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CHAPTER 5

THE COMPUTER INDUSTRY

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The development of the electronic digital computer was preceded by a long history of mechanical and electromechanical tabulating machines. In the latter years of the nineteenth century numerous office machines—typewriters, adding machines, cash registers, mechanical calculators, and billing and accounting devices—were introduced. In 1886 Herman Hollerith, a statistician employed at the U.S Census Office, designed and built an electrically run tabulator that used punch card inputs and electrical card reading (Cortada 1993; Ruttan 2001: 317-319). The Hollerith machine was able to process census data in one-third the time

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[1] In his chapter I have drawn extensively on, "The Computer and Semiconductor Industries" in Ruttan (2001: 316-367). I define the computer industry broadly to include semiconductors and software. I also use the term military procurement as a shorthand expression to include related research and procurement by the National Aeronautics and Space Administration and the Atomic Energy Commission (now the Department of Energy). I am indebted to Arthur Norberg and Jeffrey Yost for comments on an earlier draft of this chapter.

it would have taken with handwritten tally sheets (Cortada 1993; Ruttan 2001: 317-319).

In this Chapter I trace the role of military procurement on the development of the computer industry. During and immediately after World War II major efforts were made, with the support of the military, to develop fully electronic computing machines. The role of the military in driving the development of computer, semiconductor and software technologies cannot be overemphasized. These technologies were, until well into the 1960's, nourished by markets that were almost completely dependent on the defense, energy and space industries. An important subtheme in this chapter is the intimate relationship between advances in science and in technology in the development of the computer, the transistor and computer software.

INVENTING THE COMPUTER

The first fully automatic calculator was a product of collaboration between Harvard University and IBM. The Automatic Sequence Controlled Calculator (Mark I), an electro-mechanical machine, was completed in 1944. It could add, subtract, multiply, divide, and table reference. Input data were entered on punched cards and output was recorded either on punched cards or on an electric typewriter. Early models were built for the Navy and Air Force.[2] In 1947, drawing on its experience in constructing the Mark I, IBM constructed a "super calculator", the Selective Sequence Electronic Calculator. It was a "gigantic hybrid of electronic and mechanical parts, half modern computer and half punch card machine" (Watson 1990: 190).

Firing Tables and Cryptology

The first all-purpose electronic digital computer was developed by John W. Mauchly and J. Presper Eckert and associates at the University of Pennsylvania's Moore School of Electrical Engineering.[3] The Army Ballistics Research Laboratory (BRL) was confronted with the

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[2] The best short treatment of the role of military procurement in computer development is Seidel (2002). The most useful book length treatments on the development of the computer are Ceruzzi (2003) and Flamm (1987 and 1988). In this section I also drawy on Pugh (1984); Bashe et al (1986); Katz and Phillips (1982); Pugh (1984: 301-312); Shurkin (1984); Campbell-Kelly and Aspray (1996); Mowery and Rosenberg (1998: 135-151); and National Research Council (1999: 85-135).

[3] The electronic digital computer was conceived by John V. Atanasoff of Iowa State University in 1937. In December 1940 he demonstrated a small prototype and in 1941 he published a paper on the theory and design of computers. In 1941 Mauchly visited Iowa State to examine the computer, read the technical papers, and discuss his work with Atanasoff. Iowa State failed to patent the Atanasoff design. Although the issue remains controversial most historians of computing now credit Atanasoff rather than Mauchly and Eckert as the inventor of the electronic digital computer (Shurkin 1984: 114-116; Slater 1987: 53-79). For other precursors to Mauchly and Eckert in the development of the electronic digital computer see Lee (2002).

enormous labor involved in calculating artillery firing tables. Against the advice of the U.S. computing establishment it "chose to gamble on an untested technology (Flamm 1988: 252). The Mauchly-Eckert machine, called the Electronic Numerical Integrator and Calculator (ENIAC), was completed in 1946. It was capable of computing more than 1000 times faster than any then-available electromechanical machine. "The ignition of the hydrogen bomb was simulated in the first program run on the ENIAC" (Seidel 2002: 191).[4] The successful completion of the ENIAC, by stimulating further defense agency demand, provided a great impetus for the development of the computer, even though the ENIAC had no immediate commercial applications.

A second computer developed by the Moore School group, the Electronic Discreet Variable Computer (EDVAC), had an even more important impact on future computer development. It incorporated the concept of a stored program and sequential processing developed by Mauchly, Eckert, and Herman Goldstein of the Moore group and the

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[4] Flamm noted that the decision was facilitated by the support of John von Neumann, "who was concerned about the enormous computational demands of nuclear weapons design," (1988: 252). The initial cost of building the ENIAC was estimated as $50,000. The final cost was in the neighborhood of $500,000 (Edwards 1996: 51).

mathematician John von Neumann of Princeton University's Institute for Advanced Study (Princeton, NJ). In what came to be referred to as the von Neumann architecture, the processing unit of the computer fetches instructions from a central memory that stores both data and programs, operates on the data (for example adds or subtracts) and returns the results to a central memory.[5]

In the early postwar period there was a rapid formation and consolidation of firms formed, under the impetus of defense agency demand, to exploit the new technology (Norberg 2002). Eckert and Mauchly formed the Electric Control Company in June 1946 and the Eckert-Mauchly Computer Corporation (EMCC) in 1947. Because they had difficulty raising significant capital to complete their development work Eckert and Mauchly accepted an offer to be acquired by Remington Rand in 1950. The brought with them several contracts, including one with the Bureau of the Census to develop an EDVAC type computer called UNIVAC.

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[5] The first electronic digital von Neumann type stored-program computer to be placed in regular operation in the U.S. was the Standard Eastern Automatic Computer (SEAC) completed by the National Bureau of Standards in 1950. It was the source of a number of important technical innovations including the solid state logic. Its development was supported by both the Navy and the Army (Flamm 1988: 68-75).

