THE MICROELECTRONICS REVOLUTION

In the 1973 film *Live and Let Die,* the stylish secret agent James Bond traded his signature wristwatch, a Rolex Submariner, for the latest in high-tech gadgetry, a Hamilton Pulsar digital watch. Unlike a traditional timepiece, the Pulsar did not represent time using the sweep of hour and minute hands; instead, it displayed time digitally, using a recent innovation in microelectronics called the light-emitting diode, or LED. In the early 1970s, the glowing red lights of an LED display represented the cutting edge of integrated circuit technology, and digital watches were such a luxury item that, at $2100 for the 18-karat gold edition, they cost more even than an equivalent Rolex. The original Pulsar had actually been developed a few years early for the Stanley Kubrick film *2001: A Space Odyssey,* and, for a time, access to this technology was limited to the domain of science fiction and international espionage.

Within just a few years, however, the cost (and sex appeal) of a digital watch had diminished to almost nothing. By 1976 Texas Instruments was offering a digital watch for just $20 and, within a year, had reduced the price again by half. By 1979 Pulsar had lost $6 million dollars, had been sold twice, and had reverted to producing more profitable analog timepieces. By the end of the 1970s, the cost of the components required to construct a digital watch had fallen so low that it was almost impossible to sell the finished product for any significant profit. The formerly space-age technology had become a cheap commodity good—as well as something of a cliché.

The meteoric rise and fall of the digital watch illustrates a larger pattern in the unusual economics of microelectronics manufacturing. The so-called planar process for manufacturing integrated circuits, developed at Fairchild Semiconductor and perfected by companies such as Intel and Advanced Micro Devices (AMD), required a substantial initial investment in expertise and equipment, but after that the cost of production dropped rapidly. In short, the cost of building the very first of these new integrated circuit technologies was enormous, but every unit manufactured after that became increasingly inexpensive. The massive economies of scale inherent in semiconductor manufacture—combined with rapid improvements in the complexity and capabilities of integrated circuits, intense competition within the industry, and the widespread availability of new forms of venture capital—created the conditions in which rapid technological innovation was not only possible but essential. In order to continue to profit from their investment in chip design and fabrication, semiconductor firms had to create new and ever-increasing demand for their products. The personal computer, video game console, digital camera, and cellphone are all direct products of the revolution in miniature that occurred in the late 1960s and early 1970s. But while this revolution in miniature would ultimately also revolutionize the computer industry, it is important to recognize that it did not begin with the computer industry. The two key developments in computing associated with this revolution—the minicomputer and the microprocessor—were parallel strands unconnected with the established centers of electronic digital computing.

FROM MIT TO MINICOMPUTERS

Between 1965 and 1975, the introduction of integrated circuit electronics reduced the cost of computer power by a factor of a hundred, undermining the prime economic justification for time-sharing—that is, sharing the cost of a large computer by spreading it across many users. By 1970 it was possible to buy for around $20,000 a "minicomputer" with the power of a 1965 mainframe that had cost ten times as much. Rather than subscribe to a time-sharing service, which cost upward of $10 per hour for each user, it made more economic sense for a computer user to buy outright a small time-sharing system that supported perhaps a dozen users. During the 1970s the small in-house time-sharing system became the dominant mode of computing in universities, research organizations, and many businesses.

People often suppose that the minicomputer was simply a scaled-down mainframe, emerging out of the established computer industry. This is not the case: it was in effect a computer born of MIT and the East Coast microelectronics industry. The firm most associated with the minicomputer, the Digital Equipment Corporation (DEC), was formed by two members of the MIT Lincoln Laboratory. One of them, Kenneth Olsen, was a 1950 graduate in electrical engineering from MIT who went on to become a research associate on Project Whirlwind—where he did extensive work turning the prototype core-memory development into a reliable system. The other, Harlan Anderson, had studied programming at the University of Illinois, joined Lincoln Laboratory, and was working for Olsen on a new transistor-based computer. In 1957 the two men quit to start their own company.

Although Olsen retained strong links with MIT, he was more excited by turning the technologies into real products than in academic research. In 1957 he secured $70,000 of venture capital from American Research and Development (ARD). ARD was founded in 1946 by a Harvard Business School professor, General George F. Doriot—the "father of venture capital"—to finance the commercial exploitation of technologies developed during the war. ARD was the prototype venture-capital firm, and the development of such financial operations was a key factor responsible for the dynamism of the new high-tech industries in the United States. Most overseas countries found it very difficult to compete with US firms until they established their own venture-funding organizations.

