Intel's Microprocessor and the Computer Revolution

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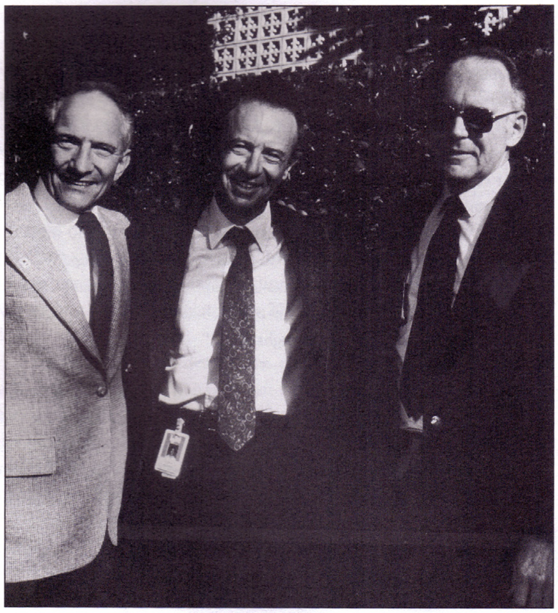

Intel's founders, left to right: Robert Noyce, Andrew Grove, and Gordon Moore.

For the head of a $16.2-billion company responsible for 26,000 employees, Andrew Grove, the chief executive officer of Intel Corporation, still has the outlook of an entrepreneur. "The best thing is to make the right decision. Making a wrong decision is okay too. The worst thing to do is hedge. To hedge is to fail."

Intel has never hedged. From the beginning it has forged relentlessly into new territory. In 1968, when Gordon Moore and Robert Noyce left the security of a large, established firm to start their own company, their plan was to manufacture a product they had yet to invent: a tiny semiconductor chip with the same capacity to store computer memory as the large magnetic cores used in mainframe computers. Under the direction of Moore and Noyce, Intel's engineers set out to pack more and more computing power on ever smaller chips. In 1971 they made a chip that could be active in the operation of the computer. The microprocessor, as it was called, is a device now ranked with McCormick's reaper and Henry Ford's assembly line as a milestone in the history of invention.

By compacting the power of a 3,000-cubic-foot computer into a chip smaller than a fingernail, Intel's microprocessor made possible the personal computer (PC). As the PC revolution gained momentum in the early 1980s, Robert Noyce (who died in 1990) observed that an "Intel-induced change occurred in our society."

The invention of the microprocessor was simply the beginning. Intel, the early technological leader, has made a strenuous effort to maintain its lead. With the help of Andrew Grove, a kinetic manager and organizational mastermind, the company has managed to stay ahead of potential competitors for two decades. Even after establishing its microprocessors, which are produced in state-of-the-art factories around the world, as the industry standard, Intel continues to operate as if it were a research institution. In recent years its annual budget for research and development has topped $1 billion.

The heavy emphasis on research is explained by two widely quoted comments made by Gordon Moore and Andy Grove, respectively. The first, now known as "Moore's law," is that "the power and the complexity of the silicon chip will double every eighteen months." The second, explaining Intel's drive to be out in front every time the silicon chip does advance, could be called "Grove's corollary": "Only the paranoid survive."

Inventing a New Industry

Gordon Moore grew up in a small coastal town south of San Francisco, where his father was a deputy sheriff and his mother ran a store. He left to pursue an education that was completed in 1954 with a Ph.D. in chemistry and physics from the California Institute of Technology. In 1956, after two years at the Applied Physics Lab at Johns Hopkins, Moore returned to California, where he took a job as a research chemist at Shockley Semiconductor. One of his co-workers there was Robert Noyce, a Grinnell College graduate with a Ph.D. in engineering from the Massachusetts Institute of Technology. Shockley Semiconductor should have been an exciting place to work; it was a well-funded research group operated by William Shockley, who won the Nobel prize in 1956 for his role in inventing the transistor. Conducting impulses through a silicon "semiconductor" pressed between two wafers, the transistor replaced vacuum tubes in electronics, paving the way for smaller radios. The breakthrough would ultimately pave the way for the personal computer.