A second pioneering computer company, Engineering Research Associated (ERA) was formed in St. Paul, Minnesota, in 1946. The founders of ERA were drawn from the Naval Communications Supplemental Activity, located in St. Paul, who had been involved in developing computers in support of the Navy's work in cryptology.[6] "With ERA, the Navy effectively privatized its wartime cryptography and was able to maintain civilian expertise through the radical postwar demobilization" (National Research Council 1999: 91). ERA's first major computer system, the Atlas, was delivered to the Navy in December 1950. A modified version designed for commercial applications, the ERA 1101, became available in 1952. ERA also ran into financial difficulties and agreed to be acquired by Remington Rand in 1952. With its Eckert-Mauchly and ERA operations, Remington Rand controlled a significant share of the total computer engineering capacity in the United States (Tomash and Cohen 1979).

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[6] As early as 1943 a team led by Alan Turing at the British Government Code and Cypher School, developed an electronic digital computer, the Colossis, designed to automate the decoding of German military communications. The machine could not store programs internally (Edwards 1996: 16-18).

Both Eckert-Mauchly and the ERA group were disappointed by Remington Rand’s lack of enthusiasm for commercial development. This lack of enthusiasm was shared by other office equipment manufacturers (Cortada 1993: 222-246). In 1950 IBM president Thomas Watson Sr. asserted that the Selective Sequence Electronic Calculator (SSEC), an electro-mechanical machine developed by IBM and on display at the IBM headquarters in New York City, was sufficient to “solve all the important scientific problems in the world involving scientific calculations” (Katz and Phillips 1982: 171). Although he apparently saw only limited commercial possibilities for computers IBM was already making substantial investment in electronics research.

It was the Korean War that led to a decision by IBM to test the market for commercial computers. Assured by letters of intent from government agencies and defense related firms, IBM initiated the Defense Calculator project in early 1951. When the prospective rental price of $15,000 per month was announced many of the prospective clients withdrew (Katz and Phillips 1982: 177). IBM decided, however, to go ahead with development of the machines, to be renamed the IBM

701. "The IBM 701 was formally dedicated on April 7, 1953. The first IBM 701 to be externally installed was at the Atomic Energy Commission's Los Alamos Laboratory at the end of March 1953 (Mackenzie 1996: 114). "Replacement of the SSEC as the show piece of IBM's computer capability signaled the transition of IBM to a new era of postwar electronic computer technology," (Pugh 1984: 32).[7]

Whirlwind and SAGE

Intensification of the Cold War in the early 1950's played a critical role in the development of IBM's capacity to market a fully transistorized commercial computer (Usselman 1993).[8] The impetus came from a decision by IBM to cooperate with the MIT Lincoln Laboratory in the design and development of a computerized air defense

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[7] Arthur Norberg has pointed out that Eckert-Mauchly (EMCC), ERA and IBM required about the same length of time to design and delivery of a computer system. EMCC began first in 1946 and delivered the Binary Automatic Computer (BINAC) to Northrup Aviation in 1949. ERA received a contract to design and build the Atlas in 1947 and delivered the machine to the National Security Agency in 1953. Development work on the IBM Defense Calculator and the IBM 650 project began in 1948. The defense calculator appeared in 1951, a commercial version, the IBM 701, became available in December 1952, and the IBM 650 in 1954. Thus by the mid 1950s the three firms had achieved roughly comparable capacity (Norberg, 1993: 193). For greater detail on the early history of Engineering Research Associates see Tomash and Cohen (1979) For a highly personal account of the cautious entry of IBM into the electronic digital computer field see Watson (1990: 130-146, 188-207, 227-238). Cortada has emphasized that the practices worked out over the previous several decades in the office machinery business "enabled IBM management to enter the computer business with proven methods of marketing and support and a customer base that could migrate to the new technology" (Cortada 1993: 127).

[8] The IBM decision was also influenced by a 1951 Justice Department antitrust suit against IBM over its policy of only leasing its tabulating machines, monopolization of the punch card market, and discrimination in punch card sales. IBM president Thomas J. Watson JR. agreed to a consent decree resolving the antitrust suit in 1956. His strategy was to forego dominance in the mature tabulating and card markets and achieve dominance in the computer market. Air Force and Atomic Energy Commission contracts contributed substantially to the success of Watson's strategy (Jorgensen 1996).

system, the Semi-Automatic Ground Environment (SAGE), funded by the U.S Air Force. The computer technology developed for the SAGE Project was a direct outgrowth of Project Whirlwind, originally intended to develop a general purpose flight simulator, that had been initiated during World War II by a group of young graduate engineers led by Jay Forrester at the MIT Servomechanisms Laboratory and funded by the Office of Navel Research.

In 1946 Forester succeeded in convincing the DoD to commit the large resources needed to expand the goal of the Whirlwind program to the design of a real-time general purpose digital computer that could serve functions other than flight simulation In 1950 as the development of the Whirlwind computer was being completed the ONR, facing increasing budgetary pressure and skeptical that Whirlwind would be as useful as had earlier been anticipated, entered into negotiations with MIT about reducing its level of funding for the project. A fortuitous visit to the Servomechanism Laboratory in January 1950 by George E. Valley, Jr., a MIT physics professor and chairman of the Air Defense System Engineering Committee, led to Valley's interest in the potential role that Whirlwind might play in an Air Force project to develop a computer based air defense system. Arrangements were made to shift the major funding of Whirlwind from ONR to the Air Force.[9]

The task envisaged for SAGE was to detect alien aircraft, select appropriate interceptor aircraft, and determine antiaircraft missile trajectories. Critical to the SAGE system would be two pieces of equipment that, in 1950, still had to be designed, built and tested: (a) A high speed electronic digital processing machine that would be located at each radar site to perform real time processing of radar signals and send the data over telephone lines to the command-and-control center and (b) a central computer located at the command-and-control center which would accept and process the data from the distributed radar sites. The system would have to store and process large amounts of information and coordinate several computers in real-time (Redmond and Smith 2000: 2). By 1951 work had progressed to the point where a

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[9] For the definitive study of the Whirlwind Project and of the role of the MIT team directed by Jay Forrester in the development of Whirlwind and SAGE see the book, *From Whirlwind to MITRE* (Redmond and Smith 2000); also National Research Council 1999: 92-95).

successful simulation test involving live aircraft could be carried out over Medford Massachusetts (Redmond and Smith 2000: 3).

