The Chip and Its Impact, 1965-1975

Just as the IBM System/360 transformed mainframe computing, so did a series of new machines transform minicomputing in the late 1960s. At first these two computing segments operated independently, but during the 1970s they began to coalesce. Behind these changes was an invention called the integrated circuit, now known universally as "the chip."

Minicomputers such as the PDP-8 did not threaten mainframe business; they exploited an untapped market and lived in symbiosis with their large cousins. Some thought it might be possible to do a mainframe's work with an ensemble of minis, at far lower cost. Mainframe salesmen, citing "Grosch's Law," argued that this tempting idea went against a fundamental characteristic of computers that favored large systems. Named for Herb Grosch (figure 6.1), a colorful figure in the computer business, this law stated that a computer system that was twice as big (i.e., that cost you twice as much money) got you not twice but four times as much computing power. If you bought two small computers, giving you two times the power of a single one, you would not do as well as you would if you used the money to buy a single larger computer.[1]

Believers in that law cited several reasons for it. Computers of that era used magnetic cores for storage. The cores themselves were cheap, but the support circuitry needed to read, write, and erase information on them was expensive. And a certain amount of that circuitry was required whether a memory capacity was large or small. That made the cost per bit higher for small memories than for large, so it was more economical to choose the latter, with an accompanying large processor system to take advantage of it. The most compelling reason was that no one really knew how to link small computers to one another and get coordinated performance out of the ensemble. It would have been like trying to fly

Figure 6.1
Herbert Grosch, ca. 1955. (*Source*: Herbert Grosch.)

passengers across the Atlantic with a armada of biplanes instead of a single jumbo jet. Eventually both barriers would fall, with the advent of semiconductor memory and new network architectures. By the time that happened-around the mid 1980s-the minicomputer itself had been replaced by a microprocessor-based workstation.[2] But as minicomputers had grown more and more capable through the late 1960s, they had slowly begun a penetration into mainframe territory while opening up new areas of application. Grosch's Law held, but it no longer ruled.

The force that drove the minicomputer was an improvement in its basic circuits, which began with the integrated circuit (IC) in 1959. The IC, or chip, replaced transistors, resistors, and other discrete circuits in the processing units of computers; it also replaced cores for the memory units. The chip's impact on society has been the subject of endless discussion and analysis. This chapter, too, will offer an analysis, recognizing that the chip was an evolutionary development whose origins go back to the circuit designs of the first electronic digital computers, and perhaps before that.

The von Neumann architecture described a computer in terms of its four basic functional units-memory, processor, input, and output. Below that level were the functional building blocks, which carried out

the logical operations "AND," "OR," "NOT," "EXCLUSIVE OR," and a few others. Below that were circuits that each required a few-up to about a dozen-components that electrical engineers were familiar with: tubes (later transistors), resistors, capacitors, inductors, and wire. In the 1940s anyone who built a computer had to design from that level. But as computer design emerged as a discipline of its own, it did so at a higher level, the level of the logical functions operating on sets of binary digits. Thus arose the idea of assembling components into modules whose electrical properties were standardized, and which carried out a logical function. Using standardized modules simplified not only computer design but also testing and maintenance, both crucial activities in the era of fragile vacuum tubes.

J. Presper Eckert pioneered in using modules in the ENIAC to handle a group of decimal digits, and in the UNIVAC to handle digits coded in binary, a key and often overlooked invention that ensured the long-term usefulness of those two computers, at a time when other computers seldom worked more than an hour at a time.[3] When IBM entered the business with its Model 701, it also developed circuit modules-over two thousand different ones were required. For its transistorized machines it developed a compact and versatile "Standard Modular System" that reduced the number of different types.[4] Digital Equipment Corporation's first, and only, products for its first year of existence were logic modules, and the success of its PDP-8 depended on "flip-chip" modules that consisted of discrete devices mounted on small circuit boards.

