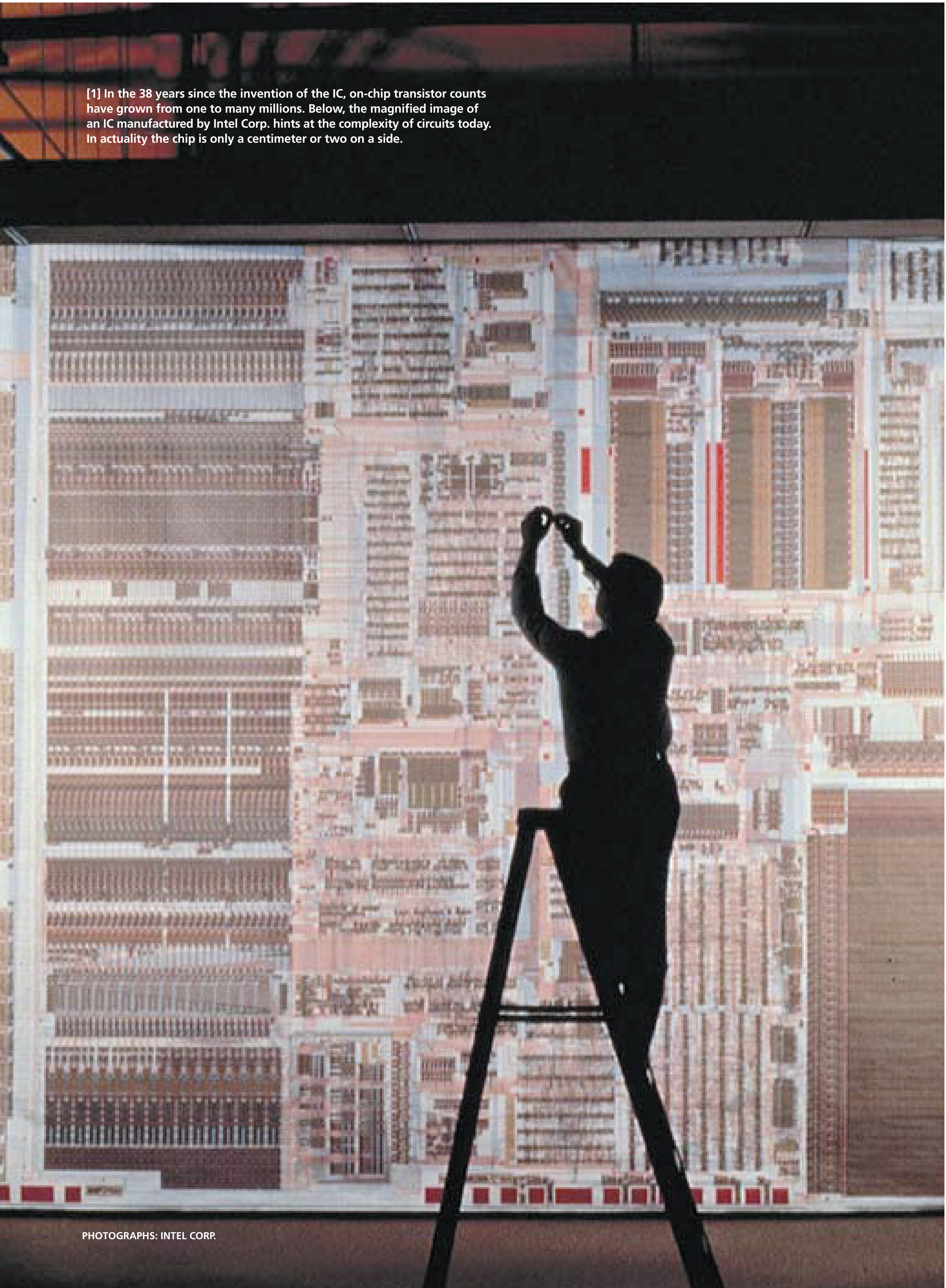

[1] In the 38 years since the invention of the IC, on-chip transistor counts have grown from one to many millions. Below, the magnified image of an IC manufactured by Intel Corp. hints at the complexity of circuits today. In actuality the chip is only a centimeter or two on a side.

PHOTOGRAPHS: INTEL CORP.

perspective

MOORE'S LAW: past, present, and future

A simple observation, made over 30 years ago, on the growth in the number of devices per silicon die has become the central driving force of one of the most dynamic of the world's industries

In 1965 Gordon E. Moore, then R&D director at Fairchild Semiconductor and these days chairman emeritus of Intel Corp., Santa Clara, Calif., quantified the astounding growth of the new technology of semiconductors in a still more astounding formula. Manufacturers, he said, had been doubling the density of components per integrated circuit at regular intervals, and they would continue to do so as far as the eye could see.

This observation has since been dubbed "Moore's Law" and is now enormously influential. Some have even termed it a self-fulfilling prophecy. Because of the accuracy with which Moore's Law has predicted past growth in IC complexity, it is viewed as a reliable method of calculating future trends as well, setting the pace of innovation, and defining the rules and the very nature of competition. And since the semiconductor portion of electronic consumer products keeps growing by leaps and bounds, the Law has aroused in users and consumers an expectation of a continuous stream of faster, better, and cheaper high-technology products. Even the policy implications of Moore's Law are significant: it is used as the baseline assumption in the industry's strategic road map for the next decade and a half.