By the middle of 1952 sufficient progress had been made in the design of Whirlwind II that the project team initiated efforts to identify a manufacturer who might have the capacity to build a prototype and a production model of the machine. Preliminary inquiry identified five firms as potential collaborators—the Bell System (Bell Telephone Laboratories and Western Electric), Radio Corporation of America, Raytheon, Remington Rand (Eckert-Mauchly and Engineering Research Associates), and IBM. Following meetings with representatives of each firm and visits to facilities by Whirlwind managers Bell and RCA withdrew from further consideration because of the pressure of prior staff commitments. Raytheon was judged to lack engineering capacity and the two divisions of Remington Rand not sufficiently integrated. IBM was judged to be the best choice for a collaborator by a substantial margin.

In the fall of 1952 managers and engineers at MIT and IBM initiated a period of intense and frequently stressful collaboration that led from the building of an air defense computer to an air defense system. In 1953 and 1954 experimental tests of the system were conducted over Cape Cod (the Cape Cod System). In 1958 the first sector of the SAGE system became fully operational. In December 15, 1961 the last North American link in the SAGE air defense system, which included 21 sectors stretching along the east and west coasts, along the northern states and into northern Canada, were turned over to the Air Defense Command. By time it was completed IBM had built 54 computers for the SAGE system.

The SAGE project was a driving force behind the commercial development of the American computer industry. It has been termed the most important learning experience in computer history. It led to many of the inventions that we have come to expect in our personal computers (Katz and Phillips 1982; Hughes 1998: 15-67). “It revolutionized the information industry by spanning in one inspired leap the prehistoric computer era of serial batch processing and the modern world of interactive systems" (Redmond and Smith 2000: 442).[10] During the first two decades of computer development the technical cutting edge of technology development was advanced primarily by government laboratories or by private industry engaged in military and defense related research (National Research Council 1999: 86-96).

By the late 1950s progress in semiconductor development was beginning to open up the possibility of designing smaller and less expensive computers. In 1957 Kenneth Olson, a former IBM employee, and Harlan Anderson founded Digital Equipment Corporation (DEC) with $30,000 in venture capital funding. Olson was committed to a vision of computers that were smaller, easier to operate, and much less expensive than an IBM mainframe (Rifkin and Harrer 1988). The first DEC computer, the PDP-1, was demonstrated in 1959. "It sold for

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[10] The innovations made in connection with the SAGE project at MIT and IBM included (1) techniques to manufacture ferrite core memory rapidly, inexpensively, and reliably, (2) computer-to-computer telecommunications, (3) real-time simultaneous use by many operators, (4) key-board terminals for man-machine interaction, (5) simultaneous use of two linked computers, (6) ability to devolve certain functions to remote locations without interfering with the dual processors, (7) use of display options independently of dual processors, (8) inclusion of an interrupt system, diagnostic programming, and maintenance warning techniques, and (9)memory development (Katz and Phillips 1982: 185; Committee on Innovation in Computers and Communications 1999: 92-94). Most of these advances were incorporated into the IBM's first fully transistorized computer, the 7090. Other IBM 7090 innovations included (radically new parallel architecture, permitting several operations to be performed simultaneously, (standard modular systems component technology, (3) printed circuit cards and improved back-wiring, (4) an 8-bit byte, (5) greatly improved transistors and the means of manufacturing them, (6) a common mode for attaching peripherals, (7) a combination of decimal and binary arithmetic, and (8) combined fixed and variable word length operations (Katz and Phillips 1982: 189). Pugh notes that the development of high-speed ferrite core memories that could be mass produced at low cost was probably the most important innovation that made stored-program computers a practical commercial reality (Pugh 1984: ix).

$120,000, contained 4K bytes of memory, was the size of a refrigerator, and included a cathode ray television-like video display built in the console" (Langlois 1991: 7). The PDP-8 introduced in 1965 was the first computer to use integrated circuits. The initial commercial success of the DEC computers encouraged the entry of other firms such as Data General, Scientific Data Systems, Hewlett-Packard and Wang to enter the minicomputer market. From a longer term perspective the significance of the minicomputers is that they provided a bridge between the mainframe and the microcomputer—"the minicomputer generated the seeds of its own destruction" (Ceruzzi 2003: 206). The minicomputer market peaked in the early 198s. The development of the microcomputer was dependent on the development of semiconductors—the transistor and the microprocessor[11].

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[11]. Military procurement played only an indirect role in the development of the microcomputer. For an excellent review of the development of the microcomputer—the personal computer, see Ceruzzi (2003: 207-241). See also Ruttan 2001: 331-337).

SEMICONDUCTORS

It was understood even in the 1940s that the speed, reliability, physical size, and heat-generating properties of the vacuum tubes used in telephone switching devices would become a major technical constraint on electric switching.[12] The first working transistor emerged out of research led by William Shockley of the Bell Telephone Laboratories solid-state research group in late 1947.[13] Shockley joined Bell in 1936 after receiving a Ph.D. degree in Physics from MIT. Shortly after joining Bell Laboratories Dr Mervin Kelley, Director of Research, emphasized to Shockley his interest in developing electronic switching, in which metal contacts would be replaced by electronic devices. In the late 1930s Shockley began to consider the possibility of an approach to developing electronic switching devices based on solid state physics.

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[12] In this section I draw heavily on Nelson (1962); Katz and Phillips (1982); Levine (1982); Mowery (1983: 183-197: Riordan and Hoddeson (1997); and Mowery and Rosenberg (1998: 124-35, 151-52). For discussion of the scientific and engineering aspects of semiconductors, including circuit design, engineering and fabrication, see Warner (1965).

