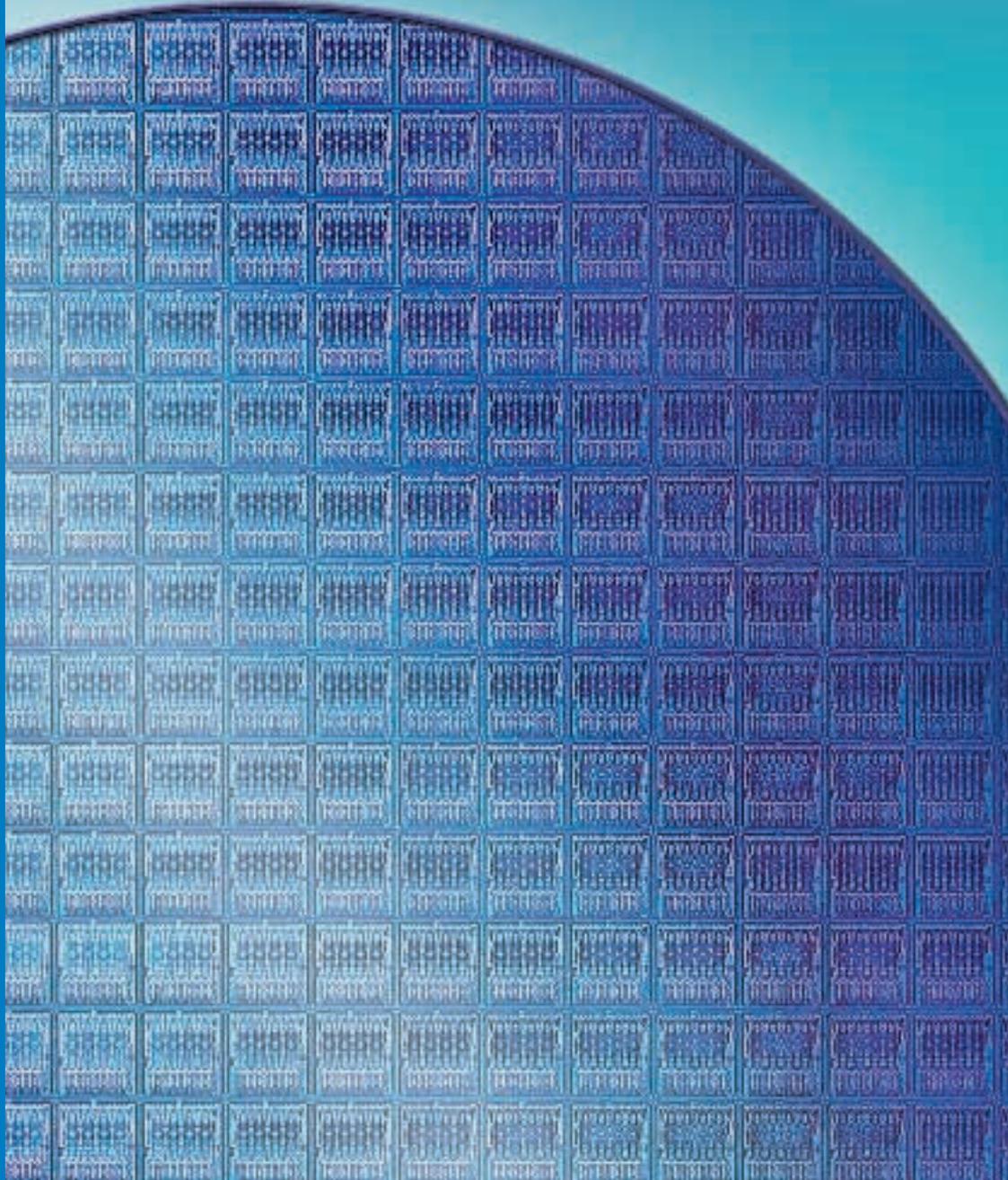




# Expanding Moore's Law

**The Exponential Opportunity**

*Fall 2002 Update*





**For more than 35 years,  
Moore's Law has guided the  
computer industry, bringing a  
seemingly unending spiral of  
falling prices and rising performance.  
Now, Intel is expanding  
Moore's Law, and its impact  
promises to touch every  
realm of human activity.**

To see a world in a grain of sand...