Projecting the capabilities of semiconductors and successor technologies out to 2050 leaves Moore's numbers still looking possible [see "Beyond Moore's Law," p. 56]. As for applications, the demand for smart cards, smart watches, smart fuel injectors, and smart toasters is insatiable, not to mention the continuing worldwide appetite for personal computers, which take a good 60 percent of the semiconductor industry's output [Fig. 1].

Besides its surprising longevity as a forecaster of hardware capabilities, the Law has set the pace for the PC-software industry and, some say, is now a techno-mantra that, if repeated often enough and sincerely enough, has the power of a self-fulfilling prophecy.

Genesis of the IC

The 1947 invention of the transfer resistor, or transistor, by William Shockley and his colleagues at Bell Laboratories, Murray Hill, N. J., ushered in the solid-state era of electronics. The concept was based on the discovery that the flow of electricity through a solid such as silicon can be controlled by adding impurities with the appropriate electronic configurations. [See "The origins of the pn junction," pp. 46–51.] The vacuum tube (which was also known as the thermionic valve) was the dominant technology for this task at the time; but the transistor proved to be significantly more reliable, required much less power, and above all, could be made incredibly smaller. And in fact, the miniaturization of the device was to become the hallmark of the semiconductor industry and the basis for Moore's Law.

Almost a decade later, Shockley and two Bell Labs colleagues, John Bardeen and Walter Brattain, were presented with the Nobel Prize for their invention. Shockley went on to start his own semiconductor laboratory, and others from his team either joined or founded the companies whose names are synonymous with the spectacular rise of the semiconductor industry: Texas Instruments, the former Fairchild Semiconductors, and Intel. Gordon Moore, a member of Shockley's team, was a key player at Fairchild and cofounder of both Fairchild and Intel.

In the late 1950s, research engineers at Fairchild developed the first planar transistor, and later the first planar IC. (Jack Kilby of Texas Instruments is credited with inventing the IC.) Although not as significant a scientific breakthrough as the transistor, the invention of the IC did reveal the potential for extending the cost and operating benefits of transistors to every mass-produced electronic circuit, including the microprocessors that control computer operations. Moore later said that the

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development of the planar transistor was the origin of his law of density-doubling.

From science to production technology

Revolutionary science supplied the theoretical basis for solid-state electronics, but without the invention of unprecedented production technologies, the spectacular growth of the industry could not have happened. "Indeed, the technology led the science in a sort of inverse linear model," Moore observed in a recent publication. Conventionally, science discovers and technology applies; here the order was reversed. The two most noteworthy inventions were the diffusion and oxide-masking process and the planar process.

The first process allowed the producer to diffuse impurities (dopants) directly into the semiconductor surface. The tedious practice of adding conducting and insulating material layers on top of the substrate was eliminated, and instead, sophisticated photographic techniques made it possible to lay intricate mask patterns on the semiconductor so that only designated areas lay open to dopants. Device reliability as well as production accuracy were greatly increased. With diffusion, production moved from a craft process of individual assembly to batch processing.

[2] Gordon Moore [right] relaxes with fellow pioneers of the electronic age: Robert Noyce [center] and Andrew Grove [left]. Moore and Noyce contributed to the development of the planar IC. Grove is now president and chief executive officer of Intel Corp.

The planar process was a logical outgrowth of the diffusion and oxide-masking process. Planarization was the brainchild of physicist Jean Hoerni of newly formed Fairchild Semiconductor. Hoerni reasoned that a design based on a plane would be easier to manufacture and to miniaturize, compared to the conventional 3-D (or mesa) transistor. Hence the planar, or flat, transistor. Flattening the mesa enabled electrical connections to be made, not laboriously by hand, but by evaporating metal film onto appropriate regions of the semiconductor wafer. Using a lithographic process in which a succession of regions were etched and plated one on top of the other on a thin, flat surface or wafer of silicon, the "chip" was born out of the planar transistor. Like the printing process itself, the planar process evolved into ever greater rates of production at even higher yields.

Better still, the planar process enabled the integration of circuits on a single substrate, since electrical connections between circuits could be accomplished internally to the chip. Robert Noyce [Fig. 2] at Fairchild quickly recognized this.

"When we were patenting this [planar transistor]," recalled Moore, "we recognized it was a significant change, and the patent attorney asked us if we really thought through all the ramifications of it. And we hadn't, so Bob Noyce got a group together to see what they could come up with. And right away he saw that this gave us a reason [for running] the metal up over the top without shorting out the junctions, so you could actually connect this one to the next-door neighbor or some other thing."

Perhaps more than any other single process innovation, planarization set the industry on its exponential rate of progress. With time, chip manufacturers improved the lithographic process with more precise photographic methods, so that photolithography became the industry's standard production method. For Moore's Law, the significance was that photolithography enabled manufacturers to go on reducing feature sizes of devices.

Birth of Moore's Law

The 19 April 1965 issue of *Electronics* magazine, marking the McGraw-Hill publication's 35th anniversary, contained an article with the title "Cramming more components onto integrated circuits." Its author, Gordon E. Moore, director, Research and Development Laboratories, Fairchild Semiconductor, had been asked to predict what would happen over the next 10 years in the semiconductor components industry. His article speculated that by 1975 it would be possible to cram as many as 65 000 components onto a single silicon chip about 6 millimeters square.

Moore based his forecast on a log-linear plot of device complexity over time. He wrote:

"The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain constant for at least 10 years."