In 1956-57, the scientists at Shockley Semiconductor were experimenting with the possibilities that lay beyond the transistor, investigating the efficacy of using it in the construction of other small electronic machines and appliances. But they were chafing under Shockley's tyrannical rule. When Noyce, Moore, and a half dozen others became hopelessly disenchanted with Shockley's administration, they sought the help of Arthur Rock, a San Francisco-based investment banker. He put them in touch with the Fairchild Camera and Instrument Corporation, a large New York company, that agreed to start a new division devoted to semiconductor research. When Fairchild Semiconductor opened in 1957, in Mountain View, California, with Noyce as division manager and Moore as the manager of engineering, it was only the second semiconductor research outfit in the area that would later be known as Silicon Valley.

Noyce was a brilliant inventor, and in 1959 he successfully tested an integrated circuit: he put an entire electrical track of multiple transistors on a single silicon chip. Before long, Fairchild Semiconductor's integrated circuitry was replacing the electromechanical switching that ran computers and other machines. Presuming that this was only the beginning of a vast reduction of scale, Gordon Moore saw endless new possibilities. If a circuit of transistors could be made to fit on a silicon chip, he reasoned, ways could be found to double the capacity of a single chip—and then redouble it. In 1965, Moore predicted that the power of the chips would double every twelve months. This prognostication—later expanded to eighteen months—became known as "Moore's law," and it justified Intel's fast-paced modus operandi in later years. (According to a 1995 article in *Forbes,* however, Moore's prediction was not quite accurate: "Double something every eighteen months for thirty years and it increases by a factor of over a million to one. Moore was close: Today's 4-megabit chip is 4 *million* times more powerful than its predecessor, the transistor.")

In 1963, while Gordon Moore was still assessing the possibilities of the silicon chip, he met the man who would do as much as anyone to turn those possibilities into reality at Intel: Andrew Grove, né Andras Grof. Grove had fled his native Hungary when he was twenty after the failed 1956 revolution and studied engineering at the City College of New York, completing his undergraduate degree in only three years, while working as a waiter. After receiving a Ph.D. in chemical engineering from the University of California at Berkeley, Grove joined Fairchild as an assistant to Moore in 1963, quickly establishing a reputation as a solid organizational manager.

By 1967, Fairchild Semiconductor had grown into a division with $130 million in sales and 15,000 employees. But it represented only a small portion of Fairchild's overall business, which was concentrated in aviation. Consequently, when Noyce and Moore advocated moving into new areas of research and technology, they were frustrated with the response from corporate management in New York. "Fairchild was steeped in an East Coast, old-fashioned, hierarchical business structure," Noyce said in a 1988 interview. "I never wanted to be part of a company like that."

Noyce and Moore wanted funds and support from Fairchild to investigate the possibilities of semiconductor memory. At the time, computer memory was stored in magnetic cores. Noyce and Moore believed they could replace the large cores with small chips. But Fairchild's lack of commitment frustrated them. One weekend in 1968, Moore visited Noyce at his home. The moment which would make them both billionaires is well-remembered: Noyce was mowing the lawn, but he stopped to talk. They griped about Fairchild's bureaucracy, and discussed setting up their own company to manufacture a semiconductor that could store memory. "We were young and arrogant," said Noyce, who was forty-one at the time. "We wanted the independence to do things our way."

Again they turned to Arthur Rock. Noyce and Moore each kicked in $250,000 of their own money and Rock raised an additional $2.5 million; Grinnell College, where Noyce was an active alumnus, invested $300,000.

Intel was incorporated on July 18, 1968, as NM Electronics (for "Noyce" and "Moore"). Rock was Chairman of the Board; Noyce was president and CEO, and Moore was executive vice president. They set up shop in Mountain View, California, just down the road from both Fairchild Semiconductor and Stanford University. Recruiting about a dozen employees from Fairchild, including Andrew Grove, they set out to fill a niche but ultimately created a new industry. "The semiconductor memory business did not exist," said Noyce. "That's key to the survival of a young company. You try to go into a business that is either underpopulated or not populated."

