

Funding a Revolution

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The following is an introduction to a National Research Council report titled *Funding a Revolution: Government Support for Computing Research* (National Research Council, 1999). The introduction represents the views of the chairperson, Thomas P. Hughes, not those of the Committee on Innovation in Computing and Communications or of the National Research Council. The final report can be ordered from National Academy Press, 2101 Constitution Avenue, NW, Box 285, Washington, DC 20055. The text of the report is now available online, and it may be ordered electronically. The URL is <http://www.nap.edu/readingroom/books/far>.

Introduction

At a time when the American style of competitive market capitalism attracts the world's attention, even its envy, it is difficult to recall and acknowledge that since World War II, the federal government has played a major role in launching and giving momentum to the information revolution that now takes pride of place among the nation's recent technological achievements. Federal funding financed development of most of the nation's early digital computers and, even as the industry matures, continues to finance breakthroughs in areas as wide ranging as computer time-sharing, networking, artificial intelligence, and virtual reality. The government also continues to support the education of undergraduate and graduate students who now populate industry and academic research centers and to fund the development of the physical infrastructure needed for leading-edge research.

This information revolution that the government has helped fund is not simply a technical change; it is a sociotechnical revolution, comparable to an industrial revolution. The British Industrial Revolution, for instance, which in the late eighteenth century ushered in

the modern era, brought not only steam power and factories but also the rise of industrial cities and a politically powerful urban middle class and a worker class soon empowered by trade unions. The profession of civil engineering grew rapidly, applying the laws of nature to the transformation of the environment.

The sociotechnical aspects of the information revolution are now becoming clear as firms producing microprocessors and software are challenging the economic power of firms with factories manufacturing automobiles and refineries producing oil. Detroit is no longer the symbolic center of an American industrial empire; Silicon Valley, California, now conjures up visions of enormous entrepreneurial vigor. Men in board rooms and gray flannel suits are giving way to the easy manners and casual dress of young founders of start-up computer companies.

Today the information revolution continues with private companies increasingly funding research and development for computing and related communications. Yet the federal government continues to play a major role, especially by funding long-term, high-risk research. Given the successful history of federal involvement, several questions arise: Are there lessons to be drawn that can inform future policy making in the realm of research and development? What roles might the government play in sustaining the information revolution and helping to initiate other comparable technological developments? The fact that the government funding produced—and will continue to produce—social as well as technical change adds to the responsibilities of those making science and technology policy.

Funding a Revolution reviews the history of innovation in computing and communications and seeks to identify factors that have contributed to the nation's suc-

cess in these fields. It presents and draws lessons from a series of case studies that trace the lineage of innovations, in particular subdisciplines of computing and communications (see box, pp. 10–11). *Funding a Revolution* also presents and seeks to draw lessons from a more general historical review of these industries since World War II. The lessons are intended to provide general guidance for those shaping current and future federal policy.

From these lessons emerge three central themes: 1) the importance of collaboration and coordination among members of the government-industry-university complex in cultivating research and development; 2) the positive results from diversity and change in the mix of federal organizations funding research and development and in their styles of research and development support; and 3) the importance of sound program management in federal agencies (see table).

Government-Industry-University Interaction

Innovation in computing and communications stems from a complementary interaction among government, industry, and universities. In this complex relationship, government agencies and private companies fund research that is conducted in a mixture of university, industry, and government laboratories. Industrial research laboratories often partner with government-funded academic research centers to conduct research and development and to generate innovations. Joint ventures, consortia, and partnerships involving government, industry, and universities have also stimulated and sustained the ongoing information revolution. These arrangements transcend the activities of individual firms that, earlier in this century, usually drew on in-house research and development.

The federal government has generally played a critical role in funding fundamental, long-term research, whereas industry tends to support research and development with more immediate and discernible market potential. At other times, however, government support has been closely tied to particular missions, whether national defense, space exploration, or health. A case in point would be government funding of military computer-based command and control systems.

Universities provide a culture conducive to fundamental research. Between 1972 and 1995, the federal government supported roughly 70 percent of university research in computer science and about 65 percent of university research in electrical engineering. Fundamental research has often found application. An example is the Project on Mathematics and Computation (MAC)

Table: Summary of Lessons*

Lessons about Government, Industry, and University Collaboration

1. Government funding of long-term, high-risk research complements the application-oriented research and development activities of industry.
2. Government (especially the military) has funded large system-building projects. In alliance with industry and universities, it has designed, researched, and developed these projects.
3. Government is the primary supporter of university research.
4. The free flow of people and ideas within the government-industry-university complex is critical to disseminating information about and spreading new styles of research and development.