[13] A semiconductor is an electric circuit component, such as a transistor (or chip) that is fabricated from a material that is neither a good conductor of electricity nor a good insulator. Pure silicon is a poor conductor of electricity but by a process called "doping" a number of atoms of another substance can be introduced into the silicon crystal to alter the electrical properties. A transistor is made of three layers of silicon. Each layer is doped with impurities in such a way that electric current passing through the transistor can be influenced by the much smaller current applied to the middle layer. An *integrated circuit* is a single chip that has more than one active device on it, such as transistors, diodes, resistors or capacitors, as part of an electric circuit. The first integrated circuits required that the connections between circuit elements be made by hand. There are three main types of integrated circuits: (1) memory chips, (2) microprocessor and (3) micro components (Ruttan 2001: 326-28).

After World War II Bell formed a Solid State Department to develop new knowledge that might be used in the development of completely new and improved components and apparatus for communications systems. In attempting to understand why a prototype semiconductor amplifier developed earlier by Shockley had failed, two colleagues, John Bardeen and Walter Brattain, produced the first working transistor (the point contact design) on December 15, 1947. Their work led to an effort by Shockley to develop the bipolar junction transistor. A satisfactory design was not achieved, however, until the spring of 1950. Advances in process engineering, particularly the development of techniques for producing germanium and silicon crystals, were required before production of the junction transistor would become feasible (Shockley 1976:597-620; Teal 1976: 621-639; Basset 2002: 12-22).[14]

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[14] Although the transistor is sometimes cited as an example of a "science push" invention, a clear demand side incentive for the development of such a device was apparent at Bell Telephone Laboratories. The motives of Bell Laboratories in establishing the solid-state physics group were that major advances in the field were likely to be fruitful in improving communications technology. Shockley's own interests embraced both the prospect of advancing semiconductor theory and of developing a solid state amplifier. The approach that Shockley and his associates at Bell undertook was to make an electronic amplifier of semiconductor material. This approach involved advancing the understanding of electron flow in semiconductor materials (Shockley 1976: 618-619).

The relationship between the development of science and technology in the work of Shockley, Bardeen and Brattain at Bell laboratories was clearly much more complex than implied by the linear model in which basic research precedes applied research and applied research precedes technology development (Figure 3.1A). The Bell Laboratories group was simultaneously involved in advancing semiconductor theory and semiconductor technology development. Although the work of Schockley, Bardeen and Brattain was directed to the solution of an immensely important engineering problem it was regarded as sufficiently fundamental that the team was awarded the Nobel Award in Physics in 1956 (Shockley 1976).

Until the late 1950s transistors were discrete devices—each transistor had to be connected to other transistors on a circuit board. In the mid-1950s Texas Instruments, then the leader in silicon transistor production, initiated a research program under the direction of Jack Kilby to repackage the semiconductor products (transistors, resistors and capacitors) as single components to reduce circuit interconnections. In 1958 Kilby's efforts resulted in a first very crude integrated circuit. The costs of assembling the separate components of Kilby's device by hand were too expensive for commercial application. At about the same time however Robert Noyce and Gordon Moore at Fairchild Semiconductor independently invented the integrated circuit. The invention, termed the planar process, involved incorporating very small transistors and resistors on a small sliver of silicon and adding microscopic wires to interconnected adjacent components.

The third major invention in the development of the semiconductor industry was the microprocessor. There are two types of integrated circuits that were critical in the development of computers. One, a memory chip, allows the computer to temporarily remember programs and other information. The other is the microprocessor that processes the information rather than storing it.[15] The first microprocessor was developed by Intel in 1969-70. Technical progress in the integrated circuit era has moved along a trajectory toward increasing the density of

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[15] The critical invention that led to the development of the microprocessor was the metal oxide semiconductor (MOS), Initially the MOS transistor was much slower than the bipolar transistor. It offered the offsetting benefit of simplicity which enabled designers to put more transistors on an integrated circuit. The MOS technology made it possible to put the entire central processing unit on an integrated circuit. The first MOS transistor was built in 1960 by RCA under an Air Force contract. The transition from the bipolar point-contact technology to the metal-0xide semiconductor technological trajectory occurred slowly. It took over 10 years to go form initial conception to commercial via viability at Intel. For a detailed exposition of the history of MOS technology see Bassett (2002).

circuit elements per chip.” In 1965 the co-founder of Intel, Gordon Moore predicted that the number of transistors per integrated circuit would double every 18 months. This has come to be referred to as Moore’s Law,” (Jovanovic and Rousseau 2002; Figure 5.1).

(Insert Figure 5.1 about here)

The potential military applications of semiconductors were immediately apparent. The transition between the initial invention of the transistor and the development of military and commercial applications of semiconductors and integrated circuits was guided and substantially funded by the Army Signal Corps. By 1953 the Army Signal Corps Engineering Laboratory was funding approximately 50 percent of transistor research and development at Bell Laboratories. The Signal Corps Engineering Laboratory at Fort Monmouth (New Jersey) developed the technology to replace hand soldering of components, a critical advance in the transition to mass production of transistor radios. In 1953 the Signal Corps underwrote the construction of a large Western Electric transistor plant at Lauredale, Pennsylvania. By the mid-1950s it had also subsidized facility construction by General Electric, Ratheon, Radio Corporation of America and Sylvania. Funding was also provided for engineering development (Misa 1985: 253-287).

Demand created by the Minuteman II missile and the Apollo space projects (Chapter 7) pushed U.S. firms rapidly down the design and production learning curves (Alic, et al., 1992: 257; Langlois and Steinmueller 1999: 35-36). The diffusion of knowledge and the entry of new firms were encouraged by the military procurement policy of "second sourcing" to avoid becoming dependent on a single supplier. "By subsidizing engineering development and the construction of manufacturing facilities, and by leading the movement to standard operating characteristics, the military catalyzed the establishment of an industrial base" (Misa, 1985: 28; see also Langlois and Steinmueller 1999: 26-28). Demand for semiconductors continued to be dominated by direct procurement for military, nuclear power and space applications and the demand for increasingly powerful computers for military, space and space applications until well into the 1970's (Wessner 2003: 13).