Patents for devices that combined more than one operation on a single circuit were filed in 1959 by Jack Kilby of Texas Instruments and Robert Noyce of Fairchild Semiconductor. Their invention, dubbed at first "Micrologic," then the "Integrated Circuit" by Fairchild, was simply another step along this path.[5] Both Kilby and Noyce were aware of the prevailing opinion that existing methods of miniaturization and of interconnecting devices, including those described above, were inadequate. A substantial push for something new had come from the U.S. Air Force, which needed ever more sophisticated electronic equipment onboard ballistic missiles and airplanes, both of which had stringent weight, power consumption, and space requirements. (A closer look at the Air Force's needs reveals that reliability, more than size, was foremost on its mind.[6]) The civilian electronics market, which wanted something as well, was primarily concerned with the costs and errors that accompanied the wiring of computer circuits by hand. For the PDP-8's production, automatic wire-wrap machines connected the flip-chip modules. That eliminated, in Gordon Bell's words, "a whole floor full of little ladies wiring computers," although building a computer was still labor-intensive.[7] In short, "[a] large segment of the technical community was on the lookout for a solution of the problem because it was clear that a ready market awaited the successful inventor.[8]

Modern integrated circuits, when examined under a microscope, look like the plan of a large, futuristic metropolis. The analogy with architectural design or city planning is appropriate when describing chip design and layout. Chips manage the flow of power, signals, and heat just as cities handle the flow of people, goods, and energy. A more illuminating analogy is with printing, especially printing by photographic methods. Modern integrated circuits are inexpensive for the same reasons that a paperback book is inexpensive-the material is cheap and they can be mass produced. They store a lot of information in a small volume just as microfilm does. Historically, the relationship between printing, photography, and microelectronics has been a close one.

Modules like Digital Equipment Corporation's flip chips interconnected components by etching a pattern on a plastic board covered with copper or some other conductor; the board was then dipped into a solvent that removed all the conductor except what was protected by the etched pattern. This technique was pioneered during the Second World War in several places, including the Centrallab Division of the GlobeUnion Company in Milwaukee, Wisconsin, where circuits were produced for an artillery fuze used by allied forces. Other work was done at the National Bureau of Standards in Washington, D.C.[9] Some of this work was based on patents taken out by Paul Eisler, an Austrian refugee who worked in England during the war, Eisler claims his printed circuits were used in the war's most famous example of miniaturized electronics, the Proximity Fuze, although others dispute that claim.[10] In his patent granted in 1948, Eisler describes his invention as "a process based on the printing of a representation of the conductive metal."[11] After the war the "printed circuit," as it became known, was adopted by the U.S. Army's Signal Corps for further development. The Army called it "AutoSembly" to emphasize production rather than its miniaturization.[12] It was the ancestor of printed circuits, familiar to both the consumer and military markets, and still in use.[13]

Throughout the 1950s, the U.S. armed services pressed for a solution to the interconnection problem, seeing it as a possible way to increase reliability Reliability was of special concern to the U.S. Air Force, which had found itself embarrassed by failures of multimillion dollar rocket

launches, failures later found to have been caused by a faulty component that cost at most a few dollars. The Air Force mounted a direct attack on this problem for the Minuteman ballistic missile program, setting up a formal procedure that penetrated deep into the production lines of the components' manufacturers.

At the same time it inaugurated an ambitious program it called "molecular electronics," whose goal was to develop new devices made of substances whose individual molecules did the switching. Just how that would be done was unspecified, but the Air Force awarded a $2 million development contract to Westinghouse in April 1959-within months of the invention of the IC-to try.[14] Later on Westinghouse received another $2.6 million. The idea never really went anywhere. Two years after awarding the contract, the Air Force and Westinghouse reported substantial progress, but the press, reporting that the "USAF Hedges Molectronics Bets," called the use of ICs an "interim step" needed to reduce the size and complexity of airborne electronics.[15] The term "molecular electronics" quietly vanished from subsequent reports.

The Air Force's push for higher reliability of parts for the Minuteman ballistic missile had a greater impact on the electronics industry because it did achieve a breakthrough in reliability. Suppliers introduced "clean rooms," where workers wore gowns to keep dust away from the materials they were working with. Invented at the Sandia National Laboratories in the early 1960s for atomic weapons assembly, such rooms were washed by a constant flow of ultra-filtered air flowing from the ceiling to the floor.[16] Eventually the industry would build fabrication rooms, or "fabs," that were many times cleaner than a hospital. They would control the impurities of materials almost to an atom-by-atom level, at temperatures and pressures regulated precisely. The electronics industry developed these techniques to make transistors for Minuteman. The culture took root.

At every step of the production of every electronic component used in Minuteman, a log was kept that spelled out exactly what was done to the part, and by whom. If a part failed a subsequent test, even a test performed months later, one could go back and find out where it had been. If the failure was due to a faulty production run, then every system that used parts from that run could be identified and removed from service. Suppliers who could not or would not follow these procedures were dropped.[17] Those who passed the test found an additional benefit: they could market their components elsewhere as meeting the "Minuteman Hi-Rel" standard, charging a premium over components produced by their competitors. Eventually the estimated hundred-fold reduction of failure rates demanded by the Air Force came to be accepted as the norm for the commercial world as well.[18] In a reverse of Gresham's Law, high-quality drove low-quality goods from the market.