Even if semiconductors could be made viable for memory storage, others in the industry predicted that they would cost about ten times as much as magnetic cores. As a result, few firms saw any commercial possibilities in developing them. Intel (the company was renamed soon after the founding) intended to change this state of affairs by continually cutting production costs while cramming ever more transistors on a single chip. Within a few years, if Moore's law held true, memory chips would become cheaper and more desirable than magnetic cores. That would constitute a scientific achievement, but Intel was a business and had to establish itself in a nascent market. "We figured we had about five years to get established before the big semiconductor companies would follow in this market and become direct competitors," Moore recalled. One of the first decisions that the management team had to make was what they called the "degree of difficulty." If they produced a very simple product, others could easily copy it. If they tried for an overly complex one, the company's resources might give out before the research was complete. In the end they chose a middle path, and predicted that within five years their new firm could have annual revenues of $25 million.

Intel had a long way to go. In its first year of business it reported negligible revenues of just $2,672. After a few false starts, Intel's scientists began to focus on producing the silicon gate metal-oxide semiconductor (MOS) in 1969. "We chose a technology that was tractable enough so that, by concentrating all our energies, we could get past unforeseen difficulties," said Moore. In 1970, Intel brought out its first successful product, the 1103 chip, which contained 1K, or a thousand bytes, of dynamic random access memory (DRAM).

DRAM, despite its name, was largely passive. Information could only be stored on it. Intel's next step was to make chips that were more than simple receptacles. The company achieved this goal, in part, with a second memory product that was developed simultaneously. One researcher, Dov Frohman, devised a chip that, like the DRAM, could store data permanently. It could also be erased, and therefore could be reprogrammed. The EPROM (erasable programmable read-only memory) chip was a quick, cheap, and easy way to store not just data but the programs that could give instructions to DRAM chips. Frohman recalled, with enormous understatement "We weren't geniuses. Invention is just a process of dreaming a lot and then asking, 'Why not?'" The EPROMs helped boost the market for Intel DRAMs, and the company's sales rose to $9.43 million in 1971. The same year, Intel further bolstered its financial standing through an initial public offering that brought in $6.8 million.

Perfecting the Process

Although the first products were major accomplishments, Intel's managers realized the company was far from realizing its goal of $25 million in annual revenues, "A lot of things are technologically possible, but only economically feasible products will become a reality," said Noyce.

From the start, the manufacture of silicon chips was complicated. In the early seventies the factory would reduce a design through photography, and then imprint it on a tiny sliver of silicon. The process was repeated time and again to pack thousands of transistors on a single chip. Production of the chips was enormously expensive, and technological breakthroughs would have languished if Intel didn't devise ways, at every stage, to produce chips at affordable rates. Andrew Grove stepped up to do just that. “Noyce and Moore were the inspiration. Grove created the organization that executed,” recalled Dun Hutcheson, an executive at the computer firm VLSI Research.

Grove, who had a mind for industrial organization, was put in charge of production and helped to direct the company’s initial experimentation with assembly lines. “The [fabrication] area looked like Willy Wonka’s factory, with hoses and wires and contraptions chugging along,” Grove recalled. “It was state-of-the-art manufacturing at the time, but by today’s standards it was unbelievably crude.” It worked well enough to make the chips en masse, substantially reducing unit costs. And since Intel had so little competition, it was able to charge a premium price. The company’s profit margins soared.

The Debut of the Microprocessor

Intel’s first years were a mere prelude to the breakthrough that would propel the company’s growth—and the proliferation of the personal computer—in the 1970s. The invention was the microprocessor, which Gordon Moore called “one of the most revolutionary products in the history of mankind.” The discovery was not a calculated event, but simply a logical step in Intel’s continuing effort to make its chips more intelligent and to reduce the size of the devices that provide computing power.

In 1969 a Japanese company had asked Intel to produce a set of chips that would allow handheld calculators to perform the kind of complex calculations workable only on adding machines or larger computers. Rather than array several chips side by side, the Intel engineer Ted Hoff happened upon the idea of using four chips in conjunction, with a single powerful one in the middle. In the process, Hoff devised a method to place an entire central processing unit (CPU) on a single chip. And that single chip—an inadvertent solution to meet a request from a customer—became the Intel 4004 microprocessor.

In a graphic illustration of Moore’s law, the 4004—which was no bigger than a flat caterpillar with metal legs—was packed with 2,300 transistors and held as much computing power as the 1946 ENIAC, the first electronic computer, which had occupied 3,000 cubic feet. The $200 chip, introduced in 1971, could complete an astonishing 60,000 operations in one second.