Olsen's aim was to go into the computer business and compete with the mainframe manufacturers. However, in the late 1950s this was not a realistic short-term goal. The barriers to entry into the mainframe business were rising. In order to enter the mainframe business, one needed three things, in addition to a central processing unit: peripherals (such as magnetic tape and disk drives), software (both applications and program development tools), and a sales force. It would cost several hundred million dollars to establish all these capabilities. Because of these formidable barriers to entering the computer industry, Doriot convinced Olsen to first establish the firm with more attainable objectives.

DEC set up operations in part of a pre–Civil War woolen mill in Maynard, Massachusetts, close to the Route 128 electronics industry. For the first three years of its existence, the company produced digital circuit boards for the booming digital electronics industry. This proved to be a successful niche and provided the funding for DEC's first computer development. DEC announced its first computer, the PDP-1, in 1960. Olsen chose the term "programmed data processor" because the new computer cost $125,000 for a basic model and existing computer users "could not believe that in 1960 computers that could do the job could be built for less than $1 million."

How was it possible for DEC to produce a computer for a fifth or a tenth of what it cost the mainframe computer industry? The answer is that in a mainframe computer, probably only 20 percent of the cost was accounted for by the central processor—the rest was attributable to peripherals, software, and marketing. Olsen aimed the PDP-1 not at commercial data-processing users, however, but at the science and engineering market. These customers did not need advanced peripherals, they were capable of writing their own software, and they did not require a professional sales engineer to analyze their applications. The PDP-1 and half a dozen other models produced over the next five years were a modest success, though they did not sell well enough to reshape the industry. This would happen with the introduction of the PDP-8 minicomputer in 1965. The PDP-8 was one of the first computers to exploit the newly emerging technology of integrated circuits, and as a result it was far smaller and cheaper than any of DEC's previous computers. The PDP-8 would fit in a packing case and sold for just $18,000.

The PDP-8 was an instant success, and several hundred systems were delivered during the following year. The success of the PDP-8 enabled DEC to make its first public offering in 1966. By that time the firm had sold a total of 800 computers (half of them PDP-8s), employed 1,100 staff members, and occupied the entirety of its Maynard woolen-mill headquarters. The offering netted $4.8 million—a handsome return on ARD's original investment. Over the next ten years, the PDP-8 remained constantly in production, eventually selling between 30,000 and 40,000 systems. Many of these new computers were used in dedicated applications, such as factory process automation, where a traditional computer would have been too expensive. Other systems were sold directly to engineering corporations for inclusion in advanced instruments such as medical scanners.

Many PDP-8s found their way into colleges and research laboratories, where their low price enabled research students and faculty to experience hands-on computing in a way that had not been possible since the 1950s. Some of these people found themselves redirecting their careers into computing, regardless of their original disciplines or intentions. Many of the users of PDP-8s became very attached to them, regarding them as their "personal" computers. Some users developed games for the machines—one of the most popular was a simulation of a moon-landing vehicle that the user had to guide to a safe landing. The experience of hands-on computing produced a strong computer hobbyist culture, not only among students and young technicians but also in the community of seasoned engineers.

One such engineer, Stephen Gray, editor of *Electronics* magazine, founded the Amateur Computer Society (ACS) in May 1966 in order to exchange information with other hobbyists about building computers. Drawing support from a widely scattered community of technically trained enthusiasts working in universities, defense firms, and electronics and computer companies, Gray began circulating his *ACS Newsletter* to 160 members in 1966. It presented information on circuit design and component availability and compatibility, and it encouraged subscribers by printing stories of successful home-built computers. In general, however, owning a computer was not a reasonable aspiration for the average computer hobbyist, when the cheapest machine cost $10,000. But in the 1970s the latent desire of computer hobbyists to own computers was a powerful force in shaping the personal computer.

By 1969, when the term *minicomputer* first came into popular use, small computers were a major sector of the computer industry. DEC had been joined by several other minicomputer manufacturers, such as Data General (formed by a group of ex-DEC engineers) and Prime Computer—both of which became major international firms. Several of the established electronics and computer manufacturers had also developed minicomputer divisions, including Hewlett-Packard, Harris, and Honeywell. DEC, as the first mover in the minicomputer industry, always had by far the strongest presence, however. By 1970 it was the world's third-largest computer manufacturer, after IBM and the UNIVAC Division of Sperry Rand. When the aging General Doriot retired from ARD in 1972, its original stake was worth $350 million.