Moore's astonishing prediction was based on empirical data from just three Fairchild data points! His starting point he pinned to the production of the first planar transistor in 1959. The next point was a scatter of the first few ICs of the early-1960s, including the production in 1964 of ICs with 32 components. His last was his own knowledge that an IC still in the laboratory and scheduled for release later in 1965 would contain 64 components. He formed his prediction of 65 000 components in 1975 by drawing a straight line out to that year [Fig. 3].

Moore revisited the subject in a paper given at the 1975 IEEE International Electron Devices Meeting. His 10-year-old forecast of 65 000 components was on the mark: a memory with that density was in production at Intel, where he was now president and chief executive officer. In the IEEE paper, he also gave explanations for the exponential increase in densities.

First, the industry could make bigger chips with fewer defects without sacrificing yields. He attributed this improvement mainly to the use of optical projection, in place of contact printing, of lithography masks on the wafers. The second explanation was ever-finer rendering of images and line widths. Together, these two observations accounted for two thirds of the improvements over the preceding decade.

Moore attributed the final third to what he called "circuit and device cleverness" that enabled manufacturers to use more of the total wafer area. Interestingly, he concluded that the cleverness had ended with the charge-coupled device (CCD), for which a then-new technique for "doping" semiconductors used controlled light beams rather than chemical means. He said:

"There is no room left to squeeze anything out by being clever. Going forward from here we have to depend on the two size factors—bigger dice and finer dimensions."

So he redrew his plot of component densities from 1975 forward with a gentler slope, one in which density doubled every 18 months, but which still behaved in a log-linear fashion. The projections were still breathtaking. Shortly after this, his plot was dubbed Moore's Law.

In 1995, Moore compared the actual performance of two kinds of devices, random-access memories and microprocessors, against his revised 1975 projection. Amazingly, both kinds tracked the slope of the exponential curve fairly closely, with the memories consistently achieving higher densities than microprocessors over the 20 years [Fig. 4]. Die sizes had gone on increasing, while line widths got smaller, at exponential rates consistent with his 1975 analysis [Fig. 5].

Seemingly mindful of Moore's focus on increasing densities, the semiconductor industry marks the evolution of its technology in terms of increasing scales of integration: medium in the '60s, large in the '70s, very large in the '80s, and ultra large in the '90s.

Today the Motorola PowerPC microprocessor contains 7 million transistors, Intel Pentium II microprocessor contains roughly 7.5 million, and Digital Equipment's 64-bit Alpha microprocessor contains almost 10 million. NEC recently announced that it had developed the world's first four-gigabit DRAM chip, which may become commercially available by 2000. Papers presented at a 1995 IEEE International Solid-State Circuits Conference said that terachips (capable of handling one trillion bits or instructions) will be available by 2010. Getting to that density will require making elements that are one ten-thousandth of a millimeter wide—about the width of a DNA coil.

Perpetual innovation machine

Perhaps the most important aspect of Moore's Law is that it has become an almost-universal predictor of the growth of an entire industry, one that has not broken stride in its exponential growth rates for more than three decades. Moore summarized the system synergies in a 1995 review of Moore's Law and the state of the industry:

"By making things smaller, everything gets better simultaneously. There is little need for tradeoffs. The speed of our products goes up, the power consumption goes down, system reliability, as we put more of the system on a chip, improves by leaps and bounds, but especially the cost of doing things electronically drops as a result of the technology."

Speaking at the Computerworld–Smithsonian Monticello lectures last summer, he acknowledged the psychological component of his law: "More than anything, once something like this gets established, it becomes more or less a self-fulfilling prophecy. The Semiconductor Industry Association puts out a technology roadmap, which continues this generation [turnover] every three years. Everyone in the industry recognizes that if you don't stay on essentially that curve they will fall behind. So it sort of drives itself."

User expectations matter

Another interpretation of Moore's Law adds to the push of new production technologies the pull of software developments.

In the youth of electronic computing, when internal memory was costly and scarce, software system designers placed a premium on "tight" code—programs with as few instructions as possible. With Moore's Law in full force, that constraint was abandoned and program complexities proliferated to thousands, then tens of thousands, and now millions of lines of code.

In 1995, Nathan Myhrvold, chief technology officer of Microsoft Inc. studied a variety of his firm's products by counting the lines of code in successive releases of the same software package. He observed that the Basic language had 4000 lines in 1975 and roughly half a million two decades later. Microsoft Word was at 27 000 lines in its first version; the latest version had about two million. Myhrvold relates this to Moore's Law:

"So we have increased the size and complexity of software even faster than Moore's Law. In fact, this is why there is a market for faster processors—software people have always consumed new capability as fast or faster than the chip people could make it available."

The reinforcing effects of complementary software developments feeding back into PC hardware—and at the core, chip innovations—are significant. Economists refer to this as dynamically increasing returns. Myhrvold suggests that a positive feedback cycle is at work: "We like what we get, we want more, which spurs people to create more. If there is a lack of positive feedback, the whole things just slows down."

As the marginal cost of additional processing power and memory literally approaches zero, system software has expanded exponentially to become an ever-larger part of information systems.

Is the end in view?

