40 YEARS OF MOORE'S LAW

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It has been 40 years since Gordon Moore first posited what would one day come to be known as Moore's Law. Gordon's ideas were more than a forecast of an industry's ability to improve, they were a statement of the ability for semiconductor technology to contribute to economic growth and even the improvement of mankind in general. More importantly, Moore's Law set forth a vision of the future that harnessed the imaginations of scientists and engineers to make it all possible.

1970/1,000

The first DRAM chip, developed in 1970, had a capacity of 1,000 bits. Contemporary 4GB DRAM chips can hold 32 billion bits—enough to store the complete works of Shakespeare four times on a single chip.

Today, we take many of the benefits of Moore's Law for granted. Yet if you look behind the curtains of the new breakthrough sciences, as well as many of the mundane, you will find semiconductors working. Much would not be possible without the relentless progress of the semiconductor industry doubling performance for the same price every two years or so, and that is what Moore's Law is all about.

The miracles of nanobiology and genetic engineering would not be possible had Moore's Law not brought affordable computing power to the table. While our children play video games on black boxes filled with chips, professionals in the medical sciences use the same technology to visualize complex models of drug interaction and even to unlock genetic codes. The Lewis & Clarks of today don't use optics to map the landscape, they use computer visualization tools to map the human genome. Meanwhile, imagine traffic congestion without computer chips to turn the lights green when you drive up. It may seem mundane, but computer chips keep America moving efficiently. Without chips, cell phones would not be there to bring help to our loved ones in unexpected emergencies or simply to make that call to bring home a quart of milk. Communication is vital to the economy, and chips have greatly expanded our abilities here. Computers are the engines of America's productivity surge that has held inflation down since the '90s—and the engines of computers are semiconductors. Chips provide better automotive power-train control systems that make for fun cars that pollute less. Chips are replacing film in digital cameras, saving untold amounts of chemical pollution. Chips are being attached to animals in the wild, so we gain an even deeper understanding of the world around us. Chips make smart bombs smart…and Moore's Law makes them smarter. Chips are critical to our national defense, make unmanned aircraft possible, and save untold lives on the battlefield. These breakthroughs and many more are directly the result of advancements in chips as predicted by Moore's Law.

Moore's Law is an amazing story of how technological progress came to affect our everyday lives and will affect our children's lives for many generations to come. But its history is far richer than the development of semiconductors, which to some extent explains why Moore's Law was so readily accepted. This history also explains why there has been an insatiable demand for more powerful computers no matter what people have thought to the contrary.

The quest to store, retrieve, process, and communicate information is one task that makes humans different. No known animal uses tools to store, retrieve, and process information. Moreover the social and technological progress of the human race can be directly traced to this attribute.

Man's earliest attempts to store, retrieve, and process information date back to prehistoric times when humans first carved images in stone walls. Then in ancient times, Sumerian clay tokens developed as a way to track purchases and assets. By 3000 B.C. this early accounting tool had developed into the first

2005/
32 billion

complete system of writing on clay tablets. Ironically, these were the first silicon-based storage technologies and would be abandoned by 2000 B.C. when the Egyptians developed papyrus-based writing materials. It would take almost four millennia before silicon would stage a comeback as the base material, with the main addition being the ability to process stored information. In 105 A.D., a Chinese court official named Ts'ai Lun invented wood-based paper. It wasn't until around 1436 that Johann Gutenberg invented the movable type printing press so that books could be reproduced cost-effectively in volume. The first large book was the Gutenberg Bible, published in 1456. So something akin to Moore's Law occurred, as Gutenberg's innovation enabled progressing from printing single pages to entire books in 20 years. At the same time, resolution also improved, allowing finer type as well as image storage. Yet, this was primarily a storage mechanism. It would take at least another 400 years before retrieval would be an issue. In 1876, Melvil Dewey published his classification system that enabled libraries to store and retrieve all the books that were being made by that time. Alan Turing's "Turing Machine," first described in 1936, was the step that would make the transformation from books to computers. So Moore's Law can be seen to have a social significance that reaches back more than five millennia.

