of research challenges (2-4,6-8). It should ensure that the major funding agencies, especially the National Science Foundation and the Defense Advanced Research Projects Agency, have strong and sustained programs for computing and communications research that are broad in scope and independent of any special initiatives that might divert resources from broadly based basic research (2,3).

Recommendation 2 The government should continue to maintain the special qualities of federal IT research support, ensuring that it complements industrial research and development in emphasis, duration, and scale (1-4,6).

This report addresses the ways that past successes can guide federal funding policy to sustain the IT revolution and its contributions to other fields.

1

Innovation in Information Technology

UNIVERSITIES, INDUSTRY, AND GOVERNMENT: A COMPLEX PARTNERSHIP YIELDING INNOVATION AND LEADERSHIP

Figure 1 illustrates some of the many cases in which fundamental research in IT, conducted in industry and universities, led 10 to 15 years later to the introduction of entirely new product categories that became billion-dollar industries. It also illustrates the complex interplay between industry, universities, and government. The flow of ideas and people—the interaction between university research, industry research, and product development—is amply evident.

Figure 1 updates Figure 4.1 from the 2002 CSTB report *Information Technology Research, Innovation, and E-Government*.¹ The originally published figure² produced an extraordinary response: it was used in presentations to Congress and to administration decision makers, and it was

¹Computer Science and Telecommunications Board, National Research Council. 2002. *Information Technology Research, Innovation, and E-Government*. National Academy Press, Washington, D.C.

²Known informally as the “tire-tracks chart” because of its appearance, the figure was first published in *Evolving the High Performance Computing and Communications Initiative to Support the Nation’s Information Infrastructure* (3; p. 2).

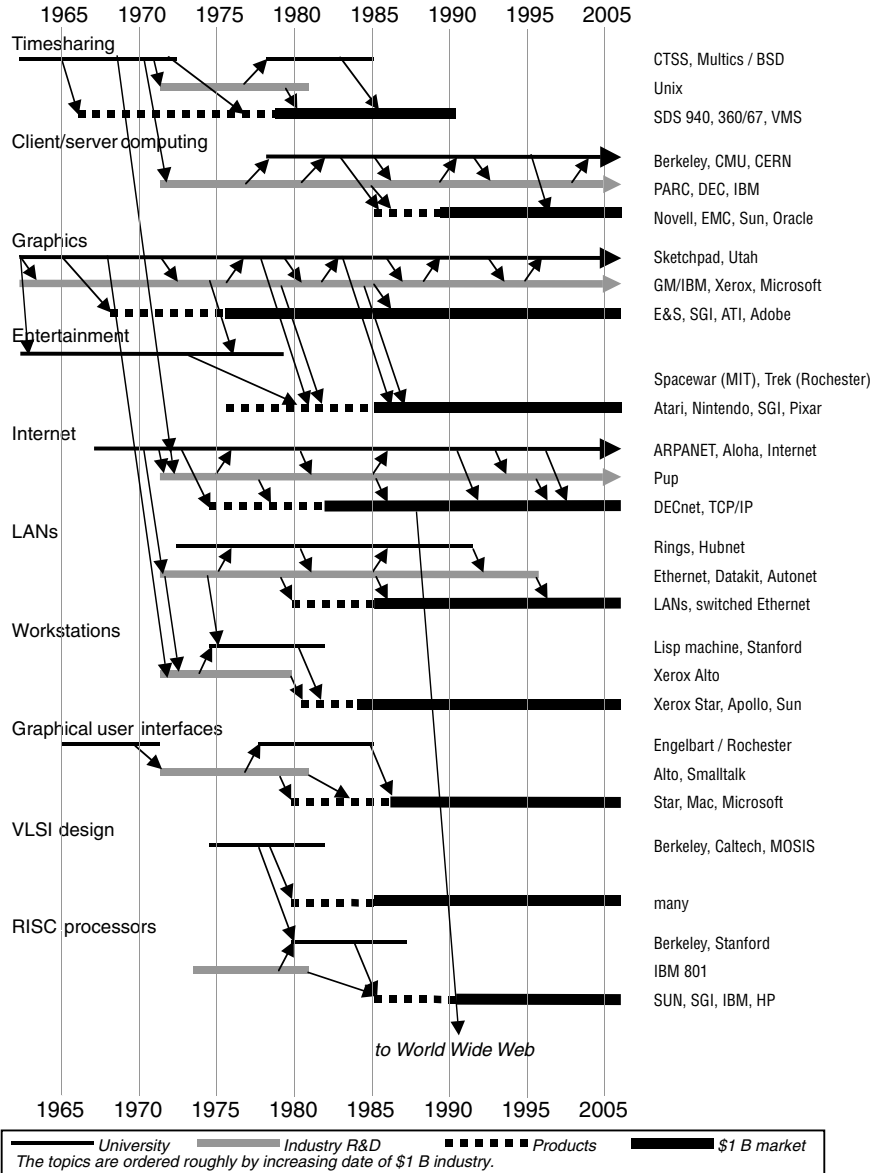
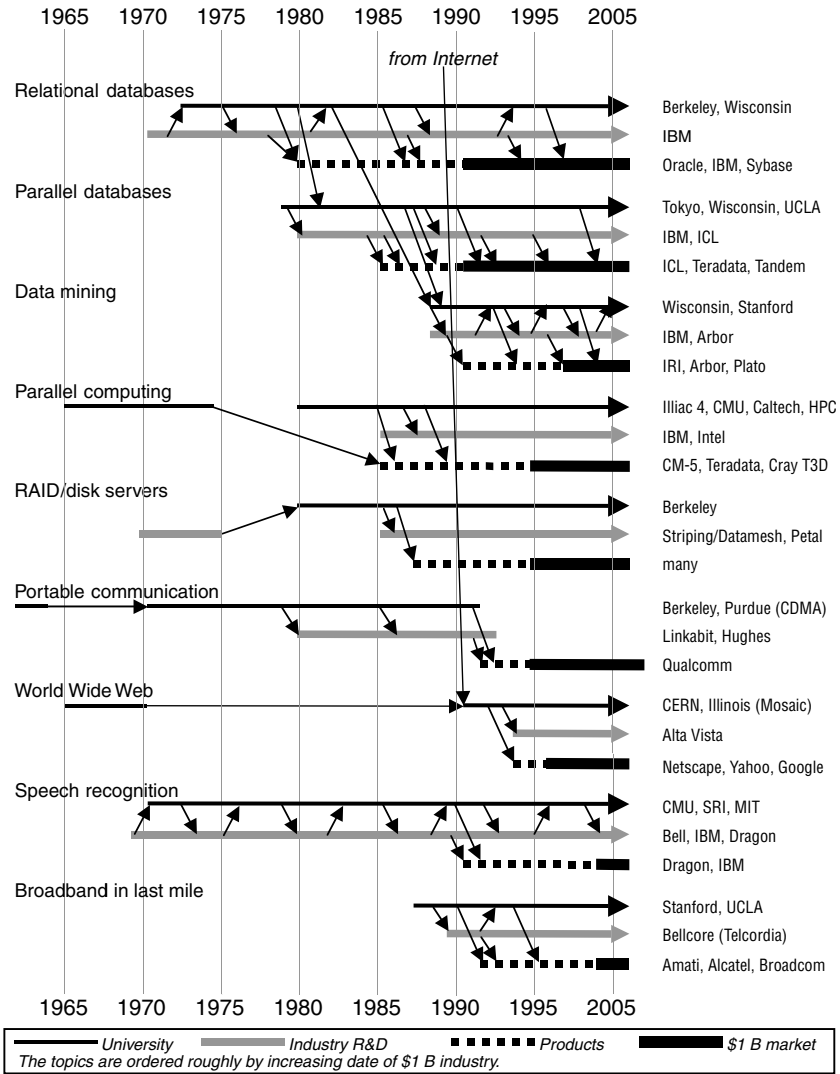


FIGURE 1 Examples of government-sponsored IT research and development in the creation of commercial products and industries. Federally sponsored research lies at the heart of many of today’s multibillion-dollar information technology industries—industries that are transforming our lives and driving our economy. Ideas and people flow in complex patterns. The interaction of research ideas



multiplies their effect. The result is that the United States is the world leader in this critical arena. Although the figure reflects input from many individuals at multiple points in time, ensuring readability required making judgments about the examples to present, which should be seen as illustrative rather than exhaustive. SOURCE: 2002 update by the Computer Science and Telecommunications Board of a figure (Figure ES.1) originally published in Computer Science and Telecommunications Board, National Research Council, 1995, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*, National Academy Press, Washington, D.C.

discussed broadly in the research community. Although IT commercial success leads some policy makers to assume that industry is self-sufficient, the tire-tracks chart underscores how much industry builds on government-funded university research, sometimes through long incubation periods (1,3).

Figure 1 also illustrates—although sketchily—the interdependencies of research advances in various subfields. There is a complex research ecology at work, in which concurrent advances in multiple subfields—in particular within computer science but extending into other fields, too, from electrical engineering to psychology—are mutually reinforcing: they stimulate and enable one another.³

One of the most important messages of Figure 1 is the long, unpredictable incubation period—requiring steady work and funding—between initial exploration and commercial deployment (1,3). Starting a project that requires considerable time often seems risky, but the payoff from successes justifies backing researchers who have vision. It is often not clear which aspect of an early-stage research project will be the most important; fundamental research produces a range of ideas, and later developers select from among them as needs emerge. Sometimes the utility of ideas is evident well after they have been generated. For example, some early work in artificial intelligence has achieved unanticipated applicability in computer games, some of which are now being investigated for decision support and other professional uses as well as recreation.

It is important to remember that real-world requirements can change quickly. Although the end of the Cold War was interpreted by some as lessening the need for research,⁴ September 11, 2001, underscored research needs in several areas: system security and robustness, automatic natural language translation, data integration, image processing, and biosensors, among others—areas in which technical problems are difficult to begin with, and may become harder when technology must be designed to both meet homeland security needs and protect civil liber-

³The idea that research in IT not only builds in part on research in physics, mathematics, electrical engineering, psychology, and other fields but also strongly influences them is consistent with what Donald Stokes has characterized in his four-part taxonomy as “Pasteur’s Quadrant” research: use- or application-inspired basic research that pursues fundamental understanding (such as Louis Pasteur’s research on the biological bases of fermentation and disease). See the discussion on pp. 26-29 in the 2000 CSTB report *Making IT Better* (2), and see Donald E. Stokes, 1997, *Pasteur’s Quadrant: Basic Science and Technological Innovation*, Brookings Institution Press, Washington, D.C.

⁴Linda R. Cohen and Roger G. Noll. 1994. “Privatizing Public Research,” *Scientific American* 271(3): 72-77.

ties.⁵ Without fundamental research, the cupboard is bare when there is a sudden need for ideas to reduce to practice.

THE ESSENTIAL ROLE OF THE FEDERAL GOVERNMENT

Federally sponsored research played a critical role in creating the enabling technologies for each of the billion-dollar market segments illustrated in Figure 1—and for many others as well. The government role coevolved with IT industries: its organization and emphases changed to focus on capabilities not ready for commercialization and on new needs that emerged as commercial capabilities grew, both moving targets (1). As this coevolution shows, successful technology development relies on flexibility in the conduct of research and in the structure of industry.

Most often, this federal investment took the form of grants or contracts awarded to university researchers by the Defense Advanced Research Projects Agency (DARPA) and/or the National Science Foundation (NSF)—although a shifting mix of other funding agencies has been involved, reflecting changes in the missions of these agencies and their needs for IT (1,3). For example, the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and the military services have supported high-performance computing, networking, human-computer interaction, and other kinds of research.⁶

Why has federal support been so effective in stimulating innovation in computing? As discussed below, many factors have been important.

1. *Federally funded programs have supported long-term research into fundamental aspects of computing, whose widespread practical benefits typically take years to realize (1).*

“Long-term” research refers to a long time horizon for the research effort and for its impact to be realized. Examples of innovations that required long-term research include speech recognition, packet radio, computer graphics, and internetworking. In every case illustrated in Figure 1, the time from first concept to successful market is measured in

⁵See Computer Science and Telecommunications Board, National Research Council. 2003. *Information Technology for Counterterrorism: Immediate Actions and Future Possibilities*. National Academies Press, Washington, D.C.

⁶In addition to research funding, complementary activities have been undertaken by other agencies, such as the National Institute of Standards and Technology, which often brings together people from universities and industry on issues relating to standards setting and measurement.

decades (see Box 2)—a contrast to the more incremental innovations that are publicized as evidence of the rapid pace of IT innovation.

Work on speech recognition, for example, which began in earnest in the early 1970s, took until 1997 to generate a successful product for enabling personal computers to recognize continuous speech (8). Work on packet radio also dates from the 1970s, and its realization in commercial ad hoc mobile networking also began in the late 1990s.⁷ Fundamental algorithms for shading three-dimensional graphics images, which were developed with federal funding in the 1960s, saw limited use on high-performance machines until they entered consumer products in the 1990s; today these algorithms are used in a range of products in the health care, entertainment, and defense industries. The research programs behind these innovations not only were long-term but also were broad enough to accommodate within a single program the development of those unanticipated results that have in many cases provided the most significant outcomes of a project.

The benefits of a long time horizon, combined with program breadth, extend to today's challenges. This point was emphasized in CSTB's 1997 report on usability, *More Than Screen Deep* (8), which explained (at p. 192):

Federal initiatives that emphasize long-term goals beyond the horizon of most commercial efforts and that may thus entail added risk have the potential to move the whole information technology enterprise into new modes of thinking and to stimulate discovery of new technologies for the coming century.

Because of unanticipated results and synergies, the exact course of fundamental research cannot be planned in advance, and its progress cannot be measured precisely in the short term. Even projects that appear to have failed or whose results do not seem to have immediate utility often make significant contributions to later technology development or achieve other objectives not originally envisioned. A striking example is the field of number theory (1): for hundreds of years a branch of pure mathematics without applications, it is now the basis for the public-key cryptography that underlies the security of electronic commerce.

⁷Similarly, commercial developments in broadband cellular radio (which has become essentially wireless Internet access in third-generation wireless) are built in part on many decades of federally supported research into Code Division Multiple Access technology, signal processing for antenna arrays, error-correction coding, and so on.

BOX 2 The Role of Federal Support for Fundamental Research in IT

CSTB's 1995 report *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure* (3) examined the payoff from several decades of federal investment in IT research. Among the conclusions of that report are these:

- *Research has kept paying off over a long period.*
- *The payoff from research takes time.* As Figure [1] shows, at least 10 years, more often 15, elapse between initial research on a major new idea and commercial success. This is still true in spite of today's shorter product cycles.
 - *Unexpected results are often the most important.* Electronic mail and the "windows" interface are only two examples. . . .
 - *Research stimulates communication and interaction.* Ideas flow back and forth between research programs and development efforts and between academia and industry [and between research programs with different foci that are proceeding concurrently].
 - *Research trains people,* who start companies or form a pool of trained personnel that existing companies can draw on to enter new markets quickly.
 - *Doing research involves taking risks.* Not all public research programs have succeeded or led to clear outcomes even after many years. But the record of accomplishments suggests that government investment in computing and communications research has been highly productive.¹

¹Computer Science and Telecommunications Board, National Research Council. 1995. *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*. National Academy Press, Washington, D.C., pp. 3-4.

2. *The interplay of government-funded and industry research has been an important factor in IT commercialization (1-8).*

The examples in Figure 1 show the interplay between government-funded research and industry research and development. In some cases, such as reduced-instruction-set computing (RISC) processors, the initial ideas came from industry, but the research that was essential to advancing these ideas came from government funding to universities. RISC was conceived at IBM, but it was not commercialized until DARPA funded additional research at the University of California at Berkeley and at Stanford University as part of its Very Large Scale Integrated Circuit (VLSI) program of the late 1970s and early 1980s (1,3). The VLSI program also supported university research that gave rise to such companies as Synopsys, Cadence, and Mentor, which have acquired dozens of smaller

companies that started as spinoffs of DARPA-funded⁸ university research; such research has also pushed the proverbial envelope in algorithms and user interfaces. The more than \$3 billion electronic design automation industry is an essential enabler to other parts of IT.