—William Blake

## Moore's Vision

It happened early in 1965, just six years after the invention of the integrated circuit (IC) and three years before Gordon Moore would help found Intel Corporation. ICs were an expensive niche technology, used primarily for military applications.

But Moore had seen the future. He observed that his engineers, many of whom became the first employees of Intel, had been achieving a doubling of the number of transistors on an integrated circuit every year. Based on this, he predicted that growth rate would continue for another decade or so.

More importantly, he saw what the associated shrinking transistor size would mean: that ICs would become steadily cheaper, more powerful, and more plentiful. And that they'd transform the electronics industry.

Moore's Law, as it came to be known, has proven more accurate, lasted longer, and produced more far-reaching changes than Dr. Moore ever expected. His prediction, so powerful in its simplicity, has held sway for nearly four decades supported by Intel's silicon engineering and manufacturing engine. What began as an observation has become both compass and engine, setting the bar for the semiconductor industry and producing an exponentially expanding universe of new applications and opportunities.

Now, rather than losing momentum, the innovations and breakthroughs gained from Intel's efforts to achieve the predictions of Moore's Law are being harnessed and applied to extend and expand it. Intel expects to produce billion-transistor processors by the end of the decade, and the range of devices that can be manufactured in silicon is expanding. So, while Intel's performance to Moore's Law has already transformed the world, its future impact is likely to be even more dramatic.

### Looking Back

Despite its name, Moore's Law is not a law of science or nature. It is a principle that describes the unique opportunity for exponential improvements provided by advances in semiconductor technology. The genesis of the law was an article Gordon Moore wrote for the 35th anniversary issue of *Electronics* magazine, published in April 1965. Moore had been asked to describe the future of electronics. Integrated circuits at the time were limited to 30 transistors, but Moore's research team was finishing a component with 60 transistors. Balancing innovation and economic factors, Moore extrapolated that the number of devices on a silicon chip could double each year for the next decade. Professor Carver Mead, a colleague at Cal Tech, later dubbed the prediction "Moore's Law," and the name stuck. By 1975, the number of devices on a chip was running slightly better than predicted. Moore, however, adjusted the doubling cycle to 24 months, to compensate for expected increases in the complexity of semiconductors. In the late 80s, an Intel executive observed that Moore's Law was driving a doubling of computing performance every 18 months.

The term Moore's Law is also used to describe the law's results: the continuing exponential growth of digital capability and improved price/performance. In the *Harvard Business Review*, Shona Brown noted that Moore's Law functions as the "time pacing of technology."

### The Article that Spawning the Law

*Electronics\**, Volume 38, Number 8, April 19, 1965



Asked to gauge the future of electronics, Dr. Gordon Moore predicted that transistors on a chip could double yearly through 1970. Ever the visionary, Moore also said integrated circuits "will lead to such wonders as home computers...automatic controls for automobiles, and personal portable communications equipment."

### Moore's Law Means More Performance



Processing power, measured in Millions of Instructions per Second (MIPS) has risen because of increased transistor counts.

“Moore’s Law is changing.”

