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Moore's Law: Rise of the Machines

by

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Introduction

Advances in technology throughout human history have never been as evident as the advances in computer technology in the latter half of the twentieth century and the early part of the twenty-first century. Technological progress is no longer seemingly liner; it is clearly exponential. The trend in the increase in computational power is predicted by Moore's Law.

Moore's Law is a term used to describe the increase in computing power over time. Moore's Law is the observation that the number of transistors on an integrated circuit (or microprocessor) doubles every two years.

A transistor is a tiny semiconductor device used to switch electronic signals. A transistor is a simple digital switch. When used in a digital circuit the transistor is either on or off.

Logic gates build on the switching power of a transistor to make more complex building blocks. A logic gate is the fundamental building block for a digital integrated circuit, and the fundamental building block for a logic gate is the transistor. Logic gates include AND, OR, NOT, NAND, NOR, XOR. All of these logic gates can be built using only NAND gates. This simplifies and reduces the complexity of integrated circuits by only using one basic type of logic gate. NAND gates can be assembled to form flip flops (like the D flip flop); these flip flops are called registers and form the basis of microprocessor cores. The heart of a computer is a microprocessor, and microprocessors are built from logic gates and the basic building block of a logic gate is a transistor.

Moore's Law

Moore's Law is named for Intel cofounder Gordon E. Moore who described this computing trend in a 1965 paper while he was the director of research and development of Fairchild Semiconductor. Moore's original statement in his 1965 publication "Cramming More Components onto Integrated Circuits", Electronics Magazine, April 19, 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.*

He stated 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. Moore's exact words from his paper were "the complexity for minimum component costs has increased at a rate of roughly a factor of two per year."

He expected this rate to continue in the short term if not increase and that this rate will be uncertain for longer periods, but if the rate was maintained then the number of components per integrated circuit would be 65,000 by 1975.