This program came at a steep price. Each Minuteman in a silo cost between $3 and $10 million, of which up to 40 percent was for the electronics.[19] And the Hi-Rel program's emphasis remained on discrete components, although the clean-room production techniques were later transferred to IC production. However successful it was for the Minuteman, the Hi-Rel program did not automatically lead to advances in commercial, much less consumer, markets.[20]

The Invention of the Integrated Circuit

In the early 1960s the Air Force initiated the development of an improved Minuteman, one whose guidance requirements were far greater than the existing missile's computer could handle. For mainly political reasons, "those who wished other capabilities from ICBMs [intercontinental ballistic missiles] were unable to start afresh with an entirely new missile. Instead, they had to seek to build what they wanted into successive generations of Minuteman."[21] The reengineering of Minuteman's guidance system led, by the mid-1960s, to massive Air Force purchases for the newly invented IC, and it was those purchases that helped propel the IC into the commercial marketplace.

Before discussing those events, it is worth looking at the circumstances surrounding the IC's invention. As important as the military and NASA were as customers for the IC, they had little to do with shaping its invention.

After graduating from the University of Illinois with a degree in Electrical Engineering in 1947, Jack Kilby took a job at Centrallab in Milwaukee-the industrial leader in printed circuits and miniaturization. At first he worked on printed circuit design; later he became involved in getting the company to make products using germanium transistors. "By 1957 . . . it was clear that major expenditures would soon be required. The military market represented a major opportunity, but required silicon devices .... The advantages of the diffused transistor were becoming apparent, and its development would also have required expenditures beyond the capabilities of Centrallab . . . . I decided to leave the company."[22] The following year he joined Texas Instruments in Dallas, already known in the industry for having pioneered the shift

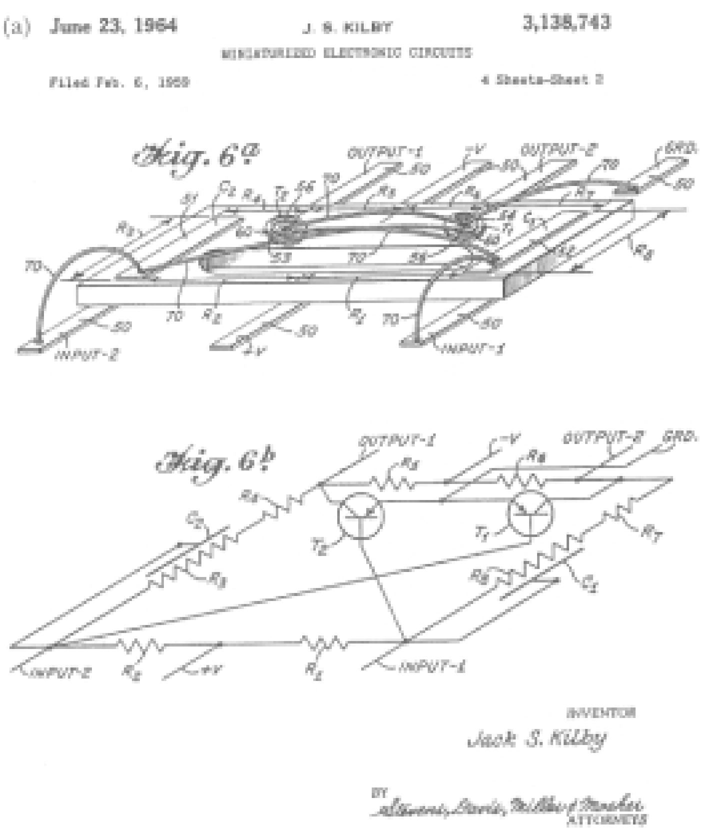
from germanium to silicon transistors. "My duties were not precisely defined, but it was understood that I would work in the general area of microminiaturization."[23] Texas Instruments (TI) was one among many companies that recognized the potential market, both military and civilian, for such devices. But how to build them?