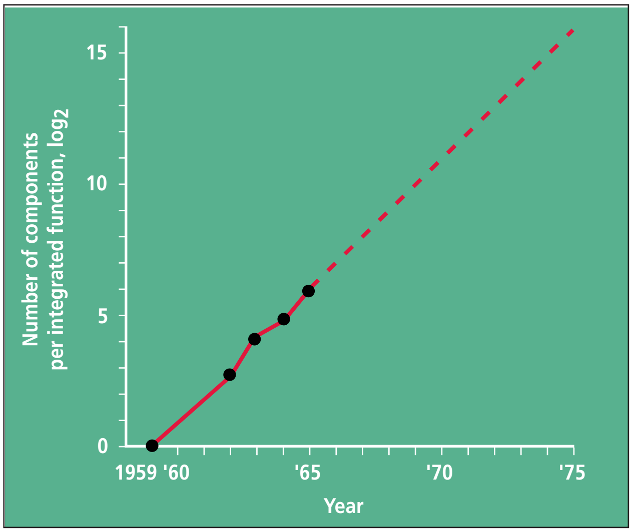
Moore's Law started out as a simple extrapolation from a simple observation. Actual performance and experience have validated it, proving Moore quite prophetic. Curiously, forecasts of its demise have been made throughout its existence, but have consistently been wrong.

They are still being made. A 1996 poll by *Forbes* of 11 industry stalwarts—chief executive officers, senior systems and software engineers, industry analysts, an industry writer, and a venture capitalist—awarded Moore's Law an average remaining life of roughly 14 years, to 2010. That would give the prediction a life span of 45 years, by any measure an incredible feat of technical insight.

At present, researchers are still learning to exploit the properties of semiconductors and production processes. But at some point this technology—like all others—will stop growing exponentially and enter the realm of diminishing marginal returns.

The physics underlying semiconductor manufacturing suggests several possible barriers to continued technical progress and density doubling. For example, the gigabit chip generation may finally force technologists up against the limits of optical lithography. There are ways around this obstacle, but the cost may be prohibitive. In fact, economics may constrain Moore's Law before physics does—an observation that others have called "Moore's second law."

For one thing, capital requirements rise exponentially along with component densities, wrote Moore in 1995. The cost of a new fabrication plant went from US $14 million in 1966 to $1500 million in 1995. By 1998, work will begin on the first $3 billion



[3] Based on just a few data points, shown in the plot above, Gordon Moore accurately predicted in 1965 that the number of components on an IC would double every year for the next 10 years—a prediction that became known as Moore's Law.

Beyond Moore's Law

If semiconductor manufacturing goes on obeying Moore's Law, PCs by 2050 will be performing a billion billion (quintillion: 10^{18}) operations per second and holding as many bytes in their memories. Indeed, researchers at the University of Minnesota announced in January that they had found a way to store a single electron in a 7-nanometer-square semiconductor, a density that would put 2.55 quadrillion (10^{15}) bytes on a 1-centimeter-square chip. If this happens in the next few years, it will have the effect of accelerating the Law by about 30 years.

Even if Moore's Law ends tomorrow, we can coast for decades, creating myriads of products that exploit the near-term projection of densities and phenomena, such as chips that hold living organisms. By themselves, super-PCs are not very interesting. The most valuable lodes to be mined from greater component densities will come from developments in three areas: platforms, networks that interconnect them, and the ability to interact with human beings and real-world information systems.

To put all this in context, it is useful first to consider alternative pathways of development for super-PCs. Back in 1975 I posited these three evolutionary paths:

- Constant or slightly lower prices and increasing performance.
- Much lower prices, with costs falling by an order of magnitude about every 10 years, creating new kinds of computers.
- The commodification of functions into microsystems-on-a-chip.

Since the '70s, most new classes of computer systems have developed along the second path. Thus US \$100 000 minicomputers emerged in the '70s to rival \$1 million mainframes that had been introduced in 1951; in the '80s we got \$20 000 workstations and \$2000 PCs; in the '90s it is personal organizers and personal digital assistants for \$100–\$500 and electronic dictionaries for even less.

We are now at a crossroads at which it is possible to take the third evolutionary path. Continuing on the path of miniaturizing mainframes will be to bypass the opportunity to create new classes of products that will dramatically enhance the universal usefulness of computing systems. We can start by developing new sensors and transducers that interface with other real-world systems. Already in development are new classes of computers with new operating platforms to exploit the advantages of global networks. Employing client-server architecture along with browser software, we are on the threshold of introducing low-cost hybrid television-telephone access to the World Wide Web.

Computer systems on a chip now appear inevitable following the announcement last September that 36 computer and semiconductor firms had formed an alliance to build such a system. This development will create a huge new microsystems industry with a market potential at least two orders of magnitude greater than the PC industry. Every PC will be connected to thousands of other systems, all built around a single-chip architecture, with its interconnection bus also on a chip. Each microsystem will contain a processor, memory hierarchy, I/O capability (including speech), and standards-compliant platform software. With more-powerful processors, firmware (software on a ROM) will replace hardware.

The table shows the evolution of computer classes in the context of the foregoing analysis, assuming that Moore's Law continues to hold. *—C. Gordon Bell*

Gordon Bell, located in Los Altos, Calif., is a senior researcher for Microsoft Corp. Considered the "father of the minicomputer," he has written widely about computer structures and start-up companies.