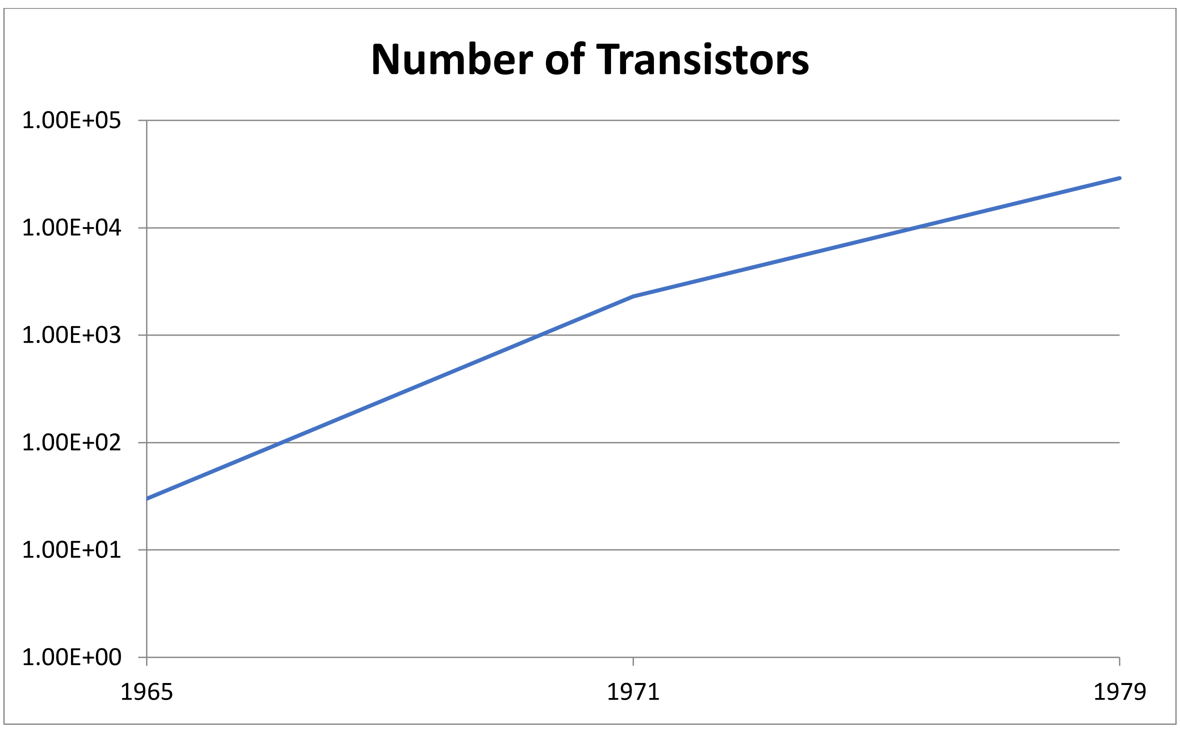

Figure 1 - Graph of 10 year trend from 1965 to 1975

Moore observed that there is a maximum density of transistors at any given point in time that will result in the lowest cost per transistor. 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 one or more defects increases. Moore noted that as the technology of photolithography improves, the density of transistors on a single chip will increase.

His prediction has proven to be amazingly accurate for almost five decades.

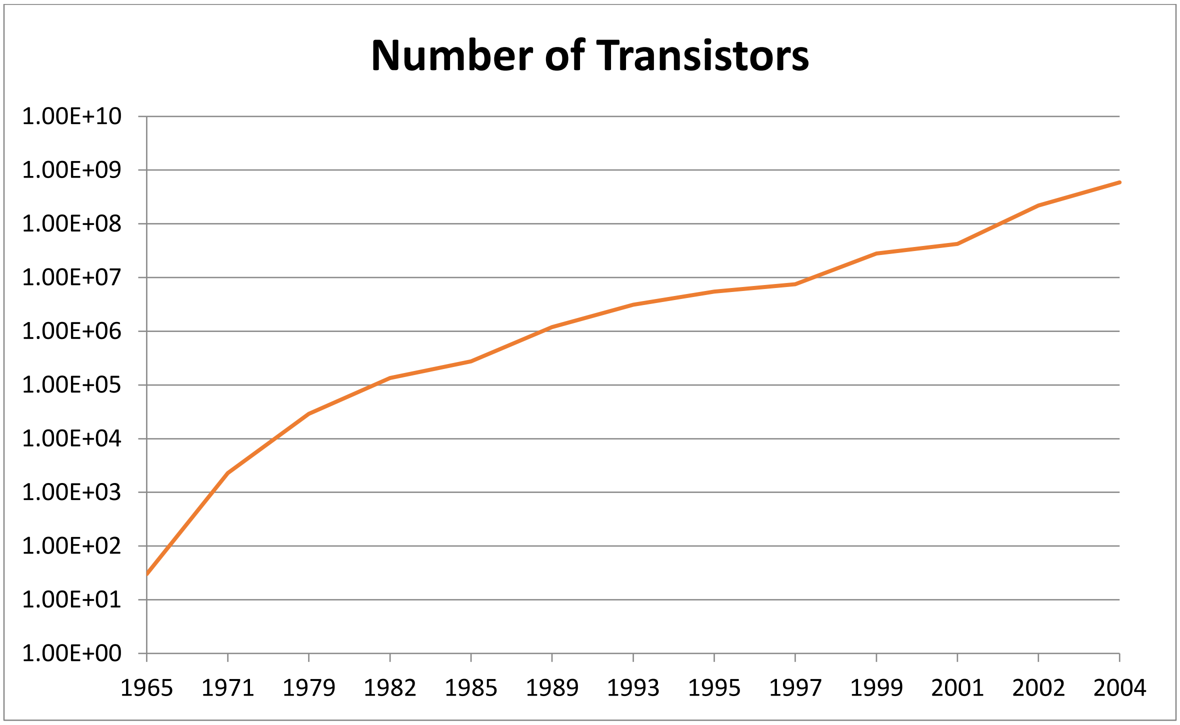

Figure 2 - Graph of 50 year trend from 1965 to 2012

The visionary Moore stated in his paper that "integrated circuits will lead to such wonders as home computers or at least terminals connected to a central computer, automatic controls for automobiles, and personal portable communications equipment." The semiconductor industry now uses Moore's observation as a guide to long-term planning and to set goals for research and development.

