Federal policy and the development of semiconductors, computer hardware, and computer software: A policy model for climate-change R&D?

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Advances in electronics technology in the postwar U.S. economy have created three new industries—electronic computers, computer software, and semiconductor components. These three industries also combined to give birth to the Internet, a "general purpose technology" that spans these and other industrial sectors. Electronics-based innovations supported the growth of new firms in these industries and revolutionized the operations of more mature industries, such as telecommunications, banking, and airline and railway transportation. Federal policy, especially federal R&D investment, played a central role in the development of all of these industries.

The military applications of semiconductors and computers meant that defense-related R&D funding and procurement were important to their early development. The "R&D infrastructure" created in U.S. universities by defense-related and other federal R&D expenditures contributed to technical developments in semiconductors, computer hardware, and computer software, in addition to training a large cadre of scientists and engineers. The Internet itself emerged from federal programs that developed a national network linking the far-flung components of the academic and industrial R&D infrastructure that had been created with federal funds. But much more than federal R&D and procurement programs were essential to the development of these technologies. Federal policies in intellectual property rights and antitrust also influenced their development, commercialization, and widespread commercial adoption of products based on them. These policies also contributed to the development of an "information technology" industry that included a large number of specialized producers of semiconductor components, computer systems, and software, in contrast to those of the European or Japanese electronics sectors, which were dominated by large, vertically integrated producers of components and systems.

Indeed, one of the most salient conclusions from the historical review presented below is the influence of public policies in other spheres on innovation, and especially technology adoption. Although R&D programs have been valuable sources of knowledge and technological options, R&D spending alone is rarely sufficient to promote the rapid adoption of new technologies. Widespread adoption was essential to the realization of the economic benefits of innovation in electronics, and this is likely to also be true in the case of technological solutions to global warming

Paradoxically, one important consequence of federal R&D programs and other policies in information technology (IT)[1] was the development of a relatively weak intellectual property rights environment and in some cases, substantial interfirm technology diffusion. Federal funding for procurement of the products of these new industries also encouraged the entry of new firms and interfirm technology diffusion. In addition, federal procurement supported the rapid attainment by supplier firms of relatively large production volumes, enabling faster rates of improvement in product quality and cost than otherwise would have been realized.

At least some of the catalytic effects of federal support for innovation in IT were enhanced by their "general purpose" characteristics, the rapid improvement in their price-performance ratios, and the tendency for these reductions in the price-performance ratio to accelerate adoption in a widening array of applications. In all of these technologies, the direct influence of federal R&D and procurement policies was strongest in the early years of their development, when federal expenditures on R&D and/or procurement accounted for the majority of such funding. . Whether and how the "lessons" of these federal programs, the influence of which on innovation and industry development appears to have been greatest in the early years of technological development when the defense industry was the primary customer, can be applied to the far more diverse and (in many sectors) more mature technologies relevant to climate change is an open question.

The semiconductor, computer hardware, and computer software industries now encompass many markets and applications beyond national defense, which accounts for a much smaller share of demand in all of these industries. Indeed, the technological "spillovers" that once flowed from defense-related technologies to civil applications now frequently move in the opposite direction, and the ability of Defense Department policymakers to influence the direction of technological change has diminished considerably. Nonetheless, the substantial role of federal programs supporting innovation in the earliest stages of development of many of these industries means that the influence of these programs on intellectual property policies, inter-firm technology flows, entry, and overall industrial structure remains significant today.

The electronics revolution that spawned the semiconductor and computer industries can be traced to two key innovations—the transistor and the computer. Both appeared in the late 1940s, and the exploitation of both was spurred by rapidly expanding defense spending in the early years of the Cold War, especially after the outbreak of the Korean War in 1950. The creation of these innovations also relied on domestic U.S. science and invention to a greater extent than many of the critical innovations of the pre-1940 era. The following sections briefly survey the development of the U.S. semiconductor, computer hardware and computer software industries, highlighting the role of federal R&D and related policies in these developments.

[1] "Information technology" is commonly used as a summary term for a broad range of technologies including semiconductors, computer hardware and software, and telecommunications and other networking technologies. This chapter focuses on the history of the first three: Shane Greenstein, in his chapter, explores the evolution of the Internet, perhaps the most interesting of the network technologies.

Semiconductors

The transistor was invented at Bell Telephone Laboratories (the research arm of AT&T) in late 1947 and marked one of the first payoffs to an ambitious program of basic research in solid-state physics that Bell Labs director Mervin Kelly had launched in the 1930s. Facing increasing demands for long-distance telephone service, AT&T sought a substitute for the repeaters and relays that would otherwise have to be employed in huge numbers, greatly increasing the complexity of network maintenance and reducing reliability. Kelly felt that basic research in the emergent field of solid-state might yield suitable technologies for this purpose (Braun and MacDonald 1982).

The postwar Bell Labs R&D effort in solid-state physics, as well as others in U.S. universities (notably, the group at Purdue University headed by Karl Lark-Horovitz) built on extensive wartime R&D in electronics and radar that had explored the properties of semiconducting materials such as germanium. Much of this R&D was managed by the MIT Radiation Laboratory, which supported the Lark-Horovitz research team. After 1945, the U.S. Signal Corps continued to support Lark-Horovitz and his colleagues, who were pursuing research in semiconducting amplifiers and were seen by the Bell Labs research team as a significant threat in the race to develop the first semiconductor-based amplifier.[2]

Bell Labs' commercial exploitation of its discovery was constrained in various ways by the antitrust suit against AT&T filed in 1949 by the U.S. Department of Justice. Faced with this threat to its existence, AT&T was reluctant to develop an entirely new line of business in the commercial sale of transistor products, and it may have wished to avoid any practice that would draw attention to its market power, such as charging high prices for transistor components or patent licenses. In addition, the military services that had begun to support Bell Labs' transistor research also encouraged the dissemination of transistor technology. In September 1951, a symposium was held at Bell Labs and attended by 139 industrial representatives, 121 military personnel, and 41 university scientists. The proceedings of this symposium were widely distributed to Bell licensees and others, aided by financial assistance from the U.S. military, which distributed 3,000 copies at public expense (Misa 1985). A 1952 symposium for attendees who had paid a $25,000 licensing fee focused on transistor production techniques for the point-contact transistor, and produced two thick volumes on semiconductor technology, known within Bell Labs as "the Bible" (Misa 1985).[3]

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[2] According to Riordan and Hoddeson (1997, p. 162), following a private demonstration of the transistor by the Bell Labs research team for senior military researchers in June 1948, "Shockley buttonholed Harold Zahl of the Army Signal Corps, which had been funding most of Purdue's research on germanium. 'Tell me one thing, Harold,' he asked him impetuously. 'Have Lark-Horovitz and his people at Purdue already discovered this effect, and perchance has the military put a TOP SECRET wrap on it?'

"A great expression of relief came over Shockley's face when Zahl told him that the Purdue physicists had not, although they were probably only six months away. Recalled Zahl, 'Bill was happy, for to him six months was infinity!'"

As this anecdote suggests, senior Bell Labs management, including Kelly, were concerned that in spite of the lack of direct funding from DoD for their work on transistors, the invention might be classified and its application to civilian uses (and markets) restricted. One reason for the private "demonstration" of the transistor was to ascertain whether the military would insist on classification. In the event, no such demands were made.

[3] Holbrook et al. (2000) point out that the 1952 symposium focused on production technologies for the point-contact transistor, which was soon to be superseded by the junction transistor that Shockley had invented subsequently to

The federal antitrust suit was settled through a consent decree in 1956, and AT&T restricted its commercial activities to telecommunications service and equipment. The 1956 consent decree also led AT&T, holder of a dominant patent position in semiconductor technology, to license its semiconductor patents at nominal rates to all comers, seeking cross-licenses in exchange for access to its patents. As a result, virtually every important technological development in the industry was accessible to AT&T and all of the patents in the industry were linked through cross-licenses with AT&T.

The transistor had important potential military applications in military electronics and computer systems. Moreover, the invention appeared just as the nascent Cold War was warming up considerably. By 1950, the Korean War and the Soviet explosion of an atomic bomb had triggered rapid growth in U.S. defense spending as part of a long-term shift to a much larger defense establishment that focused on strategic nuclear weapons and measures to defend against strategic airborne threats.[4] Considerable process R&D and "trial and error" experimentation were needed to support volume production of transistors, and military spending on industrial R&D focused on the development of production technologies. By 1953, the U.S. Defense Department was funding pilot transistor production lines operated by AT&T, General Electric, Raytheon, Sylvania, and RCA (Tilton 1971). As Figure 1 shows, R&D spending *per* se initially accounted for a relatively small share of federal technology-development contracts, reflecting the importance of production engineering and the focus of military policy maker on expanding production of even the relatively primitive early transistors. Defense-related expenditures also supported the construction of large-scale production facilities, including a large-scale Western Electric transistor plant in Pennsylvania. In combination with the political environment of near-wartime mobilization, such large-scale public funding commitments to production as well as R&D activities may have assured industrial firms of the depth and credibility of the federal commitment to this technology, encouraging complementary private investments in transistor development and production.

The R&D share of federal spending through these contracts rapidly grew, however, and by 1959 they accounted for more than 80 percent of federal spending in semiconductor-related technology development within these firms. But overall, defense-related federal R&D spending appears to have been focused on more applied activities. In this respect, the profile of defense-related R&D spending in electronics resembled the overall composition of the national defense-related R&D budget, which historically has been dominated by development activities.

According to Tilton (1971), federally supported R&D accounted for nearly 25 percent of total semiconductor-industry R&D spending in the late 1950s. Interestingly, the bulk of this federal R&D spending during the 1950s was allocated to established producers of electronic components. Indeed, Tilton (1971) shows that "new firms," including Texas Instruments, Shockley Laboratories, Transitron, and Fairchild, received only 22 percent of federal R&D contracts in 1959. These new firms nonetheless accounted for 63 percent of semiconductor sales in that year. Defense procurement contracts, which frequently were awarded to new firms,

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the team's invention of the point-contact device. As a result, much of the production knowhow disseminated at the second symposium proved to be obsolete.

[4] This shift in U.S. defense policy and spending also benefited the computer hardware industry, as I note later is this chapter.

proved to be at least as important as public funding of industry R&D in shaping this nascent industry.