—Gordon Moore

## Exponential Impact

### U.S. \$1.00 Purchasing Power circa 2000\*



1 candybar = 1 million transistors



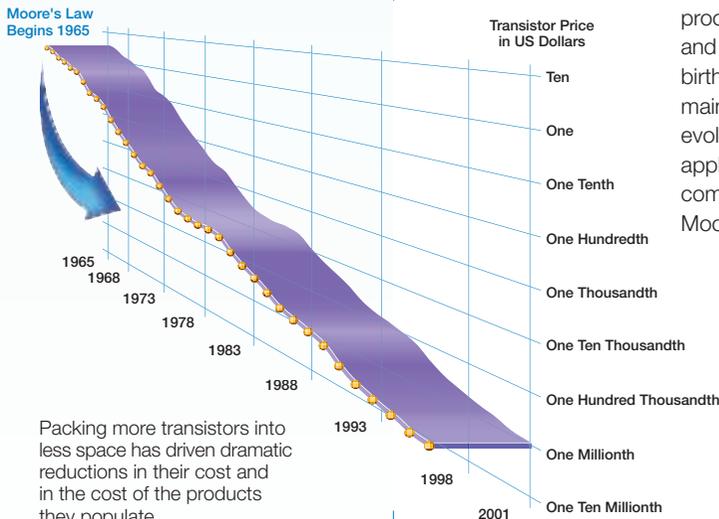
1 cup of coffee = 1 million transistors



1 daily newspaper = 1 million transistors

\*Estimates only based on USG CPI and other government and retail data indices.

### Moore’s Law Means Decreasing Costs



The impact of achieving the predictions of Moore’s Law has been profound. To look at it in simple terms of device count, the number of transistors on a chip has achieved multiple tenfold increases since 1965’s 30-transistor devices. In 1975, device count was up to 65,000. By 1989, the Intel® i486® processor had 1.4 million transistors. In January 2002, Intel announced the Intel® Pentium® 4 processor with Intel’s newest 0.13-micron technology, which packs 55 million transistors onto a piece of silicon the size of your fingernail. Soon, Intel technologists will add hundreds of millions of transistors annually.

The rising device counts, while breathtaking, are just the tip of the iceberg. Silicon’s power—and its uniqueness—is that nearly all parameters of microprocessor technology improve as transistor counts climb. For example, speed and performance have climbed even more sharply than the number of transistors. The i486 processor ran at 25 MHz. Today’s Pentium 4 processors run at 2.20 GHz and rising. The predicted billion-transistor processor will likely run at speeds approaching 20 GHz.

To look at it from another perspective, in the early 1990s it took three years to move the i486 from 25 MHz to 50 MHz. Today, Intel engineers are adding frequency at the rate of 25 MHz a week. Intel Chief Technology Officer Pat Gelsinger says that in a few years, Intel anticipates adding 25 MHz in a single day. Other attributes improved by Moore’s Law include integration, size, functionality, energy efficiency, and reliability.

Over time, inflation generally lowers the value of the dollar or other currency. “Moore’s Law Dollars” are subject to a more literal type of inflation over time: that of ever-increasing value and purchasing power. When Moore first stated his law, the cost of a single transistor was in the neighborhood of \$5. Today, \$5 will buy you 5 million transistors, or roughly 1 million transistors for \$1. It’s hard to imagine \$1 being able to buy 1 million of anything, let alone a million of these enormously potent devices. The fact that you *can* is a direct consequence of Moore’s Law and its unique value proposition: rapid cost reduction resulting in exponential value creation.

The real import of Moore’s Law is less in what it predicts than in what Intel’s efforts to make and keep it a reality have produced. Today’s micro-processors power the economy, fuel the growth of the Internet, and run everything from toys to traffic lights. A throwaway musical birthday card has more computing power than the fastest mainframes of a few decades ago. And, as silicon technology evolves, Moore’s Law catalyzes the development of whole new application areas, bringing about the seamless integration of computing and communications and extending the reach of Moore’s Law well beyond today’s digital realms.

# Extending the Law with Silicon Nanotechnology

Like prima ballerinas and basketball superstars, Intel's semiconductor technologists not only accomplish the near-impossible, they make it look easy.

It's not.