Lessons about Diversity and Change in Federal Funding

5. Research and development in computing and communications has benefited from a diversity of approaches pursued by federal funding agencies and from organizational innovation among federal agencies.
6. Federal funding has supported both fundamental research and mission-oriented research and development.

Lessons about Program Management

7. Successful research and development programs require both talented researchers and nurturing environments. Gifted program managers have helped create these environments.
8. Program managers have often stimulated fruitful collaboration between university and industrial researchers.
9. Successful federal program managers have often shown a light management touch.
10. Experienced program managers have pursued policies based upon their realization that research and development is a more complicated process than the linear applied-science model suggests.
11. Federal program managers have often funded research that is inherently unpredictable. The unanticipated results have often been fruitful.

* A revised version of the “lessons” is in *Funding a Revolution*, pp. 5–13.

at the Massachusetts Institute of Technology (MIT). Sponsored by the Defense Advanced Research Projects Agency (DARPA), this project advanced computer time-sharing techniques, demonstrated the capabilities of computer-based utilities based on time-sharing, and helped clarify many now ubiquitous notions of computer systems. Work on Project MAC also prompted the development of a simpler derivative architecture that became UNIX.

Diversity and Change

Diversity and change in government funding policies are characteristic of the ongoing revolution. Multiple agencies frequently provide funding for projects in related areas, often backing different technological approaches. Such diversity and change do not result from indecision or lack of focus but are a measured response to changes in the conditions that constitute the context for funding and to changes in the technology and organizations being supported.

Different funding agencies also focus on different phases of the research, development, and deployment process. Those responsible for funding policy realize that the research, development, and deployment process does not flow simply and directly from basic research, through commercial-supported applied research and development, to deployment. Federal program and project managers have to adjust, for instance, to the messy reality that mission-oriented technological development may stimulate fundamental research. Fundamental research, they learned, often rationalizes or explains technology developed earlier through cut-and-try experimentation. For example, the engineers who developed the interface message processors (IMPs), or gateway computers, for the ARPANET often found themselves advancing empirically beyond theory.

Defense agencies (notably DARPA) and the National Science Foundation (NSF) have been the primary federal supporters of research in computer science and electrical engineering, the two academic disciplines most closely related to computing and communications. Other agencies, such as the Department of Energy (DOE) and NASA, have supported work relevant to their missions. Each agency has its own style of operating. In the 1960s DARPA concentrated large research grants in what it called "centers of excellence." In time, these centers matured into some of the country's leading academic computer departments. Other federal agencies have supported individual researchers at a more diverse set of institutions. The Office of Naval Research and the NSF awarded numerous peer-review grants to individual researchers, especially in universities. The NSF has also been especially active in awarding fellowships to graduate students.

In summary, federal support takes many forms: support of basic and fundamental research, support of mission-oriented development projects, research grants to institutions and centers of excellence, research grants to individuals, fellowships for graduate students, and procurement of hardware and software.

Case Studies in Computing and Communications

The case studies are contained in chapters 4 through 9 of the published report. These histories of artificial intelligence, relational databases, computer networking, virtual reality, theoretical computer science, and very-large-scale integrated circuits demonstrate the interaction of government, universities, and industry in developing and commercializing new information technology. Though representing a range of technologies and timeframes, the cases display a number of interesting similarities and contrasts that highlight key elements of the innovation process. A summary of the histories follows.

Artificial Intelligence

Support for research in artificial intelligence (AI) over the past three decades has come largely from government agencies, such as the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), and the Office of Naval Research (ONR). Firms that initiated AI research programs in the 1960s eliminated or truncated them severely once they realized that commercial applications would lie many years in the future. While not attaining the original vision of creating a truly thinking machine, research in artificial intelligence has generated numerous advances in expert systems, speech recognition, and image processing. Industry is actively commercializing many of these technologies and embedding them into a range of new products.