Similarly, IBM pioneered the concept of relational databases (its System R project) but did not commercialize the technology. NSF-sponsored research at the University of California at Berkeley brought this technology to the point at which it was commercialized by several start-up companies and then by more established database companies (including IBM) (1,3). In other cases, such as timesharing, the initial ideas came from the university community, and subsequent industry research, while significant for a time, was not sustained. In none of the examples in Figure 1 did industry alone provide the necessary research.

3. There is a complex interleaving of fundamental research and focused development (1-3).

In the case of integrated circuit (VLSI) design tools, research innovation led to products and then to major industrial markets. A still-unfolding example is the theoretical research that yielded the algorithms behind the Web-content management technology underlying Akamai. In the case of relational databases, the introduction of products stimulated new fundamental research questions, leading to a new generation of products with capabilities vastly greater than those of their predecessors. The purpose of publicly funded research is to advance knowledge and to solve hard problems. The exploitation of that knowledge and those solutions in products is fundamentally important, but the form it takes is often unpredictable, as is the impact on future research (see Box 3).

4. Federal support for research has tended to complement, rather than preempt, industry investments in research.

The IT sector invests an enormous amount each year in R&D. It is critical to understand, however, that the vast majority of corporate R&D has always been focused on product and process development (2). This is what shareholders (or other investors) demand. It is harder for corporations to justify funding long-term, fundamental research. Economists

⁸In some cases, the Semiconductor Research Corporation provided the funding. For additional information, see the Web site <<http://www.src.org/member/about/history.asp>>. Accessed June 2, 2003.

BOX 3 The Technological Underpinnings of Electronic Commerce

Electronic commerce is becoming pervasive. It is changing many aspects of our lives, from the way we shop to the way we obtain government services.

The organizations and individuals that exploit electronic commerce employ commercial tools from companies such as Microsoft and Oracle. They may not think of themselves as the beneficiaries of federal investments in university-based IT research—but they are. Nearly every key technological component underlying electronic commerce has been shaped by this investment. For example:

- *The Internet*—Defense Advanced Research Projects Agency (DARPA) investments in the 1960s and 1970s were followed by National Science Foundation (NSF) investments in the 1980s and early 1990s, with research (supported by multiple agencies) continuing to this day (1).
- *Web browsers*—Mosaic, the first browser with a graphical user interface, was invented at the NSF-supported National Center for Supercomputer Applications at the University of Illinois (1).
- *Public-key cryptography for secure credit card transactions*—NSF sponsored university-based research in the 1970s that supported this innovation (1).
- *Back-end database and transaction processing systems*—NSF and DARPA supported key research on relational databases and transaction processing systems at the University of California at Berkeley, University of Wisconsin, and elsewhere, beginning in the early 1980s and continuing to this day (1).
- *Search engines*—Search engines grew out of federally supported university research programs, such as the ranking algorithm work at Stanford University that contributed to Google; the WebCrawler and MetaCrawler grew out of work at the University of Washington.

But the development is not complete: a range of technical challenges still exist, along with challenges for improving the fit between the technologies and the behavior and needs of the people who use them (2,8).

SOURCES: Pieces of this history are recounted in the previously cited CSTB reports (1-8) and in CSTB's series of reports on the Internet: *Toward a National Research Network* (1988), *Realizing the Information Future: The Internet and Beyond* (1990), *The Unpredictable Certainty: Information Infrastructure Through 2000* (1996), *The Internet's Coming of Age* (2001), and *Broadband: Bringing Home the Bits* (2002), all published by the National Academy Press, Washington, D.C.

have articulated the concept of “appropriability” to express the extent to which the results of an investment can be captured by the investor, as opposed to being available to all players in the market. The results of long-term, fundamental research are hard to appropriate for several reasons: they tend to be published openly and thus to become generally known; they tend to have broad value; the most important may be unpre-

dictable in advance; and they become known well ahead of the moment of realization as a product, so that many parties have the opportunity to incorporate the results into their thinking. In contrast, incremental research and product development can be performed in a way that is more appropriate: it can be done under wraps, and it can be moved into the marketplace more quickly and predictably.

Although individual industrial players may find it hard to justify research that is weakly appropriable, it is the proper role of the federal government to support this sort of endeavor (1,3). When companies create successful new products using the ideas and workforce that result from federally sponsored research, they repay the nation handsomely in jobs, tax revenues, productivity increases, and world leadership (1,3). Long-term research often has great benefits for the IT sector as a whole, although no particular company can be sure of reaping most of these benefits.

Appropriability helps to explain why the companies that have tended to provide the greatest support for fundamental research are large companies that enjoy dominant positions in their market (1). AT&T and IBM, for example, have historically made significant investments in fundamental research. Anything that advances IT as a whole benefits the dominant players—they may be capable of reaping a significant proportion of the returns on their research investments. As IT industries became more competitive, however, even these firms began to link their research more closely with corporate objectives and product development activities.⁹ One of them (AT&T) has radically cut back its research effort. This process began with a government proceeding that resulted in the splitting up of functions formerly aggregated under “Ma Bell” and continued with the growth and contraction of a set of industry research and development endeavors (AT&T Research, Lucent Technologies, Agere Systems, and Bellcore [now Telcordia]) where once there was the monolithic Bell Laboratories.¹⁰

Several of the companies that have recently emerged as dominant in their sectors, such as Intel and Microsoft, have increased their support for fundamental research. However, many other successful companies with large market shares (e.g., Cisco, Dell, Oracle) have chosen not to invest in fundamental research to any significant extent. And even at Microsoft, just as at AT&T and IBM before it, the investment in fundamental research

⁹Elizabeth Corcoran, 1994, “The Changing Role of U.S. Corporate Research Labs,” *Research-Technology Management* 37(4):14-20; Peter Coy, 1993, “R&D Scoreboard: In the Labs, the Fight to Spend Less, Get More,” *Business Week*, June 28, pp. 102-124.

¹⁰CSTB launched a study of the future of telecommunications R&D in 2003.

represents a relatively small proportion of overall corporate R&D. In 2002, Microsoft invested roughly \$5 billion in R&D, but the company's fundamental research arm is small enough to suggest that 95 percent of Microsoft's R&D investment is product-related.

Start-ups represent the other end of the spectrum. A hallmark of U.S. entrepreneurship, start-ups and start-up financing promote flexibility in industry structure and industry management. They have facilitated the development of high-risk products as well as an iconoclastic, risk-taking attitude among more traditional companies and managers in the IT business. *But they do not engage in research* (2). Thus, the wave of Internet-related and other IT start-ups of the 1990s is notable for two reasons: first, these start-ups attracted some researchers away from universities and research, and second, notwithstanding the popular labeling of those start-ups as "high-tech," they applied the fruits of past research rather than generating more. Start-ups illustrate the critical role of government funding in building the foundations for innovative commercial investments.

THE DISTINCTIVE CHARACTER OF FEDERALLY SUPPORTED RESEARCH

The most important characteristic of successful government research activities is their breadth of scope—both in their long time dimension and in their focus on activities that are potentially difficult to appropriate privately in their entirety. Two specific topic areas that illustrate these principles are large-scale IT systems and social applications of IT. Growing capabilities and broadening use of IT in the 1990s motivated CSTB recommendations for greatly increased federal support in these two categories (2) (see Boxes 4 and 5).

Prospects for progress in social applications—however difficult—are one reason for confidence that IT will improve as a human enabler. The beginnings evident in all of these areas are but crude indicators of what research may make possible.

An example of particular currency is that of cybersecurity. Stimulated by the events of September 11, CSTB issued the report *Cybersecurity Today and Tomorrow: Pay Now or Pay Later*, in early 2002. The report summarized the findings of seven CSTB reports issued over the preceding decade that had cybersecurity as a principal theme. *Cybersecurity Today and Tomorrow* concludes with the following paragraph:

Research and development on information systems security should be construed broadly to include R&D on defensive technology (including both underlying technologies and architectural issues), organizational and sociological dimensions of such security, forensic and recovery tools, and best policies and practices. Given the failure of the market to ad-

BOX 4
**Defining Large-Scale Systems and Social Applications
of Information Technology**

Large-scale systems are IT systems that contain many (thousands, millions, billions, or trillions or more) interacting hardware and software components. They tend to be heterogeneous—in that they are composed of many different types of components—and highly complex because the interactions among the components are numerous, varied, and complicated. They also tend to span multiple organizations (or elements of organizations) and have changing configurations. Over time, the largest IT systems have become ever larger and more complex, and at any given point in time, systems of a certain scale and complexity are not feasible or economical to design with existing methodologies.

Social applications of IT serve groups of people in shared activities. The most straightforward of these applications improve the effectiveness of geographically dispersed groups of people who are collaborating on some task in a shared context. More sophisticated applications may support the operations of a business or the functioning of an entire economy; systems for e-commerce are an example. Characteristic of social applications of IT is the embedding of IT into a large organizational or social system to form a “sociotechnical” system in which people and technology interact to achieve a common purpose—even if that purpose is not obviously social, such as efficient operation of a manufacturing line (which is a conjunction of technological automation and human workers) or rapid and decisive battlefield management (which is a conjunction of command-and-control technology and the judgment and expertise of commanders). Social applications of IT—especially those supporting organizational and societal missions—tend to be large-scale and complex, mixing technical and nontechnical design and operational elements and involving often-difficult social and policy issues such as those related to privacy and access.

SOURCE: Reprinted from Computer Science and Telecommunications Board, National Research Council. 2000. *Making IT Better: Expanding Information Technology Research to Meet Society's Needs*. National Academy Press, Washington, D.C., p. 3.

dress security challenges adequately, government support for such research is especially important.¹¹

CSTB's 2001 study on networked systems of embedded computers (7) sounds a similar theme (at p. 9):

[T]he committee (composed of people from both academia and industry) believes that while some of the questions raised in this report may

¹¹Computer Science and Telecommunications Board, National Research Council. 2002. *Cybersecurity Today and Tomorrow: Pay Now or Pay Later*. National Academy Press, Washington, D.C., pp. 14-15.

BOX 5 Research on the Social Applications of Information Technology

Research on the social applications of information technology (IT) combines work in technical disciplines, such as computing and communications, with research in the social sciences to understand how people, organizations, and IT systems can be combined to most effectively perform a set of tasks. Such research can address a range of issues related to IT systems, as demonstrated by the examples below . . . :

- *Novel activities and shifts in organizational, economic, and social structures*—What will people do (at work, in school, at play, in government, and so on) when computers can see and hear better than people can? How will activities and organizations change when robotic technology is widespread and cheap? How will individual and organizational activities change when surveillance via IT becomes effectively universal? New technologies will affect all kinds of people in many ways, and they hold particular promise for those with special situations or capabilities, because they will give them broader access to social and economic activities.

- *Electronic communities*—How can IT systems be best designed to facilitate the communication and coordination of groups of people working toward a common goal? Progress requires an understanding of the sociology and dynamics of groups of users, as well as of the tasks they wish to perform. Psychologists and sociologists could offer insight for the conceptualization and refinement of these social applications, and technologists could mold their technological aspects.

- *Electronic commerce*—How can buyers and sellers be best brought together to conduct business transactions on the Internet? What kinds of security technologies will provide adequate assurances of the identities of both parties and protect the confidentiality of their transactions without imposing unnecessary burdens on either? How will electronic commerce affect the competitive advantage of firms, their business strategies, and the structure of industries (e.g., their horizontal and vertical linkages)? Such work requires the insight of economists, organizational theorists, business strategists, and psychologists who understand consumer behavior, as well as of technologists.

- *Critical infrastructures*—How can IT be better embedded into the nation's transportation, energy, financial, telecommunications, and other infrastructures to make them more efficient and effective without making them less reliable or more prone to human error? For example, how can an air traffic control system be designed to provide controllers with sufficient information to make critical decisions without overwhelming them with data? Such work requires the insight of cognitive psychologists and experts in air traffic control, as well as of technologists.

- *Complexity*—How can the benefits of IT be brought to the citizenry without the exploding complexity characteristic of professional uses of IT? Although networks, computers, and software can be assembled and configured by professionals to support the mission-critical computing needs of large organizations, the techniques that make this possible are inadequate for information appliances designed for the home, car, or individual. Research is needed to simplify and automate

continues

BOX 5 Continued

system configuration, change, and repair. Such research will require insight from technologists, cognitive psychologists, and those skilled in user interface design.

SOURCE: Reprinted from Computer Science and Telecommunications Board, National Research Council. 2000. *Making IT Better: Expanding Information Technology Research to Meet Society's Needs*. National Academy Press, Washington, D.C., p. 7.

be answered without a concerted, publicly funded research agenda, leaving this work solely to the private sector raises a number of troubling possibilities. Of great concern is that individual commercial incentives will fail to bring about work on problems that have a larger scope and that are subject to externalities: interoperability, safety, upgradability, and so on. Moreover, a lack of government funding will slow down the sharing of the research, since the commercial concerns doing the research tend to keep the research private to retain their competitive advantage. The creation of an open research community within which results and progress are shared is vital to making significant progress in this arena.

Another example of the distinctive role that federal funding can play in computing research comes from two recent CSTB studies of the Internet. The 2001 report *The Internet's Coming of Age* examined the role of the government in funding research that leads to open standards, exemplified by the work that defined the Internet. One of the Internet's hallmarks has been its openness. Proprietary research can enhance a particular product, but research leading to open standards can create a new marketplace for products. Each company that is an Internet "player" will be tempted to diverge from the common standard if it looks possible to capture a large portion of it—we have seen this during the past decade in protocols for transport, electronic mail, instant messaging, and many other areas (see Box 6). However, a common, open standard maximizes overall social welfare as a result of the network externalities obtained from the larger market. When effective open standards are made available, they can be attractive in the marketplace and may win out over proprietary ones. The report notes:

The government's role in supporting open standards for the Internet has not been, and should not be, to directly set or influence standards. Rather, its role should be to provide funding for the networking research community, which has led to both innovative networking ideas as well

BOX 6
The Origins of Electronic Mail and Instant Messaging

The invention of timesharing systems in the 1960s not only contributed important technical developments in hardware, software, and system security but also provided the environment that led to the development of the most useful and widespread of popular applications, namely, e-mail and instant messaging (1).

Timesharing allowed concurrent multiple users to share the power of a computer, which provided a fresh way for colleagues to interact. By 1970, programmers in federally funded research laboratories had developed both asynchronous electronic mail and facilities for real-time interaction between users, in research operating systems such as Tenex, Multics, and CalTSS.

These modalities—now widely known as e-mail and instant messaging—proved so powerful that they have spread far and wide with the availability of low-cost personal computers, public networking, and client-server computing. These popular and visible tools, as well as all of the other forms of collaborative computing, have truly transformed our work and our lives. They owe their origins to the funding of IT research by the Defense Advanced Research Projects Agency and the National Science Foundation (1,3).

as specific technologies that can be translated into new open standards.¹²

A 2002 report, *Broadband: Bringing Home the Bits*, outlines an even broader role for federally funded research to enable openness in infrastructural systems:

Support research and development on access technologies, especially targeting the needs of nonincumbent players and other areas that are not targets of stable, private sector funding. . . . [One target area is] technologies that foster the accommodation of multiple competitive service providers over facilities. Such open access-ready systems might not be a natural research and development target of large incumbent providers but will be the preferred form for a variety of public sector or public-private deployments.¹³

Broadband: Bringing Home the Bits notes that federally funded research can complement the more proprietary-oriented industry approaches to innovation, whether in communications architecture or content. It also

¹²Computer Science and Telecommunications Board, National Research Council. 2001. *The Internet's Coming of Age*. National Academy Press, Washington, D.C., p. 18.

¹³Computer Science and Telecommunications Board, National Research Council. 2002. *Broadband: Bringing Home the Bits*. National Academy Press, Washington, D.C., p. 40.

calls for the support of research on economic, social, and regulatory factors relating to broadband technologies—nontechnical factors that interact with the design and deployment of broadband.

UNIVERSITY RESEARCH AND INDUSTRIAL R&D

Much of the government-funded research in IT has been carried out at universities.¹⁴ Federal support has constituted roughly 70 percent of total university research funding in computer science and electrical engineering since 1976 (2). Among the many benefits of federally funded university research, the generation of new knowledge is only one (see Box 7).