As noted above, progress in semiconductor development was beginning to open up the possibility of designing smaller and less expensive computers. When the PDP-8, the first computer to use integrated circuits, was introduced in 1965 it sold for $18,000 and could be rented for $525 per month. The transition from the minicomputer to the microcomputer—the personal computer—had to await Intel's 1969 development of the programmable chip. With the development and diffusion of the minicomputer and the microcomputer the primary sources of demand for semiconductors, primarily memory chips and microprocessors, shifted strongly in the direction of commercial technology.[16]

The development of integrated circuits has had the effect of increasing the fixed costs of innovation, which became a barrier to the entry of new firms into the industry. In the 1970s U.S. producers shifted substantial production assembly capacity to low wage developing countries, particularly Mexico, Taiwan, Singapore, Malaysia, and Korea.

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[16] The Intel memory and microprocessor were early applications of metal-oxide-semiconductor (MOS) chips produced using the planar technology. MOS chips were initially conceived by researchers at Bell Laboratory. They were developed further at RCA and Fairchild Semiconductor. When initially developed the MOS transistors was much slower than bipolar transistors. They did have the advantage of simplicity which enabled Intel to put more transistors in an integrated circuit. It was the density of MOS circuitry that led to the dramatic reductions in the cost of semiconductor memory and microprocessor chips that made the personal computer possible. Because of their emphasis on speed bipolar transistors continued to be the primary technology employed on the semiconductors by producers of mainframe computers, such as IBM, Control Data and CRAY, until well into the 1980's. For an exceedingly careful history of the development of the MOS technology see Bassett (2002). I do not in this chapter discuss the development of the personal computer. I have reviewed the early history of personal computer development in Ruttan (2001: 331-335).

By the early 1980s Japanese semiconductors makers were turning out memory chips of much higher quality and for lower prices than even the leading U.S. producers such as Intel. By the late 1980's Intel had withdrawn from the highly competitive memory chip sector to concentrate on the production of microprocessors (Ruttan 2001: 328-331).

Concern by the defense agencies with the loss of U.S. competitive advantage led to the formation of Sematech, a consortium of semiconductor companies. A primary objective was to strengthen domestic innovation and capacity in the semiconductor equipment manufacturing industry.[17] From its founding in 1987 until the mid-1990s Semitech received substantial funding from ARPA. By the end of the 1990s, however ARPA funding had fallen to about $300 million per year—approximately one fifth of the level of the early 1990s.

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[17] I have discussed issues of international competition and the formation of Sematech and its troubled history in greater detail in Ruttan (2001: 353-357). For a more recent perspective see the several papers in Wessner (2003).

SUPERCOMPUTERS

In the early 1950's there was a relatively clear-cut distinction between computers designed primarily for business and for scientific applications. The 1952 IBM 701 and the 1954 IBM 704 were regarded as scientific computers, while the 1953 IBM 702 and the IBM 705 were regarded primarily as business data processors.[18]

The weapons laboratories of the Atomic Energy Commission were early major source of demand for high speed scientific computers. In the mid 1950s the weapons designers at Livermore National Laboratory estimate that "they would need a computer having one hundred times the power of any existing system," (Mackenzie 1966: 114). Bids were sought for such a machine from both IBM and Remington Rand. Livermore National Laboratory commissioned the development of LARC from Remington Rand and the Los Alamos National Laboratory the Stretch from IBM. The LARC met the Livermore performance specifications but not its expectations! Stretch did not even meet performance specifications. Only two LARC machines were ever built:

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[18] In this section I draw heavily on the work of Donald MacKenzie (1996).

the other went to the U.S. Navy’s ship and reactor designers. Of the eight Stretch machines that were sold four were for nuclear research and development, two for other military research and development, one to the National Security Agency and one to the U.S. Weather Bureau. Although both machines contributed to the development of supercomputer capacity they were short-term financial disasters for the firms that built them (Mackenzie 1996: 114-116).

As its work on the SAGE project was coming to completion IBM faced several difficult problems. It was producing six different computer lines, all of which had incompatible operating systems. Competitors were beginning to make inroads into IBM’s market share. Software was accounting for a greater proportion of the cost of computer systems. Many of these problems were resolved with the introduction of the IBM System 360 in 1965.The 360 family of computers used integrated circuits rather than transistors. They had large ferrite core memories with fast access times and multiprogramming which allowed many programs to run simultaneously, and an improved disk memory that allowed the machines to store more information in secondary memory than had previously been thought possible.

The 360 machines were designed to meet both business and scientific applications. No matter what size, all contained the same solid-state circuits and would respond to the same set of instructions. As it came on line the System/360 platform became the industry standard for the rest of the 1960's and 1970's (Bresnahan 1999: 227-228). The decision by IBM to commit to the 360 line had not been easy. It required an enormous technical and financial commitment. "IBM literally 'bet the company' on its 360 decision" (Katz and Phillips 1982: 218).

The alternative to the path followed by IBM was to design computers that would be substantially faster than the IBM 704 or any other IBM machine at floating point arithmetic.[19] The first machine that could properly be termed a supercomputer was the 1964 Control Data 6600.[20] It was designed by Seymour Cray who would dominate

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[19] A dominant objective in the design of supercomputers has been to achieve higher speed at floating point arithmetic. Speed "conventionally expressed as the number of floating point operations ('flops') carried out per second, has increased from the thousands (kiloflops) in the 1950's to the millions (megaflops) in the 1960s to thousand million (gigaflops) in the 1980s, and may increase to the million millions (teraflops) by the end of the 1990's" (Mackenzie 1996: 100) For a more technical discussion see Mackenzie (1996: 166-175).

[20] Engineering Research Associated was acquired by Remington Rand in 1952. In 1955 Remington Rand merged with the Sperry Corporation to form Sperry Rand. In 1957 William Norris, Seymour Cray and several others left

supercomputer development for the next 30 years. Cray had designed Control Data's first computer, the CDC 1604, announced in October 1959. The 1604, built with transistors rather than vacuum tubes, was the world fastest computer. CDC had successfully challenged IBM at the technical level. It was unsuccessful, however, at challenging the commercial success of IBM—in terms of market share, revenues or profits.