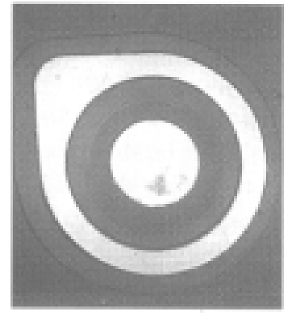
Jack Kilby is a tall, modest man whose quiet manner reflects the practical approach to problems people often associate with Midwesterners. He was born in Jefferson City, Missouri, and grew up in the farming and oil-well supply town of Great Bend, Kansas, named after the southern turn that the Arkansas River takes after coming out of the Rockies. His father was an engineer for a local electrical utility.[24] He recalls learning from his father that the cost of something was as important a variable in an engineering solution as any other.[25]

As others at TI and elsewhere were doing in 1958, Kilby looked at microminiaturization and made an assessment of the various government-funded projects then underway. Among those projects was one that TI was already involved with, called Micro-Module, which involved depositing components on a ceramic wafer.[26] Kilby did not find this approach cost effective (although IBM chose a variation of it for its System/360). In the summer of 1958 he came up with a fresh approach-to make all the individual components, not just the transistors, out of germanium or silicon. That swam against the tide of prevailing economics in the electronics business, where resistors sold for pennies, and profits came from shaving a few tenths of a cent from their production cost. A resistor made of silicon had to cost a lot more than one made of carbon. But Kilby reasoned that if resistors and other components were made of the same material as the transistors, an entire circuit could be fashioned out of a single block of semiconductor material. Whatever increased costs there were for the individual components would be more than offset by not having to set up separate production, packaging, and wiring processes for each.

Jack Kilby built an ordinary circuit with all components, including its resistors and capacitor, made of silicon instead of the usual materials, in August, 1958. In September he built another circuit, only this time all the components were made from a single piece of material-a thin 1/16-inch x 7/16-inch wafer of germanium. (The company's abilities to work with silicon for this demonstration were not quite up to the task.) He and two technicians laboriously laid out and constructed the few components on the wafer and connected them to one another by fine gold wires. The result, an oscillator, worked. In early 1959 he applied for a patent, which was granted in 1964 (figure 6.2).[27] Texas Instruments christened it the "solid circuit." It was a genuine innovation, a radical departure from the military-sponsored micromodule, molecular electronics, and other miniaturization schemes then being pursued.[28]

Robert Noyce also grew up in the Midwest, in Grinell, Iowa, where his father was a Congregational minister. Some ascribe Noyce's inventiveness to Protestant values of dissent and finding one's own road to salvation,[29] but not all Protestant faiths shared that, and one would not describe Noyce or the other Midwestern inventors as religious. A more likely explanation is the culture of self-sufficiency characteristic of Midwestern farming communities, even though only one or two of the inventors in this group actually grew up on farms. In any event, the Corn Belt in the 1930s and 1940s was fertile ground for digital electronics.

(a)


(b)


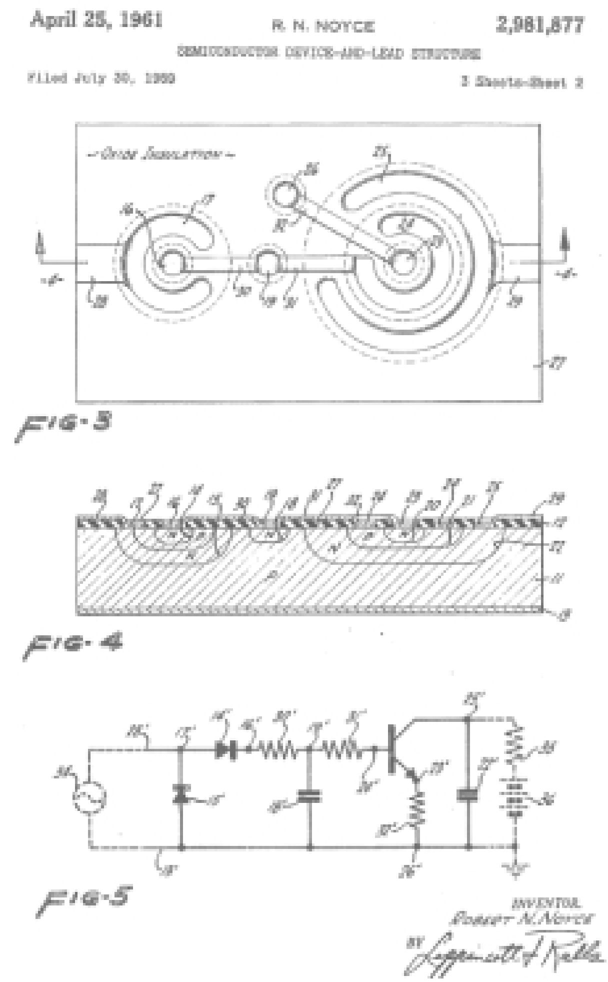
(c)


Figure 6.2

The chip. (a) Patent for integrated circuit by Jack Kilby. (b) Planar transistor. (Source: Fairchild Semiconductor.) *(c)* Patent for integrated circuit by Robert Noyce.