Strong research institutions are recognized as being among the most critical success factors in high-tech economic development (5). In computing, electronics, telecommunications, and biotechnology, evidence of the correlation abounds—in Boston (Harvard University and the Massachusetts Institute of Technology); Research Triangle Park (Duke University, the University of North Carolina, and North Carolina State University); New Jersey (Princeton University, Rutgers University, and New York City-based Columbia University); Austin (the University of Texas); southern California (the University of California at San Diego, the University of California at Los Angeles, the California Institute of Technology, and the University of Southern California); northern California (the University of California at Berkeley, the University of California at San Francisco, and Stanford University); and Seattle (the University of Washington).

In addition to creating ideas and companies, universities often import forefront technologies to their regions (e.g., the nationwide expansion of ARPANET in the 1970s and of NSFnet in the 1980s, and the continuation of those efforts through the private Internet2 activities in the 1990s and early 2000s). Universities also serve as powerful magnets for companies seeking to relocate. These contributions are not reflected in Figure 1.

Figure 1 also does not capture the most important product of universities: people. The American research university is unique in the degree to which it integrates research with education—both undergraduate and graduate education. Not only do graduating students serve to staff industry (5,6), but they also are *by far* the most effective vehicle for technol-

¹⁴The concentration of research in universities is particularly true for computer science research; industry played an important role in telecommunications research before the breakup of AT&T and the original Bell Labs.

BOX 7 The Diverse Benefits of University Research

Universities have a number of important characteristics that contribute to their success as engines of innovation. Among them are the following:

- *Universities can focus on long-term research.* Focusing on long-term research is the special role of universities—one that IT companies cannot be expected to fill to any significant extent (1-3). America's IT companies are extraordinarily adept at improving current products, but the track record is at best mixed on the invention and adoption of "disruptive technologies," and corporate research in IT has been becoming more applied (2).

- *Universities provide a neutral ground for collaboration.* Universities encourage movement and collaboration among faculty through leave and sabbatical policies that allow professors to visit industry, government, and other university departments or laboratories. These uniquely valuable components of the R&D structure in the United States are not generally present in industry. Universities also provide sites at which researchers from competing companies can come together to explore technical issues. At the same time that industry people share their wisdom and experience with university researchers, they have the opportunity to learn from one another (2,6).

- *Universities integrate research and education.* Universities provide a forum for educating the skilled IT workers of the future (5). The presence of research activities in an educational setting creates very powerful synergy (2,4). IT is a rapidly changing field. Many of the specific facts and techniques that a student learns become obsolete early in his or her career. The educational foundation for continuous learning—"keeping up with the field"—is a crucial component of IT education (5). Students, even beginning undergraduates, get that education not only in the classroom, but also by serving as apprentices on leading-edge research projects, where knowledge is being discovered, not read from a book. Often, new ideas are a by-product of what goes on in the classroom: in an attempt to explain the solutions to emerging problems, teachers often deepen their own understanding, while discovering interesting research questions whose answers are as yet unknown. Additionally, students are the most powerful vehicle for technology transfer, not only from university to industry but also between university laboratories and departments, through the hiring of postdoctoral researchers and assistant professors (5).

- *Universities are inherently multidisciplinary.* University researchers are well situated to draw on experts from a variety of other fields (2). There are often cultural barriers to cross-disciplinary collaboration, but physical proximity and collegial values go a long way in enabling collaboration. The multidisciplinary nature of universities is of historic and growing importance to computer science, which interfaces with so many other fields.

- *Universities are "open."* This characteristic of universities, which is true both literally and figuratively, can pay enormous unanticipated dividends. Chance interactions in an open environment can change the world; for example, when Microsoft founders Paul Allen and Bill Gates were students at Seattle's Lakeside School in the early 1970s, they were exposed to computing and computer science at the University of Washington and a university spinoff company, Computer Center Corporation.

ogy transfer (see Box 7). Federal support for university research drives this process (1-6). In top university computer science programs, over half of all graduate students receive financial support from the federal government, mostly in the form of research assistantships. In addition, most of the funding for research equipment—that is, research infrastructure—comes from federal agencies. Industry also contributes significantly to equipment but is usually attracted by existing research excellence and collaborations. Thus, by placing infrastructure in universities, the federal government directly and indirectly makes possible hands-on learning experiences for countless young engineers and scientists, as well as enabling university researchers to continue their work (1-6).

HALLMARKS OF FEDERALLY SPONSORED IT RESEARCH

As discussed below, the hallmarks of federally sponsored IT research include scale, diversity, vision, and flexibility.

1. Federal programs have been effective in supporting the construction of large-scale systems and testbeds that have motivated research and demonstrated the feasibility of new technological approaches (1-3).

Some research challenges are too large and require too much research infrastructure to be carried out by small, local research groups (6). In IT research, as in other areas of scientific investigation, federal programs have played an important role in stimulating and supporting large-scale efforts. DARPA's decision to construct a packet-switched network (called the ARPANET) to link computers at its many contractor sites prompted diverse, high-impact research on networking protocols, the design of packet switches and routers, software structures for managing large networks (such as the Domain Name System), and applications (such as remote log-in, file transfer, and ultimately the Web). Moreover, by constructing a successful system, DARPA demonstrated the value of large-scale packet-switched networks, motivating subsequent deployment of other networks—such as the NSF's NSFnet, which ultimately served as the foundation of the Internet—and also a series of high-speed networking testbeds (1,3).

Much of the success of major system-building efforts derives from their ability to bring together large groups of researchers from universities and industry that develop a common vocabulary, share ideas, and create a critical mass of people who subsequently extend the technology (2,6).

2. Computing research has benefited from diverse modes of research sponsored by different federal agencies (1-3).

Funding for research in computing has been provided by various federal agencies—most notably DARPA and NSF, but also including other parts of the Department of Defense (DOD) besides DARPA, and other federal agencies such as NASA, DOE, and the National Institutes of Health (NIH; in particular through the National Library of Medicine). Complementary investments have supported technology transfer to industry (e.g., activities of the National Institute of Standards and Technology, or NIST). Funding agencies have continually evolved in order to match their structures better to the needs of the research and policy-making communities (1). (See Box 8.)

In supporting research, these agencies pursue different objectives and employ different mechanisms. In contrast to NSF, for example—which has a mandate to support a very broad research agenda—“mission agencies” tend to focus on topics that appear to have the greatest relevance to their specific missions. Additionally, the early DARPA programs chose to concentrate large research awards in so-called centers of excellence (many of which over time have matured into some of the nation’s leading university computer science programs), while NSF and the Office of Naval Research have supported individual researchers at a more diverse set of institutions (1). NSF has been active in supporting educational and research needs more broadly, awarding graduate student fellowships and providing funding for research equipment and infrastructure.

CSTB has recognized the effective leadership of NSF and DARPA, calling on them to step up to larger roles (2; p. 11):

The programs run by [NSF and DARPA] should complement one another and should together [do the following]:

- Support both theoretical and experimental work;
- Offer awards in a variety of sizes (small, medium, and large) to support individual investigators, small teams of researchers, and larger collaborations;
 - Investigate a range of approaches to large-scale systems problems, such as improved software design methodologies, system architecture, reusable code, and biological and economic models . . . ;
 - Attempt to address the full scope of large-scale systems issues, including scalability, heterogeneity, trustworthiness, flexibility, and predictability; and
 - Give academic researchers some form of access to large-scale systems for studying and demonstrating new approaches.

BOX 8 **Federal Agency Evolution**

In response to proposals by Vannevar Bush and others for an organization to fund basic research, especially in universities, the U.S. Congress established the National Science Foundation (NSF) in 1950 (1). A few years earlier, the U.S. Navy had founded the Office of Naval Research to draw on science and engineering resources in the universities.

In the early 1950s, during an intense phase of the Cold War, the military services became the preeminent funders of computing and communications research. The Soviet Union's launching of Sputnik in 1957 raised fears in Congress and the country that the Soviets had forged ahead of the United States in advanced technology. In response, the U.S. Department of Defense, pressured by the Eisenhower administration, established the Advanced Research Projects Agency (ARPA, now DARPA) to fund technological projects with military implications. In 1962 DARPA created the Information Processing Techniques Office (IPTO), whose initial research agenda gave priority to further development of computers for command-and-control systems.

With the passage of time, new organizations have emerged, and old ones have often been reformed or reinvented to respond to new national imperatives and counter bureaucratic trends (2). DARPA's IPTO has transformed itself several times to bring greater coherence to its research efforts and to respond to technological developments and changes in perceived national needs for IT.

In 1967 NSF established the Office of Computing Activities, and in 1986 it formed the Computer and Information Science and Engineering Directorate to advance and coordinate support for research, education, and infrastructure in computing (1). In the 1980s NSF, which customarily has focused on fundamental research in universities, also began to encourage joint university-industry research centers through its Engineering Research Centers program (these centers focus on research and education in the context of long-time-horizon, complex engineering challenges¹) and its Science and Technology Center program (aimed at long-term research in areas that are new or that can bridge disciplines and/or institutions and sectors²).

With the growth in the IT sector and corresponding IT development together with the maturation of the field of computer science, more recent federal funding has been characterized by a series of multiagency, long-term, high-risk initiatives. The first was the High Performance Computing and Communications Initiative, which emerged in the late 1980s and broadened through the mid-1990s (1,3). By the late 1990s and the establishment of the multiagency Information Technology for the Twenty-First Century initiative (in NSF, the Information Technology Research initiative), social science research—relating IT innovation to the people who use IT—was an important complement to the science and technology research per se (3,8).

¹See <<http://www.eng.nsf.gov/eec/erc.htm>>. Accessed June 2, 2003.

²See <<http://www.nsf.gov/od/oia/programs/stc/>>. Accessed June 2, 2003.

Given the wide circle of agencies interested in and involved with IT research and the even wider circle coming to depend on large-scale IT systems, the NSF and DARPA should attempt to involve in their research other federal agencies . . . that operate large-scale IT systems and would benefit from advances in their design. Such involvement could provide a means for researchers to gain access to operational systems for analytical and experimental purposes.

The diversity of research funding objectives and program management styles offers many benefits (1,3). It helps ensure exploration of a diverse set of research topics and consideration of a range of applications. For example, DARPA, NASA, and NIH (in addition to NSF) have all supported work in expert systems. However, because the systems have had different applications—decision aids for pilots, tools for determining the structure of molecules on other planets, and medical diagnostics—each agency has supported different groups of researchers who tried different approaches. And no one's judgment is infallible. If one agency declines to support a particular topic, researchers have other sources of funding.

3. Visionary program managers who were willing to take risks have been a hallmark of many of the highest-impact federal research initiatives (1,3).

The program manager is responsible for initiating, funding, and overseeing research programs. The funding and management styles of program managers at DARPA during the 1960s and 1970s, for example, reflected an ability to marry visions for technological progress with strong technical expertise and an understanding of the uncertainties of the research process (1,3). Many of these program managers and program office directors were recruited from universities and industrial research laboratories for limited tours of duty and were themselves leading researchers. With close ties to the field, they were trusted by—and trusted—the research community. They tended to lay down broad guidelines for new research areas and to draw specific project proposals from principal investigators. They were willing to place bets—to pursue high-risk/high-gain projects.

This style of funding and management allowed researchers room to pursue new venues of inquiry. The funding style resulted in advances in areas as diverse as computer graphics, artificial intelligence, networking, and computer architecture. As that experience illustrates, because unanticipated outcomes of research are so valuable, federal mechanisms for funding and managing research need to recognize the inherent uncertainties and build in enough flexibility to accommodate midcourse changes (1,3).

LOOKING FORWARD

Federal funding agencies will have to continue to adjust their strategies and tactics as national needs and imperatives change. Today there is an escalation in concern about homeland security, the globalization of industry, a rise of commodity IT products and an IT mass market, the growing dependence of economic and social activity on networking and distributed computing capabilities, and a variety of industry retrenchments. Coevolution with industry thus means different things for federally funded computing research today than it did in the middle to late decades of the 20th century.

Challenges as well as opportunities have grown: computer science is a larger field with more subdisciplines; telecommunications is increasingly intertwined with computing while evolving across multiple media;¹⁵ the interdisciplinary problems that engage computer science and telecommunications are broader-ranging; and the number of hard problems—reflecting growth in scale, complexity, and interactions with people—has increased. Evolving capabilities motivate a range of stretch goals that can help realize the potential of information technology as a human enabler.¹⁶ Examples include new forms of prosthetics (beginning with systems that can hear, speak, or see as well as a person can) and better ways to observe or participate in activities from a distance (i.e., telepresence).

These circumstances imply that the challenge to federal research program managers has also grown. For example, while IT is at the core of a number of interdisciplinary programs (such as the multiagency Digital Libraries Initiative and NSF's Digital Government and Computing and Social System programs), it takes more work to review proposals for interdisciplinary work and to assure its quality. It may thus be more important to engage IT-using organizations in research projects, which may involve more work for the researchers (2). The growth in opportunities at the intersection of computing and biology, for example, or even computing and the arts—both topics of CSTB projects¹⁷—suggests new horizons

¹⁵Innovations are enhancing the potential of optical fiber, various forms of wireless, and even older media, such as copper.

¹⁶These and other problems were outlined by Jim Gray in his 1998 A.M. Turing Award lecture. See Jim Gray. 1998. "What's Next? A Few Remaining Problems in Information Technology." Available online at <<http://research.microsoft.com/~Gray/talks>>. Accessed June 9, 2003.

¹⁷The project on computing and the arts and design was completed in early 2003. See Computer Science and Telecommunications Board, National Research Council. 2003. *Beyond Productivity: Information Technology, Innovation, and Creativity*. National Academies Press, Washington, D.C.

for IT innovation that depend on the nurturing that is available through university-based research programs.

The challenges confronting program managers underscore the need to attract talent from universities and industry to such public service positions. Past advances fostered by federal funding leveraged the energies and wisdom of people who went from universities and industry into the government, for at least a limited period. It is ironic that their success has increased the incentives for researchers to stay in universities or to try their hand in industry instead of cultivating the field as program managers.

Government support for IT research will also be shaped by categories of problems in which it has a special interest. The events of September 11, 2001, remind us that computer and communications security, constrained by market failure, has always depended on federal investments. But so, too, has research in human-computer interaction, another arena in which market forces have been limited (8) and where the rise of e-government reinforces long-standing government interest associated with its own applications.¹⁸ The post-September 11 focus on homeland security and intelligence analysis also puts a spotlight on supercomputing architectures, numerical analysis, parallel programming languages and tools, and other areas in which IT advances have flowed from scientific and engineering computing needs within the research community at large—and in which purely commercial development was unlikely at best (1,3).

The downturn in the telecommunications industry presents opportunities for the government to stimulate new directions through its support for research. We may see a consolidation and a loss of viable competition, or a realignment of the sector boundaries to better reflect economic realities. Government funding, supporting the development of open standards, can help shape the structure of industry.¹⁹ Given the “chicken-and-egg” tension shaping advances in infrastructure and applications, government support for exploration of new kinds of applications can have great impact.²⁰ The government can encourage competition by supporting the definition of critical interfaces and demonstrations of feasibility.

¹⁸Computer Science and Telecommunications Board, National Research Council. 2002. *Information Technology Research, Innovation, and E-Government*. National Academy Press, Washington, D.C.

¹⁹See Computer Science and Telecommunications Board, National Research Council, 2001, *The Internet's Coming of Age*, National Academy Press, Washington, D.C.; and Computer Science and Telecommunications Board, National Research Council, 2002, *Broadband: Bringing Home the Bits*, National Academy Press, Washington, D.C.

²⁰This was demonstrated by the evolution of the early Internet and Web, involving development and refinement of both the underlying infrastructure and a suite of compelling

ity for open standards, and it can demonstrate new architectures through field trials and testbeds. This role was critical in the emergence of the Internet, and the relevance and importance of this sort of leadership have not waned.²¹

More generally, the 2001-2002 downturn in the economy and the crisis in the telecommunications industry caused a reduction in investment across all of IT. Spending remained down in 2003, and internal investment has dropped accordingly. Venture and equity capital has also become harder to obtain in the IT industries. In times such as these, research, especially longer-term research, is an obvious target for cost cutting. But if we as a nation do not continue to invest in the foundations of innovation, we run the risk that when an improving economy justifies an increase in investment, there may be few ideas in which to invest. For that reason this time is especially important for government-sponsored research.