With few exceptions, these "new" firms were founded by employees of established electronics firms (such as AT&T or eventually, Shockley Semiconductor), or (as in the case of Texas Instruments) diversified into the nascent semiconductor industry from other lines of business (see Klepper 2008). University-based researchers, with the exception of the Purdue research group and a few others, played a relatively modest role in these early innovations. Conversely, Shockley Semiconductor's fabrication facility near Stanford University played an important role as a site for research by Stanford faculty on fabrication techniques for semiconductors. For example, James Gibbons, who later became Stanford's dean of engineering, worked at Shockley Semiconductor while a junior faculty member at Stanford. Gibbons was sent there by the university's provost and leader of the Solid-State Laboratory to "learn the techniques required for the fabrication of silicon devices from Shockley and then transfer these techniques back to the university." (Lecuyer 2006, p. 138).

The first commercially successful transistor was produced by Texas Instruments (rather than AT&T) in 1954. Texas Instruments' silicon junction transistor was quickly adopted by the U.S. military for use in radar and missile applications. The next major advance in semiconductor electronics was the integrated circuit, which combined a number of transistors on a single silicon chip, in 1958. The integrated circuit was invented by Jack Kilby of Texas Instruments, and drew on that company's innovations in diffusion and oxide masking technologies that were first developed for the manufacture of silicon junction transistors. The development of the integrated circuit made possible the interconnection of large numbers of transistors on a single device, and its commercial introduction in 1961 spurred tremendous growth in the industry's sales.

Kilby's search for the integrated circuit was motivated by his employer's interest in producing a device that could expand the military (and, eventually, the commercial) market for semiconductors. Little of Kilby's pathbreaking R&D was supported by the U.S. military, but the military was a large-scale purchaser of integrated circuits once they became available.[5] Indeed, the prospect of large procurement contracts appears to have operated similarly to a prize, leading Texas Instruments to invest its own funds in the development of a product that met military requirements. Figure 2 highlights the significant share of IC shipments accounted for by government purchases in the early years of the industry' s history, as well as the decline in this share as commercial markets for the IC grew during the 1960s. A longer time series for the government share of semiconductor shipments (Figure 3) similarly shows the importance of government procurement in the early years of the broader semiconductor industry, as well as the

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[5] Malerba's (1985) discussion of the development of the Western European and U.S. semiconductor industries emphasizes the importance of the large scale of military R&D and procurement programs in the United States, as well as the focus of defense-related R&D on industry performers: "…the size of American [R&D] support was much greater than that of either the British or the European case generally, but particularly during the 1950s. Second, the timing of policies was different: while the United States was pushing the missile and space programs in the second half of the 1950s/early 1960s, Britain was gradually retreating from such programs. Third, American policies were more flexible and more responsive than British policies. Finally, research contracts in the United States focused more on development than on research, while in Britain, as well as in the rest of Europe, such contracts focused more on research and proportionately more funds were channeled into government and university laboratories. These last two factors meant that most R&D projects in Britain, as well as in Europe, were not connected with the commercial application of the results of R&D." (1985, p. 82).

shrinking share of demand represented by federal procurement after the 1960s. By the 1990s, military demand accounted for less than 10 percent of integrated circuit sales (Figure 4).

One result of government involvement in the early postwar semiconductor industry as both a funder of R&D and a purchaser of its products was the emergence of a new structure for the innovation and technology commercialization processes. This new structure contrasted with that of pre-1940 technology-intensive U.S. industries, such as chemicals or electrical machinery, or the semiconductor industries of such nations as Germany or Japan. In a virtual reversal of the prewar situation, large U.S. firms were much more significant as R&D performers than in producing and selling new semiconductor devices. Entrant firms' role in the introduction of new products, reflected in their often-dominant share of markets in new semiconductor devices, significantly outstripped that of larger firms. Moreover, the role of new firms grew in importance with the development of the integrated circuit.

Although the military market for integrated circuits was soon overtaken by commercial demand, military demand spurred the early industry growth and price reductions that created a large commercial market for integrated circuits. The large volume of integrated circuits produced for the military market allowed firms to move rapidly down learning curves, reducing component costs sufficiently to create a strong commercial demand.[6] According to Tilton (1971), a doubling of cumulative output produced a 20–30 percent drop in the costs of production for these early semiconductor devices. During 1962-1978, total shipments of ICs to governments fell from 100 percent to 10 percent, while the share of shipments to industrial and commercial users rose from 0 to 90 percent (Table 1).

Military procurement policies also influenced industry structure. In contrast to Western European defense ministries, which directed the bulk of their R&D funding and procurement funding to established defense suppliers (Flamm, 1983, p. 134), the U.S. military was willing to award substantial procurement contracts to firms, such as Texas Instruments, that had recently entered the semiconductor industry but had little or no history of supplying the military. The U.S. military's willingness to purchase from untried suppliers was accompanied by conditions that mandated substantial technology transfer among U.S. semiconductor firms. To reduce the risk that a system designed around a particular integrated circuit would be delayed by production problems or by the exit of a supplier, the military required its suppliers to develop a "second source" for the product—that is, a domestic producer that could manufacture an electronically and functionally identical product. To comply with second-source requirements, firms exchanged designs and shared sufficient process knowledge to ensure that the component produced by a second source was identical to the original product.

By facilitating entry and supporting high levels of knowledge diffusion among firms, public policy (e.g., the 1956 AT&T consent decree, the Department of Defense "second source" policy) and other influences increased the diversity and number of technological alternatives explored by individuals and firms within the U.S. semiconductor industry during a period of significant uncertainty about the direction of future development of this technology. Extensive entry and rapid interfirm technology diffusion also fed intense competition among U.S. firms. The competitive industry structure and conduct enforced a rigorous "selection environment,"

[6] From the beginning, Texas Instruments and other firms were aware of the commercial potential of the integrated circuit. As one of its first demonstration projects, Texas Instruments constructed a computer to demonstrate the reductions in component count and size that were possible with integrated circuits.

ruthlessly weeding out less effective firms and technical solutions. For a nation that was pioneering in the semiconductor industry, this combination of technological diversity and strong selection pressures proved to be highly effective.

As nondefense demand for semiconductor components grew and came to dominate industry demand, defense-to-civilian technology "spillovers" declined in significance and actually reversed in direction. By the 1970s, a combination of rapid product innovation in civilian technologies and longer delays in military procurement programs meant that military-specification semiconductor components often lagged behind their commercial counterparts in technical performance, although these "milspec" components could operate in more "hostile" environments of high temperatures or vibration. Nonetheless, concern among U.S. defense policymakers over this "technology gap" grew and resulted in the creation of the Department of Defense's Very High Speed Integrated Circuit (VHSIC) program in 1980. Federally funded VHSIC projects linked merchant semiconductor firms largely devoted to commercial production with semiconductor equipment manufacturers and defense-systems producers in development projects intended to produce advanced, high-speed, "milspec" components.

Originally planned for a six-year period and budgeted at slightly more than $200 million, the VHSIC program lasted for 10 years and cost nearly $900 million. Nonetheless, the program failed to meet its objectives, demonstrating the limited influence of the federal government within a U.S. semiconductor market that by the 1980s was dominated by commercial applications and products. In the wake of the VHSIC program's mixed results, some scholars have recommended that defense policymakers seek to change procurement policies to enable more rapid incorporation of commercial innovations (Alic et al. 1992).

Another federally funded R&D initiative in the semiconductor industry that highlights the changing relationship between civilian and defense-related innovation was the Semiconductor Manufacturing Technology Consortium (SEMATECH). Founded in 1987, SEMATECH supported collaborative R&D among leading U.S. semiconductor firms[7] on manufacturing processes, in an effort to improve manufacturing performance in the face of intense competition from Japanese producers. SEMATECH initially received one-half of its $200 million annual operating budget from the federal government, based on arguments by the Defense Science Board and other experts (U.S. Department of Defense 1987; Alic et al. 1992) claiming that the U.S. civilian semiconductor "industrial base" was essential to the nation's defense establishment.[8] Based on the assertion that defense-related procurement alone could no longer sustain a viable U.S. semiconductor industry, defense funds were used to support R&D on manufacturing technologies that were relevant to civilian products, many (but not all) of which had applications in defense systems as well.

Organized in considerable haste, the consortium's original R&D agenda proved to be unsustainable. The original vision of sharing sensitive manufacturing knowhow among firms that were direct competitors in many markets was never realized, and SEMATECH gradually shifted its focus to supporting collaboration between semiconductor manufacturers and producers of

[7] The founding members of SEMATECH were Advanced Micro Devices, AT&T, Digital Equipment Corporation, Harris Corporation, Hewlett-Packard Company, Intel Corporation, IBM, LSI Logic, Micron Technology,; Motorola, National Semiconductor, NCR, Rockwell International, and Texas Instruments. Micron and LSI Logic withdrew in 1991, and Harris Corporation withdrew in 1992. At the time of its formation, the 14 original members of SEMATECH accounted for more than 80 percent of U.S. semiconductor production capacity.

[8] See Grindley et al. (1994) for a more extensive discussion of SEMATECH.

semiconductor processing equipment. As SEMATECH chief executive officer William J. Spencer remarked in 1992, "We can't develop specific products or processes. That's the job of the member companies. SEMATECH can enable members to cooperate or compete as they see fit" (Burrows 1992).This approach proved to be more viable, although the consortium's support did not prevent the exit of some important U.S. equipment producers, and SEMATECH member firms were not consistently willing to follow their investments in R&D with purchases of commercial models of the equipment developed under the consortium's sponsorship. By 1997, SEMATECH had invited non-U.S. semiconductor manufacturing firms to become members (although Japanese firms did not join a subsidiary of the consortium until 2004), and federal funding had ended.

SEMATECH's effects on the U.S. semiconductor industry remain controversial (see Macher et al. 1999). Although the market shares of both U.S. manufacturers and equipment suppliers began to improve by the early 1990s, much of this improvement reflected the decline in the fortunes of Japanese manufacturers that occurred during this period, along with the entry and expansion of South Korean and Taiwanese semiconductor manufacturers, who were significant purchasers of U.S. equipment firms' products. Nevertheless, leading U.S. (and non-U.S.) manufacturers and equipment suppliers remain active in the consortium, and their willingness to maintain their investments in its R&D activities suggests that they find its "vertical" R&D strategy to be valuable. During and since its support from federal sources, SEMATECH's R&D program has not focused on basic research. Instead, the consortium has emphasized the collective development by manufacturers and suppliers of technology "roadmaps" over a 5-year future to guide R&D investments and product development, as well as facilitating agreement on technical standards and performance goals for equipment.