Driving Moore's Law and delivering on its predictions means reducing process geometries—shrinking the nominal feature size of the devices populating and powering the silicon. Shrinking the process geometries makes more space available to bring additional numbers and kinds of devices and functions to the chip. Over the last decade, Intel has shrunk its process geometries by an order of magnitude, going from just under 1 micron (a micron is  $\sim 1/100^{\text{th}}$  the width of a human hair) to minimum feature sizes of less than 100 nanometers (nm) that define nanotechnology (see inset). In the coming decade, Intel's process geometries will approach the physical limits of atomic structure, bringing new challenges relating to power, heat, and particle behavior. Intel has already demonstrated transistors with some features as thin as three atoms.

To extend Moore's Law, Intel researchers are aggressively identifying and eliminating any barriers that impede the company's ability to fulfill it. By focusing on fundamentals of silicon technology and manufacturing, including improvements and innovations in process and manufacturing technology, transistor structure and materials, and packaging—Intel breakthroughs in the past two years alone have removed barriers to the continuance of Moore's Law for at least another decade—and likely beyond.

- **Process and Manufacturing Technology** Lithography is the technology used to print the intricate patterns that define integrated circuits onto silicon wafers. Intel's current lithography technology used in volume production is a 130 nm process that features 60 nm gate length transistors and six layers of copper interconnect. (To put this in perspective: a nanometer is a *billionth* of a meter.) In August 2002, Intel unveiled the industry's most advanced logic manufacturing process yet. The new 90 nm process allows printing of individual lines smaller than a virus, features seven layers of copper interconnect and integrates a number of industry-best technologies. For starters, it features the world's smallest CMOS transistors in production, measuring only 50 nm in gate length. It also implements the thinnest gate oxide ever used in production—just 1.2 nm or less than five atomic layers thick. Already used in building the world's highest capacity SRAM chip, Intel's 90 nm process will go into volume manufacturing in 2003, providing significant advantages in performance, power efficiency, and cost.

Further out in time, a breakthrough lithography technology currently under development, will become the volume production standard. Known as Extreme Ultraviolet (EUV) lithography, this technology uses reflected rather than directly transmitted light which allows the patterning of lines smaller than 50 nm. Intel leads a consortium of semiconductor companies, the EUV LLC (Limited Liability Corporation), that's working to develop and deploy EUV technology. In March 2001, Intel delivered to the EUV LLC the first industry-standard format photomasks for EUV lithography which used a proprietary patterning process to demonstrate line widths 30 percent smaller than the most advanced masks in manufacturing today. Shortly thereafter, the LLC announced completion of the first full-scale prototype machine for making computer chips using this new lithography process. Intel anticipates building processors using EUV technology in the second half of the decade.

## A Word About Nanotechnology

*A key factor in the continuance of Moore's Law, nanotechnology, or sometimes referred to as molecular manufacturing, is nothing new to Intel. Since the launch of the Intel® Pentium® 4 processor with transistor gate widths of <70 nm, high-volume fabrication of sub 100 nm structures has been the norm at Intel. In fact, over the past three years, Intel has manufactured and sold over 50 quadrillion nano-transistors worth over \$50 billion making it one of today's largest nanotechnology manufacturers. Going forward, Intel understands that maintaining its lead in sub 100 nm transistor scaling depends on implementing a host of new, enabling nanotechnologies. One such enabler, atomic layer deposition (ALD), allows for the self-assembly of molecules one mono-atomic layer at a time based on sophisticated, naturally occurring chemical interactions. And nanotubes or nanowires, built through the controlled manipulation of materials at the atomic level, could eventually become the building blocks for some future generation of Intel® products.*

## Moore on Moore's Law

A Conversation with Dr. Gordon E. Moore  
Chairman Emeritus, Intel Corporation  
February 2002

### Did you set out to formulate a law?

**Dr. Moore:** Not at all. This was in the early days of integrated circuits, and they were still quite expensive.

I looked at what had happened so far in integrated circuits and saw that we had been doubling about every year in complexity. So I just blindly extrapolated that doubling every year for another 10 years—a thousandfold increase in complexity from about 60 components to something like 60,000. And I took that as the way we are going to make cheap electronics. I did not expect it to be accurate, I just wanted to show the trend I expected. It was not intended to be a precise prediction at all, but only a guiding idea that integrated circuits were going to change the entire economics of the electronics industry.