The market for the 4004 took off; it powered a fad for digital watches (Intel even went into the watch business for a little while) and a new dependence on handheld calculators. In 1972, Intel made good on its promise to deliver more powerful products and brought out the 8008, a much faster and more flexible microprocessor that came to be known as the eight-bit processor. Intel’s eight-bit microprocessors were the basis for most of the personal computers launched in the seventies.

The company was growing exponentially. Intel’s sales soared from $9.4 million in 1971 to $23.4 million in 1972, and nearly trebled in 1973 to $66.17 million. That year, its stock price rose to $88 a share, nearly four times the initial offering price of $23.50. Noyce and Moore each held 27 percent of the stock, which was worth about $200 million between them. Intel’s founders could have sold out and retired. But they were just getting started. Rather than pay out dividends or build lavish corporate headquarters, the men—engineers at heart—plowed their earnings into laboratories and production facilities. In 1973 the company spent three times the previous year’s profits on research and development.

Intel’s leaders didn’t believe they were simply making plastic chips. Amid all the ferment of the Vietnam War protests, this group of buttoned-down engineers and chemists knew they were changing the course of history by reducing computing power into ever smaller packages. “We are really the revolutionaries in the world today—not the kids with the long hair and beards who were wrecking the schools a few years ago,” Moore said in 1973.

Noyce concluded that memory chips could work in everything from office equipment to home appliances. Large computers and small calculators were just the beginning. Any electronic devices—microwave ovens, stereos—that could benefit from memory could theoretically use a chip. To prepare for what it hoped was an era of expansion, Intel reorganized. In an April 1975 executive shift, Noyce became chairman, Gordon Moore became chief executive officer, and Andrew Grove was named executive vice president. Arthur Rock remained on the board of directors as vice chairman. "The entrepreneurial phase is not entirely over at Intel," Noyce said, "but the emphasis is shifting to control." Grove's elevation signaled a greater emphasis on the management of production and systems, which was vital given the tenuous nature of a high-tech company's existence. "This business lies on the brink of disaster," Moore said. "As soon as you can make a device with high yield, you calculate that you can decrease costs by trying to make something four times as complex, which brings our yield down again."

Prices would start falling almost as soon as Intel put a product on the market, as clones found ways to sweep past copyright protection into the market and customers began to anticipate the next, faster model. "Essentially the thing that makes our industry unique is that the cost of everything goes down," said Moore. Sure enough, the 8008 was replaced in 1974 by the 8080, which could perform 290,000 operations per second. The appetite for the faster, more powerful memory seemed to be insatiable. Consumer electronic products like the Altair and TRS-80 became instantly popular, and each used an Intel chip. By 1978, when it introduced the 8086 chip, Intel's revenues were nearly $400 million.

Marketing Products Amid the Personal Computer Revolution

The 1970s turned Intel into a giant. Revenues rose from $4.2 million in 1970 to $661 million in 1979, a year in which it held 40 percent of the $820-million microprocessor market. By 1980 its stock had appreciated 10,000 percent from the original offering price of $23.50 per share. With no long-term debt and a dominant position in the market it had helped create, Intel felt its place in the industry was secure. Yet the company's leaders felt that they had just begun to understand the possibilities of the technology. By packing increasingly greater computing capability into silicon wafers, they believed that a single chip could hold the power of mainframes, those large workhorse computers, produced mainly by IBM, that drove most large-scale business enterprises.

Yet Intel's bold pioneers would face unexpected challenges. Neither size nor tradition guaranteed a company a future in the rapidly shifting computer market. As Howard Rudnitsky wrote in *Forbes* of the semiconductor industry in 1980: "Still ruthlessly competitive but increasingly capital-intensive and complex, it is no longer a business where you can start in a garage with $100,000 or play everywhere in the big time—even if you are an Intel, with $66 million a year in R & D and $150 million in capital expenditures."