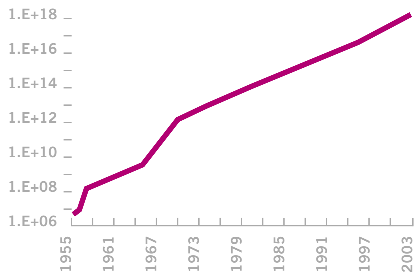
Moore's Law is also indelibly linked to the history of our industry and the economic benefits that it has provided over the years. Carver Mead, a pioneer in solid-state electronics, was the first to call the relationship "Moore's Law." Moore's observations about semiconductor technology are not without precedent. As early as 1887, Karl Marx, in predicting the coming importance of science and technology in the 20th century, noted that for every question science answered, it created two new ones—and that the answers were generated at minimal cost in proportion to the productivity gains made. More important was Marx's observation that investments in science and engineering led to technology, which paid off in a way that grew economies, not just military might.

It was this exponential growth of scientific "answers" that led to these developments, as well as to the invention of the transistor in 1947—and ultimately the integrated circuit in 1958. The integrated circuit (IC) developed rapidly, leading to Moore's observation that became known as a law—and in turn, launched the information revolution.

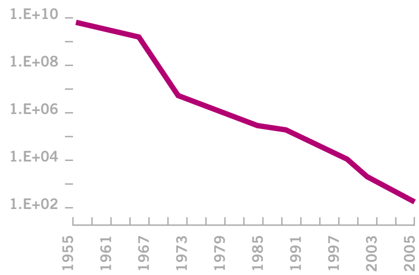
In 1964, *Electronics* magazine asked Moore, then at Fairchild Semiconductor, to write about what trends he thought would be important in the semiconductor industry over the next 10 years for its 35th anniversary issue. ICs were relatively new. Many designers didn't see a use for them and worse, some still argued over whether transistors would replace tubes. A few even saw integrated circuits as a threat: if the system could be integrated into an IC, who would need system designers?

The article, titled "Cramming more components into integrated circuits," was published by *Electronics* in its April 19, 1965, issue.

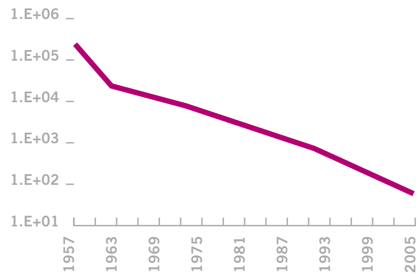
Worldwide Transistor Production



Average Price Per Transistor (nanodollars)



Semiconductor Feature Size (nanometers)



MOORE'S LAW: BY THE NUMBERS

Above are three metrics that graphically demonstrate the effects of Moore's Law. Constantly improving semiconductor technology has driven exponential increases in the number of transistors that can be placed on a chip while simultaneously driving reductions in cost and increases in performance. The result: chips that get faster, better, and cheaper every year.

This issue's contents exemplify how so few really understood the importance of the integrated circuit. Ahead of it was the cover article by RCA's legendary David Sarnoff who, facing retirement, reminisced about "*Electronics*' first 35 years" with a look ahead. After this were several more articles—with Moore's paper buried on page 114. *Electronics* was the most respected publication covering its field. Today, the magazine is defunct, not surviving Moore's Law.

Moore's paper proved so long-lasting because it was more than just a prediction. The paper provided the basis for understanding how and why integrated circuits would transform the industry. Moore considered user benefits, technology trends, and the economics of manufacturing in his assessment. Thus he had described the basic business model for the semiconductor industry—a business model that lasted through the end of the millennium.

From a user perspective, his major points in favor of ICs were that they had proven to be reliable, they lowered system costs, and they often improved performance. He concluded, "Thus a foundation has been constructed for integrated electronics to pervade all of electronics." From a manufacturing perspective, Moore's major points in favor of ICs were that integration levels could be systematically increased based on continuous improvements in largely existing manufacturing technology. He saw improvements in lithography as the key driver.

