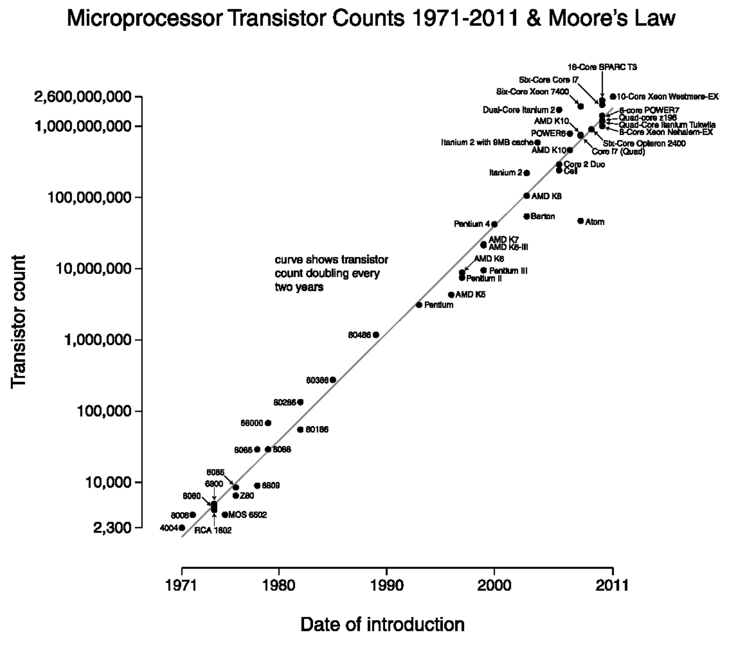
Moore's law

Moore's law is the observation that over the history of computing hardware, the number of transistors on integrated circuits doubles approximately every two years. The period often quoted as "18 months" is due to Intel executive David House, who predicted that period for a doubling in chip performance (being a combination of the effect of more transistors and their being faster).[1]



Plot of CPU transistor counts against dates of introduction. Note the logarithmic vertical scale; the line corresponds to exponential growth with transistor count doubling every two years.

The law is named after Intel co-founder Gordon E. Moore, who described the trend in his 1965 paper.[2][3][4] The paper noted that the number of components in integrated circuits had doubled every year from the invention of the integrated circuit in 1958 until 1965 and predicted that the trend would continue "for at least ten years".[5] His prediction has proven to be uncannily accurate, in part because the law is now used in the semiconductor industry to guide long-term planning and to set targets for research and development.[6]

An Osborne Executive portable computer, from 1982 with a Zilog Z80 4MHz CPU, and a 2007 Apple iPhone with a 412MHz ARM11 CPU. The Executive weighs 100 times as much, is nearly 500 times as large by volume, costs approximately 10 times as much (adjusting for inflation), and has 1/100th the clock frequency of the phone.

The capabilities of many digital electronic devices are strongly linked to Moore's law: processing speed, memory capacity, sensors and even the number and size of pixels in digital cameras.[7] All of these are improving at (roughly) exponential rates as well (see Other formulations and similar laws). This exponential improvement has dramatically enhanced the impact of digital electronics in nearly every segment of the world economy.[8] Moore's law describes a driving force of technological and social change in the late 20th and early 21st centuries.[9][10]

This trend has continued for more than half a century. Sources in 2005 expected it to continue until at least 2015 or 2020.[11][12] However, the 2010 update to the International Technology Roadmap for Semiconductors has growth slowing at the end of 2013,[13] after which time transistor counts and densities are to double only every three years.

History

The term "Moore's law" was coined around 1970 by the Caltech professor, VLSI pioneer, and entrepreneur Carver Mead in reference to a statement by Gordon E. Moore.[3][14] Predictions of similar increases in computer power had existed years prior. Alan Turing in his 1950 paper Computing Machinery and Intelligence had predicted that by the turn of the millennium, we would have "computers with a storage capacity of about 10^9", what today we would call "128 megabytes." Moore may have heard Douglas Engelbart, a co-inventor of today's mechanical computer mouse, discuss the projected downscaling of integrated circuit size in a 1960 lecture.[15] A *New York Times* article published August 31, 2009, credits Engelbart as having made the prediction in 1959.[16]

Gordon Moore in 2006

Moore's original statement that transistor counts had doubled every year can be found in his publication "Cramming more components onto integrated circuits", *Electronics Magazine* 19 April 1965:

> 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 nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000. I believe that such a large circuit can be built on a single wafer.[2]

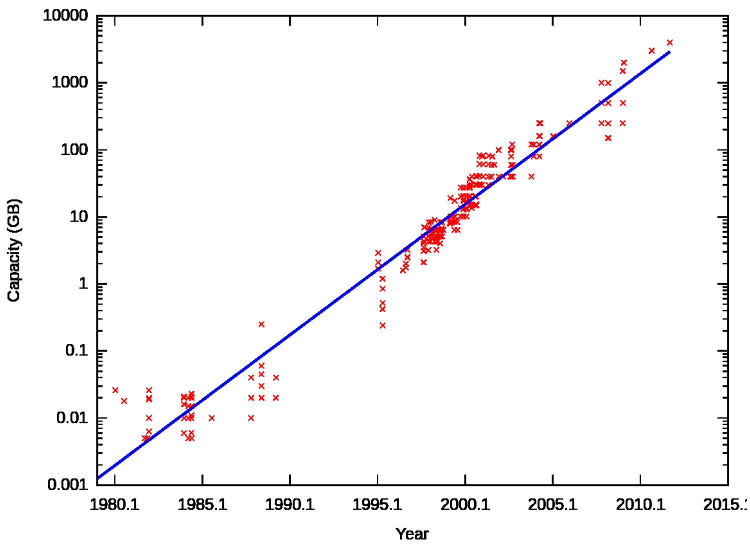
Moore slightly altered the formulation of the law over time, in retrospect bolstering the perceived accuracy of his law.[17] Most notably, in 1975, Moore altered his projection to a doubling every *two* years.[18][19] Despite popular misconception, he is adamant that he did not predict a doubling "every 18 months." However, David House, an Intel colleague, had factored in the increasing performance of transistors to conclude that integrated circuits would double in *performance* every 18 months.[20]

In April 2005, Intel offered US$10,000 to purchase a copy of the original *Electronics Magazine* issue in which Moore's article appeared.[21] An engineer living in the United Kingdom was the first to find a copy and offer it to Intel.[22]

Other formulations and similar laws

Several measures of digital technology are improving at exponential rates related to Moore's law, including the size, cost, density and speed of components. Moore himself wrote only about the density of components (or transistors) at minimum cost.

Transistors per integrated circuit. The most popular formulation is of the doubling of the number of transistors on integrated circuits every two years. At the end of the 1970s, Moore's law became known as the limit for the number of transistors on the most complex chips. The graph at the top shows this trend holds true today.



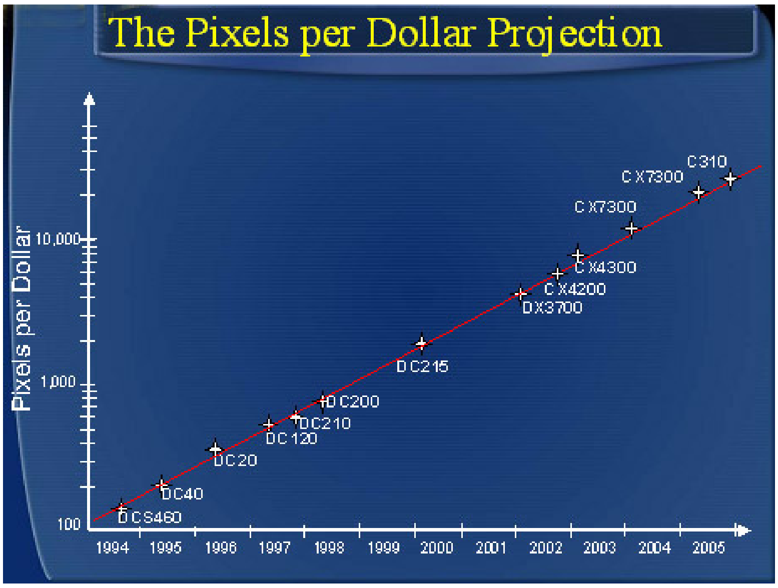
PC hard disk capacity (in GB). The plot is logarithmic, so the fitted line corresponds to exponential growth.

Density at minimum cost per transistor. This is the formulation given in Moore's 1965 paper.[2] It is not just about the density of transistors that can be achieved, but about the density of transistors at which the cost per transistor is the lowest.[23] As more transistors are put on a chip, the cost to make each transistor decreases, but the chance that the chip will not work due to a defect increases. In 1965, Moore examined the density of transistors at which cost is minimized, and observed that, as transistors were made smaller through advances in photolithography, this number would increase at "a rate of roughly a factor of two per year".[2] Current state-of-the-art photolithography tools use deep ultraviolet (DUV) light from excimer lasers with wavelengths of 248 and 193 nm — the dominant lithography technology today is thus also called "excimer laser lithography"[24][25] — which has enabled minimum feature sizes in chip manufacturing to shrink from 0.5 micrometer in 1990 to 45 nanometers and below in 2010. This trend is expected to continue into this decade for even denser chips, with minimum features approaching 10 nanometers. Excimer laser lithography has thus played a critical role in the continued advance of Moore's Law for the last 20 years.[26]

Hard disk storage cost per unit of information. A similar law (sometimes called Kryder's Law) has held for hard disk storage cost per unit of information.[27] The rate of progression in disk storage over the past decades has actually sped up more than once, corresponding to the utilization of error correcting codes, the magnetoresistive effect and the giant magnetoresistive effect. The current rate of increase in hard drive capacity is roughly similar to the rate of increase in transistor count. Recent trends show that this rate has been maintained into 2007.[28]

Network capacity. According to Gerry/Gerald Butters,[29][30] the former head of Lucent's Optical Networking Group at Bell Labs, there is another version, called Butter's Law of Photonics,[31] a formulation which deliberately parallels Moore's law. Butter's law[32] says that the amount of data coming out of an optical fiber is doubling every nine months. Thus, the cost of transmitting a bit over an optical network decreases by half every nine months. The availability of wavelength-division multiplexing (sometimes called "WDM") increased the capacity that could be placed on a single fiber by as much as a factor of 100. Optical networking and dense wavelength-division multiplexing (DWDM) is rapidly bringing down the cost of networking, and further progress seems assured. As a result, the wholesale price of data traffic collapsed in the dot-com bubble. Nielsen's Law says that the bandwidth available to users increases by 50% annually.[33]

Pixels per dollar. Similarly, Barry Hendy of Kodak Australia has plotted the "pixels per dollar" as a basic measure of value for a digital camera, demonstrating the historical linearity (on a log scale) of this market and the opportunity to predict the future trend of digital camera price, LCD and LED screens and resolution.



Pixels per dollar based on Australian recommended retail price of Kodak digital cameras

The Great Moore's Law Compensator (TGMLC), generally referred to as bloat, and also known as Wirth's law, is the principle that successive generations of computer software acquire enough bloat to offset the performance gains predicted by Moore's Law. In a 2008 article in InfoWorld, Randall C. Kennedy,[34] formerly of Intel, introduces this term using successive versions of Microsoft Office between the year 2000 and 2007 as his premise. Despite the gains in computational performance during this time period according to Moore's law, Office 2007 performed the same task at half the speed on a prototypical year 2007 computer as compared to Office 2000 on a year 2000 computer.

Library expansion was calculated in 1945 by Fremont Rider to double in capacity every 16 years, if sufficient space were made available.[35] He advocated replacing bulky, decaying printed works with miniaturized microform analog photographs, which could be duplicated on-demand for library patrons or other institutions. He did not foresee the digital technology that would follow decades later to replace analog microform with digital imaging, storage, and transmission mediums. Automated, potentially lossless digital technologies allowed vast increases in the rapidity of information growth in an era that is now sometimes called an "Information Age".

As a target for industry and a self-fulfilling prophecy

Although Moore's law was initially made in the form of an observation and forecast, the more widely it became accepted, the more it served as a goal for an entire industry. This drove both marketing and engineering departments of semiconductor manufacturers to focus enormous energy aiming for the specified increase in processing power that it was presumed one or more of their competitors would soon actually attain. In this regard, it can be viewed as a self-fulfilling prophecy.[6][36]

Moore's second law

Further information: Rock's law

As the cost of computer power to the consumer falls, the cost for producers to fulfill Moore's law follows an opposite trend: R&D, manufacturing, and test costs have increased steadily with each new generation of chips. Rising manufacturing costs are an important consideration for the sustaining of Moore's law.[37] This had led to the formulation of "Moore's second law", aka Rock's law, which is that the capital cost of a semiconductor fab also increases exponentially over time.[38][39]

Materials required for advancing technology (e.g., photoresists and other polymers and industrial chemicals) are derived from natural resources such as petroleum and so are affected by the cost and supply of these resources. Nevertheless, photoresist costs are coming down through more efficient delivery, though shortage risks remain.[40]

Major enabling factors and future trends

Numerous innovations by a large number of scientists and engineers have been significant factors in the sustenance of Moore's law since the beginning of the integrated circuit (IC) era. Whereas a detailed list of such significant contributions would certainly be desirable, below just a few innovations are listed as examples of breakthroughs that have played a critical role in the advancement of integrated circuit technology by *more than six orders of magnitude in less than five decades:*

- The foremost contribution, which is the *raison d'etre* for Moore's law, is the invention of the integrated circuit itself, credited contemporaneously to Jack Kilby at Texas Instruments[41] and Robert Noyce at Intel.[42]
- The invention of the complementary metal–oxide–semiconductor (CMOS) process by Frank Wanlass in 1963.[43] A number of advances in CMOS technology by many workers in the semiconductor field since the work of Wanlass have enabled the extremely dense and high-performance ICs that the industry makes today.
- The invention of the dynamic random access memory (DRAM) technology by Robert Dennard at I.B.M. in 1967.[44] that made it possible to fabricate single-transistor memory cells. Numerous subsequent major advances in memory technology by leading researchers worldwide have contributed to the ubiquitous low-cost, high-capacity memory modules in diverse electronic products.
- The invention of deep UV excimer laser photolithography by Kanti Jain at I.B.M. in 1982,[24][25][26] that has enabled the smallest features in ICs to shrink from 500 nanometers in 1990 to as low as 32 nanometers in 2011. With the phenomenal advances made in excimer laser photolithography tools by numerous researchers and companies, this trend is expected to continue into this decade for even denser chips, with minimum features reaching below 10 nanometers. From an even broader scientific perspective, since the invention of the laser in 1960, the development of excimer laser lithography has been highlighted as one of the major milestones in the 50-year history of the laser.[45][46][47]

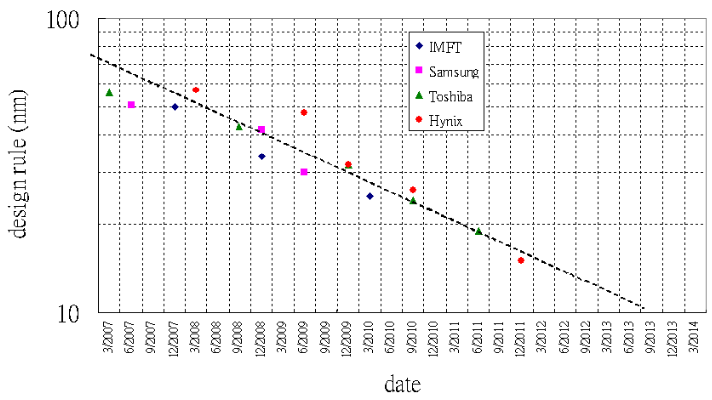
Computer industry technology "roadmaps" predict (as of 2001) that Moore's law will continue for several chip generations. Depending on and after the doubling time used in the calculations, this could mean up to a hundredfold increase in transistor count per chip within a decade. The semiconductor industry technology roadmap uses a three-year doubling time for microprocessors, leading to a tenfold increase in the next decade.[48] Intel was reported in 2005 as stating that the downsizing of silicon chips with good economics can continue during the next decade,[] and in 2008 as predicting the trend through 2029.[49]

Some of the new directions in research that may allow Moore's law to continue are:

- Researchers from IBM and Georgia Tech created a new speed record when they ran a silicon/germanium helium supercooled transistor at 500 gigahertz (GHz).[50] The transistor operated above 500 GHz at 4.5 K (−451 °F/−268.65 °C)[51] and simulations showed that it could likely run at 1 THz (1,000 GHz). However, this trial only tested a single transistor.
- As an example of the impact of deep-ultraviolet excimer laser photolithography,[24][25] in continuing the advances in semiconductor chip fabrication,[26] IBM researchers announced in early 2006 that they had developed a technique to print circuitry only 29.9 nm wide using 193 nm ArF excimer laser lithography. IBM claims that this technique may allow chip makers to use then-current methods for seven more years while continuing to achieve results forecast by Moore's law. New methods that can achieve smaller circuits are expected to be substantially more expensive.
- In April 2008, researchers at HP Labs announced the creation of a working memristor: a fourth basic passive circuit element whose existence had previously only been theorized. The memristor's unique properties allow for the creation of smaller and better-performing electronic devices.[52]
- In February 2010, Researchers at the Tyndall National Institute in Cork, Ireland announced a breakthrough in transistors with the design and fabrication of the world's first junctionless transistor. The research led by Professor Jean-Pierre Colinge was published in Nature Nanotechnology and describes a control gate around a silicon nanowire that can tighten around the wire to the point of closing down the passage of electrons without the use of

junctions or doping. The researchers claim that the new junctionless transistors can be produced at 10-nanometer scale using existing fabrication techniques.[53]

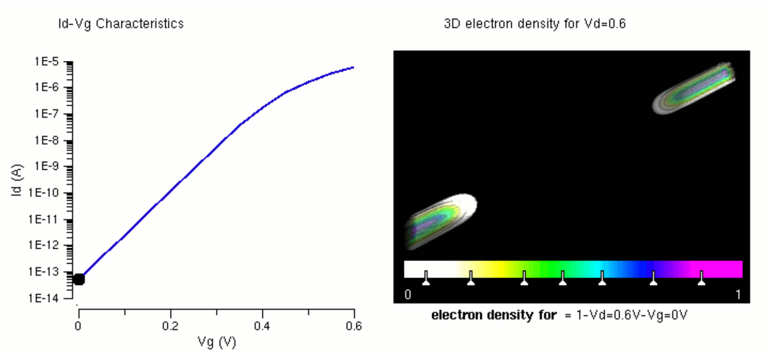
- In April 2011, a research team at the University of Pittsburgh announced the development of a single-electron transistor 1.5 nanometers in diameter made out of oxide based materials. According to the researchers, three "wires" converge on a central "island" which can house one or two electrons. Electrons tunnel from one wire to another through the island. Conditions on the third wire results in distinct conductive properties including the ability of the transistor to act as a solid state memory.[54]
- In February 2012, a research team at the University of New South Wales announced the development of the first working transistor consisting of a single atom placed precisely in a silicon crystal (not just picked from a large sample of random transistors).[55] Moore's Law expected for this milestone to be reached, in lab, by 2020.



The trend of scaling for NAND flash memory allows doubling of components manufactured in the same wafer area in less than 18 months.

Ultimate limits of the law

On 13 April 2005, Gordon Moore stated in an interview that the law cannot be sustained indefinitely: "It can't continue forever. The nature of exponentials is that you push them out and eventually disaster happens." He also noted that transistors would eventually reach the limits of miniaturization at atomic levels:



Atomistic simulation result for formation of inversion channel (electron density) and attainment of threshold voltage (IV) in a nanowire MOSFET. Note that the threshold voltage for this device lies around 0.45 V. Nanowire MOSFETs lie towards the end of the ITRS roadmap for scaling devices below 10 nm gate lengths.[48]

> In terms of size [of transistors] you can see that we're approaching the size of atoms which is a fundamental barrier, but it'll be two or three generations before we get that far—but that's as far out as we've ever been able to see. We have another 10 to 20 years before we reach a fundamental limit. By then they'll be able to make bigger chips and have transistor budgets in the billions.[56]

In January 1995, the Digital Alpha 21164 microprocessor had 9.3 million transistors. This 64-bit processor was a technological spearhead at the time, even if the circuit's market share remained average. Six years later, a state of the art microprocessor contained more than 40 million transistors. It is theorised that with further miniaturisation, by 2015 these processors should contain more than 15 billion transistors, and by 2020 will be in molecular scale production, where each molecule can be individually positioned.[57]

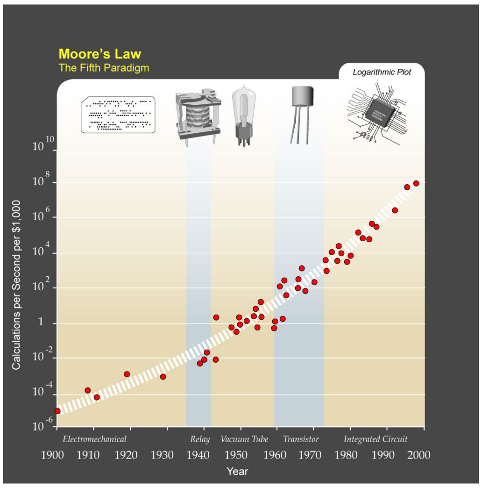
In 2003 Intel predicted the end would come between 2013 and 2018 with 16 nanometer manufacturing processes and 5 nanometer gates, due to quantum tunnelling, although others suggested chips could just get bigger, or become layered.[58] In 2008 it was noted that for the last 30 years it has been predicted that Moore's law would last at least another decade.[49]

Some see the limits of the law as being far in the distant future. Lawrence Krauss and Glenn D. Starkman announced an ultimate limit of around 600 years in their paper,[59] based on rigorous estimation of total information-processing capacity of any system in the Universe.

One could also limit the theoretical performance of a rather practical "ultimate laptop" with a mass of one kilogram and a volume of one litre. This is done by considering the speed of light, the quantum scale, the gravitational constant and the Boltzmann constant, giving a performance of 5.4258*10^50 logical operations per second on approximately 10^31 bits.[60]

Then again, the law has often met obstacles that first appeared insurmountable but were indeed surmounted before long. In that sense, Moore says he now sees his law as more beautiful than he had realized: "Moore's law is a violation of Murphy's law. Everything gets better and better."[61]

Futurists and Moore's law



Kurzweil's extension of Moore's law from integrated circuits to earlier transistors, vacuum tubes, relays and electromechanical computers.

Futurists such as Ray Kurzweil, Bruce Sterling, and Vernor Vinge believe that the exponential improvement described by Moore's law will ultimately lead to a technological singularity: a period where progress in technology occurs almost instantly.[62]

Although Kurzweil agrees that by 2019 the current strategy of ever-finer photolithography will have run its course, he speculates that this does not mean the end of Moore's law:

> Moore's law of Integrated Circuits was not the first, but the fifth paradigm to forecast accelerating price-performance ratios. Computing devices have been consistently multiplying in power (per unit of time) from the mechanical calculating devices used in the 1890 U.S. Census, to [Newman's] relay-based "[Heath] Robinson" machine that cracked the Lorenz cipher, to the CBS vacuum tube computer that predicted the election of Eisenhower, to the transistor-based machines used in the first space launches, to the integrated-circuit-based personal computer.[63]

Kurzweil speculates that it is likely that some new type of technology (e.g. optical, quantum computers, DNA computing) will replace current integrated-circuit technology, and that Moore's Law will hold true long after 2020.[63]

> Seth Lloyd shows how the potential computing capacity of a kilogram of matter equals pi times energy divided by Planck's constant. Since the energy is such a large number and Planck's constant is so small, this equation generates an extremely large number: about 5.0 * 10^{50} operations per second.[62]

He believes that the exponential growth of Moore's law will continue beyond the use of integrated circuits into technologies that will lead to the technological singularity. The Law of Accelerating Returns described by Ray

Kurzweil has in many ways altered the public's perception of Moore's Law. It is a common (but mistaken) belief that Moore's Law makes predictions regarding all forms of technology, when it was originally intended to apply only to semiconductor circuits. Many futurists still use the term "Moore's law" in this broader sense to describe ideas like those put forth by Kurzweil. Kurzweil has hypothesised that Moore's law will apply – at least by inference – to any problem that can be attacked by digital computers as is in its essence also a digital problem. Therefore, because of the digital coding of DNA, progress in genetics may also advance at a Moore's law rate. Moore himself, who never intended his law to be interpreted so broadly, has quipped:

> Moore's law has been the name given to everything that changes exponentially. I say, if Gore invented the Internet,[64] I invented the exponential.[65]

Michael S. Malone wrote of a Moore's War in the apparent success of Shock and awe in the early days of the Iraq War.[66] Michio Kaku, an American scientist and physicist, predicted in 2003 that "Moore’s Law will probably collapse in 20 years."[67] Following a trademark dispute in October 2012, however, the futurist Mark Pesce named his 52-LED ambient device (originally *LightCloud*)[68] *Moores Cloud* in honor of Moore's Law and the ubiquitous computing which it engendered. [69]

Consequences and limitations

The ensuing speed of technological change

Technological change is a combination of more and of better technology. A recent study in the journal Science shows that the peak of the rate of change of the world's capacity to compute information was in the year 1998, when the world's technological capacity to compute information on general-purpose computers grew at 88% per year.[70]

Transistor count versus computing performance

The exponential processor transistor growth predicted by Moore does not always translate into exponentially greater practical CPU performance. Let us consider the case of a single-threaded system. According to Moore's law, transistor dimensions are scaled by 30% (0.7x) every technology generation, thus reducing their area by 50%. This reduces the delay (0.7x) and therefore increases operating frequency by about 40% (1.4x). Finally, to keep electric field constant, voltage is reduced by 30%, reducing energy by 65% and power (at 1.4x frequency) by 50%, since active power = CV^2f. Therefore, in every technology generation transistor density doubles, circuit becomes 40% faster, while power consumption (with twice the number of transistors) stays the same.[71]

Another source of improved performance is due to microarchitecture techniques exploiting the growth of available transistor count. These increases are empirically described by Pollack's rule which states that performance increases due to microarchitecture techniques are square root of the number of transistors or the area of a processor.

In multi-core CPUs, the higher transistor density does not greatly increase speed on many consumer applications that are not parallelized. There are cases where a roughly 45% increase in processor transistors have translated to roughly 10–20% increase in processing power.[72] Viewed even more broadly, the speed of a *system* is often limited by factors other than processor speed, such as internal bandwidth and storage speed, and one can judge a system's *overall performance* based on factors other than speed, like cost efficiency or electrical efficiency.

Importance of non-CPU bottlenecks

As CPU speeds and memory capacities have increased, other aspects of performance like memory and disk access speeds have failed to keep up. As a result, those access latencies are more and more often a bottleneck in system performance, and high-performance hardware and software have to be designed to reduce their impact.

In processor design, out-of-order execution and on-chip caching and prefetching reduce the impact of memory latency at the cost of using more transistors and increasing processor complexity. In software, operating systems and databases have their own finely tuned caching and prefetching systems to minimize the number of disk seeks, including systems like ReadyBoost that use low-latency flash memory. Some databases can compress indexes and data, reducing the amount of data read from disk at the cost of using CPU time for compression and decompression.[73] The increasing relative cost of disk seeks also makes the high access speeds provided by solid-state disks more attractive for some applications.

Parallelism and Moore's law

Parallel computation has recently become necessary to take full advantage of the gains allowed by Moore's law. For years, processor makers consistently delivered increases in clock rates and instruction-level parallelism, so that single-threaded code executed faster on newer processors with no modification.[74] Now, to manage CPU power dissipation, processor makers favor multi-core chip designs, and software has to be written in a multi-threaded or multi-process manner to take full advantage of the hardware. Many multi-threaded development paradigms introduce overhead, and will not see a linear increase in speed vs number of processors. This is particularly true while accessing shared or dependent resources, due to lock contention. This effect becomes more noticeable as the number of processors increases. Recently, IBM has been exploring ways to distribute computing power more efficiently by mimicking the distributional properties of the human brain.[75]

Obsolescence

A negative implication of Moore's Law is obsolescence, that is, as technologies continue to rapidly "improve", these improvements can be significant enough to rapidly render predecessor technologies obsolete. In situations in which security and survivability of hardware and/or data are paramount, or in which resources are limited, rapid obsolescence can pose obstacles to smooth or continued operations.[76]

Notes

[1] "Moore's Law to roll on for another decade" (http://news.cnet.com/2100-1001-984051.html). . Retrieved 2011-11-27. "Moore also affirmed he never said transistor count would double every 18 months, as is commonly said. Initially, he said transistors on a chip would double every year. He then recalibrated it to every two years in 1975. David House, an Intel executive at the time, noted that the changes would cause computer performance to double every 18 months."

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[3] "Excerpts from A Conversation with Gordon Moore: Moore's Law" (ftp://download.intel.com/museum/Moores_Law/Video-Transcripts/Excepts_A_Conversation_with_Gordon_Moore.pdf) (PDF). Intel Corporation. 2005. p. 1. . Retrieved 2006-05-02.

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[5] Moore 1965, p. 5

[6] Disco, Cornelius; van der Meulen, Barend (1998). *Getting new technologies together* (http://books.google.com/books?id=1khslZ-jbgEC&pg=PA206&lpg=PA206&ots=D38v82mSkm&output=html&sig=ACfU3U2jPixZgKq-PYwVPHDpwO2Zt31puQ). New York: Walter de Gruyter. pp. 206–207. ISBN 3-11-015630-X. OCLC 39391108. . Retrieved 23 August 2008.

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[11] The trend begins with the invention of the integrated circuit in 1958. See the graph on the bottom of page 3 of Moore's original presentation of the idea.
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- Current Processors Chart (http://mysite.verizon.net/pchardwarelinks/current_cpus.htm)
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FAQs

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