Is there something that people don't "get" about Moore's Law?

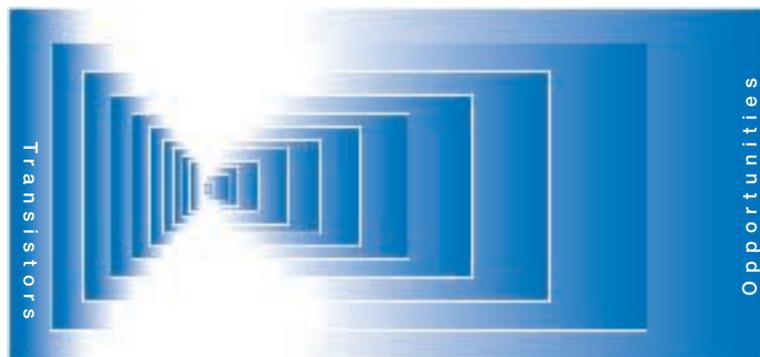
**Dr. Moore:** If there is, it is that the single most important thing Moore's Law does is decrease cost.

In order to maximize the impact of its leadership in process technology, Intel also focuses on continuous advances in manufacturing technology. Case in point: Wafer size. Wafers provide the base on which chips are manufactured. Use a bigger wafer and you reduce manufacturing costs and environmental impact and improve the yield per factory. By using 300 millimeter (12-inch) wafers on its current 130 nm process technology, Intel expects to cut costs by 30 percent and energy and water requirements by 40 percent. And while much of the industry continues transitioning production to a 130 nm process on 200 mm wafers, Intel is already moving aggressively to deploy its new 90 nm process on 300 mm wafers exclusively.

- **Transistor Structure and Materials** In June 2001, Intel announced it had developed transistors featuring structures that are just 20 nm in size. These new transistors are 30 percent smaller and 25 percent faster than the industry's previous fastest transistors, which Intel had also developed just one year earlier. By the end of 2001, Intel followed with yet another breakthrough—the world's smallest transistor, with a gate length of 15 nm. These incredibly small 15 nm transistors are approximately the size that will be needed in manufacturing toward the end of this decade.

As transistors continue to shrink and are packed more tightly onto slivers of silicon running at higher speeds, power consumption and heat can become potential limiting factors for the continuance of Moore's Law. To address this problem of power density, Intel is exploring the use of new structures, such as the tri-gate transistor, and new materials, such as strained silicon, that allow for increased performance while improving power efficiency. Intel's Terahertz transistor, announced in November 2001, is perhaps the best example of this. Featuring a depleted substrate transistor structure and a new high k gate dielectric material, this experimental device can turn on and off a trillion times per second. (It would take you more than 15,000 years to turn a light switch on and off a trillion times.) Intel expects to incorporate elements of this new transistor design into its production line in the second half of this decade.

### The Paradox of Moore's Law



As transistors grow smaller, opportunities grow larger.

**Silicon-based capability will double every 24 months by increasing the count, complexity, and convergence of components and technologies integrated on a chip.**

- **Packaging** Today's silicon chips are connected to their packaging via tiny balls of solder, or "bumps," that make the electrical and mechanical connections between the package and the chip. As the frequency of future processors increases exponentially, the performance of the bumps, thickness of the packaging, and number of connection points become concerns. In October 2001, Intel announced an innovative packaging breakthrough, Bumpless Build-up Layer (BBUL), that eliminates these bumps by growing the package around the silicon. This technique reduces the thickness of the package and enables the processor to run at a lower voltage. BBUL packaging technology is just one example of an innovative way to embed powerful computer chips into very small spaces.