"Cray had no interest in business data processing, and abhorred the complexity that arose from trying to cater to both scientific and business users," (Mackenzie 1996: 136). The profitability of the 1604 enabled Cray to negotiate an arrangement with Control Data Chairman William Norris to set up a laboratory in Chippewa Falls (Wisconsin) to conduct the development work on the CDC 6600. As IBM chairman Thomas J. Watson, Jr., watched the 6600 dominate the high-speed

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Sperry Rand and formed Control Data (Mackenzie 1996: 135). By the mid 1960s the computer industry consisted of IBM and the "seven dwarfs." The composition was (Shurkin 1984: 261):

Rank	Company	Share of Sales	Rank	Company	Share of Sales
1	IBM	65.3	5	Burroughs	3.5
2	Sperry Rand	12.1	6	General Electric	3.4
3	Control Data	5.4	7	RCA	2.9
4	Honeywell	3.8	8	NCR	2.9

By the mid 1990s only IBM was still active in the computer industry under its 1965 corporate identity.

computer market “he asked, in an acerbic memo to his staff why Cray’s team of ‘only 34—including the night janitor’—had outperformed the computing industries mightiest corporation” (MacKenzie 1996: 140).

Another Control Data team, working out of CDC headquarters in Arden Hills (Minnesota) worked on the development of the Control Data 3600 a highly successful series of computers, compatible with the 1604, with a primary orientation to the commercial market. By the early 1970’s Control Data had grown into a large diversified company. Its corporate plans included supercomputer development but not at a pace that was satisfactory to Cray.

In 1972 Cray and several colleagues left Control Data to start up a new company, Cray Research, also located in Chippewa Falls. The customer base for the world fastest computers was small—Cray estimated it at no more than 50—primarily in the nuclear weapons laboratories, the National Aeronautics and Space Agency, the Department of Defense, the National Center for Atmospheric Research and the Weather Bureau. “The Cray-1 was as much a tour-de-force as the 6600,” (Mackenzie 1966:145). It was introduced in 1976. The first sale was to the Los Alamos nuclear weapons laboratory and the second to the National Center for Atmospheric Research in Boulder, Colorado. It was followed by a more advanced machine, the Cray 2. A less expensive and even faster machine using parallel processing, the X-MP, developed by staff members Davis and Chen was introduced in1982. By 1989 the X-MP, with almost 160 sales of different versions, was the Western world's most successful supercomputer. In 1990 Cray research announced a slower and significantly less expensive mini-supercomputer, the Y-MP. The success of the Cray 2 and of the X-MP and the Y-MP enabled Cray Research, now chaired by John Rollwagen, to edge its way into the ranks of one of the dozen leading computer manufactures in the world.[21]

Seymour Cray's commitment to speed above all other objectives led to a second parting of ways. Resources were not available at Cray Research to complete the development of a Cray-3 and to pursue what were regarded as more promising development agendas. Rollwagen

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[21] By 1990 IBM had temporarily decided that high-end supercomputers represented a niche market that it could no longer afford to compete. Control Data made the same decision in 1989 when it closed its ETA subsidiary that it had established to compete with Cray Research (Mackenzie 1996: 104).

proposed the establishment of a Cray Research subsidiary, Cray Computer Corporation, to undertake the further development of the Cray 3. Cray moved his research team to Colorado Springs (Colorado). “In March 1995 the Cray Computer Corporation having failed to find a customer for the Cray 3 or a firm order for its successor the Cray-4, filed for bankruptcy protection” (Mackenzie 1996: 157). By 1995 neither Control Data nor Cray Research existed as independent firms.

At the time this chapter was written the Japanese Earth Simulator, released in the spring of 2002 and designed specifically to support geoscience research and applications, was the worlds most advanced supercomputer. Concern about the national security implications of loss of U.S. leadership led to a number of initiatives and studies, including an ARPA initiative to support the development of a new generation of economically viable high productivity computer systems by 2007-2 and the formation of a National Research Council Study on the Future of Supercomputing. The NRC Committee Interim Report identifies a number of non-military sources of demand for more advanced supercomputing such as bioinformatics, the large volume of data generated by the Human Genome Project, population genetics, and others. The Committee notes that: “In the United States, Japan and Europe, the majority of supercomputers have been purchased directly or indirectly using government funds, and the committee has no evidence that this is likely to change in the future” (National Research Council 2003: 28).[22]

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[22] Unlike the United States military procurement played a relatively minor role in computer technology development in Japan. Computer industry development was sponsored by the Ministry of International Trade and Industry (MITI). The MITI objective in computer development from 1960 through the 1970s was to catch up to IBM. By the mid-1980s Japanese firms were introducing a generation of supercomputers that approached, and in some cases exceeded, the performance of leading U.S. producers of supercomputers used for scientific purposes (Ruttan 2001: 344-347). In late 2004 IBM announced that it had designed and was building the worlds fastest computer (Crissey 2004)

SOFTWARE

A comprehensive treatment of the computer software industry would require a separate chapter. But because of its intimate relationship with the development and diffusion of the computer it will be useful to briefly discuss the role of military procurement in software development.[23]

Prior to the 1960s computer software hardly existed as a distinct technology or industry. Early electronic computers like, like their electomechanical business machine precursors, were programmed by rewiring. "Software was effectively born with the development by von Neumann of his conceptual architecture for computers … But even after the von Neuman scheme became dominant … software remained closely bound to hardware. During the 1950s, the organization designing the hardware generally designed the software as well" (Langlois and Mowery 1996: 55-56). During this period large military procurement contracts such as the SAGE air defense system, discussed above, played a particularly important role in embodied software

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[23] In this section I draw primarily on Mowery (1996); Steinmueller (1996: 15-52); Langlois and Mowery (1996: 53-85); and Mowery and Rosenberg (1998:1953-1966); Mowery (1999); Mowery (1999); and Mahoney (2002). For a highly personal account of the stages of software development see Glass (1998: 12-26).