Computer hardware

The development of the U.S. computer industry also benefited from Cold War military spending, but in other respects the origins and early years of this industry differed from semiconductors. One marked difference was the role of U.S. universities in the industry. Although they were peripheral actors in the early development of semiconductor technology, U.S. universities were important sites for the early development, as well as the research, activities that produced the earliest U.S. electronic computers. In addition, federal spending during the late 1950s and 1960s from military and nonmilitary sources provided an important basic research and educational infrastructure for the development of this new industry and the broader IT sector.

During World War II, the American military sponsored a number of projects to develop high-speed calculators to solve special military problems. The ENIAC—generally considered the first fully electronic U.S. digital computer—was funded by Army Ordnance as a device for computing firing tables for artillery. Developed by J. Presper Eckert and John W. Mauchly at the University of Pennsylvania, the ENIAC required rewiring for each new problem. In 1944, John von Neumann began advising the Eckert-Mauchly team, which was then working on the development of a new machine, the EDVAC. This collaboration developed the concept of the stored-program computer: instead of being wired for a specific problem, the EDVAC's instructions were stored in memory, facilitating their modification.

Von Neumann's abstract discussion of the concept (von Neumann 1945, reprinted 1987) circulated widely and served as the logical basis for subsequent computers. Indeed, the extensive dissemination of the EDVAC report led U.S. Army patent attorneys to rule that its basic ideas were not patentable, spurring the broad exploitation of this fundamental architectural innovation (Flamm, 1988). The subsequent settlement in 1956 of a federal antitrust suit against IBM also included liberal licensing decrees, further supporting interfirm diffusion of computer technology.

The first fully operational stored-program computer in the United States was the SEAC, built by the National Bureau of Standards in 1950 (Flamm 1988). A number of other important machines were developed for or initially sold to federal agencies, including the Princeton IAS computer, built by von Neumann at the Institute for Advanced Study in 1951, MIT's Whirlwind computer, developed in 1949, and the UNIVAC, built in 1953 by Remington Rand based on the Eckert-Mauchly technology.[9] At least 19 government-funded development projects produced electronic computers during the 1945-55 period (Flamm, 1988).

From the earliest days of their support for the development of computer technology, the U.S. armed forces sought to ensure that technical information on this innovation reach a broad industrial and academic audience. This attitude, which contrasted with that of the militaries of the United Kingdom and the Soviet Union, appears to have stemmed from the U.S. military's concern that a substantial industry and research infrastructure would be required for the development and exploitation of computer technology.[10] The technical plans for the military-sponsored IAS computer were widely circulated among U.S. government and academic research institutes, and it spawned a number of "clones," including the ILLIAC, the MANIAC, AVIDAC, ORACLE, and JOHNIAC (Flamm 1988).

By 1954, the ranks of the leading U.S. computer manufacturers were dominated by established firms in the office equipment and consumer electronics industries, including RCA; Sperry Rand (originally the typewriter producer Remington Rand, which had acquired Eckert and Mauchly's embryonic computer firm); NCR; and IBM. These firms focused on the business market as well as scientific computing, while Bendix Aviation acquired the computer operations of Northrop Aircraft and specialized in computers for scientific applications (Flamm, 1988, p. 82). The National Security Agency, the Atomic Energy Commission, and the Defense Department all supported the development of advanced computer systems for specialized applications in air defense, cryptography, and nuclear weapons design.

IBM's technology development efforts benefited from the firm's experience as supplier of more than 50 large computers for the SAGE air-defense network that was developed under the supervision of MIT's Lincoln Laboratories in the 1950s, and the firm was awarded a contract by

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[9] Table 2 contains a more complete listing of these early postwar government-supported computer development projects.

[10] Herman Goldstine, one of the leaders of the wartime project sponsored by the Army's Ballistics Research Laboratory at the University of Pennsylvania that resulted in the Eckert-Mauchly computer, notes that "A meeting was held in the fall of 1945 at the Ballistic Research Laboratory to consider the computing needs of that laboratory 'in the light of its post-war research program.' The minutes indicate a very great desire at this time on the part of the leaders there to make their work widely available. 'It was accordingly proposed that as soon as the ENIAC was successfully working, its logical and operational characteristics be completely declassified and sufficient be given to the machine...that those who are interested...will be allowed to know all details.'" (1972, p. 217). Goldstine is quoting the "Minutes, Meeting on Computing Methods and Devices at Ballistic Research Laboratory," 15 October 1945 (note 14).

the Atomic Energy Commission in 1956 for an advanced computer (referred to as the "Stretch" project) for use by Los Alamos National Laboratories. Other U.S. computer firms, including Sperry Rand and ERA, produced advanced computers in small quantities for federal intelligence and defense agencies during the 1950s. According to Flamm (1987), federal funds accounted for 59 percent of the combined computer-related R&D spending of General Electric, IBM, Sperry Rand, AT&T, Raytheon, RCA, and Computer Control Corporation during 1949-1959. Even within the mature U.S. computer industry, federal funds accounted for a significant share of overall R&D activity. Flamm (1987, p. 243) estimates that federal funds accounted for almost 13 percent of total R&D in the "office, computing, and accounting machines" industry in 1981, increasing to slightly more than 15 percent by 1984.

Business demand for computers gradually expanded during the early 1950s to form a substantial market. The most commercially successful machine of the decade, with sales of 1,800 units, was the IBM 650 (Fisher et al. 1983). Even in the case of the IBM 650, however, government procurement was still crucial: the projected sale of 50 machines to the federal government (a substantial portion of the total forecast sales of 250 machines) influenced IBM's decision to move the computer into full-scale development (Flamm 1988). Government purchase made up a substantial portion of IBM sales during the 1950s, but they became proportionally less important through the following two decades as private sector sales grew (Figure 5). Although the commercial operations of IBM and other early U.S. computer producers benefited from extensive federal R&D and procurement funding, IBM 's increasing dominance of commercial computer sales by the late 1950s also drew on the marketing and manufacturing capabilities that had been developed through the firm's long history as a major producer of office equipment.[11]

The federal share of overall computer-industry sales had declined significantly by the end of the 1950s (by 1966, federal government installations accounted for no more than 10 percent of the total U.S. installed base of computers, according to Flamm [1987]), but government purchases accounted for a larger share of high-performance computer sales. In 1972, more than 40 percent of total sales of computers in the highest-performance class ("Class 7," which includes supercomputers, along with other less advanced systems) went to the federal government. By 1980, this share was still slightly more than 13 percent. Within supercomputers alone, the federal share of overall purchases was significantly higher.

Even after the emergence of a substantial private industry dedicated to the development and manufacture of computer hardware, federal R&D funding aided the creation of the new academic discipline of computer science. In addition to their role as sites for applied and basic research in computer hardware and software, U.S. universities produced engineers and scientists active in the computer industry (see below for further discussion). By virtue of their relatively "open" research and operating environments that emphasized publication, relatively high levels

[11] "Like most 'new' technology, the computer had important antecedents, and existing firms had developed capabilities related to those antecedents. None had done so more thoroughly than IBM. Despite some superficial differences between computers and the earlier tabulating equipment that had formed the core of IBM's business, computers involved a mix of knowledge and capabilities that matched those existing at IBM extraordinarily well." (Usselman, 1993, p. 5). Usselman also emphasized the skills at IBM's Endicott, New York factory that had long been the source of many of the firm's tabulating machines: "The Endicott facility also produced a series of input-output devices that helped develop the market for both large and small computers. Though these products made use of electronics, they also drew on the mechanical skills available at Endicott. Printers and disk storage devices in particular were as distinguished [sic] as much for their rapid, precise mechanical motions as for their logical design." (p. 12). Chandler (1997) makes a similar argument.

of turnover among research staff, and the production of graduates who sought employment in industry, universities served as sites for the dissemination and diffusion of innovations throughout the industry. U.S. universities provided important channels for cross-fertilization and information exchange between industry and academia, and also between defense and civilian research efforts in software and in computer science generally.

The institution-building efforts of the National Science Foundation and the Defense Department came to overshadow private-sector contributions by the late 1950s. In 1963, about half of the $97 million spent by universities on computer equipment came from the federal government, while the universities themselves paid for 34 percent, and computer makers underwrote the remaining 16 percent (Fisher et al. 1983).). Federal funding for computer-related research accounted for a significant portion of the total (including industry- and university-funded) R&D performed outside of industry through the 1980s (see figure 6). During the 1970s and 1980s, roughly 75 percent of the mathematics and computer science research performed at universities was funded by the federal government (Flamm 1987).

According to a recent report from the National Research Council's Computer Science and Telecommunications Board, federal investments in computer science research increased fivefold during the 1976–1995 period, from $180 million in 1976 to $960 million in 1995 (in constant 1995 dollars). Federally funded basic research in computer science, roughly 70 percent of which was performed in U.S. universities, grew from $65 million in 1976 to $265 million in 1995 (National Research Council 1999). The defense share of federal computer science research funding declined from almost 60 percent in fiscal 1986 to less than 30 percent in fiscal 1990 (Clement, 1987, 1989; Clement and Edgar, 1988), and defense funding of computer science research in universities appears to have been supplanted somewhat by the growth in funding for quasi-academic research and training organizations.

The federal government's R&D spending was supplemented by procurement spending on systems for military applications. In both the hardware and software areas, the government's needs differed from those of the commercial sector, and the magnitude of purely technological "spillovers" from military R&D and procurement to civilian applications appear to have declined somewhat as the computer industry moved into the 1960s. Just as had been the case in semiconductors, military procurement demand acted as a powerful attraction for new firms to enter the industry, and many such enterprises entered the fledgling U.S. computer industry in the late 1950s and 1960s. Antitrust policy played a role here as well—another 1956 consent decree, this time settling an antitrust suit filed by the federal government against IBM, resulted in extensive licensing of the firm's patents at low royalties. Although IBM's position in computer technologies by this date was not as dominant as that of AT&T in semiconductors, the computer firm nevertheless had an extensive patent portfolio that became much more widely available to other firms through low-cost licensing agreements as a result of the 1956 settlement of the antitrust suit. Moreover, it is likely that IBM's willingness to pursue alleged infringers of its patents was curtailed by this federal suit and its settlement.