SEMICONDUCTORS AND SILICON VALLEY

For the first several decades of its existence, the geographical center of the computer industry was the East Coast of the United States, concentrated around well-established information-technology firms such as IBM and Bell Labs and elite universities such as MIT, Princeton, and the University of Pennsylvania. Beginning in the mid-1950s, however, a remarkable shift westward occurred, and by the end of the 1960s it was the Silicon Valley region of northern California that had become the place where innovation in the computer industry occurred. This thriving technological ecosystem, a productive collaboration of scientists, industry entrepreneurs, venture capitalists, military contractors, and university administrators, would become the model that other regions and countries would thereafter emulate.

Perhaps the best method for tracking this larger shift from East Coast to West is to follow the career trajectory of a single individual. In the early 1950s, Robert Noyce was a midwestern boy from the small Iowa town of Grinnell (named after Josiah Grinnell, the abolitionist minister whom the journalist Horace Greeley had famously advised to "Go West, young man"). After graduating from local Grinnell College, however, Noyce first looked east, to the Massachusetts Institute of Technology, in order to pursue his professional and academic ambitions. Through one of his Grinnell professors, Noyce had learned of the development of the transistor in 1946 by Bell Labs scientists John Bardeen, Walter Brattain, and William Shockley. The transistor performed many of the functions of a vacuum tube, but in a smaller, more durable, more energy-efficient package. Although, as we have seen, transistors were used in the construction of many of the early electronic computers, Bell Labs was primarily interested in using them as switching circuits in its telephone networks. Robert Noyce studied transistors as part of his pursuit of a PhD in physics and, later, as an employee of the Philadelphia-based electronics manufacturer Philco. Like most observers of the new technology, he reasonably assumed that the focus of development in transistors would be the established East Coast electronics firms.

The migration westward began with William Shockley, the most ambitious (and later, notorious) of the original Bell Labs inventors. By the mid-1950s Shockley had left Bell to found his own company, Shockley Semiconductor Laboratories, headquartered in the then sleepy rural college town of Palo Alto, California. There are a number of reasons why Shockley selected this otherwise inauspicious location, including its proximity to Stanford University (where an entrepreneurial engineering professor named Frederick Terman was actively recruiting electronic firms to locate nearby), its relative closeness to its parent company Beckman Instruments, and, last but not least, the fact that Shockley had grown up in Palo Alto and his mother still lived there. At the time, there was no reason to suspect that anyone but Shockley's employees would join him in this largely arbitrary relocation to northern California. One of the twelve bright young semiconductor physicists who did move west to join Shockley on his "PhD production line" was Robert Noyce, who joined the company shortly after its founding in 1956.

But while Shockley was an excellent physicist (in 1956, he and Bardeen and Brattain were awarded the Nobel Prize for the invention of the transistor), he was a difficult and demanding boss, and not a particularly astute entrepreneur (the particular form of transistor technology that he chose to develop had limited commercial possibilities). By 1957 he had alienated so many of his employees that eight of them (the so-called Shockley Eight, or, as Shockley himself referred to them, the "Traitorous Eight") left to form their own start-up company aimed at competing directly with Shockley Semiconductor. The leader of this group was Robert Noyce, who by this time had developed a reputation for being not only brilliant but charismatic. Among his other responsibilities, Noyce was charged with raising capital for the new firm, which at this point required him to again look to East Coast establishments. Noyce not only succeeded in raising $1.5 million from the Fairchild Camera and Instrument Company (acquiring at the same time the name for his new company, Fairchild Semiconductor) but, in the process, also attracted to Northern California Arthur Rock, the young banker who would become one of the founding fathers of the modern venture-capital industry. The combination of semiconductor manufacturing, venture capital, and military contracting would soon transform the apricot and prune orchards around Palo Alto into the best-known high-tech development center in the world.

More than any other company, it was Fairchild Semiconductor that spawned the phenomenon we now know as Silicon Valley. To begin with, unlike Shockley Semiconductor, Fairchild focused on products that had immediate profit potential, and quickly landed large corporate and military clients. In 1959 Fairchild co-founder Jean Hoerni developed a novel method for manufacturing transistors called the planar process, which allowed for multiple transistors to be deposited on a single wafer of silicon using photographic and chemical techniques. Robert Noyce, then head of research at Fairchild Semiconductor, extended the planar process to allow for the connection of these transistors into complete circuits. It was these wafers of silicon that would give Silicon Valley its name, and their transformation into "integrated circuits" or "chips" that would consolidate the region's status as the birthplace of the revolution in miniature (as well as its central role in subsequent developments in personal computing and the Internet). Integrated circuits built using the planar process could be used to replace entire subsystems of electronics, packing them into a single durable and relatively low-cost chip that could be mass-produced in high volumes.