Intel is also pushing the packaging envelope with a variety of significant new technologies in chip scale packaging, creating higher density, "system-in-a-package" solutions that use the world's most advanced folded stacked chip scale packaging. These packaging solutions not only allow for higher in-package silicon density while simultaneously reducing the overall package footprint, but also offer new and flexible methods for improved functional integration of dissimilar silicon devices.

Driving Moore's Law also requires increased networking and collaboration with consortia (like International SemaTech), standards-setting bodies, suppliers, collaborators, and customers. Intel has implemented a unique "research without walls" approach that's creating an expanded innovation ecosystem. The company has funded labs at leading universities, such as the Intel Research Berkeley lab at the University of California, where tiny "mote technology" sensor chips are in development. Intel also supports promising academic research around the world, and Intel Capital provides assistance to start-ups developing next-generation technologies.

## Expanding on the Law: Beyond Transistors

Intel researchers are also expanding Moore's Law—identifying and aggressively pursuing technologies that take silicon beyond just transistors and performance, and making it possible to integrate new devices that deliver entirely new capabilities. As silicon-based transistor count doubles every 24 months, so will our ability to increase their complexity and integrate the convergence of many varieties of devices on a chip. This combination—count, complexity, and convergence—means a richer set of resources for increasing capability and functionality and improving the flexibility with which it can be applied.

- **Count.** Increasing transistor count on a chip is fundamental to Moore's Law. The more that can be integrated on a chip, the greater the potential for increased performance, functionality, and new capabilities. And as ever-shrinking transistor sizes enable increased transistor counts, they likewise reduce the space necessary for a particular logic or memory function, freeing room for new devices.



Count



Complexity



Convergence

**What role does Moore's Law play today?**

**Dr. Moore:** Moore's Law has become a self-fulfilling prophecy. The fact that things are changing exponentially has now generally been recognized by all the participants in the industry. Every company knows that unless they keep moving at that pace, they are going to fall behind. It has kind of become a guideline of how fast things have to continue to evolve. It has become the driver of what happens, because of people's recognition that you have to stay on it or ahead of it to be competitive.

**Count, Complexity, and Convergence**

By expanding beyond the single variable of device count, Moore's Law better comprehends the increasing complexity of on-chip devices and the convergence of new functions and technologies into silicon.

**What effect has Moore's Law had on Intel?**

**Dr. Moore:** The impact on Intel has been similar to what it has been on the rest of the industry. Over the last 10 years or so Moore's Law has become absolutely a driving force. Now, had there never been a Moore's Law, I do not know how different it would be. Competitive pressures obviously push us in this direction. But it gives us a benchmark that we can measure ourselves against. We can see our rate of progress, we can see what our rate of progress has to be if we are going to stay ahead of the industry. In that respect I think it has had an impact. But I am sure had I not plotted the curves in 1965, similar kinds of parameters would have been measured and this exponential trend would generally have been recognized as important and really driving the industry by now.

- **Complexity.** Gordon Moore has often cited rising complexity as a key factor in realizing Moore's Law. Rising complexity can include such advances as incorporating air gaps, moving parts, antennae or other new structures to deliver new functionality through silicon.
- **Convergence.** Convergence brings together multiple, diverse functions and heterogeneous technologies onto a single chip to maximize integration and functionality. Convergence offers extra opportunity for innovation, bringing new functionality and increased value to semiconductor products. New opportunities include combining traditional transistor-based functionality with new Microelectromechanical Systems (MEMS) devices such as radio frequency (RF) antennae to provide an existing logic chip product with fully-integrated low-cost silicon radio with intelligent roaming or adding microradiators that minimize or eliminate the need for supplementary cooling solutions associated with such logic chip products.