1. Evolution of computer classes and components

Year	Generation	Platform	User interface	Network
1951	Direct and batch use	Computer, vacuum tube, transistor, core, drum, magnetic tape	Card, paper tape direct control evolving to batch op system	None (originally stand-alone computers)
1965	Interactive timesharing via commands; minicomputers	Integrated circuit, disk, minicomputer; multiprogramming	Glass teletype and keypunch, control by command language	Telephone using modem, and proprietary wide-area networks
1981	Distributed PCs and workstations	Microprocessor PCs, workstations, floppy, small disk, distributed operating system	WIMP (windows, icons, mouse, pull-down menus)	Wide- and local-area networks
1994	World Wide Web access through PCs and workstations	Evolutionary PCs and workstations, servers everywhere, Web op system	Browser	Optical-fiber backbone, World Wide Web, hypertext transfer protocol
1998	Web computers: network, telephone, TV computers	Client software from server using JAVA, ActiveX, and so forth	Telephone, simple videophone, television access to the web	Subscriber digital lines for telephone or cable access for high-speed data
1998	SNAP: scalable network and platforms	PC uni- or multiprocessor commodity platform	To multimedia Web clients	System area network for clusters
2001	"Do what I say" speech-controlled computers	Embedded in PCs, hand-held devices, phones, digital assistants	Speech	Infrared and radio LANs for network access
2010	One info dial tone: phone, videophone, TV, and data	Video-capable devices of all types	Video as a primary data type	Single high-speed network access; home net
2020	Anticipatory by "observing" user behavior	Room monitoring, gesture	Vision, gesture control	Home Net
2025	Body Net: vision, hearing, monitoring, control, communication, location	Artificial retina, cochlea, glasses for display, monitoring and recording of everything we see, hear, and say	Implanted sensors and actuators for virtually every part of a body	Body Network, gateway to local IR or radio nets everywhere. Humans are part of cyberspace
2048	Robots for home, office, and factory	General-purpose robot; appliances become robotic	Radar, sonar, vision, mobility, arms, hands	IR and radio LAN for home and local areas

fabrication plant. These increases are no problem as long as chips improve still faster. That happened between 1984 and 1990, when chip performance tripled, while the cost of a fab plant only doubled. For the next generation of chips, however, the capital needed will double again, but performance is expected to increase only by half. If the exponential trend in fab costs continues, by 2005 the cost of a single fab plant will be more than $10 billion in 1995 dollars—more than half of Intel's current net worth.

What can semiconductor manufacturers do? One possibility: team up with customers, competitors, suppliers, or even countries to share fab construction and R&D costs. For example, the R&D price tag for dynamic RAMs, which rose from US $400 million for the 4 Mb chip to more than $1 billion for the 1 Gb device, led to the well-known alliance of IBM, Germany's Siemens, and Japan's Toshiba for the development of advanced DRAMs. In Korea and Singapore, state-organized consortia appear to be on the rise. Global alliances are emerging as the new model for competition in semiconductors.

Another economic threat to Moore's Law is the possibility that transistors will become so cheap that there will be no profit in making them cheaper. Dan Hutcheson, president of VLSI Research Inc., San Jose, Calif., reached that conclusion in 1995: "The price per transistor will bottom out sometime between 2003 and 2005. From that point on, there will be no economic point in making transistors smaller. So Moore's Law ends in seven years."

Apart from the apparent constraints of physics and economics, one respondent to the *Forbes* poll, Dan Lynch, president and chief executive officer of CyberCash Inc., offers a starkly different view about the future of Moore's Law, stating, "We'll be dead when Moore's Law is played out." His reasoning: "Moore's Law is about human ingenuity, not physics."

Enter the equipment maker

By the early '50s, the invention of the point contact transistor by Bell Laboratories had led to the emergence of a new industry: semiconductor manufacturing. During the infancy of the semiconductor industry—and before the invention of ICs—the companies producing semiconductors also generally produced the equipment needed to manufacture them. The semiconductor equipment manufacturers, in fact, evolved out of the chip manufacturers. Eric von Hippel, an analyst of this evolution, detailed 15 major innovations in silicon semiconductors in which the chip maker took the lead in developing a new process or equipment. For example, mask alignment using split-field optics was first developed in house by Fairchild and later offered commercially by an equipment manufacturer. In this case, the "independent" supplier was himself a former Fairchild employee.

Moore recalls one such experience in his early days at Fairchild, involving a technician who was paid to work at home on nights and weekends to make the capillary tubes used in a critical gold-bonding process:

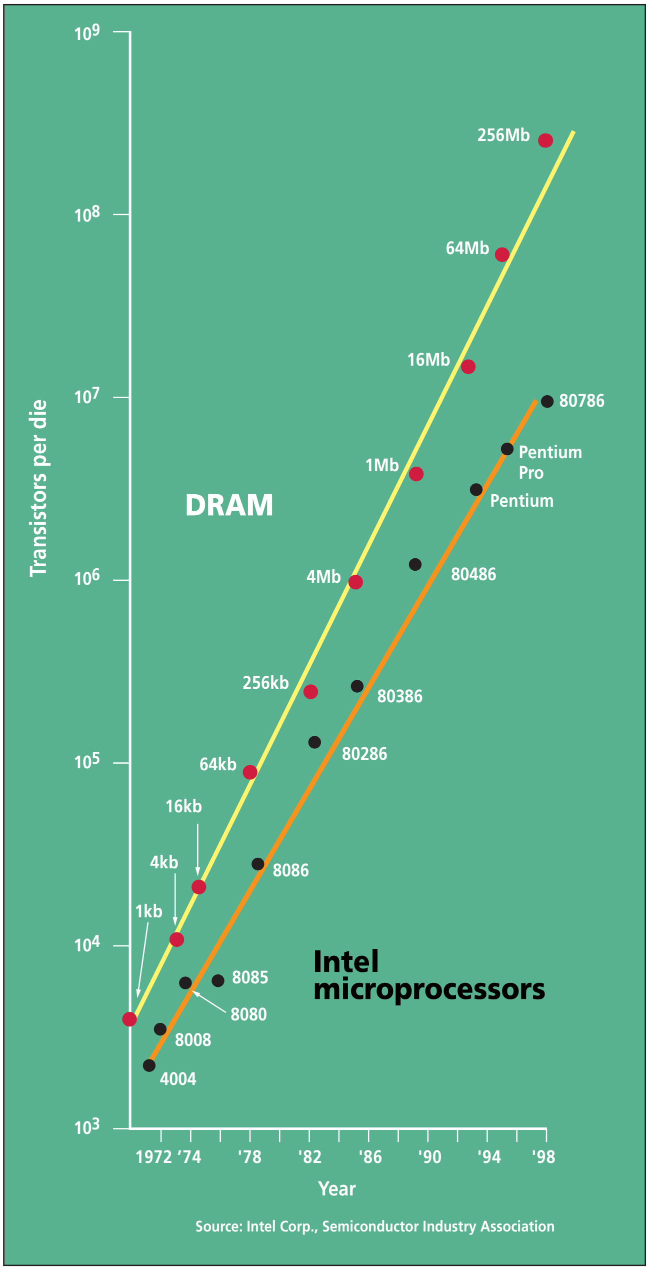
"Pretty soon that business got so big that he quit and set up Electroglass, which was the first one of these equipment companies that I know of…and he'd also been helping me build furnaces—we had to build our own furnaces in those days. So he took the basic furnace design and started building furnaces, first for us, then for the industry."

Von Hippel points out that this free movement of skilled personnel is characteristic of the semiconductor industry, especially in its earlier stages. Moore's own career is a case in point. He met Robert Noyce when both were at William Shockley's laboratory. Moore and Noyce left to cofound Fairchild Semiconductor in 1957. In turn, Fairchild spawned some 150 companies, among them Intel, which Moore and Noyce cofounded in 1968.

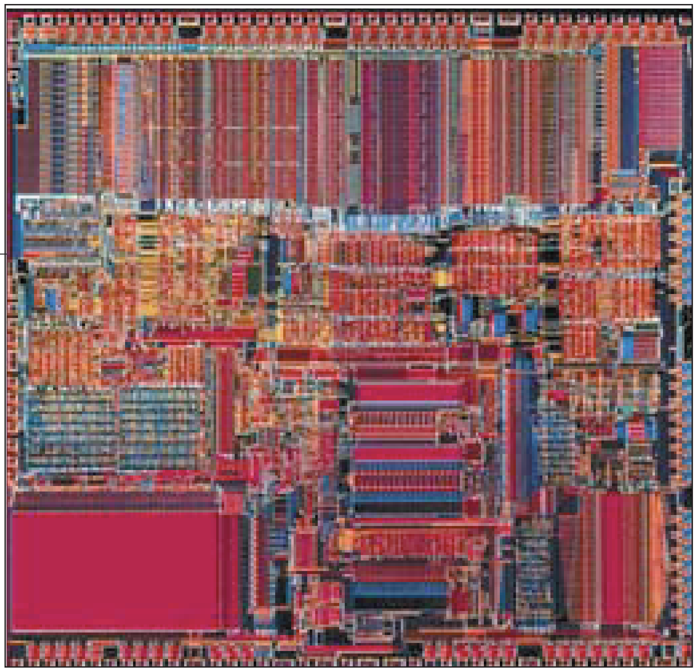
This pattern intensified in the '60s, when volume production of ICs called for new production equipment capable of much clearer resolutions, narrower line widths, and more exacting alignment specifications than those used to produce discrete electronic components. The printing of complex circuit designs onto highly polished wafers required the development of sophisticated photolithographic and other wafer-processing techniques, such as ion implanting and etching, as well as new testing and assembly operations.

Semiconductor manufacturing processes began being automated almost from the start. Today, with virtually every step of every process automated, manufacturing improvements depend on innovations in capital equipment. For example, the narrowest possible line widths and hence the greatest possible attainable integration in pursuit of Moore's Law are literally defined by the capabilities of lithographic equipment.

Now as in the past, the relationship between chip makers and capital equipment makers is very close because of this mutual



[4] For 25 years, microprocessors and dynamic RAMs have followed closely a revised Moore's Law, which stipulates the doubling in circuit complexity every 18 months. By the end of this century, DRAM densities will be approaching a billion transistors per chip.



[5] The exponential growth in the IC transistor count was a result of three factors, according to Gordon Moore: decreasing line widths, circuit cleverness, and growing die size. Intel microprocessors illustrate the third factor. Shown from left to right are the 4004, the very first microprocessor; the 386; and the PentiumPro.

dependence—in striking contrast to the traditional U.S. practice of "arm's length and cautious" relationships between suppliers and buyers. Equipment makers have long recognized their role as primary players in this technology-driven industry. Partnership arrangements, formal and informal, facilitate collaboration between equipment makers and device makers. This collaboration takes the form of technical seminars and publications, trade association meetings, industry conventions, and whatever else proves necessary to stay on the Moore's Law curve of perpetual improvements in productivity and cost reduction.