Robert Noyce was working at Fairchild Semiconductor in Mountain View, California, when he heard of Kilby's invention. He had been thinking along the same lines, and in January 1959 he described in his lab notebook a scheme for doing essentially the same thing Kilby had done, only with a piece of silicon.[30] One of his coworkers at Fairchild, Swiss-born Jean Hoerni, had paved the way by developing a process for making silicon transistors that was well-suited for photo-etching production techniques, making it possible to mass-produce ICs cheaply.[31] It was called the "planar process," and as the name implies, it produced transistors that were flat. (Other techniques required raised metal lines or even wires somehow attached to the surface to connect a transistor.) The process was best suited to silicon, where layers of silicon oxide-"one of the best insulators known to man," Noyce recalledcould be built up and used to isolate one device from another. [32] For Noyce the invention of the IC was less the result of a sudden flash of insight as of a gradual build-up of engineering knowledge about materials, fabrication, and circuits, most of which had occurred at Fairchild since the company's founding in 1957. (By coincidence, the money used to start Fairchild Semiconductor came from a camera company, Fairchild Camera and Instrument. Sherman Fairchild, after whom the company was named, was the largest individual stockholder in IBM-his father helped set up IBM in the early part of the century.)[33]

Noyce applied for a patent, too, in July 1959, a few months after Kilby. Years later the courts would sort out the dispute over who the "real" inventor was, giving each person and his respective company a share of the credit. But most acknowledge that Noyce's idea to incorporate Hoerni's planar process, which allowed one to make the electrical connections in the same process as making the devices themselves, was the key to the dramatic progress in integrated electronics that followed.

Hoerni did not share in the patents for the integrated circuit, but his contribution is well known. "I can go into any semiconductor factory in the world and see something I developed being used. That's very satisfying."[34] His and Noyce's contributions illustrate how inventors cultivate a solution to a problem first of all visually, in what historian Eugene Ferguson calls the "mind's eye."[35] Although the invention required a thorough knowledge of the physics and chemistry of silicon and the minute quantities of other materials added to it, a nonverbal, visual process lay behind it. [36]

These steps toward the IC's invention had nothing to do with Air Force or military support. Neither Fairchild nor Texas Instruments were

among the first companies awarded Air Force contracts for miniaturization. The shift from germanium to silicon was pioneered at Texas Instruments well before it was adopted for military work. Kilby's insight of using a single piece of material to build traditional devices went against the Air Force's molecular electronics and the Army's micromodule concepts. And the planar process was an internal Fairchild innovation.[37]

But once the IC was invented, the U.S. aerospace community played a crucial role by providing a market. The "advanced" Minuteman was a brand-new missile wrapped around an existing airframe. Autonetics, the division of North American Aviation that had the contract for the guidance system, chose integrated circuits as the best way to meet its requirements. The computer they designed for it used about 2,000 integrated and 4,000 discrete circuits, compared to the 15,000 discrete circuits used in Minuteman I, which had a simpler guidance requirement.[38] Autonetics published comparisons of the two types of circuits to help bolster their decision. According to Kilby, "In the early 1960s these comparisons seemed very dramatic, and probably did more than anything else to establish the acceptability of integrated circuits to the military."[39] Minuteman II first flew in September 1964; a year later the trade press reported that "Minuteman is top Semiconductor User," with a production rate of six to seven missiles a week.[40] The industry had a history of boom and bust cycles caused by overcapacity in its transistor plants. Were it not for Minuteman II they would not have established volume production lines for ICs: "Minuteman's schedule called for over 4,000 circuits a week from Texas Instruments, Westinghouse, and RCA. [41]

Fairchild was not among the three major suppliers for Minuteman. Noyce believed that military contracts stifled innovation-he cited the Air Force's molecular electronics as an example of approaching innovation from the wrong direction. He was especially bothered by the perception that with military funding,

> the direction of the research was being determined by people less competent in seeing where it ought to go, and a lot of time of the researchers themselves was spent communicating with military people through progress reports or visits or whatever. [42]

However, before long, the company recognized the value of a military market: "Military and space applications accounted for essentially the entire integrated circuits market last year [1963], and will use over 95 percent of the circuits produced this year."[43]

Although reluctant to get involved in military contracts, Fairchild did pursue an opportunity to sell integrated circuits to NASA for its Apollo Guidance Computer (figure 6.3).[44] Apollo, whose goal was to put a man on the Moon by the end of the 1960s, was not a military program. Its guidance system was the product of the MIT Instrumentation Laboratory, which under the leadership of Charles Stark Draper was also responsible for the design of guidance computers for the Polaris and Poseidon missiles. Like Minuteman, Apollo's designers started out with modest on-board guidance requirements. Initially most guidance was to be handled from the ground; as late as 1964 it was to use an analog computer.[45] However, as the magnitude of the Lunar mission manifested itself the computer was redesigned and asked to do a lot more. The lab had been among the first to purchase integrated circuits from TI in 1959. After NASA selected the Instrumentation lab to be responsible for the Apollo guidance system in August 1961, Eldon Hall of the lab opened discussions with TI and Fairchild (figure 6.4). The IC's small size and weight were attractive, although Hall was concerned about the lack of data on manufacturing reliable numbers of them in quantity. In a decision that looks inevitable with hindsight, he decided to use ICs in the computer, adopting Fairchild's "micrologic" design with production chips from Philco-Ford, Texas Instruments, and Fairchild. His selection of Fairchild's design may have been due to Noyce's personal interest in the MIT representatives who visited him several times in 1961 and 1962. (Noyce was a graduate of MIT.)[46] NASA approved Hall's decision in November 1962, and his team completed a prototype that first operated in February 1965, about a year after the Minuteman II was first flown.[47]

In contrast to the Minuteman computer, which used over twenty types of ICs, the Apollo computer used only one type, employing simple logic.[48] Each Apollo Guidance Computer contained about 5,000 of these chips.[49] The current "revolution" in microelectronics thus owes a lot to both the Minuteman and the Apollo programs. The Minuteman was first: it used integrated circuits in a critical application only a few years after they were invented. Apollo took the next and equally critical step: it was designed from the start to exploit the advantages of integrated logic.

Around 75 Apollo Guidance Computers were built, of which about 25 actually flew in space. During that time, from the initial purchase of prototype chips to their installation in production models of the Apollo

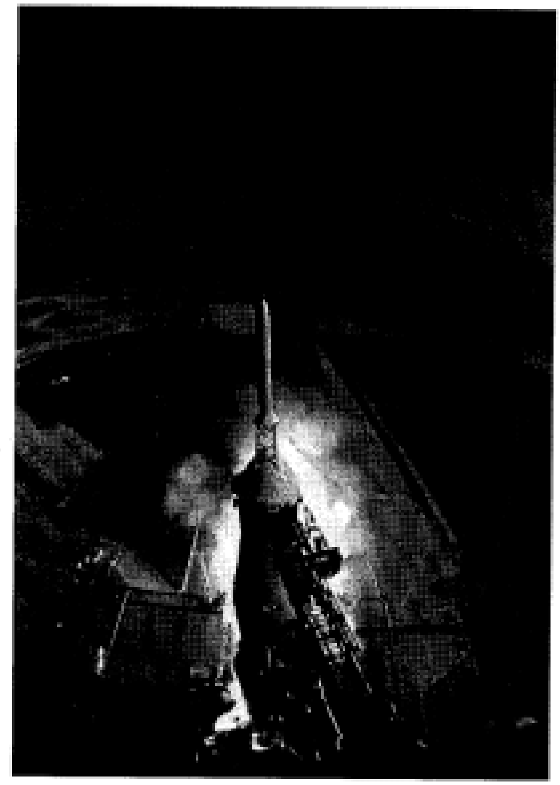


Figure 6.3
Launch of the Saturn V/Apollo 11 spacecraft, July 1969. The relationship between the U.S. space program and the advance of computing technology was a complex one. The demands of programs like Apollo and Minuteman advanced the state of the art of microelectronics and computer circuits. Advances in computing, on the other hand, shaped the way programs like Apollo were designed and operated. *(Source: NASA.)*

computer, the price dropped from $1,000 a chip to between $20 and $30.[50] The Apollo contract, like the earlier one for Minuteman, gave semiconductor companies a market for integrated circuits, which in turn they could now sell to a civilian market. By the time of the last Apollo flight in 1975 (the Apollo-Soyuz mission), one astronaut carried a pocket calculator (an HP-65) whose capabilities were greater than the on-board computer's. Such was the pace of innovation set in motion by the aerospace community.