By 1980, Intel no longer had the field to itself. Companies like Zilog and Motorola had invested substantial sums to improve their capabilities. And with these worthy competitors seeking to gain market share, Intel could never be sure that its chips would be chosen as standard components when computer manufacturers designed their products. If Intel didn't gain a sufficient number of these so-called "design wins," the groundbreaking work of the prior decade would have been for naught. "In the semiconductor business, the only market share you really care about is the one you maintain when the market is mature," Intel executive William Davidow wrote in his book, *Marketing High Technology.*

The newly minted 8086/8088 chips, introduced in 1978, were fast approaching maturity when Intel embarked upon a campaign to make its microprocessor chip the industry standard. In December 1979 a group of Intel executives convened to discuss strategy. Silicon chips were becoming a commodity, with many different companies producing them. The Intel executives recognized that their company had strengths, especially in the development of microprocessors. Intel had the reputation of being ahead of its time, and its chips were viewed as high-performance products. To exploit these advantages, the company embarked upon Operation Crush, a campaign of public relations and trade advertising that stressed Intel's role in creating the microprocessor. The objective was to achieve 2,000 "design wins" over competition from other technology firms. They ended up with 2,500. "By the time Crush was over [at the end of 1980], our victory was almost complete. Intel all but owned the business application segment of the 16-bit microprocessor market," wrote Davidow. Among all the design wins, one, in particular, was crucial. "The one large client we had to win over was IBM," he said. In 1980, IBM chose the Intel 8088 microprocessor as the power plant for its upcoming personal computer, which also used Microsoft's MS-DOS operating system.

The introduction of the IBM-PC changed the computing world. With the backing of a powerhouse like "Big Blue," personal computers—machines with both a "brain" and a memory—quickly became hot products for individuals and businesses alike. The IBM-PCs immediately established Intel's 8086 as the industry standard. Since IBM didn't develop much proprietary technology relating to the PC, companies could replicate the PC without too much difficulty. So when makers of clones, like Compaq Computers Corporation, sought to copy IBM's architecture, they naturally turned to Intel, which was one of the main beneficiaries of the IBM-PC and the clone boom of the early 1980s. The company's sales rose rapidly from $789 million in 1981 to $1.6 billion in 1984. One segment of its business was under tremendous pressure, however, as competition from Japanese manufacturers brought the price of DRAM down below the cost of production for a company like Intel. The company abruptly withdrew from the market and concentrated on areas in which it could control prices with advancements in technology.

High Output Management

Although Moore and Noyce remained at the top of Intel's corporate ladder, Andrew Grove was the driving force behind the company's powerful expansion, having been named president and chief operating officer in 1979. Extraordinarily direct and hard-driving, Grove was nicknamed the "Prussian General." He was known to keep a list of workers who arrived after 8 a.m., and in 1981, when the company was experiencing difficulties during the recession, he came up with the "125 percent solution." All professional employees were forced to clock in for fifty-hour weeks with no increase in pay.

But Grove was no mere taskmaster. He was an effective manager, who thought a great deal about the optimal methods of organizing an industrial and technological company. He developed an "output-oriented approach to management," which he described in his popular 1983 book, *High Output Management*. (For many years he also wrote a syndicated column on management called "One-on-One with Andy Grove.") In his view, output wasn't limited to engineers and factory workers; it reflected on every clerk and administrator as well. At Intel, employees were responsible not only to their boss but also to their colleagues. "… [Here] everybody writes down what they are going to do and reviews how they did it, how they did against those objectives, not to management, but to a peer group and management," Robert Noyce once explained.

Intel also tried to instill a team-based approach. Even the most senior employees worked in open cubicles, rather than in offices. The office design emphasized another one of Grove's main goals: breaking down barriers and developing personal relationships between managers and employees. Similarly, Grove advocated that managers meet employees one-on-one, to gain and impart information, and create a sense of a shared corporate culture. "[The] main purpose is mutual teaching and exchange of information," he wrote.

Though Intel had remained true to its founders' determination not to stymie creativity under layers of typical corporate bureaucracy, not everybody chose to remain with the company. Just as Grove, Moore, and Noyce had left a larger firm to seek their own fortunes, various senior members of Intel's research staff left Intel in the early 1980s to start companies such as Convergent Technologies and Seeq Technology.

Marketing High Technology in an Era of Competition

Intel had difficulty maintaining dominance in the 1980s. Since the barrier to enter the microprocessor industry was remarkably high, the firms that did encroach on Intel's wildly profitable niche were major firms with deep pockets: Texas Instruments, Motorola, and, increasingly, Japanese firms. Due to the competition, the price of the chips kept falling, so that by 1985 Intel charged just $20 for the 8086 chip. This cut into the company's famously high profit margins. In fact, revenues declined in both 1985 and 1986, falling from $1.6 billion in 1984 to $1.2 billion in 1986, Grove responded with typical precision and speed. To save money, Intel announced in October 1985 that it would slash pay 10 percent and close operations for six days in late December. The company ultimately laid off 2,600 workers (or 30 percent of the workforce).