Moore's Law as metaphor

Increasingly, Moore's Law is used as a metaphor for anticipated rapid rates of change—not only in semiconductors, but in economic and social contexts. Moore himself acknowledges that the Law "gives us a shorthand to talk about things."

Recently a software representative was quoted in *The New York Times* as saying, "The length of eternity is 18 months, the length of a product cycle." In some sense, Moore's Law has taken on a life of its own as it finds its way into the broader community of users and other institutions affected by the technology.

To assess the effect, this writer did an Internet keyword search on "Moore's Law." Out of well over 100 pertinent references, more than two dozen were of good quality. Most of these came from downstream user communities—including PC users and people involved with software and network applications.

Interestingly enough, Moore's Law has many imitations in fields related and unrelated. One of the former is "Metcalf's Law," attributed to Robert Metcalf, former Xerox researcher, inventor of the Ethernet, and founder of 3Com, Santa Clara, Calif. This law states that network performance increases exponentially with the addition of each new user.

As the ensuing sampler of such references demonstrates, writers in the fields of education and even marketing have referred to Moore's Law. Note that processing power seems to be replacing circuit density as the new basis of the Law.

- "Management is not telling a researcher, 'You are the best we could find, here are the tools, please go off and find something that will let us leapfrog the competition.' Instead, the attitude is, 'Either you and your 999 colleagues double the performance of our microprocessors in the next 18 months, to keep up with the competition, or you are fired.' " (Andrew Odlyzko on the Internet, 1995)
- "Moore's Law may one day be as important to marketing as the Four Ps: product, price, place, and promotion…If it is borne out in the future the way it has in the past, the powerful Pentium on your desktop will seem as archaic as a 286 PC in a few years." (Gene Koprowski on the Internet, 1996)
- "We have become addicted to speed. Gordon Moore is our pusher. Moore's Law, which states that processing power will double every year and a half, has thus far held true. CPU designers, always in search of a better fix, drain every possible ounce of fat from processor cores, squeeze clock cycles, and cram components into smaller and smaller dies." (Alan Joch on the Internet, 1996)
- "The End of Moore's Law: Thank God! …The end of Moore's Law will mean the end to certain kinds of daydreaming about amazing possibilities for the Next Big Thing; but it will also be the end of a lot of stress, grief, and unwanted work." (Calgary Unix Users Group on the Internet, 1996)
- "Computer-related gifts must be the only Christmas presents that follow Moore's Law." (*Sydney Morning Herald* 1995)
- "Moore's Law is why…smart people start saving for the next computer the day after they buy the one they have…Things are changing so fast that everyone's knowledge gets retreaded almost yearly. Thank you, Mr. Moore. . . [for] the Internet, a creature of Moore's Law." (Robert Hettinga on the Internet, 1996)

Is Moore's Law unique?

Looking at one subject from the perspective of another often sheds light on its nuances. For example, in arguing for the uniqueness of the million-fold cost reductions and performance improvements in semiconductors, Moore has jokingly mused that if similar progress were made in transportation technologies such as air travel, a modern-day commercial aircraft would cost $500, circle the earth in 20 minutes, and use only five gallons of fuel. The catch is that it might be only the size of a shoe box.

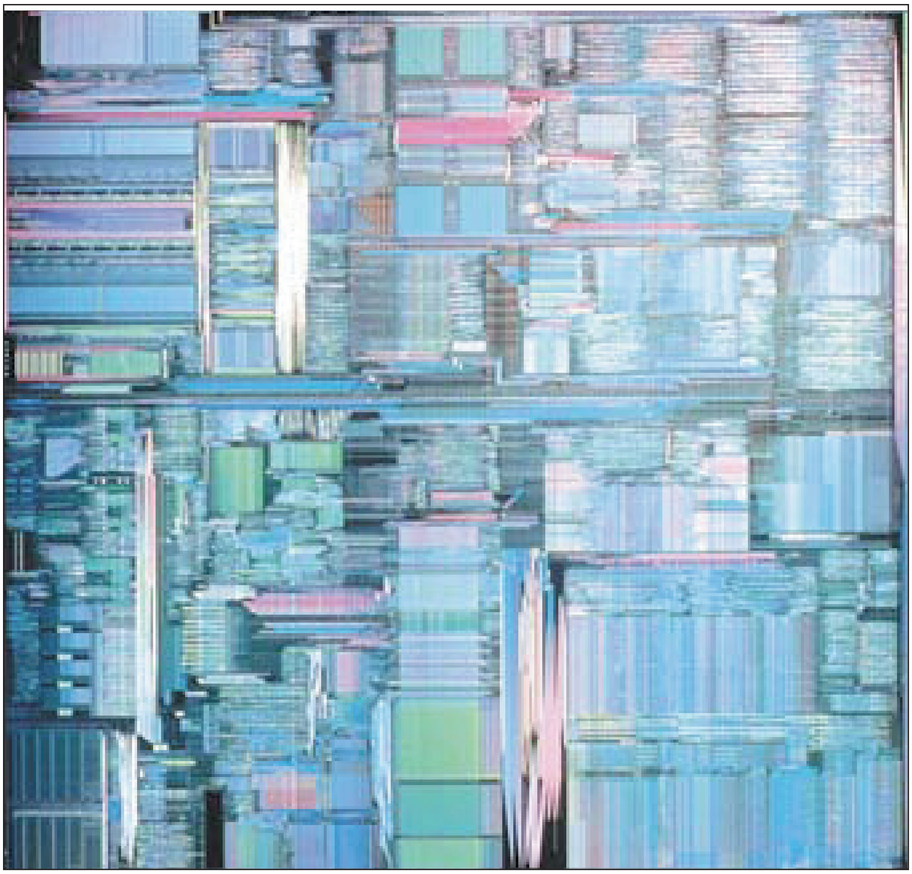
But Stephen Kline, professor of mechanical engineering at Stanford University in California, suggests that the analogy might be more suitable if the reference chosen was the era of rapid advances in aircraft speed and performance.