44. Paul E. Ceruzzi, *Beyond the Limits: Flight Enters the Computer Age* (Cambridge: MIT Press, 1989), chapter 6.

45. Donald C. Fraser, and Philip Felleman, "Digital Fly-by-Wire: Computers Lead the Way," *Astronautics and Aeronautics* 12: 7/8 (1974): 24-32.

46. Eldon C. Hall, *journey to the Moon: the History of the Apollo Guidance Computer* (Reston, VA: AIAA, 1996): 82; also A. Michal McMahon, "The Computer and the Complex: a Study of Technical Innovation in Postwar America," October 1986, NASA History Office, Washington, DC, 30.

47. Eldon Hall, "The Apollo Guidance Computer: a Designer's View," Computer Museum, Boston, *Report* (Fall 1982): 2-5.

48. A NOR-gate with three inputs. The chip contained three transistors and four resistors.

49. James Tomayko, "Computers in Spaceflight: the NASA Experience," (Washington, DC: NASA Contractor Report 182505, 1988): 28-30.

50. A. Michal McMahon, "The Computer and the Complex: a Study of Technical Innovation in Postwar America."

51. Pugh et al., *IBM's 360 and Early 370 Systems*, 76-83; also E. M. Davis et al., "Solid Logic Technology: Versatile, High Performance Microelectronics," *IBM ,journal*, 8 (April 1964) : 102-114.

52. The first quotation is from Bob Henle, quoted in Pugh et al., 105. The second is from John Haanstra, "Monolithics and IBM," report of September 1964, unpaginated, IBM Archives, Valhalla, NY. I am grateful to Emerson Pugh for providing me with a copy of this document.

53. Pugh et al., *IBM's 360 and Early 370; C.* Gordon Bell, "The Mini and Micro Industries," IEEE *Computer* (October 1984): 14-29; *Datamation* (November 1968): 72-73; *Datamation (July* 1974): 50-60.

54. Bell, "The Mini and Micro Industries," 14-29.

55. Don Lancaster, TTL *Cookbook* (Indianapolis: Howard Sams, 1974).

56. *IEEE Spectrum* 25: 11 (1970): 70; also Tom Monte and Ilene Pritikin, *Pritikin: the Man who Healed America's Heart* (Emmaus, PA: Rodale Press, 1988).

57. "SYMBOL: A Large Experimental System Exploring Major Hardware Replacement of Software," in Daniel Siewiorek, C. Gordon Bell, and Allen Newell, eds. *Computer Structures: Principles and Examples* (New York: McGraw-Hill, 1982): 489507.

58. Major changes have been the advent of "Complementary Metal-Oxide Semiconductor" (CMOS) in place of TTL, and the gradual replacement of the DIP housing to "Single In-Line Memory Modules" (SIMM), and flat packaging for products like laptops.

59. W. Buchholz, "Origins of the Word Byte," *Annals of the History of Computing* 10: 4 (1989): 340.

60. Gardner Hendrie, "From the First 16-bit Mini to Fault-Tolerant Computers," Computer Museum Report (Spring 1986): 6-9.

61. Arthur Norberg, Judy O'Neill, and Kerry Freedman, "A History of the Information Processing Techniques Office of the Defense Advanced Research Projects Agency" (Minneapolis, MN: Charles Babbage Institute, 1992).

62. Siewiorek, Bell, and Newell, *Computer Structures*, chapter 24.

63. Adele Goldberg, ed., *A History of Personal Workstations* (Reading, MA: Addison-Wesley, 1988): 151; also Siewiorek, Bell, and Newell, *Computer Structures*, 396-397.

64. Goldberg, *History of Personal Workstations*, 150-151.

65. As of this writing, the Smithsonian Institution is not among the museums that has collected an IMP.

66. Glenn Rifkin and George Harrar, *The Ultimate Entrepreneur: the Story of Ken Olsen and Digital Equipment Corporation* (Chicago: Contemporary Books, 1988): 86-92.

67. Tom Wolfe, "The Tinkerings of Robert Noyce," *Esquire* (December 1983): 356.

68. Fred Brooks, "Keynote Address: Language Design as Design," in Thomas J. Bergin and Richard G. Gibson, eds., *History of Programming Languages-II* (Reading, MA: Addison-Wesley, 1996): 4-16. Steve Wozniak, designer of another "elegant" computer, the Apple II, also acknowledged the Nova as an influence. The Radio Shack TRS-80 Model 100, and the IBM 7090 are also regarded as "elegant"; but few other computers are spoken of that way.

69. Michael Hord, *The Illiac IV the First Supercomputer* (Rockville, MD: Computer Science Press, 1982). It is worth noting that HAL, the famous computer of the film 2001: *a Space Odyssey*, was "born" in Urbana, Illinois. That film was being made as the Illiac IV was being built. Arthur C. Clarke, the author of the screenplay, later claimed that he chose Urbana because one of his professors had moved there from England.

70. "A Revolution in Progress: a History of Intel to Date," brochure (Santa Clara, CA: Intel Corporation, 1984).

71. Ibid.

72. These included offerings from two companies much larger than DEC: Divisions of both Lockheed and Hewlett-Packard were offering 16-bit minicomputers, as was a start-up, Interdata, that was later purchased by the military contractor Perkin-Elmer.

73. C. Gordon Bell, interview with author, 16 June 1992, Los Altos, CA; also "Decworld," newsletter from Digital Equipment Corporation, May 1980, Special Edition on the PDP-11, copy in the author's collection.

74. Harvard University Computation Laboratory *A Manual of Operation for the Automatic Sequence Controlled Calculator*, reprint of 1946 edition (Cambridge: MIT Press, 1985), chapter 2.

75. Digital Equipment Corporation, PDP-11 *Processor Handbook* (Maynard, MA: Digital Equipment Corporation, 1981), chapter 2; according to Braun and McDonald, Texas Instruments had taken out patents on the concept of a bus architecture; see Braun and Macdonald, *Revolution in Miniature* 109.

76. Personal computers built around the Intel 8086-series of microprocessors have data buses that are not as general as the PDP-11's. They do resemble the PDP-11 in other ways. The Motorola 68000 series of microprocessors was more closely patterned on the PDP-11.

77. Jamie Pearson, *Digital at Work* (Bedford, MA: Digital Press, 1992): 47, 59, 67.

78. Digital Equipment Corporation, PDP-11 *Processor Handbook*, (Maynard, MA: Digital Equipment Corporation, 1981) : v.

79. Dick Rubenstein, telephone interview with the author, February 5, 1993.

80. C. Gordon Bell, J. Craig Mudge, and John E. McNamara, *Computer Engineering: a DEC View of Hardware Systems Design* (Bedford, MA: Digital Press, 1978) : 383.

81. James W. Cortada, *Historical Dictionary ofDataProcessing: Technology* (Westport, CT: Greenwood Press, 1987): 142.

82. Pugh et al., *IBM's 360 and Early 370 Systems*, chapter 9.

83. Jim Geraghty, CICS *Concepts and Uses* (New York: McGraw-Hill, 1994).

84. Saul Rosen, "PUFFT-the Purdue University Fast Fortran Translator," in Saul Rosen, ed., *Programming Systems and Languages* (New York: McGraw-Hill, 1967) : 253-263; also *Encyclopedia of Computer Science*, 3rd ed. (New York: McGrawHill, 1993): 768.

85. "25th Anniversary Issue," University of Waterloo, Department of Computing Services Newsletter (October 1982): 2.

86. Ray Argyle, "Industry Profile . . . Wes Graham of Waterloo U," *ComputerData: the Canadian Computer Magazine* (May 1976): 29-30.

87. Paul Cress, Paul Dirkson, and J. Wesley Graham, *Fortran IV with WATFOR and WATFIV* (Englewood Cliffs, NJ: Prentice Hall, 1970).

88. John G. Kemeny, *Man and the Computer* (New York: Scribner's, 1972): vii.

89. Thomas E. Kurtz, "BASIC," in Richard Wexelblat, ed., *History ofProgramming Languages* (New York: Academic Press, 1981): 518-519.

90. The choice of the name is obvious; however, it is also an acronym for "Beginner's All-purpose Symbolic Instruction Code." Hence it is written in all capitals.

91. William Aspray and Bernard O. Williams, "Arming American Scientists: NSF and the Provision of Scientific Computing Facilities for Universities, 1950-1973," *Annals of the History of Computing* 16: 4 (1994): 60-74.

92. Mark Bramhall, telephone interview with the author, 10 May, 1997.

93. Some of the "sacred" principles abandoned were the mandatory use of "Let" in an assignment statement; having only one statement on a line; and not allowing a statement to continue beyond a single line. Kemeny later developed "True Basic" to return the language to its pure roots, but it never caught on.