THE FAIRCHILDREN

Almost as significant as Fairchild Semiconductor's technological innovations were its contributions to the creation of a unique "technological community" that soon took shape in Silicon Valley. The rebellious and entrepreneurial spirit that made possible the founding of Fairchild remained part of its fundamental culture. Engineers at Fairchild, many of whom were young men with little industry experience and no families, worked long hours in a fast-paced industry that encouraged risk-taking and individual initiative, in a company that discouraged hierarchy and bureaucracy. And just as Fairchild itself was a spin-off of Shockley Semiconductor, so too it spun off many start-ups, which then proceeded to spin-off still others. Half of the eighty-five major semiconductor manufacturers in the United States originated at Fairchild, including such notable firms as Intel, AMD, and National Semiconductor. Most top managers in the Silicon Valley semiconductor firms spent some period of their careers in the company; at a conference in Sunnyvale, California, in 1969, it was said that of the four hundred engineers present, fewer than two dozen had never worked for Fairchild. "Fairchild University," as it was called, served as the training ground for an entire generation of industry entrepreneurs, many of whom relocated nearby (largely in order to make it easier to recruit other ex-Fairchild employees). In the years between 1957 and 1970, almost 90 percent of all semiconductor firms in the United States were located in Silicon Valley.

Perhaps the most famous of all the "Fairchildren" was Intel, the second of the start-up firms founded by Robert Noyce. Frustrated with the growing bureaucracy at Fairchild Semiconductor, as well as with the fact that much of the profits were being funneled back to its parent company back east, Noyce once again defected. This time, he and his partner Gordon Moore had no problem raising capital. By this point Arthur Rock had established his own venture-capital firm in nearby San Francisco and, with nothing more than a verbal presentation from Noyce, was able to raise almost $3 million in start-up money. Noyce and Moore recruited away from Fairchild the best experts in planar process manufacturing, and within two years of its incorporation in the summer of 1968, Intel (a combination of the words *integrated electronics*) was profitably producing integrated-circuit memory chips for the computer industry. Within five years it was a $66 million company with more than 2,500 employees.

In stark contrast to what they saw as slow-moving, overly bureaucratic East Coast electronics and computer firms, the new breed of Silicon Valley start-ups such as Intel prided themselves on being fast, flexible, and meritocratic. They kept their organizational structure "flat" by eliminating middle managers and encouraging (and empowering) engineers to be entrepreneurial. There were no dress codes, no hierarchies or protocols. At Intel, every employee had access to everyone, even top executives like Noyce and Moore. No one had offices, or even cubicles: everyone worked in a shared space separated only by shallow partitions. Employees were encouraged to be autonomous and creative, and were provided with everything that they needed to be productive; in return, they were expected to work long hours, including nights and weekends, and to prioritize their work over all other interests.

During the 1960s the pace of semiconductor innovation was furious. There were two main reasons for this. The first was technological: the planar process, once perfected, promised regular and dramatic improvements in transistor density—and, as a result, processing power. The first integrated circuits produced in the early 1960s cost about $50 and contained an average of half a dozen active components per chip. After that, the number of components on a chip doubled each year. By 1970 it was possible to make LSI chips (for Large Scale Integration) with a thousand active components. These were widely used in computer memories, and during the early 1970s they decimated the core-memory industry. The rapidly increasing density of semiconductor chips was first commented upon by Gordon Moore (the co-founder of Intel) in 1965, when he observed that the number of components on a chip had "increased at a rate of roughly a factor of two per year" and that "this rate can be expected to continue for at least ten years." This projection became known as "Moore's Law," and he calculated "that by 1975, the number of components per integrated circuit will be 65,000." In fact, while the rate of doubling settled down at about eighteen months, the phenomenon persisted into the twenty-first century, by which time integrated circuits contained tens of millions of components. Every investment in the underlying chip manufacturing process translated directly into improvements in the end product—and, by extension, all of the increasing number of technological systems built using integrated circuits.

A second reason for rapid development of integrated circuits had to do with the unique nature of the early market. The most important client for the emerging semiconductor industry was the US government. One of Fairchild Semiconductor's first important contracts was for integrated circuits used by the Minuteman missile system, and in 1963 the company began providing circuits of the Apollo rocket program. In fact, in the 1950s the US military represented 70 percent of the semiconductor market. More so than any other potential clients, NASA and the military were willing to pay a premium for the reliability, resistance to interference, and small size of transistor and integrated-circuit technology. Perhaps even more significantly, in order to ensure that national security not be overly dependent on a single manufacturer, the US government mandated a policy of "second sourcing," meaning that all military contractors were required to share their designs with competitors. One of the other most influential of the "Fairchildren," AMD, thrived for many decades as a second source of Fairchild and Intel products. The guaranteed market for semiconductors provided by the military, combined with the forced circulation of knowledge and personnel created by second sourcing, reduced the risks associated with investment in cutting edge chip fabrication technology. Both factors also encouraged competition, innovation, and a relentless pursuit of incremental product improvement.