Today's research investments are essential to tomorrow's world leadership in IT. From its position of leadership today—reinforced by an aggregation of universities, companies, government programs, and talent—the United States is better positioned than other nations are to make the most of nonappropriable research (and even appropriable research). Properly managed, publicly funded research in IT will continue to create important new technologies and industries, some of them unimagined today. The process will continue to take 10 to 15 years from the inception of a new idea to the creation of a billion-dollar industry. Without continued federal investment in fundamental research there would still be innovation, but the quantity and range of new ideas for U.S. industry to draw from would be greatly diminished—as would the flow of people edu-

applications by researchers focused not only on IT but also on other fields of science and engineering in which people used IT. The Internet probably could never have developed commercially without this phase of government-supported experimentation and refinement coordinated between infrastructure and applications. For a discussion of new opportunities in the support of applications, see Computer Science and Telecommunications Board, National Research Council, 2002, *Broadband: Bringing Home the Bits*, National Academy Press, Washington, D.C.

²¹For a discussion of the role of government in setting a vision, see Computer Science and Telecommunications Board, National Research Council, 1994, *Realizing the Information Future: The Internet and Beyond*, National Academy Press, Washington, D.C. For a discussion of government leadership and the importance of government funding of research as a policy tool, see Computer Science and Telecommunications Board, National Research Council, 1996, *The Unpredictable Certainty: Information Infrastructure Through 2000*, National Academy Press, Washington, D.C.

cated at the forefront, the most important product of the nation's research universities (1-8).

The lessons of history are clear, as many CSTB studies in the past decade have shown, and many of those lessons are relevant to 21st-century realities. A complex partnership among government, industry, and universities has made the United States the world leader in IT, and information technology has become essential to our national security and economic and social well-being. Turn-of-the-century turmoil and structural changes in IT industries have diminished their inherently limited capacity to support fundamental IT research. The role of the federal government in sponsoring fundamental research in IT—largely university-based—has been and will continue to be essential.

2

Excerpts from Earlier CSTB Reports

This section contains excerpts from three CSTB reports:

- *Making IT Better: Expanding Information Technology Research to Meet Society's Needs* (2000),
- *Funding a Revolution: Government Support for Computing Research* (1999), and
- *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure* (1995).

While this synthesis report is based on all the CSTB reports listed in Box 1 in the "Summary and Recommendations," the excerpts from these three reports are the most general and broad. To keep this report to a reasonable length, nothing was excerpted from the other five reports. Readers are encouraged to read all eight reports, which can be found online at <http://www.nap.edu>.

For the sake of simplicity and organizational clarity, footnotes and reference citations appearing in the original texts have been omitted from the reprinted material that follows. A bar in the margins beside the excerpted material is used to indicate that it is extracted text. Section heads show the topics addressed.

**MAKING IT BETTER: EXPANDING INFORMATION TECHNOLOGY
RESEARCH TO MEET SOCIETY'S NEEDS (2000)**

CITATION: Computer Science and Telecommunications Board (CSTB), National Research Council. 2000. *Making IT Better: Expanding Information Technology Research to Meet Society's Needs*. National Academy Press, Washington, D.C.

The Many Faces of Information Technology Research

(From pp. 23-26): IT research takes many forms. It consists of both theoretical and experimental work, and it combines elements of science and engineering. Some IT research lays out principles or constraints that apply to all computing and communications systems; examples include theorems that show the limitations of computation (what can and cannot be computed by a digital computer within a reasonable time) or the fundamental limits on capacities of communications channels. Other research investigates different classes of IT systems, such as user interfaces, the Web, or electronic mail (e-mail). Still other research deals with issues of broad applicability driven by specific needs. For example, today's high-level programming languages (such as Java and C) were made possible by research that uncovered techniques for converting the high-level statements into machine code for execution on a computer. The design of the languages themselves is a research topic: how best to capture a programmer's intentions in a way that can be converted to efficient machine code. Efforts to solve this problem, as is often the case in IT research, will require invention and design as well as the classical scientific techniques of analysis and measurement. The same is true of efforts to develop specific and practical modulation and coding algorithms that approach the fundamental limits of communication on some channels. The rise of digital communication, associated with computer technology, has led to the irreversible melding of what were once the separate fields of communications and computers, with data forming an increasing share of what is being transmitted over the digitally modulated fiber-optic cables spanning the nation and the world.

Experimental work plays an important role in IT research. One modality of research is the design experiment, in which a new technique is proposed, a provisional design is posited, and a research prototype is built in order to evaluate the strengths and weaknesses of the design. Although much of the effect of a design can be anticipated using analytic techniques, many of its subtle aspects are uncovered only when the prototype is studied. Some of the most important strides in IT have been made through such experimental research. Time-sharing, for example, evolved

in a series of experimental systems that explored different parts of the technology. How are a computer's resources to be shared among several customers? How do we ensure equitable sharing of resources? How do we insulate each user's program from the programs of others? What resources should be shared as a convenience to the customers (e.g., computer files)? How can the system be designed so it's easy to write computer programs that can be time-shared? What kinds of commands does a user need to learn to operate the system? Although some of these trade-offs may succumb to analysis, others—notably those involving the user's evaluation and preferences—can be evaluated only through experiment.

Ideas for IT research can be gleaned both from the research community itself and from applications of IT systems. The Web, initiated by physicists to support collaboration among researchers, illustrates how people who use IT can be the source of important innovations. The Web was not invented from scratch; rather, it integrated developments in information retrieval, networking, and software that had been accumulating over decades in many segments of the IT research community. It also reflects a fundamental body of technology that is conducive to innovation and change. Thus, it advanced the integration of computing, communications, and information. The Web also embodies the need for additional science and technology to accommodate the burgeoning scale and diversity of IT users and uses: it became a catalyst for the Internet by enhancing the ease of use and usefulness of the Internet, it has grown and evolved far beyond the expectations of its inventors, and it has stimulated new lines of research aimed at improving and better using the Internet in numerous arenas, from education to crisis management.

Progress in IT can come from research in many different disciplines. For example, work on the physics of silicon can be considered IT research if it is driven by problems related to computer chips; the work of electrical engineers is considered IT research if it focuses on communications or semiconductor devices; anthropologists and other social scientists studying the uses of new technology can be doing IT research if their work informs the development and deployment of new IT applications; and computer scientists and computer engineers address a widening range of issues, from generating fundamental principles for the behavior of information in systems to developing new concepts for systems. Thus, IT research combines science and engineering, even though the popular—and even professional—association of IT with systems leads many people to concentrate on the engineering aspects. Fine distinctions between the science and engineering aspects may be unproductive: computer science is special because of how it combines the two, and the evolution of both is key to the well-being of IT research.

Implications for the Research Enterprise

(From pp. 42-43): The trends in IT suggest that the nation needs to reinvent IT research and develop new structures to support, conduct, and manage it. . . .

As IT permeates many more real-world applications, additional constituencies need to be brought into the research process as both funders and performers of IT research. This is necessary not only to broaden the funding base to include those who directly benefit from the fruits of the research, but also to obtain input and guidance. An understanding of business practices and processes is needed to support the evolution of e-commerce; insight from the social sciences is needed to build IT systems that are truly user-friendly and that help people work better together. No one truly understands where new applications such as e-commerce, electronic publishing, or electronic collaboration are headed, but business development and research together can promote their arrival at desirable destinations.

Many challenges will require the participation and insight of the end user and the service provider communities. They have a large stake in seeing these problems addressed, and they stand to benefit most directly from the solutions. Similarly, systems integrators would benefit from an improved understanding of systems and applications because they would become more competitive in the marketplace and be better able to meet their estimates of project cost and time. Unlike vendors of component technologies, systems integrators and end users deal with entire information systems and therefore have unique perspectives on the problems encountered in developing systems and the feasibility of proposed solutions. Many of the end-user organizations, however, have no tradition of conducting IT research—or technological research of any kind, in fact—and they are not necessarily capable of doing so effectively; they depend on vendors for their technology. Even so, their involvement in the research process is critical. Vendors of equipment and software have neither the requisite experience and expertise nor the financial incentives to invest heavily in research on the challenges facing end-user organizations, especially the challenges associated with the social applications of IT. Of course, they listen to their customers as they refine their products and strategies, but those interactions are superficial compared with the demands of the new systems and applications. Finding suitable mechanisms for the participation of end users and service providers, and engaging them productively, will be a big challenge for the future of IT research.

Past attempts at public-private partnerships, as in the emerging arena of critical infrastructure protection, show it is not so easy to get the public

and private sectors to interact for the purpose of improving the research base and implementation of systems: the federal government has a responsibility to address the public interest in critical infrastructure, whereas the private sector owns and develops that infrastructure, and conflicting objectives and time horizons have confounded joint exploration. As a user of IT, the government could play an important role. Whereas historically it had limited and often separate programs to support research and acquire systems for its own use, the government is now becoming a consumer of IT on a very large scale. Just as IT and the widespread access to it provided by the Web have enabled businesses to reinvent themselves, IT could dramatically improve operations and reduce the costs of applications in public health, air traffic control, and social security; government agencies, like private-sector organizations, are turning increasingly to commercial, off-the-shelf technology.

Universities will play a critical role in expanding the IT research agenda. The university setting continues to be the most hospitable for higher-risk research projects in which the outcomes are very uncertain. Universities can play an important role in establishing new research programs for large-scale systems and social applications, assuming that they can overcome long-standing institutional and cultural barriers to the needed cross-disciplinary research. Preserving the university as a base for research and the education that goes with it would ensure a workforce capable of designing, developing, and operating increasingly sophisticated IT systems. A booming IT marketplace and the lure of large salaries in industry heighten the impact of federal funding decisions on the individual decisions that shape the university environment: as the key funders of university research, federal programs send important signals to faculty and students.

The current concerns in IT differ from the competitiveness concerns of the 1980s: the all-pervasiveness of IT in everyday life raises new questions of how to get from here to there—how to realize the exciting possibilities, not merely how to get there first. A vital and relevant IT research program is more important than ever, given the complexity of the issues at hand and the need to provide solid underpinnings for the rapidly changing IT marketplace.

(From p. 93): Several underlying trends could ultimately limit the nation's innovative capacity and hinder its ability to deploy the kinds of IT systems that could best meet personal, business, and government needs. First, expenditures on research by companies that develop IT goods and services and by the federal government have not kept pace with the expanding array of IT. The disincentives to long-term, fundamental research have become more numerous, especially in the private sector,

which seems more able to lure talent from universities than the other way around. Second, and perhaps most significantly, IT research investments continue to be directed at improving the performance of IT components, with limited attention to systems issues and application-driven needs. Neither industry nor academia has kept pace with the problems posed by the large-scale IT systems used in a range of social and business contexts—problems that require fundamental research. . . . New mechanisms may be needed to direct resources to these growing problem areas.

(From pp. 6-9): Neither large-scale systems nor social applications of IT are adequately addressed by the IT research community today. Most IT research is directed toward the *components* of IT systems: the microprocessors, computers, and networking technologies that are assembled into large systems, as well as the software that enables the components to work together. This research nurtures the essence of IT, and continued work is needed in all these areas. But component research needs to be viewed as part of a much larger portfolio, in which it is complemented by research aimed directly at improving large-scale systems and the social applications of IT. The last of these includes some work (such as computer-supported cooperative work and human-computer interaction) traditionally viewed as within the purview of computer science. Research in all three areas—components, systems, and social applications—will make IT systems better able to meet society's needs, just as in the medical domain work is needed in biology, physiology, clinical medicine, and epidemiology to make the nation's population healthier.

Research on large-scale systems and the social applications of IT will require new modes of funding and performing research that can bring together a broad set of IT researchers, end users, system integrators, and social scientists to enhance the understanding of operational systems. Research in these areas demands that researchers have access to operational large-scale systems or to testbeds that can mimic the performance of much larger systems. It requires additional funding to support sizable projects that allow multiple investigators to experiment with large IT systems and develop suitable testbeds and simulations for evaluating new approaches and that engage an unusually diverse range of parties. Research by individual investigators will not, by itself, suffice to make progress on these difficult problems.

Today, most IT research fails to incorporate the diversity of perspectives needed to ensure advances on large-scale systems and social applications. Within industry, it is conducted largely by vendors of IT components: companies like IBM, Microsoft, and Lucent Technologies. Few of the companies that are engaged in providing IT services, in integrating large-scale systems (e.g., Andersen Consulting [now Accenture], EDS, or

Lockheed Martin), or in developing enterprise software (e.g., Oracle, SAP, PeopleSoft) have significant research programs. Nor do end-user organizations (e.g., users in banking, commerce, education, health care, and manufacturing) tend to support research on IT, despite their increasing reliance on IT and their stake in the way IT systems are molded. Likewise, there is little academic research on large-scale systems or social applications. Within the IT sector, systems research has tended to focus on improving the performance and lowering the costs of IT systems rather than on improving their reliability, flexibility, or scalability (although systems research is slated to receive more attention in new funding programs). Social applications present an even greater opportunity and have the potential to leverage research in human-computer interaction, using it to better understand how IT can support the work of individuals, groups, and organizations. Success in this area hinges on interdisciplinary research, which is already being carried out on a small scale.

One reason more work has not been undertaken in these areas is lack of sufficient funding. More fundamentally, the problems evident today did not reach critical proportions until recently. . . . From a practical perspective, conducting the types of research advocated here is difficult. Significant cultural gaps exist between researchers in different disciplines and between IT researchers and the end users of IT systems.

FUNDING A REVOLUTION: GOVERNMENT SUPPORT FOR COMPUTING RESEARCH (1999)

CITATION: Computer Science and Telecommunications Board (CSTB), National Research Council. 1999. *Funding a Revolution: Government Support for Computing Research*. National Academy Press, Washington, D.C.

(From p. 1): The computer revolution is not simply a technical change; it is a sociotechnical revolution comparable to an industrial revolution. The British Industrial Revolution of the late 18th century not only brought with it steam and factories, but also ushered in a modern era characterized by the rise of industrial cities, a politically powerful urban middle class, and a new working class. So, too, the sociotechnical aspects of the computer revolution are now becoming clear. Millions of workers are flocking to computing-related industries. Firms producing microprocessors and software are challenging the economic power of firms manufacturing automobiles and producing oil. Detroit is no longer the symbolic center of the U.S. industrial empire; Silicon Valley now conjures up visions of enormous entrepreneurial vigor. Men in boardrooms and gray flannel suits are giving way to the casually dressed young founders of start-up computer and Internet companies. Many of these entrepreneurs had their early hands-on computer experience as graduate students conducting federally funded university research.

As the computer revolution continues and private companies increasingly fund innovative activities, the federal government continues to play a major role, especially by funding research. Given the successful history of federal involvement, several questions arise: Are there lessons to be drawn from past successes that can inform future policy making in this area? What future roles might the government play in sustaining the information revolution and helping to initiate other technological developments?

Lessons from History

(From pp. 5-13): Why has federal support been so effective in stimulating innovation in computing? Although much has depended on the unique characteristics of individual research programs and their participants, several common factors have played an important part. Primary among them is that federal support for research has tended to *complement*, rather than *preempt*, industry investments in research. Effective federal research has concentrated on work that industry has limited incentive to pursue: long-term, fundamental research; large system-building efforts that require the talents of diverse communities of scientists and engi-

neers; and work that might displace existing, entrenched technologies. Furthermore, successful federal programs have tended to be organized in ways that accommodate the uncertainties in scientific and technological research. Support for computing research has come from a diversity of funding agencies; program managers have formulated projects broadly where possible, modifying them in response to preliminary results; and projects have fostered productive collaboration between universities and industry. The lessons below expand on these factors. The first three lessons address the complementary nature of government- and industry-sponsored research; the final four highlight elements of the organizational structure and management of effective federally funded research programs. . . .

1. Government supports long-range, fundamental research that industry cannot sustain.

Federally funded programs have been successful in supporting long-term research into fundamental aspects of computing, such as computer graphics and artificial intelligence, whose practical benefits often take years to demonstrate. Work on speech recognition, for example, which was begun in the early 1970s (some started even earlier), took until 1997 to generate a successful product for enabling personal computers to recognize continuous speech. Similarly, fundamental algorithms for shading three-dimensional graphics images, which were developed with defense funding in the 1960s, entered consumer products only in the 1990s, though they were available in higher-performance machines much earlier. These algorithms are now used in a range of products in the health care, entertainment, and defense industries.