The impact of Intel's ability to achieve the predictions of Moore's Law reaches far beyond the computer. The breakaway power of having millions and eventually billions of transistors on a chip, along with the added dimensions of complexity and convergence, offer increasing opportunities to make the resulting benefits of driving Moore's Law available to an even broader range of technologies, application areas, and product spaces. The expanding impact of Moore's Law is shaping the next generation of such diverse technologies as:

- MEMS
- Fluidics
- Wireless connectivity
- Self-configuring sensor networks
- Optical transmission and processing
- Biological technologies

The goal in each case is not simply to improve performance but to deliver new functionality and provide an open platform for expanded innovation. Combined with our increasingly networked world, this shift opens the door to a host of new applications and moves Moore's Law into new domains—from cars to kitchens to intelligent objects.

The effect of Moore's Law can also transform an arcane, niche technology into a ubiquitous one—as it did in the case of the integrated circuit itself. Niche technologies are typically designed for a unique attribute of or application in a vertical market. Because they're specialized and have limited utility, they're usually expensive. Intel's delivery of Moore's Law can make the technology more affordable, which increases demand, which makes the technology widely available. The niche technology becomes part of the mainstream. And, given new functionality and made ubiquitous, it opens the door to new markets, products, and user populations.

# An Expanding Innovation Industry

Silicon is the raw material for the innovation ecosystem of the 21st century, much as the manufacture and use of steel were in the early 20th century. Moore's Law silicon has propelled the world into the information age by miniaturizing and connecting electronics. With Intel's relentless extension and expansion of Moore's Law, silicon is destined to become the bridge between the physical and electronic universes—connecting the world of atoms to the world of bits, photons to electrons, and electrons to radio waves.

As the impact of delivering to Moore's Law expands, so too do the industries built on Intel's technology. The continued evolution of integrated circuit capability as a result of the predictions of Moore's Law both enriches traditional businesses with new capability, and propels the technology industry into a larger universe. For example, ad hoc sensor networks with on-chip wireless communications will generate huge volumes of new data and information for data centers and desktops, and will extend the size, reach and value of the traditional server and PC products, and will expand the market for applications and services that create value information.

Intel's pursuit of making Moore's Law a reality has transformed our world. But future opportunity far exceeds past benefits. In a world where most of the world's population still has little or no access to digital technology, meeting the predictions of Moore's Law will help bring developing nations into the digital world. A wealth of new market spaces will emerge as factors of cost, size, and connectivity continue to bring something magical to virtually every human realm and activity.

## A New Computing and Communications Geography

By applying the principles of Moore's Law to new classes of functionality, Intel is bringing about a new computing and communications geography, making these new technologies more affordable and widespread, and opening the door to broad new areas of innovation where computing and communications converge. Here are three examples:



**Ad hoc sensor networks** combine silicon advances with self-organizing networking research to enable thousands of embedded sensing devices to wirelessly connect and share information. These sensor networks lend themselves to a wide range of applications including a recently deployed nonintrusive habitat monitoring network. In support of a study to monitor the

nesting habitat of the Leach's Storm Petrel on Great Duck Island, Maine, a sensor network provides scientists with key data without disruptive human presence. As a result, this collaboration between the Intel Research Lab at Berkeley and the College of the Atlantic is already yielding higher productivity, more accurate data, new insights and greater efficiency for the project overall.



**Silicon radios** will help extend expensive wireless chipsets into ubiquitous (and very inexpensive) on chip silicon radios. Intel's ongoing ability to apply the principles of Moore's Law will make it possible to have dynamically reconfigurable silicon radios, which consume less power and occupy less space on a chip via tighter integration while adding valuable capabilities and

flexibility. With recent successes in MEMS, smart antenna systems and CMOS integration of transceiver chain components, Intel continues to deliver toward its long-term vision of providing radio-readiness on every chip.