The capability and processing power of digital electronic devices are strongly linked to Moore's Law: processing speed, memory capacity, and the number and size of pixels in digital cameras.

Moore stated that "Integrated electronics will make electronic techniques more generally available throughout all of society, performing many functions that presently are done adequately by other techniques or not done at all."

All of these capabilities are increasing exponentially. These improvements to processing power and memory capacity have impacted almost every sector of modern life as well as the world economy.

Examples of this computing trend affecting life:

- personal computers
- communication
- transportation (electronics in cars, airplanes, trucks, trains, etc.)
- the Internet
- medical instrumentation
- social media
- world stock markets (algorithms computing market trends)
- agriculture
- teaching (from preschool to post-graduate college)
- search engines
- navigation devices

Semiconductor Technology

The transistor (or "transfer resistor") was invented in 1947 at AT&T's Bell Labs. John Bardeen, Walter Brattain and William Shockley were experimenting with gold point contacts on a germanium crystal and the effects on signals that pass through it. They found that the output signal had greater power than the input (a condition known as amplification). This amplification effect, the potential for its small size, and the ability to be mass produced using highly automated processes made the vacuum tube almost instantly obsolete. The transistor may be considered one of the greatest inventions of the 20th century. Its greatest potential is its ability to act as a miniature electronic switching device. It is the key building block in an integrated circuit.

The first integrated circuit was invented in the late 1950s by Jack Kilby at Texas Instruments and Robert Noyce at Intel. Kilby described his new device as "a body of semiconductor material...wherein all the components of the electronic circuit are completed integrated." Kilby's chip was made of germanium. Noyce's chip was made of silicon and solved many of the problems of Kilby's germanium chip.

Without the invention of the transistor, the integrated circuit would not be possible. Without the integrated circuit, there would be no microprocessors, no advanced electronics, no cell phones, no Information Age.

Small-Scale Integration

In the early 1960s the first integrated circuits contained only a few transistors. This level of integration is called small-scale integration (SSI). Digital integrated circuits contained only tens of transistors per chip. This amount of transistors could produce only a few logic gates.

The Minuteman Missile program and the Apollo space program accelerated the SSI state of the art to medium-scale integration for the need for lightweight digital circuits for their inertial guidance systems.

Medium-Scale Integration

The transition from small-scale integration to medium-scale integration (MSI) occurred in the late 1960s. MSI allows for hundreds of transistors on each chip. MSI devices allow for more complex systems to be produced for about the same cost as an SSI device. An MSI device has the capacity of multiple logic gates per integrated circuit.

Large-Scale Integration

In the mid-1970s medium-scale integration took a back seat to large-scale integration (LSI). LSI allows for thousands of transistors per chip. LSI circuits allow for even more complex systems to be produced. The development of LSI produced the first microprocessors and computer memories. The development of LSI and the progression to very large-scale integration (VLSI) is the point at which truly practical computers became a reality.

Very Large-Scale Integration

The development of VLSI occurred in the early 1980s. With this level of integration, it was possible to put tens of thousands to hundreds of thousands of transistors per chip. With the development of VLSI technology, high density memory chips and faster, more complicated microprocessors became a reality.

Ultra-Large-Scale Integration

The development of ultra-large-scale integration (ULSI) technology occurred in the mid-2000s. With ULSI, the integration level of transistors on a single chip is in the millions and even billions. Intel's 486 and Pentium processors both use ULSI technology. At the time of this writing current technology can build several billion transistors on a single chip. ULSI made possible the advent of the system on a chip (SoC). A SoC is an integrated circuit in which all of the components needed for a given system are included on a single chip.