Industry does fund some long-range work, but the benefits of fundamental research are generally too distant and too uncertain to receive significant industry support. Moreover, the results of such work are generally so broad that it is difficult for any one firm to capture them for its own benefit and also prevent competitors from doing so. . . . Not surprisingly, companies that have tended to support the most fundamental research have been those, like AT&T Corporation and IBM Corporation, that are large and have enjoyed a dominant position in their respective markets. As the computing industry has become more competitive, even these firms have begun to link their research more closely with corporate objectives and product development activities. Companies that have become more dominant, such as Microsoft Corporation and Intel Corporation, have increased their support for fundamental research.

2. Government supports large system-building efforts that have advanced technology and created large communities of researchers.

In addition to funding long-term fundamental research, federal programs have been effective in supporting the construction of large systems that have both motivated research and demonstrated the feasibility of new technological approaches. The Defense Advanced Research Projects Agency's (DARPA's) decision to construct a packet-switched network (called the ARPANET) to link computers at its many contractor sites prompted considerable research on networking protocols and the design of packet switches and routers. It also led to the development of structures for managing large networks, such as the domain name system, and development of useful applications, such as e-mail. Moreover, by constructing a successful system, DARPA demonstrated the value of large-scale packet-switched networks, motivating subsequent deployment of other networks, like the National Science Foundation's NSFnet, which formed the basis of the Internet.

Efforts to build large systems demonstrate that, especially in computing, innovation does not flow simply and directly from research, through development, to deployment. Development often precedes research, and research rationalizes, or explains, technology developed earlier through experimentation. Hence attempts to build large systems can identify new problems that need to be solved. Electronic telecommunications systems were in use long before Claude Shannon developed modern communications theory in the late 1940s, and the engineers who developed the first packet switches for routing messages through the ARPANET advanced empirically beyond theory. Building large systems generated questions for research, and the answers, in turn, facilitated more development.

Much of the success of major system-building efforts derives from their ability to bring together large groups of researchers from academia and industry who develop a common vocabulary, share ideas, and create a critical mass of people who subsequently extend the technology. Examples include the ARPANET and the development of the Air Force's Semi-Automatic Ground Environment (SAGE) project in the 1950s. Involving researchers from MIT, IBM, and other research laboratories, the SAGE project sparked innovations ranging from real-time computing to core memories that found widespread acceptance throughout the computer industry. Many of the pioneers in computing learned through hands-on experimentation with SAGE in the 1950s and early 1960s. They subsequently staffed the companies and laboratories of the nascent computing and communications revolution. The impact of SAGE was felt over the course of several decades.

3. Federal research funding has expanded on earlier industrial research.

In several cases, federal research funding has been important in advancing a technology to the point of commercialization after it was first explored in an industrial research laboratory. For example, IBM pioneered the concept of relational databases but did not commercialize the technology because of its perceived potential to compete with more-established IBM products. National Science Foundation (NSF)-sponsored research at UC-Berkeley allowed continued exploration of this concept and brought the technology to the point that it could be commercialized by several start-up companies—and more-established database companies (including IBM). This pattern was also evident in the development of reduced instruction set computing (RISC). Though developed at IBM, RISC was not commercialized until DARPA funded additional research at UC-Berkeley and Stanford University as part of its Very Large Scale Integrated Circuit (VLSI) program of the late 1970s and early 1980s. A variety of companies subsequently brought RISC-based products to the marketplace, including IBM, the Hewlett-Packard Company, the newly formed Sun Microsystems, Inc., and another start-up, MIPS Computer Systems. For both relational databases and VLSI, federal funding helped create a community of researchers who validated and improved on the initial work. They rapidly diffused the technology throughout the community, leading to greater competition and more rapid commercialization.

4. Computing research has benefited from diverse sources of government support.

Research in computing has been supported by multiple federal agencies, including the Department of Defense (DOD)—most notably the Defense Advanced Research Projects Agency and the military services—the National Science Foundation, National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and National Institutes of Health (NIH). Each has its own mission and means of supporting research. DARPA has tended to concentrate large research grants in so-called centers of excellence, many of which over time have matured into some of the country's leading academic computer departments. The Office of Naval Research (ONR) and NSF, in contrast, have supported individual researchers at a more diverse set of institutions. They have awarded numerous peer-review grants to individual researchers, especially in universities. NSF has also been active in supporting educational and research needs more broadly, awarding graduate student fellowships and providing funding for research equipment and infrastructure. Each of these organizations employs a different set of mechanisms to support research,

from fundamental research to mission-oriented research and development projects, to procurement of hardware and software.

Such diversity offers many benefits. It not only provides researchers with many potential sources of support, but also helps ensure exploration of a diverse set of research topics and consideration of a range of applications. DARPA, NASA, and NIH have all supported work in expert systems, for example, but because the systems have had different applications—decision aids for pilots, tools for determining the structure of molecules on other planets, and medical diagnostics—each agency has supported different groups of researchers who tried different approaches.

Perhaps more importantly, no single approach to investing in research is by itself a sufficient means of stimulating innovation; each plays a role in the larger system of innovation. Different approaches work in concert, ensuring continued support for research areas as they pass through subsequent stages of development. Organizations such as NSF and ONR often funded seed work in areas that DARPA, with its larger contract awards, later magnified and expanded. DARPA's Project MAC, which gave momentum to time-shared computing in the 1960s, for example, built on earlier NSF-sponsored work on MIT's Compatible Time-Sharing System. Conversely, NSF has provided continued support for projects that DARPA pioneered but was unwilling to sustain after the major research challenges were resolved. For example, NSF funds the Metal Oxide Semiconductor Implementation Service (MOSIS)—a system developed at Xerox PARC and institutionalized by DARPA that provides university researchers with access to fast-turnaround semiconductor manufacturing services. Once established, this program no longer matched DARPA's mission to develop leading-edge technologies, but it did match NSF's mission to support university education and research infrastructure. Similarly, NSF built on DARPA's pioneering research on packet-switched networks to construct the NSFnet, a precursor to today's Internet.

5. Strong program managers and flexible management structures have enhanced the effectiveness of computing research.

Research in computing, as in other fields, is a highly unpredictable endeavor. The results of research are not evident at the start, and their most important contributions often differ from those originally envisioned. Few expected that the Navy's attempt to build a programmable aircraft simulator in the late 1940s would result in the development of the first real-time digital computer (the Whirlwind); nor could DARPA program managers have anticipated that their early experiments on packet switching would evolve into the Internet and later the World Wide Web.

The potential for unanticipated outcomes of research has two implications for federal policy. First, it suggests that measuring the results of federally funded research programs is extremely difficult. Projects that appear to have failed often make significant contributions to later technology development or achieve other objectives not originally envisioned. Furthermore, research creates many intangible products, such as knowledge and educated researchers whose value is hard to quantify. Second, it implies that federal mechanisms for funding and managing research need to recognize the uncertainties inherent in computing research and to build in sufficient flexibility to accommodate mid-course changes and respond to unanticipated results.

A key element in agencies' ability to maintain flexibility in the past has been their program managers, who have responsibility for initiating, funding, and overseeing research programs. The funding and management styles of program managers at DARPA during the 1960s and 1970s, for example, reflected an ability to marry visions for technological progress with strong technical expertise and an understanding of the uncertainties of the research process. Many of these program managers and office directors were recruited from academic and industry research laboratories for limited tours of duty. They tended to lay down broad guidelines for new research areas and to draw specific project proposals from principal investigators, or researchers, in academic computer centers. This style of funding and management resulted in the government stimulating innovation with a light touch, allowing researchers room to pursue new avenues of inquiry. In turn, it helped attract top-notch program managers to federal agencies. With close ties to the field and its leading researchers, they were trusted by—and trusted in—the research community.

This funding style resulted in great advances in areas as diverse as computer graphics, artificial intelligence, networking, and computer architectures. Although mechanisms are clearly needed to ensure accountability and oversight in government-sponsored research, history demonstrates the benefits of instilling these values in program managers and providing them adequate support to pursue promising research directions.

6. Collaboration between industry and university researchers has facilitated the commercialization of computing research and maintained its relevance.

Innovation in computing requires the combined talents of university and industry researchers. Bringing them together has helped ensure that industry taps into new academic research and that university researchers

understand the challenges facing industry. Such collaboration also helps facilitate the commercialization of technology developed in a university setting. All of the areas described in this report's case studies—relational databases, the Internet, theoretical computer science, artificial intelligence, and virtual reality—involved university and industry participants. Other projects examined, such as SAGE, Project MAC, and very large scale integrated circuits, demonstrate the same phenomenon.

Collaboration between industry and universities can take many forms. Some projects combine researchers from both sectors on the same project team. Other projects involve a transition from academic research laboratories to industry (via either the licensing of key patents or the creation of new start-up companies) once the technology matures sufficiently. As the case studies demonstrate, effective linkages between industry and universities tended to emerge from projects, rather than being thrust upon them. Project teams assembled to build large systems included the range of skills needed for a particular project. University researchers often sought out productive avenues for transferring research results to industry, whether linking with existing companies or starting new ones. Such techniques have often been more effective than explicit attempts to encourage collaboration, many of which have foundered due to the often conflicting time horizons of university and industry researchers.

7. Organizational innovation and adaptation are necessary elements of federal research support.

Over time, new government organizations have formed to support computing research, and organizations have continually evolved in order to better match their structure to the needs of the research and policy-making communities. In response to proposals by Vannevar Bush and others that the country needed an organization to fund basic research, especially in the universities, for example, Congress established the National Science Foundation in 1950. A few years earlier, the Navy founded the Office of Naval Research to draw on science and engineering resources in the universities. In the early 1950s during an intense phase of the Cold War, the military services became the preeminent funders of computing and communications. The Soviet Union's launching of Sputnik in 1957 raised fears in Congress and the country that the Soviets had forged ahead of the United States in advanced technology. In response, the U.S. Department of Defense, pressured by the Eisenhower administration, established the Advanced Research Projects Agency (ARPA, now DARPA) to fund technological projects with military implications. In 1962 DARPA created the Information Processing Techniques Office (IPTO), whose initial re-

search agenda gave priority to further development of computers for command-and-control systems.

With the passage of time, new organizations have emerged, and old ones have often been reformed or reinvented to respond to new national imperatives and counter bureaucratic trends. DARPA's IPTO has transformed itself several times to bring greater coherence to its research efforts and to respond to technological developments. NSF in 1967 established the Office of Computing Activities and in 1986 formed the Computer and Information Sciences and Engineering (CISE) Directorate to couple and coordinate support for research, education, and infrastructure in computer science. In the 1980s NSF, which customarily has focused on basic research in universities, also began to encourage joint academic-industrial research centers through its Engineering Research Centers program. With the relative increase in industrial support of research and development in recent years, federal agencies such as NSF have rationalized their funding policies to complement short-term industrial R&D. Federal funding of long-term, high-risk initiatives continues to have a high priority.

As this history suggests, federal funding agencies will need to continue to adjust their strategies and tactics as national needs and imperatives change. The Cold War imperative shaped technological history during much of the last half-century. International competitiveness served as a driver of government funding of computing and communications during the late 1980s and early 1990s. With the end of the Cold War and the globalization of industry, the U.S. computing industries need to maintain their high rates of innovation, and federal structures for managing computing research may need to change to ensure that they are appropriate for this new environment.

Sources of U.S. Success

(From pp. 27-28): That the United States should be the leading country in computing and communications was not preordained. Early in the industry's formation, the United Kingdom was a serious competitor. The United Kingdom was the home of the Difference Engine and later the Analytical Engine, both of which were programmable mechanical devices designed and partially constructed by Charles Babbage and Ada, Countess of Lovelace, in the 19th century. Basic theoretical work defining a universal computer was the contribution of Alan Turing in Cambridge just before the start of World War II. The English defense industry—with Alan Turing's participation—conceived and constructed vacuum tube computers able to break the German military code. Both machines and their accomplishments were kept secret, much like the efforts and suc-

cesses of the National Security Agency in this country. After the war, English universities constructed research computers and developed computer concepts that later found significant use in U.S. products. Other European countries, Germany and France in particular, also made efforts to gain a foothold in this new technology.

How then did the United States become a leader in computing? The answer is manifold, and a number of external factors clearly played a role. The state of Europe, England in particular, at the end of World War II played a decisive role, as rebuilding a country and industry is a more difficult task than shifting from a war economy to a consumer economy. The movement of people among universities, industry, and government laboratories at the end of World War II in the United Kingdom and the United States also contributed by spreading the experience gained during the war, especially regarding electronics and computing. American students and scholars who were studying in England as Fulbright Scholars in the 1950s learned of the computer developments that had occurred during the war and that were continuing to advance.

Industrial prowess also played a role. After World War II, U.S. firms moved quickly to build an industrial base for computing. IBM and Remington Rand recognized quite early that electronic computers were a threat to their conventional electromechanical punched-card business and launched early endeavors into computing. . . . Over time, fierce competition and expectations of rapid market growth brought billions in venture money to the industry's inventors and caused a flowering of small high-tech innovators. Rapid expansion of the U.S. marketplace for computing equipment created buyers for new computing equipment. The rapid post-World War II expansion of civilian-oriented industries and financial sources created new demands for data and data processing. Insurance companies and banks were at the forefront of installing early computers in their operations. New companies, such as Engineering Research Associates, Datamatic, and Eckert-Mauchly, as well as established companies in the data processing field, such as IBM and Sperry Rand, saw an opportunity for new products and new markets. The combination of new companies and established ones was a powerful force. It generated fierce competition and provided substantial capital funds.

These factors helped the nation gain an early lead in computing that it has maintained. While firms from other nations have made inroads into computing technology—from memory chips to supercomputers—U.S. firms have continued to dominate both domestic and international markets in most product categories. This success reflects the strength of the nation's innovation system in computing technology, which has continually developed, marketed, and supported new products, processes, and services.

Research and Technological Innovation

(From pp. 28-31): Innovation is generally defined as the process of developing and putting into practice new products, processes, or services. It draws upon a range of activities, including research, product development, manufacturing, and marketing. Although often viewed as a linear, sequential process, innovation is usually more complicated, with many interactions among the different activities and considerable feedback. It can be motivated by new research advances or by recognition of a new market need. Government, universities, and industry all play a role in the innovation process.

Research is a vital part of innovation in computing. In dollar terms, research is just a small part of the innovation process, representing less than one-fifth of the cost of developing and introducing new products in the United States, with preparation of product specifications, prototype development, tooling and equipment, manufacturing start-up, and marketing start-up comprising the remainder. Indeed, computer manufacturers allocated an average of just 20 percent of their research and development budgets to research between 1976 and 1995, with the balance supporting product development. Even in the largest computer manufacturers, such as IBM, research costs are only about 1 to 2 percent of total operating expenses. Nevertheless, research plays a critical role in the innovation process, providing a base of scientific and technological knowledge that can be used to develop new products, processes, and services. This knowledge is used at many points in the innovation process—generating ideas for new products, processes, or services; solving particular problems in product development or manufacturing; or improving existing products, for example. . . .

Traditionally, research expenditures have been characterized as either basic or applied. The term “basic research” is used to describe work that is exploratory in nature, addressing fundamental scientific questions for which ready answers are lacking; the term “applied research” describes activities aimed at exploring phenomena necessary for determining the means by which a recognized need may be met. These terms, at best, distinguish between the motivations of researchers and the manner in which inquiries are conducted, and they are limited in their ability to describe the nature of scientific and technological research. Recent work has suggested that the definition of basic research be expanded to include explicitly both basic scientific research and basic technological research. This definition recognizes the value of exploratory research into basic technological phenomena that can be used in a variety of products. Examples include research on the blue laser, exploration of biosensors, and much of the fundamental work in computer engineering.

(From pp. 21-23): Clearly, the future of computing will differ from the history of computing because both the technology and environmental factors have changed. Attempts by companies to align their research activities more closely with product development processes have influenced the role they may play in the innovation process. As the computing industry has grown and the technology has diffused more widely throughout society, government has continued to represent a proportionally smaller portion of the industry.

The Benefits of Public Support of Research

(From pp. 46-47): The development of scientific and technological knowledge is a cumulative process, one that depends on the prompt disclosure of new findings so that they can be tested and, if confirmed, integrated with other bodies of reliable knowledge. In this way open science promotes the rapid generation of further discoveries and inventions, as well as wider practical exploitation of additions to the stock of knowledge.

The economic case for public funding of what is commonly referred to as basic research rests mainly on that insight, and on the observation that business firms are bound to be considerably discouraged by the greater uncertainties surrounding investment in fundamental, exploratory inquiries (compared to commercially targeted R&D), as well as by the difficulties of forecasting when and how such outlays will generate a satisfactory rate of return.

The proposition at issue here is quantitative, not qualitative. One cannot adequately answer the question "Will there be enough?" merely by saying, "There will be some." Economists do not claim that without public patronage (or intellectual property protection), basic research will cease entirely. Rather, their analysis holds that there will not be enough basic research—not as much as would be carried out were individual businesses (like society as a whole) able to anticipate capturing all the benefits of this form of investment. Therefore, no conflict exists between this theoretical analysis and the observation that R&D-intensive companies do indeed fund some exploratory research into fundamental questions. Their motives for this range from developing a capability to monitor progress at the frontiers of science, to identifying ideas for potential lines of innovation that may be emerging from the research of others, to being better positioned to penetrate the secrets of their rivals' technological practices.

Nevertheless, funding research is a long-term strategy, and therefore sensitive to commercial pressures to shift research resources toward advancing existing product development and improving existing processes,

rather than searching for future technological options. Large organizations that are less asset constrained, and of course the public sector, are better able to take on the job of pushing the frontiers of science and technology. Considerations of these kinds are important in addressing the issue of how to find the optimal balance for the national research effort between secrecy and disclosure of scientific and engineering information, as well as in trying to adjust the mix of exploratory and applications-driven projects in the national research portfolio.

(From p. 137): Quantifying the benefits of federal research support is a difficult, if not impossible, task for several reasons. First, the output of research is often intangible. Most of the benefit takes the form of new knowledge that subsequently may be instantiated in new hardware, software, or systems, but is itself difficult to measure. At other times, the benefits take the form of educated people who bring new ideas or a fresh perspective to an organization. Second, the delays between the time a research program is conducted and the time the products incorporating the research results are sold make measurement even more difficult. Often, the delays run into decades, making it difficult to tell midcourse how effective a particular program has been. Third, the benefits of a particular research program may not become visible until other technological advances are made. For example, advances in computer graphics did not have widespread effect until suitable hardware was more broadly available for producing three-dimensional graphical images. Finally, projects that are perceived as failures often provide valuable lessons that can guide or improve future research. Even if they fail to reach their original objectives, research projects can make lasting contributions to the knowledge base.

Maintaining University Research Capabilities

(From pp. 139-140): Federal funding has . . . maintained university research capabilities in computing. Universities depend largely on federal support for research programs in computer science and electrical engineering, the two academic disciplines most closely aligned with computing and communications. Since 1973, federal agencies have provided roughly 70 percent of all funding for university research in computer science. In electrical engineering, federal funding has declined from its peak of 75 percent of total university research support in the early 1970s, but still represented 65 percent of such funding in 1995. Additional support has come in the form of research equipment. Universities need access to state-of-the-art equipment in order to conduct research and train students. Although industry contributes some equipment, funding for uni-

versity research equipment has come largely from federal sources since the 1960s. Between 1981 and 1995, the federal government provided between 59 and 76 percent of annual research equipment expenditures in computer science and between 64 and 83 percent of annual research equipment expenditures in electrical engineering. Such investments have helped ensure that researchers have access to modern computing facilities and have enabled them to further expand the capabilities of computing and communications systems.

Universities play an important role in the innovation process. They tend to concentrate on research with broad applicability across companies and product lines and to share new knowledge openly. Because they are not usually subject to commercial pressures, university researchers often have greater ability than their industrial counterparts to explore ideas with uncertain long-term payoffs. Although it would be difficult to determine how much university research contributes directly to industrial innovation, it is telling that each of the case studies and other major examples examined in [the source] report—relational databases, the Internet, theoretical computer science, artificial intelligence, virtual reality, SAGE, computer time-sharing, very large scale integrated circuits, and the personal computer—involved the participation of university researchers. Universities play an especially effective role in disseminating new knowledge by promoting open publication of research results. They have also served as a training ground for students who have taken new ideas with them to existing companies or started their own companies. Diffusion of knowledge about relational databases, for instance, was accelerated by researchers at the University of California at Berkeley who published the source code for their Ingres system and made it available free of charge. Several of the lead researchers in this project established companies to commercialize the technology or brought it back to existing firms where they championed its use.

Creating Human Resources

(From pp. 140-141): In addition to supporting the creation of new technology, federal funding for research has also helped create the human resources that have driven the computer revolution. Many industry researchers and research managers claim that the most valuable result of university research programs is educated students—by and large, an outcome enabled by federal support of university research. Federal support for university research in computer science grew from \$65 million to \$350 million between 1976 and 1995, while federal support for university research in electrical engineering grew from \$74 million to \$177 million (in constant 1995 dollars). Much of this funding was used to support gradu-

ate students. Especially at the nation's top research universities, the studies of a large percentage of graduate students have been supported by federal research contracts. Graduates of these programs, and faculty researchers who received federal funding, have gone on to form a number of companies, including Sun Microsystems, Inc. (which grew out of research conducted by Forest Baskett and Andy Bechtolsheim with sponsorship from DARPA) and Digital Equipment Corporation (founded by Ken Olsen, who participated in the SAGE project). Graduates also staff academic faculties that continue to conduct research and educate future generations of researchers.

Furthermore, the availability of federal research funding has enabled the growth and expansion of computer science and computer engineering departments at U.S. universities, which increased in number from 6 in 1965 to 56 in 1975 and to 148 in 1995. The number of graduate students in computer science also grew dramatically, expanding more than 40-fold from 257 in 1966 to 11,500 in 1995, with the number of Ph.D. degrees awarded in computer science increasing from 19 in 1966 to over 900 in 1995. Even with this growth in Ph.D. production, demand for computing researchers still outstrips the supply in both industry and academia.

Beyond supporting student education and training, federal funding has also been important in creating networks of researchers in particular fields—developing communities of researchers who could share ideas and build on each other's strengths. Despite its defense orientation, DARPA historically encouraged open dissemination of the results of sponsored research, as did other federal agencies. In addition, DARPA and other federal agencies funded large projects with multiple participants from different organizations. These projects helped create entire communities of researchers who continued to refine, adopt, and diffuse new technology throughout the broader computing research community. Development of the Internet demonstrates the benefits of this approach: by funding groups of researchers in an open environment, DARPA created an entire community of users who had a common understanding of the technology, adopted a common set of standards, and encouraged their use broadly. Early users of the ARPANET created a critical mass of people who helped to disseminate the technology, giving the Internet Protocol an important early lead over competing approaches to packet switching.

The Organization of Federal Support: A Historical Review

(From pp. 85-86): Rather than a single, overarching framework of support, federal funding for research in computing has been managed by a set of agencies and offices that carry the legacies of the historical periods in which they were created. Crises such as World War II, Korea, Sputnik,

Vietnam, the oil shocks, and concerns over national competitiveness have all instigated new modes of government support. Los Alamos National Laboratory, for example, a leader in supercomputing, was created by the Manhattan Project and became part of the Department of Energy. The Office of Naval Research and the National Science Foundation emerged in the wake of World War II to continue the successful contributions of wartime science. The Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration (NASA) are products of the Cold War, created in response to the launch of Sputnik to regain the nation's technological leadership. The National Bureau of Standards, an older agency, was transformed into the National Institute of Standards and Technology in response to . . . concerns about national competitiveness. Each organization's style, mission, and importance have changed over time; yet each organization profoundly reflects the process of its development, and the overall landscape is the result of numerous layers of history.

Understanding these layers is crucial for discussing the role of the federal government in computing research. [The following sections briefly set] out a history of the federal government's programmatic involvement in computing research since 1945, distinguishing the various layers in the historical eras in which they were first formed. The objective is to identify the changing role the government has played in these different historical periods, discuss the changing political and technological environment in which federal organizations have acted, and draw attention to the multiplicity, diversity, and flexibility of public-sector programs that have stimulated and underwritten the continuing stream of U.S. research in computing and communications since World War II. In fulfilling this charge, [the following text] reviews a number of prominent federal research programs that exerted profound influence on the evolving computing industry. These programs are illustrative of the effects of federal funding on the industry at different times. Other programs, too numerous to describe here, undoubtedly played key roles in the history of the computing industry but are not considered here.

1945-1960: Era of Government Computers

(From pp. 86-87): In late 1945, just a few weeks after atomic bombs ended World War II and thrust the world into the nuclear age, digital electronic computers began to whirl. The ENIAC (Electronic Numerical Integrator and Computer), built at the University of Pennsylvania and funded by the Army Ballistics Research Laboratory, was America's first such machine. The following 15 years saw electronic computing grow from a laboratory technology into a routine, useful one. Computing hard-

ware moved from the ungainly and delicate world of vacuum tubes and paper tape to the reliable and efficient world of transistors and magnetic storage. The 1950s saw the development of key technical underpinnings for widespread computing: cheap and reliable transistors available in large quantities, rotating magnetic drum and disk storage, magnetic core memory, and beginning work in semiconductor packaging and miniaturization, particularly for missiles. In telecommunications, American Telephone and Telegraph (AT&T) introduced nationwide dialing and the first electronic switching systems at the end of the decade. A fledgling commercial computer industry emerged, led by International Business Machines (IBM) (which built its electronic computer capability internally) and Remington Rand (later Sperry Rand), which purchased Eckert-Mauchly Computer Corporation in 1950 and Engineering Research Associates in 1952. Other important participants included Bendix, Burroughs, General Electric (GE), Honeywell, Philco, Raytheon, and Radio Corporation of America (RCA).

In computing, the technical cutting edge, however, was usually pushed forward in government facilities, at government-funded research centers, or at private contractors doing government work. Government funding accounted for roughly three-quarters of the total computer field. A survey performed by the Army Ballistics Research Laboratory in 1957, 1959, and 1961 lists every electronic stored-program computer in use in the country (the very possibility of compiling such a list says a great deal about the community of computing at the time). The surveys reveal the large proportion of machines in use for government purposes, either by federal contractors or in government facilities.

The Government's Early Role

(From pp. 87-88): Before 1960, government—as a funder and as a customer—dominated electronic computing. Federal support had no broad, coherent approach, however, arising somewhat ad hoc in individual federal agencies. The period was one of experimentation, both with the technology itself and with diverse mechanisms for federal support. From the panoply of solutions, distinct successes and failures can be discerned, from both scientific and economic points of view. After 1960, computing was more prominently recognized as an issue for federal policy. The National Science Foundation and the National Academy of Sciences issued surveys and reports on the field.

If government was the main driver for computing research and development (R&D) during this period, the main driver for government was the defense needs of the Cold War. Events such as the explosion of a Soviet atomic bomb in 1949 and the Korean War in the 1950s heightened

international tensions and called for critical defense applications, especially command-and-control and weapons design. It is worth noting, however, that such forces did not exert a strong influence on telecommunications, an area in which most R&D was performed within AT&T for civilian purposes. Long-distance transmission remained analog, although digital systems were in development at AT&T's Bell Laboratories. Still, the newly emergent field of semiconductors was largely supported by defense in its early years. During the 1950s, the Department of Defense (DOD) supported about 25 percent of transistor research at Bell Laboratories.

However much the Cold War generated computer funding, during the 1950s dollars and scale remained relatively small compared to other fields, such as aerospace applications, missile programs, and the Navy's Polaris program (although many of these programs had significant computing components, especially for operations research and advanced management techniques). By 1950, government investment in computing amounted to \$15 million to \$20 million per year.

All of the major computer companies during the 1950s had significant components of their R&D supported by government contracts of some type. At IBM, for example, federal contracts supported more than half of the R&D and about 35 percent of R&D as late as 1963 (only in the late 1960s did this proportion of support trail off significantly, although absolute amounts still increased). The federal government supported projects and ideas the private sector would not fund, either for national security, to build up human capital, or to explore the capabilities of a complex, expensive technology whose long-term impact and use was uncertain. Many federally supported projects put in place prototype hardware on which researchers could do exploratory work.

Establishment of Organizations

(From pp. 88-95): The successful development projects of World War II, particularly radar and the atomic bomb, left policymakers asking how to maintain the technological momentum in peacetime. Numerous new government organizations arose, attempting to sustain the creative atmosphere of the famous wartime research projects and to enhance national leadership in science and technology. Despite Vannevar Bush's efforts to establish a new national research foundation to support research in the nation's universities, political difficulties prevented the bill from passing until 1950, and the National Science Foundation (NSF) did not become a significant player in computing until later in that decade. During the 15 years immediately after World War II, research in computing and communications was supported by mission agencies of the federal government, such as DOD, the Department of Energy (DOE), and NASA. In

retrospect, it seems that the nation was experimenting with different models for supporting this intriguing new technology that required a subtle mix of scientific and engineering skill.

Military Research Offices

Continuity in basic science was provided primarily by the Office of Naval Research (ONR), created in 1946 explicitly to perpetuate the contributions scientists made to military problems during World War II. In computing, the agency took a variety of approaches simultaneously. First, it supported basic intellectual and mathematical work, particularly in numerical analysis. These projects proved instrumental in establishing a sound mathematical basis for computer design and computer processing. Second, ONR supported intellectual infrastructure in the infant field of computing, sponsoring conferences and publications for information dissemination. Members of ONR participated in founding the Association for Computing Machinery in 1947.

ONR's third approach to computing was to sponsor machine design and construction. It ordered a computer for missile testing through the National Bureau of Standards from Raytheon, which became known as the Raydac machine, installed in 1952. ONR supported Whirlwind, MIT's first digital computer and progenitor of real-time command-and-control systems. John von Neumann built a machine with support from ONR and other agencies at Princeton's Institute for Advanced Study, known as the IAS computer. The project produced significant advances in computer architecture, and the design was widely copied by both government and industrial organizations.

Other military services created offices on a model similar to that of ONR. The Air Force Office of Scientific Research was established in 1950 to manage U.S. Air Force R&D activities. Similarly, the U.S. Army established the Army Research Office to manage and promote Army programs in science and technology.

National Bureau of Standards

Arising out of its role as arbiter of weights and measures, the National Bureau of Standards (NBS) had long had its own laboratories and technical expertise and had long served as a technical advisor to other government agencies. In the immediate postwar years, NBS sought to expand its advisory role and help U.S. industry develop wartime technology for commercial purposes. NBS, through its National Applied Mathematics Laboratory, acted as a kind of expert agent for other government agencies, selecting suppliers and overseeing construction and delivery of

new computers. For example, NBS contracted for the three initial Univac machines—the first commercial, electronic, digital, stored-program computers—one for the Census Bureau and two for the Air Materiel Command.

NBS also got into the business of building machines. When the Univac order was plagued by technical delays, NBS built its own computer in-house. The Standards Eastern Automatic Computer (SEAC) was built for the Air Force and dedicated in 1950, the first operational, electronic, stored-program computer in this country. NBS built a similar machine, the Standards Western Automatic Computer (SWAC) for the Navy on the West Coast. Numerous problems were run on SEAC, and the computer also served as a central facility for diffusing expertise in programming to other government agencies. Despite this significant hardware, however, NBS's bid to be a government center for computing expertise ended in the mid-1950s. Caught up in postwar debates over science policy and a controversy over battery additives, NBS research funding was radically reduced, and NBS lost its momentum in the field of computing.

Atomic Energy Commission

Nuclear weapons design and research have from the beginning provided impetus to advances in large-scale computation. The first atomic bombs were designed only with desktop calculators and punched-card equipment, but continued work on nuclear weapons provided some of the earliest applications for the new electronic machines as they evolved. The first computation job run on the ENIAC in 1945 was an early calculation for the hydrogen bomb project "Super." In the late 1940s, the Los Alamos National Laboratory built its own computer, MANIAC, based on von Neumann's design for the Institute for Advanced Study computer at Princeton, and the Atomic Energy Commission (AEC) funded similar machines at Argonne National Laboratory and Oak Ridge National Laboratory.