development.[24] Mowery indicates that even as late as the early 1980s Defense Department accounted for the largest share of the U.S. software market. Military procurement of contract software accounted for approximately half of the U.S. traded software market (Mowery 1999: 145). Because the specialized function of such development efforts, however, there was often limited direct spillover to commercial application. Langlois and Mowery argued, for example, that one of the greatest contributions of SAGE was the training of a large cadre of skilled systems programmers (Langlois and Mowery 1996: 59).[25]

In the mid and late 1960s three events contributed to the "disintegration" of the computer and software industries (Steinmueller 1996: 24-26). One was the introduction, beginning in 1964, of the IBM System 360 family of computers. The System 360 gave independent software service companies and vendors an opportunity to develop and

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[24] The defining moment for the software contracting industry came in 1956 when the RAND Corporation established the Systems Development Corporation (SDC) to assume responsibility for computer program development for the SAGE air defense project. When the SAGE project was winding down in 1960 SDS continued to grow by taking on other military and defense related projects. By 1963 it had an annual income of $57 million generated by contract s with the Air Force, NASA, The Office of Civil Defense, the ARPA and other defense and defense related-sector projects (Campbell-Kelly 2003: 41).

[25] At a time when the entire population of programmers in the U.S. was about 1,200 some 700 were employed on the SAGE project. "The first and classic civilian real-time project was the IBM-American Airlines SABRE airline reservation system. Though SABRE did not become fully operational until 1964, it was the outcome of more than 10 years of planning, technical assessment, and system building" (Campbell-Kelley 2003: 42). SABRE was a direct spin-off, of in the SAGE project (National Research Council 1999: 94).

market the same product to a variety of users. A second event was the decision by IBM in 1969 to unbundle the sale of hardware and software. This provided an incentive for independent software developers to produce software compatible with IBM products. The third important event was the development of the minicomputer industry.

Minicomputers made it possible for small organizations to begin to purchase and operate their own computers. Each of the many different uses of minicomputers—“as primary computers in smaller organizations, as ‘front ends’ for mainframes, in data communication systems, and in process central systems--required very different software” (Steinmueller 1996: 28). Since the early 1980s the success of the personal computer has led to an explosive growth in the mass-market software products industry.[26]

Defense related research support for the computer software industry has differed substantially from the patterns followed in the

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[26] A number of the important software innovations that contributed to the rapid adoption of the personal computer beginning in the early 1980s were spin-offs from the MIT Project Mac (Later Laboratory for Computer Science) funded by the ARPA Information Processing Office beginning in 1963. Project MAC’s development of software to compose and edit programs and documents online laid the groundwork for word processors. Other Project MAC software spin-offs included the spreadsheet, early versions of internet protocols for the PC, and the UNIX operating system (National Research Council 1999: 103-105).

computer and semiconductor industries. In the case of computers and semiconductors, defense agency research support occurred primarily through direct procurement. “In software, by contrast, defense related R&D funded computer science in much the 1950s and 1960s … was directed to facilitating advances in fundamental knowledge of computer architecture, software languages, and design that found application in both the civilian and defense sectors. … Military-civilian spillovers in software occurred as a result of defense-related R&D spending rather than from direct software procurement” (Langlois and Mowery 1996:14; see also Flamm 1987: 42-92; Norberg and O’Neill 1996).[27]

In the mid and late 1960s computer science departments were established at Stanford, Carnegie Mellon and MIT. From the early 1970s through the mid 1980s more than half of academic compute science R&D was accounted for by defense-related agencies. After the mid-1980’s there was a shift in defense related support for computer science at academic institutions toward application. Since the mid 1980’s the

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[27] “Between 1976 and 1995 DOD provided some 60 percent of total federal research funding for computer science and over 75 percent of total funding in electrical engineering (National Research Council 1999: 56). For a listing of defense to civilian “spillovers” in the U.S. software industry between 1950 and 1975 see Flamm (1988: 266-268).

defense share of federal support for computer science funding declined from almost 60 percent to less than 30 percent (Langlois and Mowery 1996: 71).

The history of technology development in software production has differed from that in computer production in one other important respect. Technical change in computer production and performance has led to very substantial growth in labor productivity in the production of computers (Jorgenson 2001; Ruttan 2001: 357-362). In cost war, software production has remained exceedingly labor intensive. In 1955 software constituted less than 20 percent of the costs of a computer system. By the mid-1980s software costs were estimated upwards of 90 percent of the cost of installing a system (Boehm 1973; Mahoney 2002). By the late 1990s slow productivity growth in software design and production had become an obstacle to productivity growth in the computer industry and the computer-intensive defense and commercial sectors.

PERSPECTIVE

The invention and early development of the electronic digital computer was supported entirely by Army and Navy contracts. Defense and defense related agencies were the dominant supporters of the scientific and technical innovations and the primary market for computers until at least the early 1960's. These agencies, particularly the laboratories of the Atomic Energy Commission (later the National Energy Department) were highly influential in influencing the direction of technology development and have been the primary source of demand for increasingly powerful supercomputers (Mackenzie 1996: 117).

In the case of semiconductors the Department of Defense went beyond procurement to support research and development at Bell Laboratories and to subsidize the private sector facilities development to create an industrial base and to assure a competitive structure in the semiconductor industry. In the case of software and artificial intelligence the military supported fundamental research and invested in the establishment of academic computer science training capacity

Donald MacKenzie, in concluding his paper on nuclear weapons laboratories and supercomputing, raised the question of what does it mean for an institution to have influenced the development of an area of technology? His answer is that “without Los Alamos and Livermore we would doubtless have a category of supercomputing—a class of high performance computers—but the criterion of performance that would have evolved would have been much less clear cut” (MacKenzie 1966: 126).

Others have been less cautious. Flamm has argued that even without the impetus of military procurement the modern electronic computer would probably have been developed but “the pace of development would have been far slower” (Flamm 1988: 251). Edwards insists that without the very large funding and the sense of urgency associated with the war effort computer development in the U.S. would have been delayed for at least a decade (Edwards 1886: 52).

My own reading of the literature, is that the development and commercialization of computers—mainframes, minicomputers and micro-computers, would have occurred even more slowly than suggested by Flamm and Edwards. Without the impetus of the SAGE project, for example, a cautious IBM and a financially constrained Remington Rand would have substantially delayed the investment necessary for the emergence of the technology that set the stage for the development of the mainframe computers. Efforts to develop increasingly powerful computers played an important role in shaping the architecture and performance of mainstream computers ranging from workstations to personal computers

It has been difficult until quite recently to assess either the social rates of return to investment in the development of computers or the contribution of computers to U.S. economic growth (Flamm 1987: 223-239; Jorgenson and Stiroh 1999; Ruttan 2001: 357-362). There can be little question, however, that adoption of business and personal computers contributed importantly to the recovery of productivity growth in the U.S. economy beginning in the early 1990s. And there can be little doubt that, in the absence of the impetus for development and commercialization associated with military procurement significant contribution of the computer and related information technology to the growth of the U.S. economy would have been delayed until well into the twenty first century.

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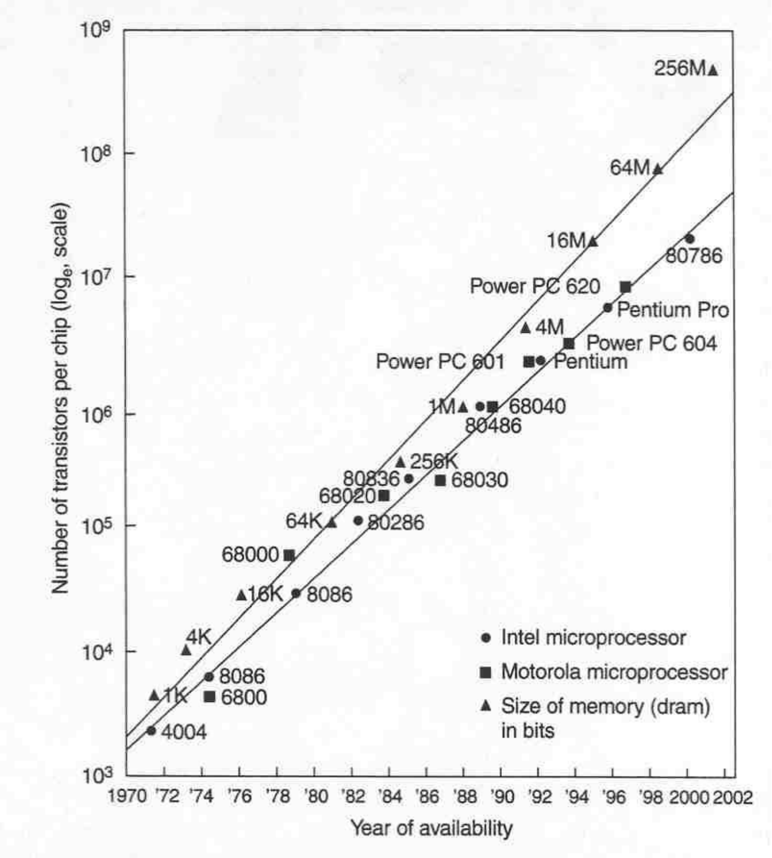
Figure 5.1

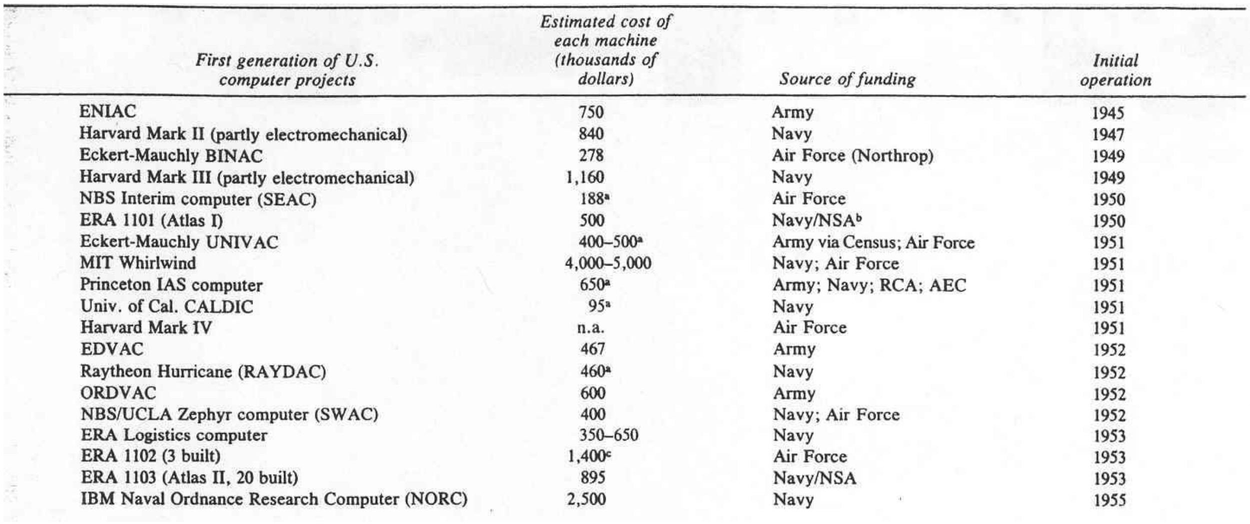
Transistor Densities on Micro Processors and Memory Chips



Source: Adapted from G. Dan Hutchinson and Jerry D. Hutcheson, *Technology and Economics in the Semiconductor Industry*. Scientific American 274 (January 1996: 61).

Table 5.1

Early U.S. Support for Computers



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 (partly electromechanical)	840	Navy	1947
Eckert-Mauchly BINAC	278	Air Force (Northrop)	1949
Harvard Mark III (partly electromechanical)	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[a]	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: Kenneth H. Flamm, *Creating the Computer: Government, Industry and High Technology*. Washington, D.C.: The Brookings Institution, 1988, p. 76.