Self-Fulfilling Prophecy

Some industry professionals consider Moore's Law a self-fulfilling prophecy. It served as a goal for the entire semiconductor industry. This drove semiconductor manufacturers to invest enormous amounts of time and money to meet the trend set by Moore's Law for processing power because it was presumed that one or more of their competitors would soon attain the same goal. Thus, Moore's Law in this sense may be viewed as a self-fulfilling prophecy

Fundamental Limits

Eventually within the next few of decades a fundamental limit will most likely be reached as technology pushes the size limits down even further. Technology is shrinking individual transistors down approaching the size of atoms or at least molecules which is a fundamental barrier.

Technological Singularity

A singularity in physics is a point in space-time where the current laws of physics break down. The point in human history where life or even existence after the event based on technological progress is unpredictable or incomprehensible is known as the technological singularity.

The event is technological in nature. In other words, not something brought on by some sort of natural disaster. The technology relevant for radical change is the semiconductor and computer industries in terms of processing power.

Wikipedia describes the technological singularity as "the theoretical emergence of greater-than-human super intelligence through technological means." Since the capabilities of such an artificial intelligence are beyond our comprehension, this event (assuming that it will occur) is viewed by some as an intellectual event horizon, beyond which events cannot be predicted.

The term "singularity" as it relates to society was introduced by John von Neumann in the mid-1950s in which he spoke of "ever accelerating progress of technology and changes in the mode of human life, which gives the appearance of approaching some essential singularity in the history of the race beyond which human affairs, as we know them, could not continue." This singularity as von Neumann described it would cause an eventual unpredictable outcome in society.

Science fiction writer and futurist Vernor Vinge described the technological singularity in his 1993 paper "The Coming Technological Singularity: How to Survive in the Post-Human Era."

> *Within thirty years, we will have the technological means to create superhuman intelligence. Shortly after, the human era will be ended.*
>
> *The acceleration of technological progress has been the central feature of this century. I argue in this paper that we are on the edge of change comparable to the rise of human life on Earth. The precise cause of this change is the imminent creation by technology of entities with greater than human intelligence. There are several means by which science may achieve this breakthrough (and this is another reason for having confidence that the event will occur):*
>
> *The development of computers that are "awake" and superhumanly intelligent...*
>
> *Large computer networks (and their associated users) may "wake up" as a superhumanly intelligent entity.*
>
> *Computer/human interfaces may become so intimate that users may reasonably be considered superhumanly intelligent.*
>
> *Biological science may find ways to improve upon the natural human intellect.*

An extremely intelligent machine could design better machines, improving on its own design; these machines could in turn design even better versions of themselves, thus resulting in an "intelligence explosion".

Some analysts expect the singularity to occur sometime in the 21st century.

I.J. Good described the notion of an "intelligence explosion" in 1965:

> *Let an ultra-intelligent machine be defined as a machine that can be defined as a machine that can far surpass all the intellectual activities of any man however clever. Since the design of machines is one of these intellectual activities, an ultra-intelligent machine could design even better machines; there would then unquestionably be an 'intelligence explosion,' and the intelligence of man would be left far behind. Thus the first ultra-intelligent machine is the last invention that man need ever make.*

There are at least two avenues for an intelligence explosion to come to fruition: artificial intelligence (or pure machine intelligence) and intelligence amplification (artificial circuits interfacing with the human brain). Artificial intelligence is the branch of science and engineering behind creating a non-biological (or manmade) system that perceives its environment and takes actions that maximize its chances of success. Intelligence amplification is the biomedical engineering attempt to enhance or augment the human brain by artificial means.

An intelligence explosion depends on several factors, such as the accelerating factor, diminishing returns, and a hard upper limit. First, the accelerating factor is the time and effort required to improve on each enhancement or each generation of machine. