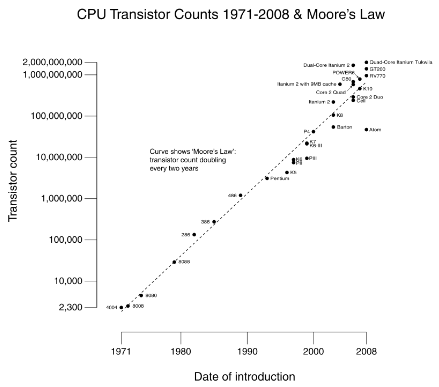
Moore's law

Moore's law describes a long-term trend in the history of computing hardware. The number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every 18 months.[1] The trend has continued for more than half a century and is not expected to stop until 2015 or later.[2]



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

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.[3] All of these are improving at (roughly) exponential rates as well.[4] This has dramatically increased the usefulness of digital electronics in nearly every segment of the world economy.[5] [6]

The law is named after Intel co-founder Gordon E. Moore, who described the trend in his 1965 paper.[7] [8] [9] The paper noted that 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".[10] His prediction has proved 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.[11] This fact would support an alternative view that the "law" unfolds as a self-fulfilling prophecy, where the goal set by the prediction charts the course for realized capability.

An Osborne Executive portable computer, from 1982, and an iPhone, released 2007. The Executive weighs 100 times as much, has nearly 500 times the volume, cost 10 times as much, and has a 100th the processing power of the iPhone.

History

The term "Moore's law" was coined around 1970 by the Caltech professor, VLSI pioneer, and entrepreneur Carver Mead.[8] [12] Predictions of similar increases in computer power had existed years prior. Alan Turing in a 1950 paper had predicted that by the turn of the millennium, computers would have a billion words of memory.[13] 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.[14] A *New York Times* article published August 31, 2009, credits Engelbart as having made the prediction in 1959.[15]

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:

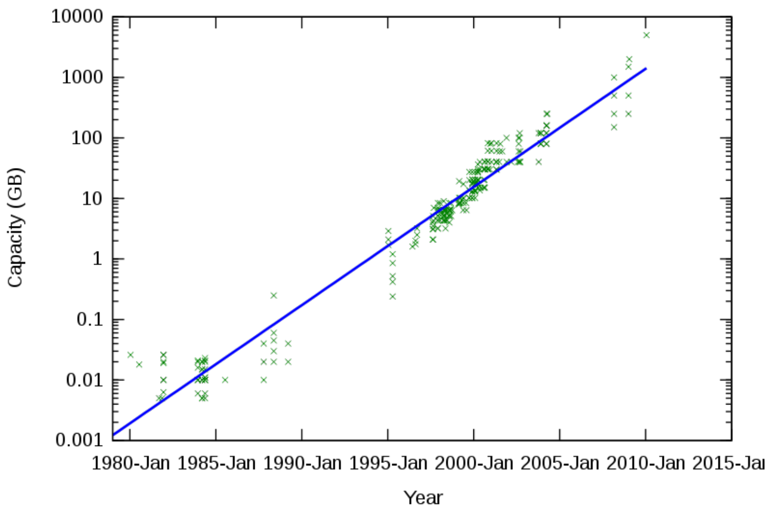
> The complexity for minimum component costs has increased at a rate of roughly a factor of two per year... Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe 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.[7]

Moore slightly altered the formulation of the law over time, in retrospect bolstering the perceived accuracy of his law .[16] Most notably, in 1975, Moore altered his projection to a doubling every 2 years.[17] Despite popular misconception, he is adamant that he did not predict a doubling "every 2 years". However, David House, an Intel colleague,[18] had factored in the increasing performance of transistors to conclude that integrated circuits would double in *performance* every 18 months.[19]

In April 2005, Intel offered US$10,000 to purchase a copy of the original *Electronics Magazine*.[20] David Clark, an engineer living in the United Kingdom, was the first to find a copy and offer it to Intel.[21]

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.



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

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. Recent trends show that this rate has been maintained into 2007.[22]

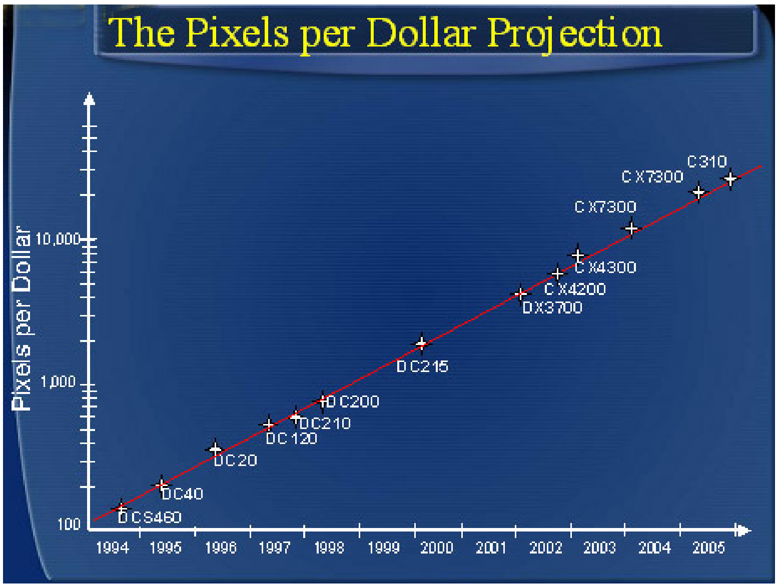
Density at minimum cost per transistor. This is the formulation given in Moore's 1965 paper.[7] It is not just about the density of transistors that can be achieved, but about the density of transistors at which the cost per transistor is the lowest.[23] As more transistors are put on a chip, the cost 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".[7]

Power consumption. The power consumption of computer nodes doubles every 18 months.[24]

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.[25] 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.[22]

Network capacity. According to Gerry/Gerald Butters,[26] [27] the former head of Lucent's Optical Networking Group at Bell Labs, there is another version, called Butter's Law of Photonics,[28] a formulation which deliberately parallels Moore's law. Butter's law[29] 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.[30]

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**, 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,[31] 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.

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.[11] [32]

Relation to manufacturing costs

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.[33] This had led to the formulation of "Moore's second law", which is that the capital cost of a semiconductor fab also increases exponentially over time.[34] [35]

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.[36]

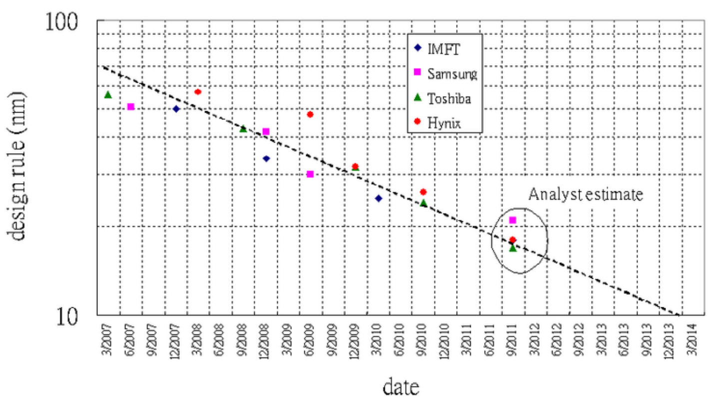
The cost to tape-out a chip at 90 nm is at least US$1,000,000 and exceeds US$3,000,000 for 65 nm.[37]

Future trends

Computer industry technology "road maps" 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.[38] Intel was reported in 2005 as stating that the downsizing of silicon chips with good economics can continue during the next decade[2] and in 2008 as predicting the trend through 2029.[39]

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

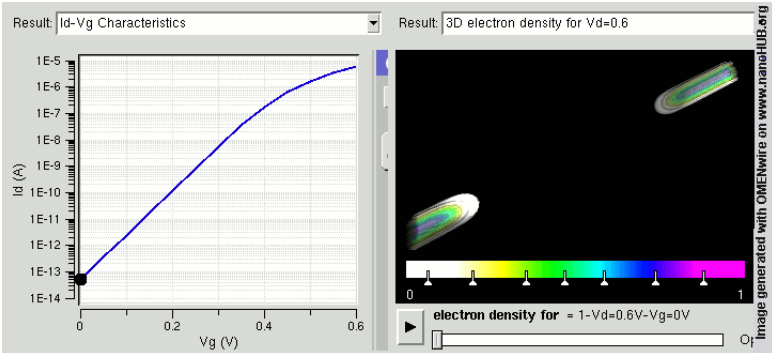
- Researchers from IBM and Georgia Tech created a new speed record when they ran a silicon/germanium helium supercooled transistor at 500 gigahertz (GHz).[40] The transistor operated above 500 GHz at 4.5 K (−451 °F/−268.65 °C)[41] and simulations showed that it could likely run at 1 THz (1,000 GHz). However, this trial only tested a single transistor.
- In early 2006, IBM researchers announced that they had developed a technique to print circuitry only 29.9 nm wide using deep-ultraviolet (DUV, 193-nanometer) optical lithography. IBM claims that this technique may allow chipmakers 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.[42] This memristor bears some resemblance to resistive memory [43] (CBRAM or RRAM) developed independently and recently by other groups for non-volatile memory applications.
- 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.[44]



The trend of scaling for NAND flash memory allows doubling of components manufactured in the same wafer area in less than 2 years.

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:



Atomisic 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 ITRS.[38] roadmap for scaling devices below 10 nm gate lengths

> 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.[45]

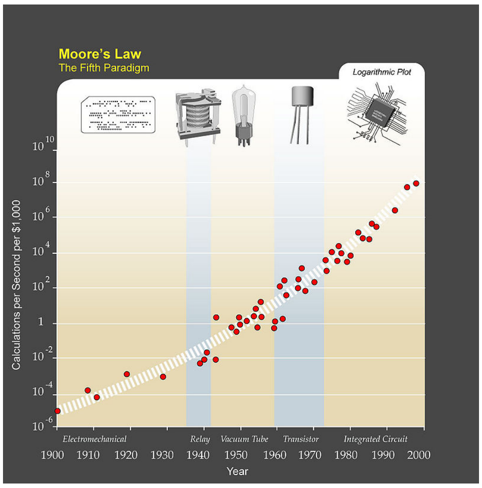
In January 1995, the Digital Alpha 21164 microprocessor had 9.3 million transistors. This 64-bit processor was a technological spearhead at the time, even if the circuit's market share remained average. Six years later, a state of the art microprocessor contained more than 40 million transistors. It 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.[46]

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.[47] 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.[39]

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,[48] based on rigorous estimation of total information-processing capacity of any system in the Universe.

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."[49]

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.[50]

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.[51]

Kurzweil speculates that it is likely that some new type of technology (possibly optical or quantum computers) will replace current integrated-circuit technology, and that Moore's Law will hold true long after 2020.

> 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 Plancks's constant is so small, this equation generates an extremely large number: about $5.0 * 10^{50}$ operations per second.[50]

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 has only actually been demonstrated clearly for semiconductor circuits. However many people including Richard Dawkins have observed that Moore's law will apply - at least by inference - to any problem that can be attacked by digital computers and is in it essence also a digital problem. Therefore progress in genetics where the coding is digital 'the genetic coding of GATC' may also advance at a Moore's law rate. Many futurists still use the term "Moore's law" in this broader sense to describe ideas like those put forth by Kurzweil but do not fully understand the difference between linear problems and digital problems.