In addition to building their own computers, the AEC laboratories were significant customers for supercomputers. The demand created by AEC laboratories for computing power provided companies with an incentive to design more powerful computers with new designs. In the early 1950s, IBM built its 701, the Defense Calculator, partly with the assurance that Los Alamos and Livermore would each buy at least one. In 1955, the AEC laboratory at Livermore, California, commissioned Remington Rand to design and build the Livermore Automatic Research Computer (LARC), the first supercomputer. The mere specification for LARC advanced the state of the art, as the bidding competition required the use of transistors instead of vacuum tubes. IBM developed improved

ferrite-core memories and supercomputer designs with funding from the National Security Agency, and designed and built the Stretch supercomputer for the Los Alamos Scientific Laboratory, beginning it in 1956 and installing it in 1961. Seven more Stretch supercomputers were built. Half of the Stretch supercomputers sold were used for nuclear weapon research and design.

The AEC continued to specify and buy newer and faster supercomputers, including the Control Data 6600, the STAR 100, and the Cray 1 (although developed without AEC funds), practically ensuring a market for continued advancements. AEC and DOE laboratories also developed much of the software used in high-performance computing including operating systems, numerical analysis software, and matrix evaluation routines. In addition to stimulating R&D in industry, the AEC laboratories also developed a large talent pool on which the computer industry and academia could draw. In fact, the head of IBM's Applied Science Department, Cuthbert Hurd, came directly to IBM in 1949 from the AEC's Oak Ridge National Laboratory. Physicists worked on national security problems with government support providing demand, specifications, and technical input, as well as dollars, for industry to make significant advances in computing technology.

Private Organizations

Not all the new organizations created by the government to support computing were public. A number of new private organizations also sprang up with innovative new charters and government encouragement that held prospects of initial funding support. In 1956, at the request of the Air Force, the Massachusetts Institute of Technology (MIT) created Project Lincoln, now known as the Lincoln Laboratory, with a broad charter to study problems in air defense to protect the nation from nuclear attack. The Lincoln Laboratory then oversaw the construction of the Semi-Automatic Ground Environment (SAGE) air-defense system. In 1946, the Air Force and Douglas Aircraft created a joint venture, Project RAND, to study intercontinental warfare. In the following year RAND separated from Douglas and became the independent, nonprofit RAND Corporation.

RAND worked only for the Air Force until 1956, when it began to diversify to other defense and defense-related contractors, such as the Advanced Research Projects Agency and the Atomic Energy Commission, and provided, for a time, what one researcher called "in some sense the world's largest installation for scientific computing [in 1950]." RAND specialized in developing computer systems, such as the Johnniac, based on the IAS computer, which made RAND the logical source for the pro-

gramming on SAGE. While working on SAGE, RAND trained hundreds of programmers, eventually leading to the spin-off of RAND's Systems Development Division and Systems Training Program into the Systems Development Corporation. Computers made a major impact on the systems analysis and game theoretic approaches that RAND and other similar think tanks used in attempts to model nuclear and conventional warfighting strategies.

Engineering Research Associates (ERA) represented yet another form of government support: the private contractor growing out of a single government agency. With ERA, the Navy effectively privatized its wartime cryptography organization and was able to maintain civilian expertise through the radical postwar demobilization. ERA was founded in St. Paul, Minnesota, in January 1946 by two engineers who had done cryptography for the Navy and their business partners. The Navy moved its Naval Computing Machine Laboratory from Dayton to St. Paul, and ERA essentially became the laboratory. ERA did some research, but it primarily worked on task-oriented, cost-plus contracts. As one participant recalled, "It was not a university atmosphere. It was 'Build stuff. Make it work. How do you package it? How do you fix it? How do you document it?'" ERA built a community of engineering skill, which became the foundation of the Minnesota computer industry. In 1951, for example, the company hired Seymour Cray for his first job out of the University of Minnesota.

As noted earlier, the RAND Corporation had contracted in 1955 to write much of the software for SAGE owing to its earlier experience in air defense and its large pool of programmers. By 1956, the Systems Training Program of the RAND Corporation, the division assigned to SAGE, was larger than the rest of the corporation combined, and it spun off into the nonprofit Systems Development Corporation (SDC). SDC played a significant role in computer training. As described by one of the participants, "Part of SDC's nonprofit role was to be a university for programmers. Hence our policy in those days was not to oppose the recruiting of our personnel and not to match higher salary offers with an SDC raise." By 1963, SDC had trained more than 10,000 employees in the field of computer systems. Of those, 6,000 had moved to other businesses across the country.

Observations

(From pp. 95-96): In retrospect, the 1950s appear to have been a period of institutional and technological experimentation. This diversity of approaches, while it brought the field and the industry from virtually nothing to a tentative stability, was open to criticisms of waste, duplica-

tion of effort, and ineffectiveness caused by rivalries among organizations and their funding sources. The field was also driven largely by the needs of government agencies, with relatively little input from computer-oriented scientists at the highest levels. Criticism remained muted during the decade when the military imperatives of the Cold War seemed to dominate all others, but one event late in the decade opened the entire system of federal research support to scrutiny: the launch of Sputnik in 1957. Attacks mounted that the system of R&D needed to be changed, and they came not only from the press and the politicians but also from scientists themselves.

1960-1970: Supporting a Continuing Revolution

(From p. 96): Several significant events occurred to mark a transition from the infancy of information technology to a period of diffusion and growth. Most important of these was the launching of Sputnik in 1957, which sent convulsions through the U.S. science and engineering world and redoubled efforts to develop new technology. President Eisenhower elevated scientists and engineers to the highest levels of policy making. Thus was inaugurated what some have called the golden age of U.S. research policy. Government support for information technology took off in the 1960s and assumed its modern form. The Kennedy administration brought a spirit of technocratic reform to the Pentagon and the introduction of systems analysis and computer-based management to all aspects of running the military. Many of the visions that set the research agendas for the following 15 years (and whose influence remains today) were set in the early years of the decade.

Maturing of a Commercial Industry

(From pp. 96-97): Perhaps most important, the early 1960s can be defined as the time when the commercial computer industry became significant on its own, independent of government funding and procurement. Computerized reservation systems began to proliferate, particularly the IBM/American Airlines SABRE system, based in part on prior experience with military command-and-control systems (such as SAGE). The introduction of the IBM System/360 in 1964 solidified computer applications in business, and the industry itself, as significant components of the economy.

This newly vital industry, dominated by "Snow White" (IBM) and the "Seven Dwarfs" (Burroughs, Control Data, GE, Honeywell, NCR, RCA, and Sperry Rand), came to have several effects on government-supported R&D. First, and most obvious, some companies (mostly IBM) became

large enough to conduct their own in-house research. IBM's Thomas J. Watson Research Center was dedicated in 1961. Its director, Emanuel Piore, was recruited from ONR, and he emphasized basic research. Such laboratories not only expanded the pool of researchers in computing and communications but also supplied a source of applied research that allowed or, conversely, pushed federal support to focus increasingly on the longest-term, riskiest ideas and on problems unique to government. Second, the industry became a growing employer of computer professionals, providing impetus to educational programs at universities and making computer science and engineering increasingly attractive career paths to talented young people.

These years saw turning points in telecommunications as well. In 1962, AT&T launched the first active communications satellite, Telstar, which transmitted the first satellite-relay telephone call and the first live transatlantic television signal. That same year, a less-noticed but equally significant event occurred when AT&T installed the first commercial digital-transmission system. Twenty-four digital speech channels were time multiplexed onto a repeatered digital transmission line operating at 1.5 megabits per second. In 1963, the first Stored Program Control electronic switching system was placed into service, inaugurating the use of digital computer technology for mainstream switching.

The 1960s also saw the emergence of the field called computer science, and several important university departments were founded during the decade, at Stanford and Carnegie Mellon in 1965 and at MIT in 1968. Hardware platforms had stabilized enough to support a community of researchers who attacked a common set of problems. New languages proliferated, often initiated by government and buoyed by the needs of commercial industry. The Navy had sponsored Grace Hopper and others during the 1950s to develop automatic programming techniques that became the first compilers. John Backus and a group at IBM developed FORTRAN, which was distributed to IBM users in 1957. A team led by John McCarthy at MIT (with government support) began implementing LISP in 1958, and the language became widely used, particularly for artificial intelligence programming, in the early 1960s. In 1959, the Pentagon began convening a group of computer experts from government, academia, and industry to define common business languages for computers. The group published a specification in 1959, and by 1960 RCA and Remington Rand Univac had produced the first COBOL compilers. By the beginning of the 1960s, a number of computer languages, standard across numerous hardware platforms, were beginning to define programming as a task, as a profession, and as a challenging and legitimate subject of intellectual inquiry.

The Changing Federal Role

(From pp. 98-107): The forces driving government support changed during the 1960s. The Cold War remained a paramount concern, but to it were added the difficult conflict in Vietnam, the Great Society programs, and the Apollo program, inaugurated by President Kennedy's 1961 challenge. New political goals, new technologies, and new missions provoked changes in the federal agency population. Among these, two agencies became particularly important in computing: the new Advanced Research Projects Agency and the National Science Foundation.

The Advanced Research Projects Agency

The founding of the Advanced Research Projects Agency (ARPA) in 1958, a direct outgrowth of the Sputnik scare, had immeasurable impact on computing and communications. ARPA, specifically charged with preventing technological surprises like Sputnik, began conducting long-range, high-risk research. It was originally conceived as the DOD's own space agency, reporting directly to the Secretary of Defense in order to avoid interservice rivalry. Space, like computing, did not seem to fit into the existing military service structure. ARPA's independent status not only insulated it from established service interests but also tended to foster radical ideas and keep the agency tuned to basic research questions: when the agency-supported work became too much like systems development, it ran the risk of treading on the territory of a specific service.

ARPA's status as the DOD space agency did not last long. Soon after NASA's creation in 1958, ARPA retained essentially no role as a space agency. ARPA instead focused its energies on ballistic missile defense, nuclear test detection, propellants, and materials. It also established a critical organizational infrastructure and management style: a small, high-quality managerial staff, supported by scientists and engineers on rotation from industry and academia, successfully employing existing DOD laboratories and contracting procedures (rather than creating its own research facilities) to build solid programs in new, complex fields. ARPA also emerged as an agency extremely sensitive to the personality and vision of its director.

ARPA's decline as a space agency raised questions about its role and character. A new director, Jack Ruina, answered the questions in no uncertain terms by cementing the agency's reputation as an elite, scientifically respected institution devoted to basic, long-term research projects. Ruina, ARPA's first scientist-director, took office at the same time as Kennedy and McNamara in 1961, and brought a similar spirit to the

agency. Ruina decentralized management at ARPA and began the tradition of relying heavily on independent office directors and program managers to run research programs. Ruina also valued scientific and technical merit above immediate relevance to the military. Ruina believed both of these characteristics—*independence and intellectual quality*—were critical to attracting the best people, both to ARPA as an organization and to ARPA-sponsored research. Interestingly, ARPA's managerial success did not rely on innovative managerial techniques per se (such as the computerized project scheduling typical of the Navy's Polaris project) but rather on the creative use of existing mechanisms such as "no-year money," unsolicited proposals, sole-source procurement, and multiyear forward funding.

ARPA and Information Technology. From the point of view of computing, the most important event at ARPA in the early 1960s, indeed in all of ARPA's history, was the establishment of the Information Processing Techniques Office, IPTO, in 1962. The impetus for this move came from several directions, including Kennedy's call a year earlier for improvements in command-and-control systems to make them "more flexible, more selective, more deliberate, better protected, and under ultimate civilian authority at all times." Computing as applied to command and control was the ideal ARPA program—it had no clearly established service affinity; it was "a new area with relatively little established service interest and entailed far less constraint on ARPA's freedom of action," than more familiar technologies. Ruina established IPTO to be devoted not to command and control but to the more fundamental problems in computing that would, eventually, contribute solutions.

Consistent with his philosophy of strong, independent, and scientific office managers, Ruina appointed J.C.R. Licklider to head IPTO. The Harvard-trained psychologist came to ARPA in October 1962, primarily to run its Command and Control Group. Licklider split that group into two discipline-oriented offices: Behavioral Sciences Office and IPTO. Licklider had had extensive exposure to the computer research of the time and had clearly defined his own vision of "man-computer symbiosis," which he had published in a landmark paper of 1960 by the same name. He saw human-computer interaction as the key, not only to command and control, but also to bringing together the then-disparate techniques of electronic computing to form a unified science of computers as tools for augmenting human thought and creativity. Licklider formed IPTO in this image, working largely independently of any direction from Ruina, who spent the majority of his time on higher-profile and higher-funded missile defense issues. Licklider's timing was opportune: the 1950s had produced a stable technology of digital computer hardware, and the big systems

projects had shown that programming these machines was a difficult but interesting problem in its own right. Now the pertinent questions concerned how to use “this tremendous power . . . for other than purely numerical scientific calculations.” Licklider not only brought this vision to IPTO itself, but he also promoted it with missionary zeal to the research community at large. Licklider’s and IPTO’s success derived in large part from their skills at “selling the vision” in addition to “buying the research.”

Another remarkable feature of IPTO, particularly during the 1960s, was its ability to maintain the coherent vision over a long period of time; the office director was able to handpick his successor. Licklider chose Ivan Sutherland, a dynamic young researcher he had encountered as a graduate student at MIT and the Lincoln Laboratory, to succeed him in 1964. Sutherland carried on Licklider’s basic ideas and made his own impact by emphasizing computer graphics. Sutherland’s own successor, Robert Taylor, came in 1966 from a job as a program officer at NASA and recalled, “I became heartily subscribed to the Licklider vision of interactive computing.” While at IPTO, Taylor emphasized networking. The last IPTO director of the 1960s, Lawrence Roberts, came, like Sutherland, from MIT and Lincoln Laboratory, where he had worked on the early transistorized computers and had conducted ARPA research in both graphics and communications.

During the 1960s, ARPA and IPTO had more effect on the science and technology of computing than any other single government agency, sometimes raising concern that the research agenda for computing was being directed by military needs. IPTO’s sheer size, \$15 million in 1965, dwarfed other agencies such as ONR. Still, it is important to note, ONR and ARPA worked closely together; ONR would often let small contracts to researchers and serve as a talent agent for ARPA, which would then fund promising projects at larger scale. ARPA combined the best features of existing military research support with a new, lean administrative structure and innovative management style to fund high-risk projects consistently. The agency had the freedom to administer large block grants as well as multiple-year contracts, allowing it the luxury of a long-term vision to foster technologies, disciplines, and institutions. Further, the national defense motivation allowed IPTO to concentrate its resources on centers of scientific and engineering excellence (such as MIT, Carnegie Mellon University, and Stanford University) without regard for geographical distribution questions with which NSF had to be concerned. Such an approach helped to create university-based research groups with the critical mass and stability of funding needed to create significant advances in particular technical areas. But although it trained generations of young researchers in those areas, ARPA’s funding style did little to help them pursue the

same lines of work at other universities. As an indirect and possibly unintended consequence, the research approaches and tools and the generic technologies developed under ARPA's patronage were disseminated more rapidly and widely, and so came to be applied in new nonmilitary contexts by the young M.S. and Ph.D. graduates who had been trained in that environment but could not expect to make their research careers within it.

ARPA's Management Style. To evaluate research proposals, IPTO did not employ the peer-review process like NSF, but rather relied on internal reviews and the discretion of program managers as did ONR. These program managers, working under office managers such as Licklider, Sutherland, Taylor, and Roberts, came to have enormous influence over their areas of responsibility and became familiar with the entire field both personally and intellectually. They had the freedom and the resources to shape multiple R&D contracts into a larger vision and to stimulate new areas of inquiry. The education, recruiting, and responsibilities of these program managers thus became a critical parameter in the character and success of ARPA programs. ARPA frequently chose people who had training and research experience in the fields they would fund, and thus who had insight and opinions on where those fields should go.

To have such effects, the program managers were given enough funds to let a large enough number of contracts and to shape a coherent research program, with minimal responsibilities for managing staffs. Program budgets usually required only two levels of approval above the program manager: the director of IPTO and the director of ARPA. One IPTO member described what he called "the joy of ARPA. . . . You know, if a program manager has a good idea, he has got two people to convince that that is a good idea before the guy goes to work. He has got the director of his office and the director of ARPA, and that is it. It is such a short chain of command."

Part of ARPA's philosophy involved aiming at radical change rather than incremental improvement. As Robert Taylor put it, for example, incremental innovation would be taken care of by the services and their contractors, but, ARPA's aim was "an order of magnitude difference." ARPA identified good ideas and magnified them. This strategy often necessitated funding large, group-oriented projects and institutions rather than individuals. Taylor recalled, "I don't remember a single case where we ever funded a single individual's work. . . . The individual researcher who is just looking for support for his own individual work could [potentially] find many homes to support that work. So we tended not to fund those, because we felt that they were already pretty well covered. Instead, we funded larger groups—teams." NSF's peer-review process worked

well for individual projects, but was not likely to support large, team-oriented research projects. Nor did it, at this point in history, support entire institutions and research centers, like the Laboratory for Computer Science at MIT. IPTO's style meshed with its emphasis on human-machine interaction, which it saw as fundamentally a systems problem and hence fundamentally team oriented. In Taylor's view, the university reward structure was much more oriented toward individual projects, so "systems research is most difficult to fund and manage in a university." This philosophy was apparent in ARPA's support of Project MAC, an MIT-led effort on time-shared computing. . . .

ARPA, with its clearly defined mission to support DOD technology, could also afford to be elitist in a way that NSF, with a broader charter to support the country's scientific research, could not. "ARPA had no commitment, for example, to take geography into consideration when it funded work." Another important feature of ARPA's multiyear contracts was their stability, which proved critical for graduate students who could rely on funding to get them through their Ph.D. program. ARPA also paid particular attention to building communities of researchers and disseminating the results of its research, even beyond traditional publications. IPTO would hold annual meetings for its contract researchers at which results would be presented and debated. These meetings proved effective not only at advancing the research itself but also at providing valuable feedback for the program managers and helping to forge relationships between researchers in related areas. Similar conferences were convened for graduate students only, thus building a longer-term community of researchers. ARPA also put significant effort into getting the results of its research programs commercialized so that DOD could benefit from the development and expansion of a commercial industry for information technology. ARPA sponsored conferences that brought together researchers and managers from academia and industry on topics such as time-sharing, for example.

Much has been made of ARPA's management style, but it would be a mistake to conclude that management per se provided the keys to the agency's successes in computing. The key point about the style, in fact, was its light touch. Red tape was kept to a minimum, and project proposals were turned around quickly, frequently into multiple-year contracts. Typical DOD research contracts involved close monitoring and careful adherence to requirements and specifications. ARPA avoided this approach by hiring technically educated program managers who had continuing research interests in the fields they were managing. This reality counters the myth that government bureaucrats heavily-handedly selected R&D problems and managed the grants and contracts. Especially during the 1960s and 1970s, program managers and office directors were not

bureaucrats but were usually academics on a 2-year tour of duty. They saw ARPA as a pulpit from which to preach their visions, with money to help them realize those visions. The entire system displayed something of a self-organizing, self-managing nature. As Ivan Sutherland recalled, "Good research comes from the researchers themselves rather than from the outside."

National Science Foundation

While ARPA was focusing on large projects and systems, the National Science Foundation played a large role in legitimizing basic computer science research as an academic discipline and in funding individual researchers at a wide range of institutions. Its programs in computing have evolved considerably since its founding in 1950, but have tended to balance support for research, education, and computing infrastructure. Although early programs tended to focus on the use of computing in other academic disciplines, NSF subsequently emerged as the leading federal funder of basic research in computer science.

NSF was formed before computing became a clearly defined research area, and it established divisions for chemistry, physics, and biology, but not computing. NSF did provide support for computing in its early years, but this support derived more from a desire to promote computer-related activities in other disciplines than to expand computer science as a discipline, and as such was weighted toward support for computing infrastructure. For example, NSF poured millions of dollars into university computing centers so that researchers in other disciplines, such as physics and chemistry, could have access to computing power. NSF noted that little computing power was available to researchers at American universities who were not involved in defense-related research and that "many scientists feel strongly that further progress in their field will be seriously affected by lack of access to the techniques and facilities of electronic computation." As a result, NSF began supporting computing centers at universities in 1956 and, in 1959, allocated a budget specifically for computer equipment purchases. Recognizing that computing technology was expensive, became obsolete rapidly, and entailed significant costs for ongoing support, NSF decided that it would, in effect, pay for American campuses to enter the computer age. In 1962, it established its first office devoted to computing, the program for Computers and Computing Science within the Mathematical Sciences Division. By 1970, the Institutional Computing Services (or Facilities) program had obligated \$66 million to university computing centers across the country. NSF intended that use of the new facilities would result in trained personnel to fulfill increasing needs for computer proficiency in industry, government, and academia.

NSF provided some funding for computer-related research in its early years. Originally, such funding came out of the mathematics division in the 1950s and grew out of an interest in numerical analysis. By 1955, NSF began to fund basic research in computer science theory with its first grants for the research of recursion theory and one grant to develop an analytical computer program under the Mathematical Sciences Program. Although these projects constituted less than 10 percent of the mathematics budget, they resulted in significant research.

In 1967, NSF united all the facets of its computing support into a single office, the Office of Computing Activities (OCA). The new office incorporated elements from the directorates of mathematics and engineering and from the Facilities program, unifying NSF's research and infrastructure efforts in computing. It also incorporated an educational element that was intended to help meet the radically increasing demand for instruction in computer science. The OCA was headed by Milton Rose, the former head of the Mathematical Sciences Section, and reported directly to the director of NSF.

Originally, the OCA's main focus was improving university computing services. In 1967, \$11.3 million of the office's \$12.8 million total budget went toward institutional support. Because not all universities were large enough to support their own computing centers but would benefit from access to computing time at other universities, the OCA also began to support regional networks linking many universities together. In 1968, the OCA spent \$5.3 million, or 18.6 percent of its budget, to provide links between computers in the same geographic region. In the 1970s, the computer center projects were canceled, however, in favor of shifting emphasis toward education and research.

Beginning in 1968, through the Education and Training program, the OCA began funding the inauguration of university-level computer science programs. NSF funded several conferences and studies to develop computer science curricula. The Education and Training program obligated \$12.3 million between 1968 and 1970 for training, curricula development, and support of computer-assisted instruction.

Although the majority of the OCA's funding was spent on infrastructure and education, the office also supported a broad range of basic computer science research programs. These included compiler and language development, theoretical computer science, computation theory, numerical analysis, and algorithms. The Computer Systems Design program concentrated on computer architecture and systems analysis. Other programs focused on topics in artificial intelligence, including pattern recognition and automatic theory proving.

1970-1990: Retrenching and International Competition

(From p. 107): Despite previous successes, the 1970s opened with computing at a critical but fragile point. Although produced by a large and established industry, commercial computers remained the expensive, relatively esoteric tools of large corporations, research institutions, and government. Computing had not yet made its way to the common user, much less the man in the street. This movement would begin in the mid-1970s with the introduction of the microprocessor and then unfold in the 1980s with even greater drama and force. If the era before 1960 was one of experimentation and the 1960s one of consolidation and diffusion in computing, the two decades between 1970 and 1990 were characterized by explosive growth. Still, this course of events was far from clear in the early 1970s.

Accomplishing Federal Missions

(From pp. 141-142): In addition to supporting industrial innovation and the economic benefits that it brings, federal support for computing research has enabled government agencies to accomplish their missions. Investments in computing research by the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), and the National Institutes of Health (NIH), as well as the Department of Defense (DOD), are ultimately based on agency needs. Many of the missions these agencies must fulfill depend on computing technologies. DOD, for example, has maintained a policy of achieving military superiority over potential adversaries not through numerical superiority (i.e., having more soldiers) but through better technology. Computing has become a central part of information gathering, management, and analysis for commanders and soldiers alike.

Similarly, DOE and its predecessors would have been unable to support their mission of designing nuclear weapons without the simulation capabilities of large supercomputers. Such computers have retained their value to DOE as its mission has shifted toward stewardship of the nuclear stockpile in an era of restricted nuclear testing. Its Accelerated Strategic Computing Initiative builds on DOE's earlier success by attempting to support development of simulation technologies needed to assess nuclear weapons, analyze their performance, predict their safety and reliability, and certify their functionality without testing them. In addition, NASA could not have accomplished its space exploration or its Earth observation and monitoring missions without reliable computers for controlling spacecraft and managing data. New computing capabilities, including the World Wide Web, have enabled the National Library of Medicine to expand access to medical information and have provided tools for researchers who are sequencing the human genome.

EVOLVING THE HIGH PERFORMANCE COMPUTING AND COMMUNICATIONS INITIATIVE TO SUPPORT THE NATION'S INFORMATION INFRASTRUCTURE (1995)

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Continued Federal Investment Is Necessary to Sustain Our Lead

(From pp. 23-25): What must be done to sustain the innovation and growth needed for enhancing the information infrastructure and maintaining U.S. leadership in information technology? Rapid and continuing change in the technology, a 10- to 15-year cycle from idea to commercial success, and successive waves of new companies are characteristics of the information industry that point to the need for a stable source of expertise and some room for a long-term approach. Three observations seem pertinent.

1. *Industrial R&D cannot replace government investment in basic research.* Very few companies are able to invest for a payoff that is 10 years away. Moreover, many advances are broad in their applicability and complex enough to take several engineering iterations to get right, and so the key insights become "public" and a single company cannot recoup the research investment. Public investment in research that creates a reservoir of new ideas and trained people is repaid many times over by jobs and taxes in the information industry, more innovation and productivity in other industries, and improvements in the daily lives of citizens. This investment is essential to maintain U.S. international competitiveness. . . .

Because of the long time scales involved in research, the full effect of decreasing investment in research may not be evident for a decade, but by then, it may be too late to reverse an erosion of research capability. Thus, even though many private-sector organizations that have weighed in on one or more policy areas relating to the enhancement of information infrastructure typically argue for a minimal government role in commercialization, they tend to support a continuing federal presence in relevant basic research.

2. *It is hard to predict which new ideas and approaches will succeed.* Over the years, federal support of computing and communications research in universities has helped make possible an environment for exploration and experimentation, leading to a broad range of diverse ideas from which the marketplace ultimately has selected winners and losers. . . . [I]t is

difficult to know in advance the outcome or final value of a particular line of inquiry. But the history of development in computing and communications suggests that innovation arises from a diversity of ideas and some freedom to take a long-range view. It is notoriously difficult to place a specific value on the generation of knowledge and experience, but such benefits are much broader than sales of specific systems.

3. *Research and development in information technology can make good use of equipment that is 10 years in advance of current "commodity" practice.* When it is first used for research, such a piece of equipment is often a supercomputer. By the time that research makes its way to commercial use, computers of equal power are no longer expensive or rare. . . .

The large-scale systems problems presented both by massive parallelism and by massive information infrastructure are additional distinguishing characteristics of information systems R&D, because they imply a need for scale in the research effort itself. In principle, collaborative efforts might help to overcome the problem of attaining critical mass and scale, yet history suggests that there are relatively few collaborations in basic research within any industry, and purely industrial (and increasingly industry-university or industry-government) collaborations tend to disseminate results more slowly than university-based research.

The government-supported research program . . . is small compared to industrial R&D . . . but it constitutes a significant portion of the research component, and it is a critical factor because it supports the exploratory work that is difficult for industry to afford, allows the pursuit of ideas that may lead to success in unexpected ways, and nourishes the industry of the future, creating jobs and benefits for ourselves and our children. The industrial R&D investment, though larger in dollars, is different in nature: it focuses on the near term—increasingly so, as noted earlier—and is thus vulnerable to major opportunity costs. The increasing tendency to focus on the near term is affecting the body of the nation's overall R&D. Despite economic studies showing that the United States leads the world in reaping benefits from basic research, pressures in all sectors appear to be promoting a shift in universities toward near-term efforts, resulting in a decline in basic research even as a share of university research. Thus, a general reduction in support for basic research appears to be taking place.

It is critical to understand that there are dramatic new opportunities that still can be developed by fundamental research in information technology—opportunities on which the nation must capitalize. These include high-performance systems and applications for science and engineering; high-confidence systems for applications such as health care, law enforcement, and finance; building blocks for global-scale information utilities (e.g., electronic payment); interactive environments for applica-

tions ranging from telemedicine to entertainment; improved user interfaces to allow the creation and use of ever more sophisticated applications by ever broader cross sections of the population; and the creation of the human capital on which the next generation's information industries will be based. Fundamental research in computing and communications is the key to unlocking the potential of these new applications.

How much federal research support is proper for the foreseeable future and to what aspects of information technology should it be devoted? Answering this question is part of a larger process of considering how to reorient overall federal spending on R&D from a context dominated by national security to one driven more by other economic and social goals. It is harder to achieve the kind of consensus needed to sustain federal research programs associated with these goals than it was under the national security aegis. Nevertheless, the fundamental rationale for federal programs remains:

That R&D can enhance the nation's economic welfare is not, by itself, sufficient reason to justify a prominent role for the federal government in financing it. Economists have developed a further rationale for government subsidies. Their consensus is that most of the benefits of innovation accrue not to innovators but to consumers through products that are better or less expensive, or both. Because the benefits of technological progress are broadly shared, innovators lack the financial incentive to improve technologies as much as is socially desirable. Therefore, the government can improve the performance of the economy by adopting policies that facilitate and increase investments in research. [Linda R. Cohen and Roger G. Noll. 1994. "Privatizing Public Research," *Scientific American* 271(3): 73]

What Is CSTB?

As a part of the National Research Council, the Computer Science and Telecommunications Board (CSTB) was established in 1986 to provide independent advice to the federal government on technical and public policy issues relating to computing and communications. Composed of leaders from industry and academia, CSTB conducts studies of critical national issues and makes recommendations to government, industry, and academia. CSTB also provides a neutral meeting ground for consideration of complex issues where resolution and action may be premature. It convenes discussions that bring together principals from the public and private sectors, assuring consideration of key perspectives. The majority of CSTB's work is requested by federal agencies and Congress, consistent with its National Academies context.

A pioneer in framing and analyzing Internet policy issues, CSTB is unique in its comprehensive scope and effective, interdisciplinary appraisal of technical, economic, social, and policy issues. Beginning with early work in computer and communications security, cyber-assurance and information systems trustworthiness have been a cross-cutting theme in CSTB's work. CSTB has produced several reports known as classics in the field, and it continues to address these topics as they grow in importance.

To do its work, CSTB draws on some of the best minds in the country and from around the world, inviting experts to participate in its projects as a public service. Studies are conducted by balanced committees without direct financial interests in the topics they are addressing. Those

committees meet, confer electronically, and build analyses through their deliberations. Additional expertise is tapped in a rigorous process of review and critique, further enhancing the quality of CSTB reports. By engaging groups of principals, CSTB gets the facts and insights critical to assessing key issues.

The mission of CSTB is to

- *Respond to requests* from the government, nonprofit organizations, and private industry for advice on computer and telecommunications issues and from the government for advice on computer and telecommunications systems planning, utilization, and modernization;
- *Monitor and promote the health of the fields* of computer science and telecommunications, with attention to issues of human resources, information infrastructure, and societal impacts;
- *Initiate and conduct studies* involving computer science, technology, and telecommunications as critical resources; and
- *Foster interaction* among the disciplines underlying computing and telecommunications technologies and other fields, at large and within the National Academies.

CSTB projects address a diverse range of topics affected by the evolution of information technology. Recently completed reports include *Beyond Productivity: Information Technology, Innovation, and Creativity*; *Cybersecurity Today and Tomorrow: Pay Now or Pay Later*; *Youth, Pornography, and the Internet*; *Broadband: Bringing Home the Bits*; *The Digital Dilemma: Intellectual Property in the Information Age*; *IDs—Not That Easy: Questions About Nationwide Identity Systems*; *The Internet Under Crisis Conditions: Learning from September 11*; and *IT Roadmap to a Geospatial Future*. For further information about CSTB reports and active projects, see <<http://cstb.org>>.