Virtual Reality

Innovation in computer graphics and virtual reality stems from the convergence of advances in numerous interrelated fields, such as computer graphics, psychology, computer networking, robotics, and computer hardware. It has been both pushed by technological advances in these underlying areas and pulled by creative attempts to devise particular applications, such as flight simulators, virtual surgery, engineering design, and tools for molecular modeling. Much of the underlying research has been conducted by universities, with federal support from agencies such as DARPA, the NSF, and NASA, but industry has played an important role in commercializing technologies and identifying key research needs. Interdisciplinary research efforts have been the norm in this field, as exemplified by the collaborative research effort between the computer graphics lab at the University of North Carolina, Chapel Hill, and Hewlett-Packard.

Networking

The nation's voice and data communications networks have different histories characterized by different relations between government and industry. Much of the infrastructure for voice communications was developed and deployed during a period in which AT&T enjoyed monopoly rights to the telephone market. This government-granted monopoly ensured widespread availability of service and effectively subsidized communications research. Subsequent development of data communications networking and the Internet grew largely out of government-sponsored research and deployment programs. DARPA funded development of packet switching as a collaborative effort with industry and academia. It subsequently created the interconnection protocols used over the Internet. The NSF provided additional funding for networking infrastructure for research and educational use and in effect laid the groundwork for today's Internet. The World Wide Web and browser technology currently used to navigate the Internet were devised by Timothy Berners-Lee at CERN and Marc Andreessen, then a student at the NSF-sponsored National Center for Supercomputing Applications at the University of Illinois.

Relational Databases

Development of relational database technology—now a billion-dollar industry dominated by such U.S. companies as Informix, Sybase, IBM, and Oracle—relied on the complementary efforts of industry and government-sponsored academics. Though originating within IBM, relational database technology was not rapidly commercialized because it competed with existing database products. The NSF funded the Ingres project at the University of California at Berkeley, which refined and promulgated the technology, thus spread-

ing expertise and rekindling market interest in relational databases. Many of the companies now producing relational databases are populated by—or were founded by—participants in Ingres.

Theoretical Computer Science

Though typically viewed as the province of academia, theoretical computer science has benefited from the efforts of both industry and university researchers. While some advances—such as number theory and cryptology—have translated directly into practice, many others (such as finite state machines and complexity theory) have more subtly entered engineering practice and education, influencing the way researchers and product developers approach and think about problems. Progress in theory has both informed practice and been driven by practical developments that have challenged or outpaced existing theory.

Very-Large-Scale Integrated Circuits

Work on very-large-scale integrated (VLSI) circuits began in industry, with many companies devising proprietary design rules and forging only limited links to academic research. DARPA's VLSI program attempted to better link academic research to industry needs and to push the state-of-the-art, not only in semiconductor technology but in computer capabilities driven by such technologies. Research sponsored by DARPA at MIT, Stanford University, and the University of California at Berkeley resulted in several new architectures for parallel computing, reduced instruction set computing (RISC), and graphics (the geometry engine). Researchers from these programs assisted in commercializing the technology through start-up companies such as Thinking Machines, Sun Microsystems, and Silicon Graphics, respectively.

In the past, other forms of government support of technological change were common. During the first half of this century, the telephone industry flourished in the United States without substantial government funding but with government-granted natural monopolies. The patent system also provided means for industrial research laboratories, such as Bell Laboratories, to receive a return on their research and development investments. More recently, the government has supported the defining of technical standards, such as the Internet protocols, and standard programming languages, such as COBOL.

Federal procurement has also driven research and

development. During the Semiautomatic Ground Environment (SAGE) project, the Air Force procured a number of advanced computers that were installed at MIT's Lincoln Laboratory. In the 1950s and early 1960s, many of the pioneers in computing learned through hands-on experimentation with these machines. The SAGE project can be compared to the learning experiences associated with the construction of the Erie Canal early in the last century. Contemporary engineers referred to the canal as the leading engineering school in the United States. Through grants placing computing equipment in engineering schools and universities, the NSF has also made possible hands-on learning

experiences for countless young engineers and scientists. The DOE has also stimulated advances in supercomputers through procurement.