**What new applications will we see as we go forward with Moore's Law—as we increase the complexity and convergence and add embedded machines to the chip?**

**Dr. Moore:** That is a very, very difficult question. If you had asked me about new applications in 1980, I would have missed the PC. If you had asked me in 1990, I would have missed the Internet. Knowing that, I think the combination of a large, powerful network, which the Internet should become, particularly when we can get broadband out to the ends with easy, cheap, available computing power—that's going to have an impact that is hard for any of us to imagine. Another thing that intrigues me is when my computer has really good speech recognition, when you can ask it a question in ordinary English and get an answer back in ordinary English. These things are not that far away, and I think they profoundly change the way people work with machines and interact with one another. That's just one example. But the power of a network of very, very powerful machines that couple humans together, I think is going to have an impact that is far beyond my comprehension.

From 55 million today, Intel expects to produce billion-transistor chips by the end of the decade.

Moore's Law is increasingly used as a benchmark for improved performance rather than any mechanical reason for it. Are you comfortable with that?

**Dr. Moore:** I think so. I think improved performance ties closely enough to the technology that it is a corollary of what we have been doing. Now, it is not the only way to improve performance. One of the principal aspects of Moore's Law has been getting this improved performance at the same or lower cost all the time. We have been taking advantage of the original idea I was after with the article in 1965—that electronics were going to be cheap because we were going to put an awful lot of them in a small area.

What is the most exciting thing ahead from your point of view?

**Dr. Moore:** The most exciting thing is going to be the surprises I cannot predict. The most important things are usually the ones that people within the industry do not see. They tend to develop outside the industry. I do not know. I just wait to be surprised with the next one that comes along.



**Silicon photonics** brings optical networking technologies into silicon, extending the cost, size, and performance advantages realized by applying the principles of Moore's Law to a new and important arena. In February 2002, Intel demonstrated a prototype of a silicon-based tunable filter that could reduce the cost by orders of magnitude. More recently, Intel used a similar type of silicon-based tunable filter to illustrate how such a technology might be used to improve the performance of a readily available and inexpensive laser to that of higher performance laser use in today's optical networks. These examples and future demonstrations of developing optical building blocks in silicon will someday allow tighter integration, improve performance and reduce costs by orders of magnitude. As Intel continues to deliver innovation in the optical arena, silicon photonics could allow faster adoption into the data center and platforms and someday to the processor.

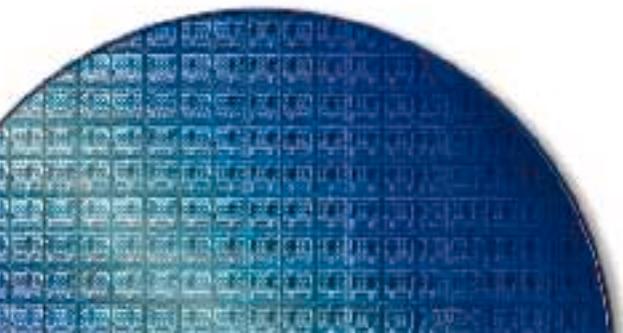
## Making the Most of Moore's Law

When Gordon Moore formulated the law that bears his name, he hoped to promote wider use of semiconductors in everyday life by showing that the technology would become increasingly cost efficient. He achieved that and more: his law became a blueprint for the growth of semiconductor capability over the next four decades, and it remains a reliable guide to the future.

Gordon Moore once commented to Carver Mead that delivering innovative technology always takes longer than you expected. "But then," he added, "Things go much further than you would ever believe!"

Moore's Law began as an expression of one man's confidence in the expanding capability of semiconductor technology. Now, as the law carries us further into the future, one thing is certain: no one knows how to make Moore's Law a reality better than Intel or is more committed to deliver it. Intel is aggressively eliminating barriers to achieving the predictions of Moore's Law, expanding Moore's Law scope with new resources, and extending the power of silicon to new arenas. By relentlessly pursuing the opportunities enabled by increased device count, complexity, and convergence on a chip, Intel continues to drive exponential increases in silicon capability—ensuring that technology providers and users can continue to count on the powerful predictions of Moore's Law for decades to come.

To learn more about Intel research and development and Moore's Law, go to [www.intel.com/technology/](http://www.intel.com/technology/)







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