Carver Mead, semiconductor industry visionary and professor at the California Institute of Technology, Pasadena, finds an analogy in the related field of magnetic data storage. He notes that PC hard drives have evolved from megabyte to gigabyte capacity in roughly a decade. This thousandfold improvement approaches Moore's original extrapolation. Mead has done some scaling calculations and continues to be amazed with the phenomenon. "I still don't understand that," he admits.

Mead and Erich Bloch have suggested an analogy in the field of biology, beginning with James Watson's and Francis Crick's discovery of DNA at Cambridge University.

While other analogies might be apt and useful, some miss the mark in trying to force-fit a comparison. Take, for example, the following analogy to railroads offered by *The Economist* ("The End of the Line," July 15, 1995, pp. 61–62):

"Consider the development of America's railways as an example. In 1830, the industry boasted a mere 37 kilometers (23 miles) of track. Ten years later it had twice as much. Then twice that, and twice again—every decade for 60 years. At that rate 19th-century train buffs might have predicted that the country would have millions of kilometers of track by 1995. In fact there are fewer than 400 000 km. Laying rails was too expensive to justify



connecting smaller towns; people simply did not need track everywhere. Exponential growth gave way to something more usual—a leveling off around a stable value at which economic pressures were balanced…Americans stopped building railways, but they did not stop becoming more mobile. As rail's S-curve tailed off, Americans took to driving cars and built roads."

Clearly, the railroad analogy is a flawed one. Increasing railroad tracks (or roads, sea routes, bandwidth, or whatever) really deal with the implementation or diffusion of technology (transportation infrastructure in this case). Moore's Law is about the pace of innovation.

Moore's Law reconsidered

Beginning as a simple observation of trends in semiconductor device complexity, Moore's Law has become many things. It is an explanatory variable for the qualitative uniqueness of the semiconductor as a base technology. It is now recognized as a benchmark of progress for the entire semiconductor industry. And increasingly it is a metaphor for technological progress on a broader scale. As to explaining the real causes of Moore's Law, the examination has just begun.

For example, the positive feedback hypothesis that semiconductor device users' expectations feed back and self-reinforce the attainment of Moore's Law is still far from being validated or disproved. What has been learned is the critical role that process innovations in general—and manufacturing equipment innovations in particular—play in providing the technological capability to fabricate smaller and smaller semiconductor devices. The most notable of process innovations was the planar diffusion process in 1959—the origin of Moore's Law.

Many observers have described the semiconductor era as a "microelectronics revolution." Indeed, the broad applications and pervasive technological, economic, and social changes that continue to come forth from the semiconductor industry seem almost endless. Others, though, describe this phenomenon as a steady evolution, albeit at an exponential rate.

In that vein, Moore's Law is definitely one measure of the pace of that "steady evolution." Its regularity is daunting. The invention of the transistor, and to a lesser degree the IC a decade later, represented scientific and technological breakthroughs that engendered an entire new semiconductor industry at the expense of the large electronics firms that had dominated the preceding era of vacuum tube technology. The period of transition from old to new technology is characterized by instability, and factors that lead to very irregular performance. But the essence of Moore's Law is predictability. The destruction wrought by innovations in the semiconductor industry has been far more creative than deleterious, coinciding with a long period of U.S. and global prosperity.

Clearly, the semiconductor experience and Gordon Moore's remarkable insight hold a rich store of topics for further study. Even if his Law is repealed by physics or economics or changing fads next year, it will have had a great run, setting markers for the evolution of the modern economy's most important industry. Beyond this, for many it has been a source of personal inspiration. As Carver Mead stated in 1992:

"[Moore's Law is] really a thing about human activity, it's about vision, it's about what you're allowed to believe. Because people are really limited by their beliefs, they limit themselves by what they allow themselves to believe is possible…When [Moore] made this observation early on, he really gave us permission to believe that it would keep going. And so some of us went off and did some calculations about it and said, 'Yes, it can keep going.' And that then gave other people permission to believe it could keep going. And [after believing it] for the last two or three generations, 'maybe I can believe it for a couple more, even though I can't see how to get there'…The wonderful thing about [Moore's Law] is that it is not a static law; it forces everyone to live in a dynamic, evolving world." ◆

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To probe further

For the original article in which Gordon E. Moore presented his density-doubling plot and extrapolation for IC manufacture, see Gordon E. Moore, "Cramming More Components Onto Integrated Circuits," by Gordon E. Moore, *Electronics Magazine* (Vol. 38, no. 8), April 19, 1965, pp. 114–117. A more recent view is in "Lithography and the Future of Moore's Law," by Gordon E. Moore, *Optical/Laser Microlithography VIII: Proceedings of the SPIE*, 2440, Feb. 20, 1995, pp. 2–17.

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