Besides diversity of funding, organizational innovation is a theme emerging from the history of computing and communications. In response to the insistence of Vannevar Bush, wartime head of the Office of Scientific Research and Development, and others that the country needed an organization to fund basic research, especially in the universities, 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 caused concern 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 an Information Processing Techniques Office (IPTO), whose initial research agenda gave precedence 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 re-formed or re-invented to respond to new national imperatives and to counter bureaucratic trends. DARPA's IPTO has transformed itself several times in order to bring greater coherence to its research efforts and to respond to technological developments. The NSF in 1986 formed the Computer and Information Sciences and Engineering Directorate (CISE) to couple and coordinate support for research, education, and infrastructure in computer science. The NSF, which customarily focused on basic research in universities, also began encouraging joint academic-industrial research centers. With the relative increase in venture capital and other private support of research and development in recent years, federal agencies such as the NSF have rationed their funding policies to complement funding by industry of short-term industrial research and development. Federal funding of long-term, high-risk initiatives continues to have a high priority.

As history suggests, federal funding agencies—established and yet to be established—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 diminishing concerns about the competitiveness of the U.S. computer and communications industries, new missions may emerge as the rallying cry for technological development. Tomorrow, for instance, education or health may become the driving imperative.

Program Management

Individuals as well as organizations have shaped greatly the course of government funding over the past decades. The contributions of agency program managers are of critical importance but are not well known outside the managers' respective technical communities. Program managers in government funding agencies have responsibility for the initiation, funding, and oversight management of such projects as Project MAC and the ARPANET, which is the predecessor of the Internet. The most successful have married visions for technological progress with strong technical expertise and an understanding of the uncertainties of the research process. The funding and management styles of program managers flourished at ARPA during its early computer networking and artificial intelligence-funding decades. The activities of Joseph Carl Robnett Licklider provide a salient example of the program manager's role.

Head of ARPA's Information Processing Techniques Office and manager of projects from 1962 to 1964, Licklider came to ARPA on leave from the customary research and managerial activities at research universities and innovative computer firms. He was more familiar with the academic approach to problem solving and projects than the government's. After laying down extremely broad guidelines, Licklider preferred to draw specific project proposals from principal investigators or researchers in academic computer centers rather than define projects centrally. This style of funding and management allowed the government to stimulate innovation with a light touch, allowing researchers room to pursue new avenues of inquiry.

As further evidence of the light touch, government agencies, besides ARPA, manage the industrial and academic components of a funded system at an oversight level, leaving industry and universities considerable leeway in fulfilling contract specifications. In the case of grants, successful funding agencies often respond to

agendas generated by researchers in the departments and centers. NSF grants have often supported virtually unfettered basic research that has produced significant advances.

Part of Licklider's success in using this style was his familiarity with leading research—and researchers—of the time. Working at the frontier of computer development, Licklider cultivated a small network of gifted researchers in the leading research universities. They and he had similar backgrounds, having mostly been educated or having taught in the Boston area, especially at MIT, and having worked with the early government-funded mainframe computers at MIT's Lincoln Laboratory.

As the field of computing has expanded, it has become more difficult for program managers to personally know an avant garde network of researchers and to intimately grasp details of diverse fields of inquiry.

Program managers now rely more on peer review and organizational procedures in deciding whom to support.

Why a Historical Approach?

This report and its lessons are grounded in a historical approach. By contrast, science and technology policy issues are usually approached in an analytical and quantitative way, which projects the future from the present by extrapolating quantitative data. A historical approach, as used in this report, assumes that the future may resemble the past as well as the present. Such a historical approach can provide a host of alternatives to current policy. For example, if another cold war involving the United States should break out, the role of government funding in sparking new technology might be more like the one played by the government in the 1950s than the one it plays today.

Furthermore, historical narrative accommodates messy complexity more easily than a tightly structured analytical essay. The approach also facilitates reflection on long-term process development and evolution. The case histories in this report present finely nuanced accounts, which also convey the ambiguities and contradictions common to real life experiences. An outstanding case in point is the SAGE project. Intended in the 1950s to provide a defense against air attack by bombers, SAGE's most influential and unintended long-term consequence was the training-by-doing of thousands of computer engineers, scientists, and software programmers. They subsequently staffed the nascent computing and communications revolution. The impact of the learning experience from this project was felt over the course of several decades.

Even though the historical approach offers insights, history cannot, however, demonstrate what might have happened if events had unfolded differently. For example, history can show the influence of federal funding on innovation in computing and communications, but it cannot suggest the direction the industry would have taken without federal intervention.

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Reference

National Research Council, Committee on Innovations in Computing and Communications. (1999). *Lessons from history*. Washington, DC: National Academy Press.