Moore himself, who never intended his eponymous 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,[52] I invented the exponential.[53]

Consequences and limitations

Transistor count versus computing performance

The exponential processor transistor growth predicted by Moore does not always translate into exponentially greater practical CPU performance. For example, the higher transistor density in multi-core CPUs doesn't 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.[54] 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.[55] 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.[56] 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.

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 obsolete predecessor technologies. 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.

See also

- Accelerating change
- Amdahl's law
- Bell's law
- Metcalfe's law
- Experience curve effects
- Exponential growth
- Haitz's Law
- History of computing hardware (1960s–present)
- Hofstadter's law
- Kryder's law
- Logistic growth
- Microprocessor chronology
- Nielsen's law
- Observations named after people
- Quantum computing
- Rock's law
- Second half of the chessboard
- Semiconductor
- Wirth's law
- Klaiber's Law

Further reading

- *Understanding Moore's Law: Four Decades of Innovation.* Edited by David C. Brock. Philadelphia: Chemical Heritage Press, 2006. ISBN 0941901416. OCLC 66463488.

External links

News

- Hewlett Packard outlines computer memory of the future [57] BBC News, Thursday, 8 April 2010

Articles

- Moore's Law - Raising the Bar [58]
- Intel's information page on Moore's Law [59] – With link to Moore's original 1965 paper
- Intel press kit [60] released for Moore's Law's 40th anniversary, with a 1965 sketch [61] by Moore
- The Lives and Death of Moore's Law [62] – By Ilkka Tuomi; a detailed study on Moore's Law and its historical evolution and its criticism [63] by Kurzweil.
- Moore says nanoelectronics face tough challenges [64] – By Michael Kanellos, CNET News.com, 9 March 2005
- It's Moore's Law, But Another Had The Idea First [65] by John Markoff
- Gordon Moore reflects on his eponymous law [66] Interview with W. Wayt Gibbs in Scientific American
- Law that has driven digital life: The Impact of Moore's Law [67] – A comprehensive BBC News article, 18 April 2005
- No More Moore's Law? [68] – BBC News article, 22 July 2004
- IBM Research Demonstrates Path for Extending Current Chip-Making Technique [69] – Press release from IBM on new technique for creating line patterns, 20 February 2006
- Understanding Moore's Law By Jon Hannibal Stokes [70] 20 February 2003
- The Technical Impact of Moore's Law [71] IEEE solid-state circuits society newsletter; September 2006
- MIT Technology Review article: Novel Chip Architecture Could Extend Moore's Law [72]
- Moore's Law seen extended in chip breakthrough [73]
- Intel Says Chips Will Run Faster, Using Less Power [74]
- A ZDNet article detailing the limits [75]
- No Technology has been more disruptive... [76]
- Online talk Moore's Law Forever? [77] by Dr. Lundstrom

Data

- Intel (IA-32) CPU Speeds [78] since 1994. Speed increases in recent years have seemed to slow down with regard to percentage increase per year (available in PDF or PNG format).
- A case for PC upgrade [79], 2002–2007.
- Current Processors Chart [80]
- Background on Moore's Law [58]
- International Technology Roadmap for Semiconductors (ITRS) [81]

FAQs

- A C|net FAQ about Moore's Law [82]

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[2] 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 (ftp://download.intel.com/museum/Moores_Law/Articles-Press_Releases/Gordon_Moore_1965_Article.pdf). The limits of the trend are discussed here: Kanellos, Michael (19 April 2005). "New Life for Moore's Law" (http://news.cnet.com/New-life-for-Moores-Law/2009-1006_3-5672485.html). cnet. . Retrieved 2009-03-19.

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[28] As We May Communicate (http://www.tmcnet.com/articles/comsol/0100/0100pubout.htm)
[29] Speeding net traffic with tiny mirrors (http://www.eetimes.com/story/OEG20000926S0065)
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