Intel's salvation came—as it always had—through the invention of a new product that made its own previous standards, and those of rivals, seem logy. In October 1985 Intel introduced the 386 microprocessor, the development of which had cost more than $100 million. "A miracle of miniaturization, the microprocessor is 1/4-inch square, yet performs with the power and speed of many full-size computers," *Forbes* reported in June 1986.

By the mid-1980s, Intel had come to realize that marketing was an integral part of the business process. And so it set out to create a distinctive image for its new generation of products. The way that each new microprocessor rendered the previous one obsolete was highlighted in an advertising campaign for the 386 SX. The so-called Red X campaign featured two-page ads. One page showed the earlier "286" with a large red "X" through it. The other page had "386" with a large "SX" under it. "We were speaking directly to PC consumers for the first time, rather than marketing only to OEMs [manufacturers]," said Dennis Carter, an Intel marketing executive. Even though the company had been in business for fifteen years, it had never made a strong effort to introduce itself to the people who ultimately used its products; no semiconductor company had. As late as 1987, Grove told Barron's, "I really have no feel for end- use sales in the PC industry. We supply to the manufacturers. . . ." But when Intel noticed that sales of machines using the 386 began to pick up after the Red X campaign, the company changed its view. "What we learned from the Red X campaign was that we *could* communicate arcane technical ideas that, in fact, people wanted to hear them," said Dennis Carter.

The use of marketing represented a new phase in Intel's maturity. And the company grew up in other ways as well. The founders began to take a less active role in its management. Robert Noyce devoted more and more time to outside interests, including serving as a trustee at Grinnell College. In 1988 he left Intel altogether to head Sematech, a government-backed consortium of twelve semiconductor firms that banded together to conduct research. In 1990 he died of a heart attack.

Moore assumed the role of vice chairman, and later chairman, but still worked forty-five to fifty hours a week in his cubicle. One of the most respected executives in the country, he is known as a quiet man, whose words carry weight in the entire industry. "Gordon knows where to spend the money and allocate assets," Arthur Rock said of him. "He's the guy who said in a downturn we've got to build plants and mothball them and be ready when the business starts to turn up again. He's had that vision. . . . He's been willing to bet the company over and over."

In 1987, Andy Grove assumed the title of chief executive officer. As such, he had the opportunity to implement high output management from top to bottom at Intel. "We can get more output out of our existing organization," he said.

More output wasn't enough, however. Double the output was essential. In order to make an impact with a new product, Intel had to prove it was actually replacing the previous generation, not merely improving upon it. The case of the 386 chip neatly illustrates this shift in strategy. In 1988, when the company's revenues soared to $2.9 billion, about $1.1 billion came from the 386. Rather than continuing to milk the cash cow, however, Intel was already planning to put it out to pasture. In 1988 the company introduced a successor, the 486 microprocessor, developed at a cost of $300 million. The transistors themselves were only about one micron thick, or one percent of the width of a human hair; one million of them fit on one 386 chip.

Intel Keeps Running

The 386 and 486 (known officially as the 80386 and 80346) were standard in IBM-compatible personal computers. It was estimated that in 1990 about 14 million of the 22 million PCs made worldwide included an Intel microprocessor. With each chip costing an estimated $50 to produce, and carrying a $200 retail price, Intel was raking in money. "As the sole supplier of the computer industry's most important single part, the 80386 microprocessor, Intel enjoys profit margins far greater than those of its competitors," wrote Richard Shaffer in *Forbes*.

Under Grove, Intel found it necessary to introduce a substantially improved microprocessor as often as every year or so, in order to insure its place in the market. Every time a rival like Advanced Micro Devices began shipping a chip that approached Intel's standard, the pioneering company's profit margins began to fall. "It cannot achieve supremacy in a product and sit back and count the money rolling in forever," *Forbes* wrote of Intel in 1990. "It must keep pushing back the frontiers of innovation and technology."

And that is precisely what Intel continued to do, in production as well as in design. No sooner did a new plant open than Intel's design and engineering staff began to plot the construction of a larger, cleaner, more efficient plant. "In this business you have to build your own capacity," Grove remarked.