From an economics perspective, Moore recognized the business import of these manufacturing trends and wrote, "Reduced cost is one of the big attractions of integrated electronics, and the cost advantage continues to increase as the technology evolves toward the production of larger and larger circuit functions on a single semiconductor substrate. For simple circuits, the cost per component is nearly inversely proportional to the number of components, the result of the equivalent package containing more components."

The essential economic statement of Moore's Law is that the evolution of technology brings more components and thus greater functionality for the same cost. Computing power improves essentially for free, driving productivity in the economy, and thus fueling demand for more semiconductors. This is why the growth in transistor production has been so explosive. Lower cost of production has led to an amazing ability to not only produce transistors on a massive scale, but to consume them as well.

The economic value of Moore's Law is that it has been a powerful deflationary force in the world's macro-economy. Inflation is a measure of price changes without any qualitative change—so if price per function is declining, it is deflationary. This effect has never been fully accounted for in government statistics. The decline in price per bit has been stunning.

In 1954, five years before the IC was invented, the average selling price of a transistor was $5.52. Fifty years later, in 2004,

$0.000,000,001

Today, the cost per bit of DRAM memory is an astounding 1 nanodollar (one billionth of a dollar).

this had dropped to 191 nanodollars (a billionth of a dollar). If the semiconductor were fully adjusted for inflation, its size in 2004 would have been 6 million-trillion dollars. That is many orders of magnitude greater than Gross World Product! So it is hard to understate the long-term economic impact of the semiconductor industry. Much of this impact has come directly to America, because it has been the world's leader in semiconductors.

So what makes Moore's Law work? There are three primary technical factors: reductions in feature size, increased yield, and increased packing density. The first two are largely driven by improvements in manufacturing and the latter largely by improvements in design methodology.

Reductions in feature sizes have made the largest contributions by far, accounting for roughly half of the gains since 1976. Feature sizes are reduced by improvements in lithography. Transistors can be made smaller and hence more can be packed into a given area.

These gains have come from new lithography tools, resist processing tools and materials, and etch tools. Lithography tools were not always the most costly tool in the factory. The camel's hair brush, first used in 1957 to paint on hot wax for the mesa transistors, cost little more than a dime. But since that time prices have escalated rapidly, increasing roughly an order of magnitude every decade and a half. The industry passed the $10M mark in 2003 and some tools now cost as much as $20M.

Over the decades, these cost increases have been consistently pointed to as a threat to the continuance of Moore's Law. It is testimony to the power of this law that these costs can be absorbed with little effect.

At some point the effect of these technologies translating into high costs will cause Moore's Law to cease. This is why the spotlight is always on costs and how to defray them.

The idea of Moore's Law meeting Moore's Wall and the show stopping, or the contrary belief that there will be unending prosperity in the 21st century buoyed by Moore's Law, have been recurring themes in the media and technical community since the mid-'70s. I have built my career, in part, by predicting that the end of Moore's Law was not coming anytime soon. Many others have lost theirs over the past 30 years by predicting its demise due to physical limits. I have always had faith in the ability of the brightest minds in science and technology to come up with the ideas needed to overcome these limits. But I am growing concerned.

The costs of the research to keep Moore's clock ticking are rising with each node. I fear the day that it becomes too expensive for the private sector, and the clock stops. In part because of the many conveniences, but mostly because of the dramatic effect it has had in driving America's productivity and thus its leadership in the global economy, when Moore's clock stops the consequences to the economy should be obvious.

What will America do as a nation when Moore's Law has beat its last heartbeat, when it no longer delivers its productivity gains and anti-inflationary effects? How will we pay for ever-rising healthcare costs? What will happen if America's economy falls behind and the U.S. is no longer the global leader? Other nations recognize the importance of semiconductors at the public level and are investing heavily. These are important questions for legislators to consider.

As Gordon commented on his law a few years back, "No exponential lasts forever. But forever can be postponed." Let's invest to postpone it.

To learn more, see "The Economic Implications Of Moore's Law" in *High Dielectric Constant Materials, Springer Series in Advanced Microelectronics*, Volume 16, Springer-Verlag, New York, 2004.