Computer software[12]

By the 1980s, the development of the semiconductor and computer industries had laid the groundwork for the expansion of another "new" industry, the production of standardized

[12] A more detailed discussion of the U.S. and other industrial nations' software industries, on which this section draws, may be found in Mowery (1999).

computer software for commercial markets (as opposed to the commercial production of custom software or user-developed custom software). The growth of the U.S. computer software industry has been marked by at least four distinct eras. During the earliest years of the first era (1945–1965), covering the development and early commercialization of the computer, software as it is currently known did not exist. The concept of computer software as a distinguishable component of a computer system was effectively born with the advent of the von Neumann architecture for stored-program computers. But even after the von Neumann scheme became dominant in the 1950s, software remained closely bound to hardware, and the organization producing the hardware generally developed the software as well. As computer technology developed and the market for its applications expanded after 1970, however, users, independent developers and computer service firms began to play prominent roles in software development.

The development of a U.S. software industry began only when computers began to be adopted on a large scale in commercial uses, a development spurred by the success of the IBM 650. Widespread adoption of a single computer platform contributed to the growth of "internal" software production by large users. But the primary suppliers of the software and services for mainframe computers well into the 1960s were the manufacturers of these machines. In the case of IBM, which leased rather than sold many of its machines, the costs of software and services were "bundled" with the lease payments. By the late 1950s, however, a number of independent firms had entered the custom software industry. These firms included the Computer Usage Company and Computer Sciences Corporation, both of which were founded by former IBM employees (Campbell-Kelly 1995). In the late 1950s, the Computer Usage Company secured contracts with NASA and had a successful initial public offering of shares. Many more independent firms entered the mainframe software industry during the 1960s.

Procurement of products and services by the federal government was an important factor in the early development of the software industry. IBM was the primary supplier of computers for the SAGE air defense project, but the RAND Corporation was the contractor responsible for the bulk of the huge amount of software required for SAGE. RAND in turn created a Software Development Division to produce the software. This division separated from RAND in 1956, forming the Systems Development Corporation. Since large-scale software development projects of this sort were well beyond the technological or scientific “frontier” of academic computer science (a discipline that itself scarcely existed in the early 1950s), the SAGE software development project acted as a “university” of sorts for hundreds of software programmers, laying the foundations for the software industry’s future development within the United States (Campbell-Kelly 1995). To facilitate this training role, and in part because the Systems Development Corporation was restricted by Air Force pay scales, the company encouraged turnover of employees. The “SAGE alumni” in turn contributed to the development of the broader software industry (Langlois and Mowery 1996) For example, One such programmer noted in the early 1980s, “the chances are reasonably high that on a large data processing job in the 1970s you would find at least one person who had worked with the SAGE system” (Benington 1983, p 351).

In the late 1950s and early 1960s, defense contractors, including TRW, MITRE Corporation, and Hughes, began to produce large-scale systems software for military applications under federal contracts. IBM and other mainframe computer manufacturers also produced one-of-a-kind software applications for customers and became important suppliers in the software-contracting industry. Much of the software-related knowhow developed from defense contracts and the Apollo manned space flight program "spilled over" to commercial applications. For example, IBM's collaboration with American Airlines to develop the SABRE reservation system drew upon IBM's background with the SAGE development program (Campbell-Kelly 1995).

Federal procurement programs influenced the evolution of specific programming languages as well. A Department of Defense effort to establish a standard programming language resulted in the widely used "common business-oriented language," COBOL. The DoD required that general-purpose computers purchased by the military support COBOL, and that any business-related applications for defense programs be written in the language. Since the DoD accounted for such a large share of the market for custom applications software, its procurement requirements facilitated the development and diffusion of COBOL (Flamm 1987).

The second era in the software industry's development – roughly from 1965 to 1978 -- witnessed significant entry by independent producers of standard software. Although independent suppliers of software had begun to enter the industry by the 1960s in the United States, computer manufacturers and users remained important sources of both custom and standard software during this period. Some service bureaus that had provided users with operating services and programming solutions began to unbundle the pricing of their services from software sales, providing yet another cohort of entrants into the independent development and sale of traded software. Sophisticated users of computer systems, especially users of mainframe computers, also developed expertise in creating solutions for their applications and operating system needs. A number of leading U.S. suppliers of commercial software were founded by computer specialists formerly employed by major mainframe users.

Steinmueller (1996) argues that three developments contributed to the expansion of the independent software industry in the United States during the 1960s. First, IBM's introduction of the 360 in 1965 provided a single mainframe architecture that utilized a standard operating system spanning all machines in this product family. This development increased the installed base of mainframe computers that could use packaged software designed to operate specific applications, and it made entry by independent developers more attractive. Second, IBM "unbundled" its pricing and supply of software and services in 1968, a decision that was encouraged by the threat of antitrust prosecution.[13] The "unbundling" of its software by the dominant manufacturer of hardware (a firm that remains among the leading software suppliers worldwide) provided opportunities for the growth of independent software vendors. Third, the introduction of the minicomputer in the mid-1960s by firms that typically did not provide "bundled" software and services opened up another market segment for independent software vendors.

During the late 1970s and 1980s, the development and diffusion of the desktop computer produced explosive growth in the traded software industry. Once again, the United States was the "first mover" in this transformation and quickly emerged as the largest single market for packaged software. Rapid adoption of the desktop computer in the United States supported the early emergence of a few "dominant designs" in desktop computer architecture, creating the first

[13] As the U.S. International Trade Commission (1995) points out, U.S. government procurement of computer services from independent suppliers aided the growth of a sizeable population of such firms by the late 1960s. These firms were among the first providers of custom software for mainframe computers after IBM's unbundling of services and software.

mass market for packaged software. The independent software vendors (ISVs) that entered during this period were largely new to the industry. Few of the major suppliers of desktop software came from the ranks of the leading independent producers of mainframe and minicomputer software.

The large size of the U.S. packaged software market, as well as the fact that it was the first large market to experience rapid growth (reflecting the earlier appearance and rapid diffusion of mainframe and minicomputers, followed by the rapid growth of desktop computer use during the 1980s), gave the U.S. firms that pioneered in their domestic packaged software market a formidable "first-mover" advantage that they exploited internationally. During the 1990s, U.S. firms' market shares in their home market exceeded 80 percent in most classes of packaged software, and exceeded 65 percent in non-U.S. markets for all but "applications" software.[14]

Much of the rapid growth in custom software firms during the 1970s reflected expansion in federal demand, which in turn was dominated by DoD demand. But just as had been the case in the semiconductor industry, defense markets gradually were outstripped by commercial markets, although this trend occurred more gradually in software than in hardware or semiconductors. There exists no reliable time series of DoD expenditures on software procurement that employs a consistent definition of software (e.g., separating embedded software from custom applications or operating systems and packaged software). Nevertheless, the available, imperfect data suggest that in constant-dollar terms, DoD expenditures on software increased more than thirtyfold between 1964 and1990 (Figure 7; see also Mowery and Langlois 1996). Throughout this period, DoD software demand was dominated by custom software, and DoD and federal government markets for custom software accounted for a substantial share of total revenues in this segment of the U.S. software industry. But despite this increase in DoD demand, by the early 1990s the defense department accounted for a declining share of the U.S. software industry's revenues.

This declining share of meant that the defense market no longer exerted sufficient influence on the path of R&D and product development to benefit from generic academic research and product development—defense and commercial needs had diverged. The tangled history of the Defense Department's "generic" software language, Ada, unveiled in 1984, illustrates the declining influence of federal procurement on the rapidly growing software industry. Billed as a solution to the problems of system maintenance and software development resulting from the bewildering variety of software languages in use within defense systems, Ada was designed to be employed in all defense applications.

Ada proponents argued that by standardizing all DoD programs around a single language, the commercial developers that no longer served the military market would be motivated to produce software that could be used in both civilian and military applications. But these aspirations were largely unrealized. Partly because of the huge difficulties associated with "inserting" Ada into the enormous "installed base" of defense-related software, the language failed to attract the attention of commercial developers. The contrast between the failure of this

[14] Most analyses of packaged-software markets distinguish among "operating systems" (the software used to control the operations of a given desktop, mainframe, or minicomputer), "applications" (software designed to support specific, generic functions such as word-processing or spreadsheets), and "development tools" such as programming languages, application development programs). For further details, see U.S. Department of Commerce (2000).

DoD-supported language to take hold and COBOL's rapid diffusion into military and commercial applications highlights the tendency for the influence of defense-related R&D and procurement demand on the overall trajectory of innovation in a given technology to decline as commercial markets expand.

The fourth era in the development of the software industry, which began in the early 1990s, has been dominated by the growth of networking among desktop computers both within enterprises through local area networks linked to a server and among millions of users through the Internet. The growth of the Internet has facilitated the development of "open source" software. User-active innovation in software is hardly new, and the exchange by users of "shareware" also has a long history; but the Internet supports modifications in open-source software without the creation of competing, incompatible versions. As with the previous eras of this industry's development, the growth of network users and applications has been more rapid in the United States than in other industrial economies, and U.S. firms have maintained dominant positions in these markets.

The development of both the U.S. computer hardware and computer software industries rested on a research and personnel infrastructure supported by federal R&D investments. Perhaps the most important result of these investments was the development of a large university-based research complex that provided a steady stream of new ideas, some new products, and a large number of entrepreneurs and engineers eager to participate in this industry. Like postwar defense-related funding of R&D and procurement in semiconductors, federal policy toward the software industry was motivated mainly by national security concerns; nevertheless, federal financial support for a broad-based research infrastructure proved quite effective in spawning a vigorous civilian industry.

As in other segments of the IT industry, U.S. antitrust policy played an important role in the development of the software industry. The unbundling of software from hardware was almost certainly hastened by the threat of antitrust action against IBM in the late 1960s. Moreover, as noted earlier, many of the independent vendors that responded to the opportunities created by the new IBM policy had been suppliers of computer services to federal government agencies. In addition, the relatively liberal U.S. policy toward imports of computer hardware and components supported rapid declines in price-performance ratios in most areas of computer hardware and thereby accelerated domestic adoption of the hardware platforms that provided the mass markets for software producers. By comparison, Western European and Japanese governments' protection of their regional hardware industries was associated with higher hardware costs and slower rates of domestic adoption, ultimately impeding the growth of their domestic software markets.

The Development of Human Capital

One of the most important contributions of federal R&D investments in IT was the creation of a substantial pool of scientists and engineers who contributed to innovation in IT and related technologies across a broad array of applications. As the discussion of computer hardware and software above emphasizes, federal investments in university research supported the creation of a new academic discipline, computer science. The number of computer science departments in U.S. and Canadian universities that were granting Ph.D. degrees grew from 6 in 1965 to 56 by 1975 and 148 in 1995 (Andrews, 1997, cited in National Research Council, 1999a). In other U.S. research universities, computer science Ph.D.'s were awarded by established electrical engineering departments, so these figures understate somewhat the growth in advanced degree programs in computer science. The number of computer science bachelor's degrees awarded by U.S. and Canadian universities grew from 89 in 1966 to 42,000 by 1986.