In 1992, when Intel's IBM-PC market share remained at a solid 75 percent, Motorola, its biggest competitor, was a distant second, with 14 percent of the market. Yet that year Intel spent $1.2 billion of its $5 billion in sales on plants and equipment and another $800 million on research and development.

In June 1989, Intel began to develop the Pentium Processor. With 3.1 million transistors operating in a single chip, it was faster, smaller, and more powerful than any previous Intel processor or any other on the market. The company faced a debacle when, after a well-orchestrated launch, the new microprocessor was found to have a bug. At first Andy Grove dismissed it as a remote, statistical problem: "If you know where a meteor will land, you can go there and get hit," he responded, when asked if even a rare problem was still a problem. Eventually, Intel offered to replace Pentium Processors at no charge. Grove later admitted that he had a lot to learn about dealing with the public.

Even as Intel began to ship the $995 Pentium, in March 1993, the pace at Intel continued to quicken. In December 1993 Intel said it would double the capacity of its chips in the next year, slashing the product development interval of eighteen to twenty-four months down to one year. "The operative word is focus," Grove said in 1993. "You have to put all your effort behind the thing that you do better than the other people in the business, and then not hedge your bets. . . . If you focus and you're wrong, you lose—but if you're right, you win big time."

Maximizing Miniaturization Technology

For each new generation of chips, Intel has had to develop the parallel technologies of the chip itself and the means to produce it commercially. That's where all the research and development money goes.

The power of the microprocessor increased exponentially over its first two decades because engineers found ways to make the main components, the transistors, smaller and smaller and smaller. Transistors were no longer bits of metal and plastic, as they had been when most people first saw them inside a pocket radio. They were specks of chemicals, and it would take hundreds of them to make a ring around a human hair. Arranging millions of them in effective circuitry telescoped the capacity of a much larger machine onto a chip the size of a postage stamp. But even as specks, transistors had to be precisely drawn.

On an old-fashioned transistor, an impurity the size of, say, a cookie crumb, could interfere with performance. Next to a transistor measuring less than one micron, a germ—a single bacterium—looks like a boulder and renders the whole chip worthless. Intel had to design production rooms in which all the air was filtered every few seconds, leaving less than one such particle per cubic foot. Humans, those roving dust storms of dandruff, viruses, spit, and lint, had to be sealed inside special suits in order to work in "clean rooms."

Inside the clean rooms, the photographic process of imprinting arrays of transistors was extremely sensitive as the detail shrank. Site selection for production facilities became a matter of geology: the slightest tremor, imperceptible to humans, would distort the circuitry being exposed. Most places on earth shake almost continually at extremely low levels. A crucial factor in Intel's expansion to places such as Ireland and Israel is that the ground itself is stable in those places.

According to Gordon Moore, Intel has to produce a new generation of processor technology every three years in order to maintain its advantage in chip engineering. "We just continue to push narrower and narrower line widths and more and more complex processes, so we can increase the density of electronics on the wafer," he said in 1993. "Get more and more stuff on a chip, essentially."

In the first week of April 1994, Intel announced that it planned to spend $150 million to market the Pentium—a stunning amount of money for a piece of silicon. Pentium, though dominant, was competing with a growing array of products made by companies like Advanced Micro Devices, Cyrix, and IBM, along with the new Power PC chip made by Apple and Motorola. The purpose of Intel's latest marketing campaign, with the tag line "Intel Inside," was to make the chip's brand name a household word, as familiar to the American consumer as McDonald's or Coca-Cola. As an inducement, the company offered to pick up half the tab for advertisements its computer-producing partners ran that used Intel logos in the ads.

In 1995, when Intel had $16.2 billion in sales and $4.9 billion in profits, Noyce and Moore's bold prediction of a quarter century earlier seemed, if anything, a major underestimation. Gordon Moore's net worth, measured largely in Intel stock, was pegged at over $2 billion by *Forbes.*

Under Grove's leadership, Intel was still paranoid in a healthy way. After all, staying at the vanguard of the computer revolution requires a sort of perpetual motion. Like a jogger running on an accelerating treadmill, Intel has had to run faster just to maintain its position—and even faster just to stay ahead of everybody else.