CHIPS IN CONSUMER PRODUCTS

The "upside-down economics" of integrated circuits—the fact that prices so quickly went down even as performance rose—meant that firms like Intel were driven to innovate, in terms of both improving existing product lines and creating new markets. An excellent example of this is their expansion into the calculator industry. The first electronic calculating machines, developed in the mid-1960s, used both off-the-shelf and custom chips—as many as a hundred in a machine. They were very expensive, and the old electromechanical technology remained competitive until the late 1960s. With the use of integrated circuits, however, the cost of building a calculator could be reduced dramatically.

Price competition in the calculator transformed it from a low-volume market of primarily business users to a high-volume one for educational and domestic users. The first hand-held calculators were introduced around 1971 at a price of $100; by 1975 this had fallen to under $5. The drop in prices drove many of the US calculator firms out of business, leaving production to Japanese and Far East firms—

although they remained dependent on US-designed chips. In a similar manner, the market for digital watches would first rise and then collapse, as the technology became a commodity and world production shifted to the "rising Tigers" of Japan, Tiawan, and Korea. At the same time, however, new industries were being created around the widespread availability of off-the-shelf electronics being churned out by Silicon Valley.

Of these new users of high-density integrated circuits, perhaps the most significant was the video game industry. Although there were some early amateur video games developed for electronic computers (often for the entertainment of bored graduate students), the commercial video game industry developed independently of (and parallel to) the electronic computer industry. Although some of the early entrants into this industry, such as Magnavox, were outgrowths of traditional electronics firms, the most influential, Atari, was associated with the amusement industry. Atari was founded in 1971 by a thirty-eight-year-old entrepreneur, Nolan Bushnell. Its first product was an electronic table-tennis game called Pong (so called to avoid trademark infringement on the name Ping-Pong). The company initially supplied its Pong game for use in amusement arcades, much as the rest of the amusements industry supplied pinball machines and jukeboxes. Its success spawned both US and Japanese competitors, and video games became an important branch of the amusements industry.

Whereas other firms were devastated by the collapse in chip prices, Bushnell saw an opportunity to move Atari from low-volume production for arcades to high-volume production for the domestic market, much as had happened with calculators. Atari developed a domestic version of Pong, which plugged into the back of an ordinary TV set. The home version of Pong hit the stores in time for Christmas 1974 and sold for $350. Atari followed up with a string of domestic games, and by 1976 the firm had annual sales of $40 million, even though the price of a typical game had dropped to $50. By this time video games had become a major industry with many firms. Because the value of a video game system was largely in the software (the games themselves) rather than in the increasingly commodified hardware, the intense price cutting in the underlying technology did not cause the same degree of disruption that it did for calculator and digital watch manufacturers. If anything, the rising cost of developing games software led to further consolidation in the industry around a few key manufacturers. In fact, in 1976 Bushnell felt the need to sell Atari to Time-Warner, which had sufficient money to develop the business.

Although the video game industry would collapse briefly in the early 1980s, ultimately video games would become one of the largest entertainment industries in the world, rivaling even television and the motion picture industries. In the late 1970s their popularity helped define the market for electronic consumer electronics and, in many ways, shaped the course of the development of the personal computer. The two technologies were closely related, with many microcomputers (as they were then known) being purchased primarily to play games, and many video game manufacturers (including Atari) also manufacturing microcomputers. Both industries were a direct outgrowth of the semiconductor firms that took root in Silicon Valley in the previous decade rather than of established electronic-computing companies like IBM or DEC. It was only in the early 1980s that these two industries (semiconductors and electronic computers) would converge around a single product—the personal computer.

As we will see in the following chapter, the story of the personal computer is often told as a "triumph of the nerds"—young amateur techno-enthusiasts whose obsessive focus and technological wizardry allowed them to accomplish what the so-called experts thought was impossible. There is some truth in such David versus Goliath mythologies. But it is important to understand the many threads of development that came together to create the personal computer. By the beginning of the 1970s several developments—the widespread availability of easy-to-use computer languages like BASIC; the new expectations for a more individual, interactive computer experience enabled by the minicomputer; the flood of new products coming out of the semiconductor manufacturers of Silicon Valley; and the opportunities for funding provided by the venture capitalists—had brought together almost all of the elements necessary to produce the first truly mass-market electronic computer. It is no coincidence that this technology emerged where and when it did, and why it was adopted so quickly and so readily.