Although the 1966 figures almost certainly underestimate the actual number of undergraduate degrees in this field (because many electrical engineering degrees awarded in 1966 covered virtually identical coursework and research), the growth in training of computer science personnel is remarkable. Master's degrees in computer science grew at an average annual rate of more than 14 percent during 1966–1995, and Ph.D. degrees increased from 19 in 1966 to more than 900 by 1995 (National Research Council 1999). Electrical engineering undergraduate degree production also grew during the 1966–1986 period, more than doubling from 11,000 to 27,000.

Federal research funds played a central role in supporting this expanded production of electrical engineering and computer science degree holders. The National Research Council's 1999 study of federal R&D in information technology estimates that the share of graduate students in U.S. universities' computer science and electrical engineering departments supported by federal funds through fellowships, teaching assistantships, or research assistantships rose from 14 to 20 percent during 1985–1996, and that more than one-half of this financial support was provided in the form of research assistantships. The contributions of federal funds to degree production in the leading U.S. research universities were even higher, according to the 1999 study. Between 1985 and 1996, roughly 56 percent of graduate students in the computer science and electrical engineering departments at MIT, Carnegie-Mellon University, and U.C. Berkeley were supported entirely or partly by federal funds, with 46 percent of these students being supported by federally funded research assistantships. Twenty-seven percent of graduate students at Stanford University's electrical engineering and computer science departments received federal funds, and 50–60 percent of the Ph.D. students enrolled in these departments were supported in whole or in part by federal funds.

Conclusions

This summary of technological and industrial development within semiconductor, computer hardware, and computer software highlights the important and constructive role played by federal policy. One of the most striking characteristics of federal policy was the fact that it extended well beyond the "conventional" technology policy tool of R&D spending to include military procurement, intellectual property rights, and antitrust policies. Although these various dimensions were not coordinated or formulated with any coherent strategy in mind, they had the effect of supporting both the "supply" of knowledge, knowhow, and trained personnel, and the "demand" for adoption of the technologies emerging from the R&D process.

Federal policies also consistently supported a striking degree of competition among R&D funders, competition among R&D performers (including competition among R&D performers for the award of R&D and procurement contracts), and competition among the various actors seeking to commercialize new applications. An important factor contributing to competition among R&D performers was the reliance on extramural R&D performers in many federal R&D programs in the information technology sector (the same could be said of federal R&D spending in biomedical science, another area of highly productive public R&D investments). U.S. research universities in particular proved to be effective sources of both basic knowledge and technological advances, as well as skilled engineers, scientists, and entrepreneurs. Much of the effectiveness of these institutions rested on the intense inter-institutional competition for resources, prestige, students, and faculty that characterizes the U.S. higher education system. Inter-institutional competition motivated university administrators and faculty to seek resources from both the federal government and industry, a competitive dynamic that proved to be highly successful in generating technical and commercial advances.

This competitive environment for R&D performers and commercializers also benefited from a tough federal antitrust policy in the information technology sector. Leading firms in both computers and semiconductors licensed their technological portfolios more widely and at lower cost, and may have avoided pursuing infringers of their intellectual property, because of federal antitrust oversight. Antitrust policy, as well as federal R&D and procurement policies, reinforced and contributed to an environment of relatively weak intellectual property rights in these industries for much of their early years. Interfirm knowledge flows, entry by new firms, and experimentation with new approaches to commercial applications all were almost certainly more significant in this environment of relatively weak formal intellectual property rights that would have been true in a "strong patent" environment. The merits of strong, broad patent protection thus must be considered with care and some skepticism in the early, formative years of a new technology-based industry (See Mowery and Nelson, 1999, for further discussion).

The effectiveness of federal R&D spending in the information technology sector also was enhanced by the sheer scale of its R&D and related procurement efforts, reflecting the positive externalities in innovation that flow from a large installed base in these technologies. As Bresnahan and Greenstein (1996) have pointed out, much of the innovation process in information technology involves "co-invention" on the part of users as well as technology suppliers. The importance of this co-invention means that large-scale deployment of a given new technology can spark more user-driven experimentation, thereby accelerating refinement, innovation, and improvement. The history of the packaged software industry in the United States clearly indicates the advantages of scale. Similar advantages may well inhere in large-scale experiments with either a technological "infrastructure" or small-scale technologies in other sectors, including energy.

Federal policy in information technology complemented support for R&D with support for adoption in the early years of the development of semiconductors and computers, where federal procurement contracts proved to be as influential as federal R&D funding of industrial firms in supporting innovation and firm entry. Federal procurement was less salient in computer software, although early federal contracts for computer support and custom software development aided the growth of at least some firms that subsequently became important suppliers of mainframe software.

The commercial development and eventual adoption of semiconductor and computer hardware technologies benefited significantly from the large military purchases of early versions of these technologies for national-security applications. In addition, the structure of these procurement programs often encouraged entry by new firms and significant technology flows among firms. In contrast, U.S. energy-R&D programs have tended to combine instability in R&D funding with little systematic effort to support demand for early versions of new technologies (National Research Council 2001).

In short, federal R&D and other policies were of great importance to the development of economically vibrant semiconductor and computer hardware and software industries that literally did not exist 60 years ago. Of course the historical structure of these federal policies differs in some important respects (notably, in intellectual property rights) from their current posture in energy and other sectors. Moreover, the influence of public R&D and procurement efforts in IT waned as the technologies underpinning this sector matured. The "lessons" of federal policy toward IT innovation accordingly must be applied to other sectors, such as innovation directed toward solutions to global climate change, with considerable discrimination and caution.

REFERENCES

Alic, John A., Lewis M. Branscomb, Harvey Brooks, Ashton B. Cater, and Gerald L. Epstein, Beyond Spinoff: Military and Commercial Technologies in a Changing World (Boston: Harvard Business School Press, 1992).

[BDSA? (from figure 3) would go here?]see below, under "U.S. Department of Commerce"
Benington, H.D., "Production of Large Computer Programs," Annals of the History of Computing 5, 1983, 350-361.

Borrus, M., J.E. Millstein, and J. Zysman, "Trade and Development in the Semiconductor Industry: Japanese Challenge and American Response," in J. Zysman and L. Tyson, eds., American Industry in International Competition (Ithaca, NY: Cornell University Press, 1983).

Braun, S., and S. Macdonald, Revolution in Miniature, 2d ed. (New York: Cambridge University Press, 1982).

Bresnahan, T.F., and S. Greenstein, 'Technical Progress and Co-invention in Computing and in the Uses of Computers," Brookings Papers: Microeconomics, 1996.

Burrows, P., "Bill Spencer struggles to reform SEMATECH," Electronic Business, May 18, 1992.

Caminer, D., ed., LEO: The Incredible Story of the World's First Business Computer (London: McGraw-Hill, 1998).

Campbell-Kelly, M., "Development and Structure of the International Software Industry, 1950-1990," Business and Economic History 24, 1995, 73-110.

Chandler, A.D., Jr., Inventing the Electronic Century (New York: Free Press, 2001).

Clement, J.R.B., "Computer Science and Engineering Support in the FY 1988 Budget," in Intersociety Working Group, ed., AAAS Report XII: Research & Development, FY 1988 (Washington, D.C.: American Association for the Advancement of Science, 1987).

Clement, J.R.B., "Computer Science and Engineering Support in the FY 1990 Budget," in Intersociety Working Group, ed., AAAS Report XIV: Research & Development, FY 1990 (Washington, D.C.: American Association for the Advancement of Science, 1989).

Clement, J.R.B. and D. Edgar, "Computer Science and Engineering Support in the FY 1989 Budget," in Intersociety Working Group, ed., AAAS Report XIII: Research & Development, FY 1989 (Washington, D.C.: American Association for the Advancement of Science, 1988).

Electronic Industries Association, Electronic Industries Yearbook, 1969, Washington, 1969.

Fabrizio, K., and D.C. Mowery, "The Federal Role in Financing Major Innovations: Information Technology during the Postwar Period," in N. Lamoreaux and K. Sokoloff, eds., Financing Innovation in the United States, 1870 to the Present (Cambridge, MA: MIT Press, 2007).

Fisher, Franklin M., James W. McKie, and Richard B. Mancke, IBM and The U. S. Data Processing Industry (New York: Praeger, 1983).

Flamm, Kenneth, Targeting the Computer (Washington, DC: The Brookings Institution, 1987).

Flamm, Kenneth, Creating the Computer (Washington, DC: The Brookings Institution, 1988).

Goldstine, H.H., The Computer from Pascal to Von Neumann, 2d ed. (Princeton, NJ: Princeton University Press, 1993).

Grindley, P., D.C. Mowery, and B. Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia," Journal of Policy Analysis & Management 13, 1994, 723 – 758.

Holbrook, D., W.M. Cohen, D.A. Hounshell, and S. Klepper, "The Nature, Sources, and Consequences of Firm Differences in the Early History of the Semiconductor Industry," Strategic Management Journal 21, 2000, 1017-1041.

Klepper, S., "Silicon Valley—A Chip off the old Detroit Bloc," forthcoming in D. Audretsch and R. Strom, eds., Entrepreneurship, Growth, and Public Policy (New York: Cambridge University Press, 2008).

Langlois, R. N., and D. C. Mowery. "The federal government role in the development of the U.S. software industry" in D. C. Mowery ed., The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure (New York: Oxford University Press, 1996).

Langlois, R.N., and W.E. Steinmueller, "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry, 1947-1996," in D.C. Mowery and R.R. Nelson, eds., Sources of Industrial Leadership (New York: Cambridge University Press, 1999).

Lecuyer, C., Making Silicon Valley (Cambridge, MA: MIT Press, 2006).

Levin, R.C.,"The Semiconductor Industry," in Nelson, Government and Technical Progress (New York: Pergamon, 1982).

Macher, J.T., D.C. Mowery, and D.A. Hodges, "Semiconductors," in D.C. Mowery, ed., U.S. Industry in 2000 (Washington, D.C.: National Academies Press, 1999).

Malerba, F., The Semiconductor Business: The Economics of Rapid Growth and Decline (Madison: University of Wisconsin Press, 1985).

Misa, T.J., "Military Needs, Commercial Realities, and the Development of the Transistor, 1948-1958," in M.R. Smith, ed., Military Enterprise and Technological Change (Cambridge, MA: MIT Press, 1985).

Mowery, D.C., The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure, (Oxford University Press, 1996).

Mowery, D.C., "The Computer Software Industry," in D.C. Mowery and R.R. Nelson, eds., Sources of Industrial Leadership (New York: Cambridge University Press, 1999).

Mowery, D.C., and R.R. Nelson, "Conclusion: Explaining Industrial Leadership," in D.C. Mowery and R.R. Nelson, eds., Sources of Industrial Leadership (New York: Cambridge University Press, 1999).

Mowery, D.C., and N. Rosenberg, Paths of Innovation (New York: Cambridge University Press, 1999).

Mowery, D.C., and Langlois, R., "Spinning Off and Spinning On(?): The Federal Government Role in the Development of the U.S. Computer Software Industry," Research Policy, 1996.

National Research Council, Funding a Revolution: Government Support for Computing Research, (National Academy Press, 1999).

National Research Council, Energy Research at DOE (Washington, D.C.: National Academy Press, 2001).

Pugh, E.W., Building IBM (Cambridge, MA: MIT Press, 1995).

Redmond, Kent C., and Thomas M. Smith, Project Whirlwind: History of a Pioneer Computer (Bedford, MA: Digital Press, 1980).

Riordan, M., and L. Hoddeson, Crystal Fire (New York: Norton, 1997).

Steinmueller, W.E., "The U.S. Software Industry: An Analysis and Interpretive History," in D.C. Mowery, ed., The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure(New York: Oxford University Press, 1996).

Tilton, J.H., International Diffusion of Technology: The Case of Semiconductors (Washington, D.C.: Brookings Institution, 1971).

U.S. Department of Commerce, Business and Defense Services Administration (BDSA), Electronic Component: Production and Related Data, 1952-1959, Washington, D.C. 1960.

U.S. Department of Commerce, Business and Defense Services Administration (BDSA), “Consolidated Tabulation: Shipments of Selected Electronic components,” mimeo, Washington, D.C., annually, 1960-68.

U.S. Department of Commerce, Bureau of Census, Current Industrial Reports, Series MA-175, “Shipments of Defense-Oriented Industries,” Washington, D.C., annually, 1969-77

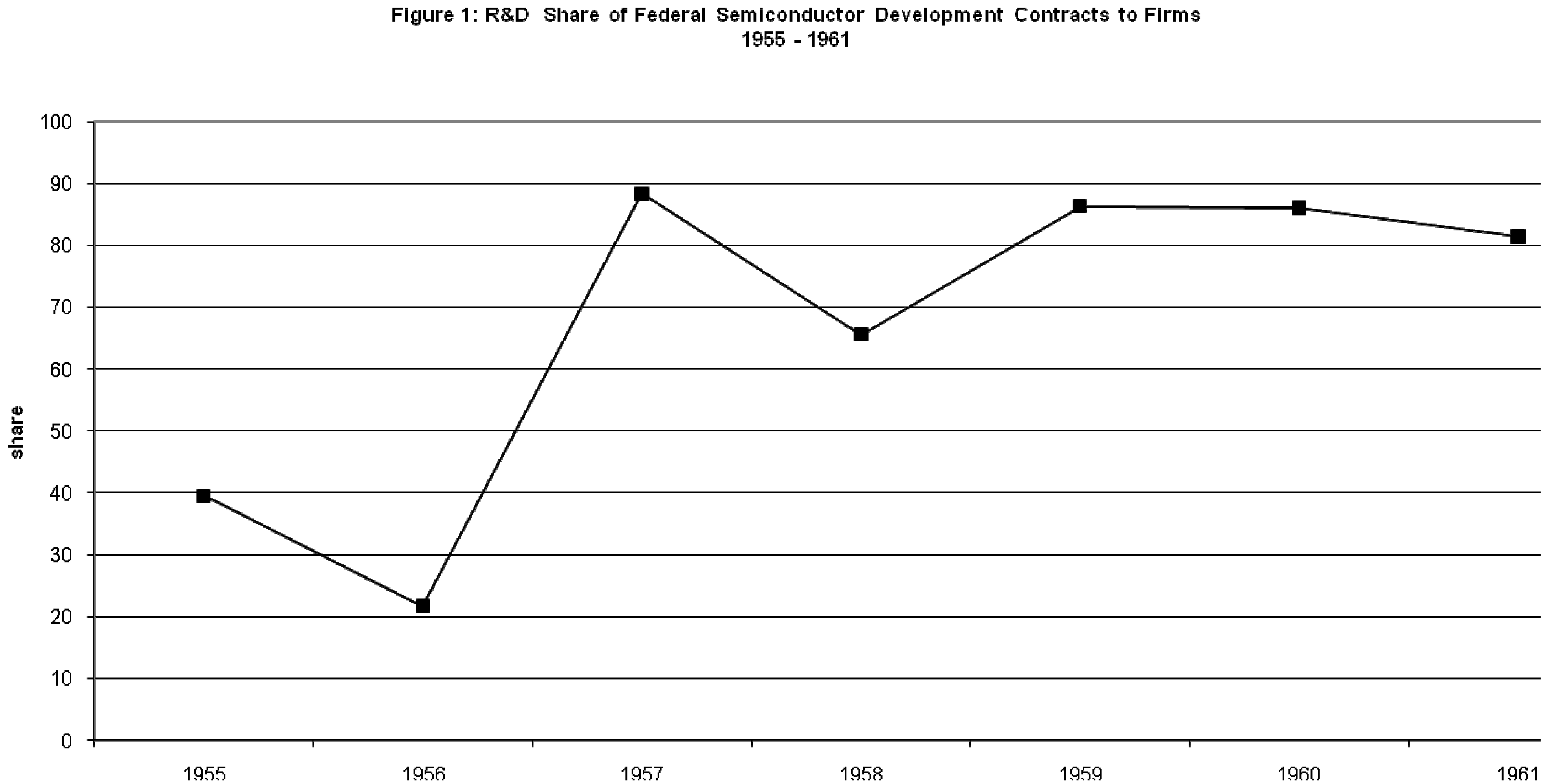
U.S. Department of Commerce, U.S. Industry & Trade Outlook 2000 (Washington, D.C.: USGPO, 2000).

U.S. Department of Defense, Joint Service Task Force on Software Problems, Report of the DOD Joint Service Task Force on Software Problems (Washington, D.C.: U.S. Department of Defense, 1982).

U.S. Department of Defense, Defense Science Board (DSB), “Report of the DSB Task Force on Defense Semiconductor Dependency” (Washington, D.C.: U.S. Department of Defense, 1987).

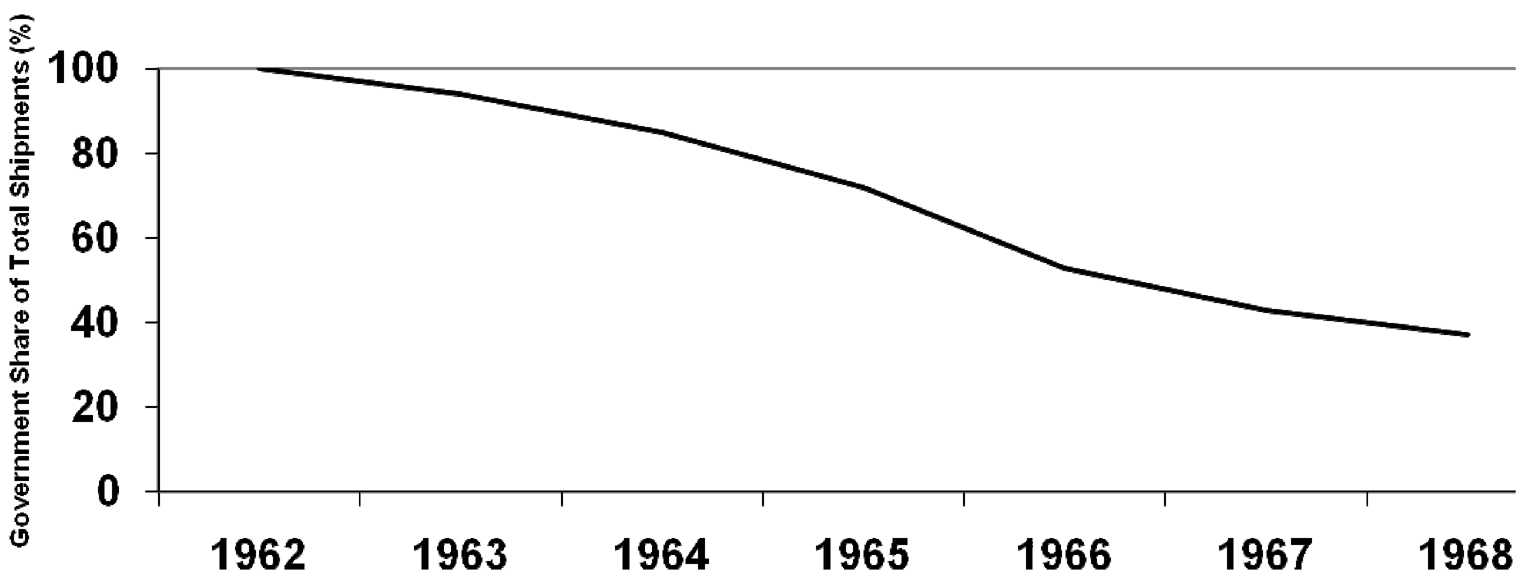
U.S. International Trade Commission, A Competitive Assessment of the U.S. Computer Software Industry (Washington, D.C.: U.S. International Trade Commission, 1995).Usselman, S., “IBM and its Imitators: Organizational Capabilities and the Emergence of the International Computer Industry,” Business & Economic History 22, 1993, 1-35.

Von Neumann, John, "First Draft of a Report on the EDVAC," 1945; reprinted in William Aspray and Arthur Burks, eds., Papers of John von Neumann on Computing and Computer Theory (Cambridge: MIT Press, 1987).



Source: John Tilton, International Diffusion of Technology: The Case of Semiconductors (Brookings, 1971).

Figure 2: Government Purchases of Integrated Circuits as a Share of Total Shipments



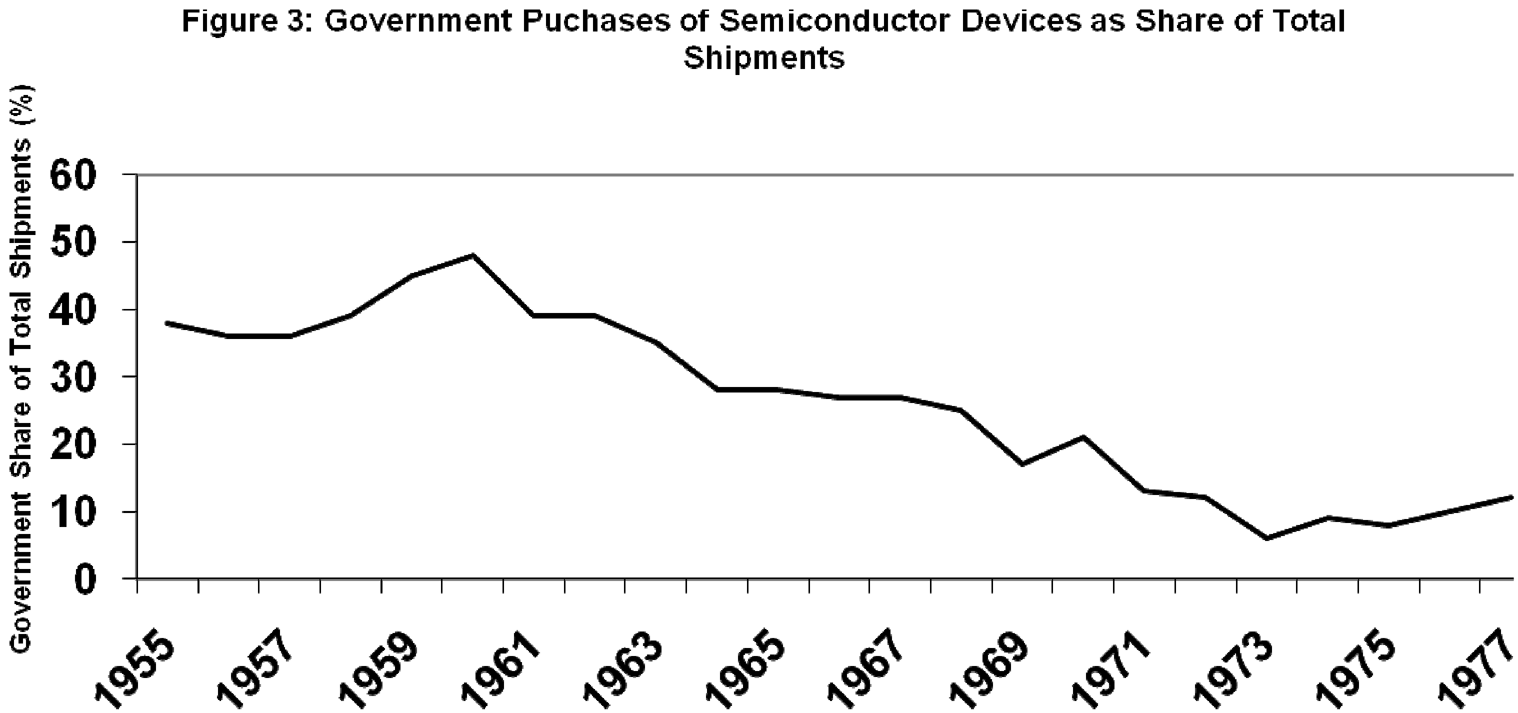
Source: Levin, "The Semiconductor Industry," in Nelson, Government and Technical Progress, p. 63, Table 2.17. Government Purchases of Integrated Circuits, 1962 – 1968.

Notes from Levin:

a. Includes circuits produced for Department of Defense, Atomic Energy Commission, Central Intelligence Agency, Federal Aviation Agency, and National Aeronautics and Space Administration.

b. Estimated by Tilton (1971).

Original Sources: Tilton (1971), p. 91. Total shipments data originally drawn from Electronic Industries Association, Electronic Industries Yearbook, 1969, Washington, 1969. Government share calculated by Tilton from data in BDSA, "Consolidated Tabulation: Shipment of Selected Electronic Components."



Source: Levin, "The Semiconductor Industry," in Nelson, Government and Technical Progress, p. 63. Table 2.16. "Government Purchases of Semiconductor Devices, 1955 – 1977."

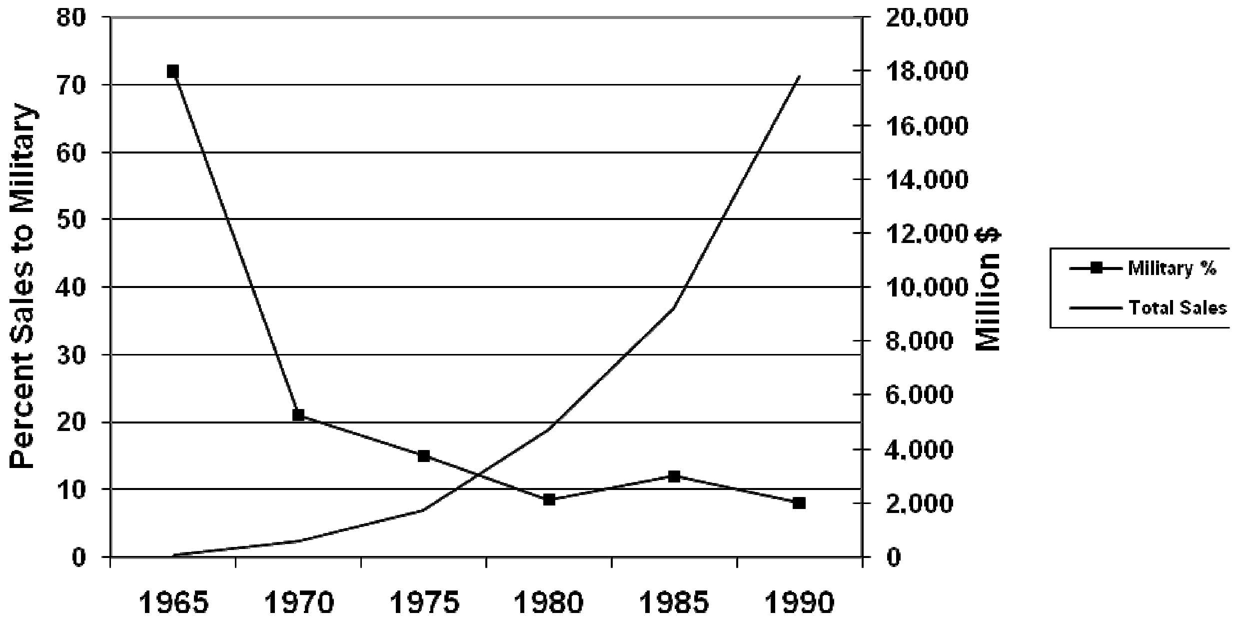
Notes from Levin: Includes devices produced for Department of Defense, Atomic Energy Commission, Central Intelligence Agency, Federal Aviation Agency, and National Aeronautics and Space Administration equipment.

Original Sources: 1952 – 29 data from U.S. Department of Commerce, Business and Defense Services Administration, Electronic Component: Production and Related Data, 1952-1959, Washington, D.C. 1960.

1960 – 68 data from BDSA, "Consolidated Tabulation: Shipments of Selected Electronic components," mimeo, Washington, D.C., annually.

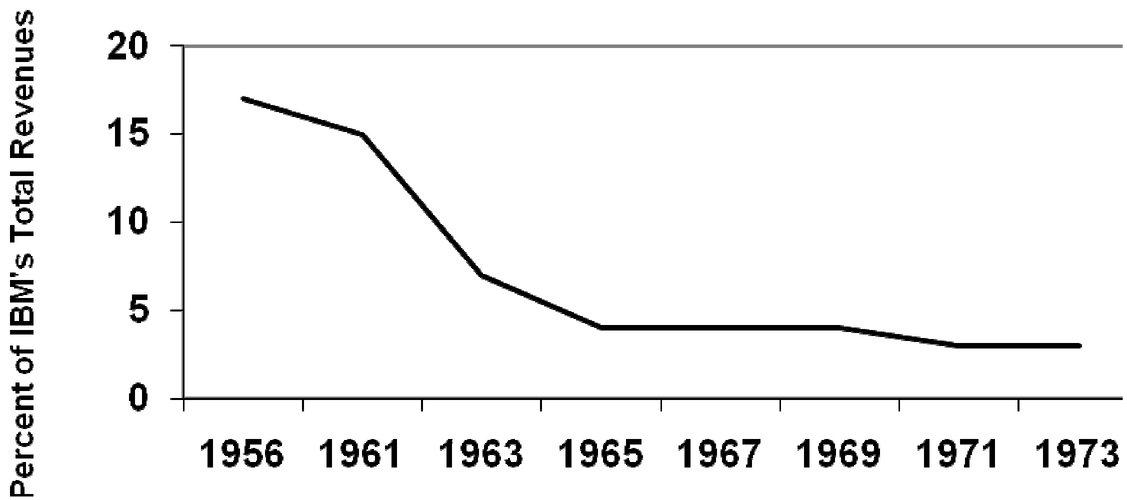
1969 – 77 data from U.S. Department of Commerce, Bureau of Census, Current Industrial Reports, Series MA-175, "Shipments of Defense-Oriented Industries," Washington, D.C., annually.

Figure 4: Total Sales and Military Share of U.S. Integrated Circuit Sales



Source: Alic, John A., Lewis M. Branscomb, Harvey Brooks, Ashton B. Carter, and Gerald L. Epstein, Beyond Spinoff: Military and Commercial Technologies in a Changing World (Boston: Harvard Business School Press, 1992), Table 8-1, page 260.Original Sources: 1965, 1970: Normal J. Asher and Leland D. Strom, "The Role of the Department of Defense in the Development of Integrated Circuits," IDA Paper P-1271 (Arlington, VA: Institute for Defense Analyses, May 1977), p 73; 1975: Estimated, based on *A Report on the U.S. Semiconductor Industry* (Washington, DC: Department of Commerce, September 1979), pp. 39, 44; 1980: *As Assessment of the Impact of the Department of Defense Very High Speed Integrated Circuit Program*, National Materials Advisory Board Report NMAB-382 (Washington, DC: National Research Council, January 1982), p. 64; 1985: *Report of the Defense Science Board on Use of Commercial Components in Military Equipment* (Washington, DC: Office of the Under Secretary of Defense for Acquisition, June 1989), p. A-14; 1990: Estimated, based on figures from Dataquest and the Semiconductor Industry Association.

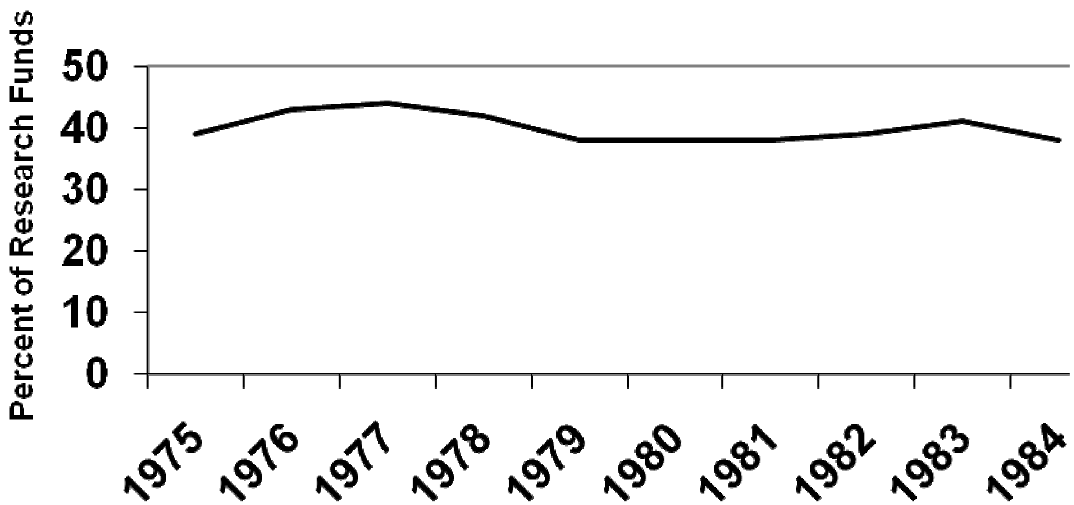
Figure 5:
IBM Sales of Special Products and Services to U.S. Governement Agencies



Source: Flamm, Targeting the Computer, page 108, Table 4-7.

Original Source: Montgomery Phister, Jr., *Data Processing Technology and Economics*, 2d ed. (Bedford, Mass: Digital Press, and Santa Monica Publishing Co., 1979), p. 310.

Figure 6:
Federal Math & Computer Science Funds as a Share of All Computer-Related Research Performed in Universities and Nonindustrial Research Organizations



Source: Flamm, Targeting the Computer, page 104, Table 4-5: "The Federal Role in Computer-Related Research, Fiscal Years 1967-84."

Original Sources: NSF, *Research and Development in Industry, 1984*, pp. 20, 23; NSF, *Federal Funds for Research and Development: Federal Obligations for Research by Agency and Detailed Field of Science, Fiscal Years 1967-86* (GPO, 1985), pp. 5, 31; NSF*, Academic Science/Engineering: R&D Funds, Fiscal Year 1982*, NSF 84-308 (GPO, 1984), pp. 129-30; NSF data obtained though computer database; NSF, *Academic Science/Engineering: 1972-83*, pp. 43-44; and NSF, *Academic Science/Engineering: R&D Funds, Fiscal Year 1983*, pp. 16, 130-31.

Figure 7. U.S. Department of Defense Software Procurement, 1959–1990

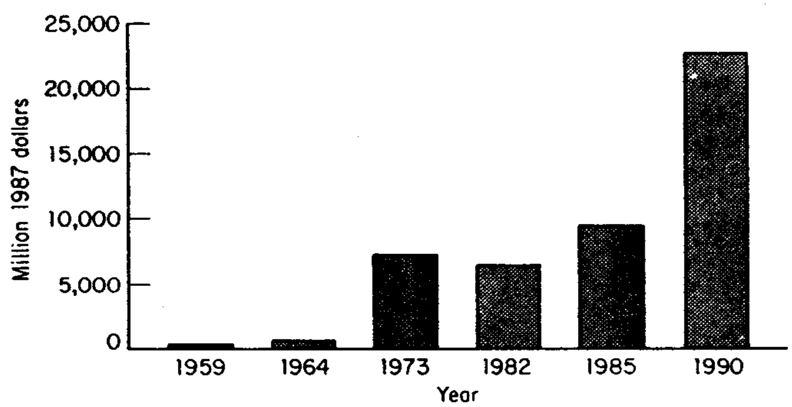


Figure 3-4. Department of Defense software procurement, 1959–90. *Source:* 1959 and 1964 estimates from Phillips 1985; 1973 from Fisher 1978; 1982 from U.S. Department of Defense 1982; 1985 from U.S. Department of Defense 1987; 1990 from U.S. Department of Defense 1992.

Source: Langlois & Mowery "The Federal Government Role in the Development of the U.S. Software Industry," p. 69.

Table 1: End-Use Shares of Total U.S. Sales of Integrated Circuits and Total Market Value 1962-1978

Markets	1962	1965	1969	1974	1978
Government	100%	55%	36%	20%	10%
Computer	0%	35%	44%	36%	37.5%
Industrial	0%	9%	16%	30%	37.5%
Consumer	0%	1%	4%	15%	15%
Total U.S. domestic shipments (millions)	$4	$79	$413	$1,204	$2,080

Source: Langlois & Steinmueller, "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry, 1947-1996," in Mowery & Nelson Sources of Industrial Leadership, p. 37, Table 2.7.

Borrus er al. (1983, p. 159)

Table 2: Early Federal government computer-development programs**First Generation of U.S. Computer Projects**	**Estimated Cost of Each Machine (thousands of dollars)**	**Source of Funding**	**Initial Operation**
ENIAC	750	Army	1945
Harvard Mark II	840	Navy	1947
Eckert-Mauchly BINAC	178	Air Force (Northrop)	1949
Harvard Mark III	1,160	Navy	1949
NBS Interim computer (SEAC)	188[a]	Air Force	1950
ERA 1101 (Atlas I)	500	Navy/NSA[b]	1950
Eckert-Mauchly UNIVAC	400-500	Army via census; Air Force	1951
MIT Whirlwind	4,000-5,000	Navy; Air Force	1951
Princeton IAS computer	650[a]	Army; Navy; RCA; AEC	1951
Univ. of Cal. CALDIC	95[a]	Navy	1951
Harvard Mark IV	n.a.	Air Force	1951
EDVAC	467	Army	1952
Raytheon Hurricane (RAYDAC)	460[a]	Navy	1952
ORDVAC	600	Army	1952
NBS/UCLA Zephyr computer (SWAC)	400	Navy; Air Force	1952
ERA Logistics computer	350-650	Navy	1953
ERA 1102 (3 built)	1,400[c]	Air Force	1953
ERA 1103 (Atlas II, 20 built)	895	Navy/NSA	1953
IBM Naval Ordnance Research Computer (NORC)	2,500	Navy	1955

Source: Flamm, Creating the Computer, page 76

Original Sources: Herman H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton University Press, 1972), pp. 242-45, 316-18, 326, 328; Arthur D. Little, Inc., with the White, Weld & Co. research department, *The Electronic Data Processing Industry: Present Equipment, Technological Trends, Potential Markets* (New York: White, Weld & Co., 1956), p. 82; Martin H. Weik, " A Third Survey of Domestic Electronic Digital Computing Systems," Report 115 (Aberdeen Proving Ground, Md: Ballistic Research Laboratories, 1961), pp. 213, 236, 282, 393, 567, 635, 639, 676-77, 732, 848, 900, 1016, 1081-83; Martin H. Weik, "A Fourth Survey of Domestic Electronic Digital Computing Systems," report 1227 (Aberdeen Proving Ground, Md: Ballistic Research Laboratories, 1964), p. 373; Nancy Stern, *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers* (Digital Press, 1981), pp. 37, 51, 62, 105, 113, 117, 122-23, 132; Kent C. Raymond and Thomas M. Smith, *Project Whirlwind: The History of a Pioneer Computer* (Digital Press, 1980), pp. 107, 110, 127-28, 156-58, 166; Ralph A. Niemann*, Dahlgren's Participation in the Development of Computer Technology* (Dahlgren, Va.: Naval Surface Weapons Center, 1982), pp. 4, 5, 11, 16; Samuel S. Snyder, "Influence of U.S. Cryptologic Organizations on the Digital Computer Industry," SRH 003, declassified National Security Agency report released to the National Archives, p. 7; Samuel S. Snyder, "Computer Advances Pioneered by Cryptologic Organizations," *Annals of the History of Computing*, vol. 2 (January 1980), pp. 60-63. M.R. Williams, "Howard Aiken and the Harvard Computation Laboratory," *Annals of the History of Computing*, vol. 6 (April 1984), p. 160; ONR, *Digital Computer Newsletter*, various issues, 1949-56; S.N. Alexander, "Introduction," in U.S. Department of Commerce, National Bureau of Standards, Computer Development (SEAC and DYSEAC) at the National Bureau of Standards, Washington, D.C., NBS circular 551 (Government Printing Office, 1955), p. 3; H.D. Huskey, "The National Bureau of Standards Western Automatic Computer (SWAC)," *Annals of the History of Computing*, vol. 2 (April 1980), pp. 111-21; John W. Carr III, "Instruction Logic of the MIDAC," in C. Gordon Bell and Allen Newell, eds., *Computer Structures: Readings and Examples* (McGraw-Hill, 1971), p. 209; John Varick Wells, "The Origins of the Computer Industry: A Case Study in Radical Technological Change" (Ph.D. dissertation, Yale University, 1978), p. 268; and the following citations in N. Metropolis, J. Howlettm and Gian-Carlo Rota, eds., *A History of Computing in the Twentieth Century: A Collection of Essays* (Academic Press, 1980): J.C. Chu, "Computer Development at Argonne National Laboratory," p. 346; James E. Robertson, "The ORDVAC and the ILLIAM," pp. 346-47; Henry D. Huskey, "The SWAC: The National Bureau of Standards Western Automatic Computer," pp. 421, 428, 430; M. Metropolis, "The MANIAC," p. 462; and Erwin Tomash, "The Start of an ERA: Engineering Research Associations, Inc., 1946-1955," p. 491.

n.a. Not available

a. Estimated cost in 1950, in "Report on Electronic Digital Computers by the Consultants to the Chairmand of the Research and Development Board," June 15, 1950, app. 4, cited by Kent C. Redmond and Thomas M. Smith, *Project Whirlwind: The History of a Pioneer Computer* (Digital Press, 1980), p. 166.

b. The National Security Agency (NSA) includes Army and Navy predecessor agencies.

c. Cost for three machines.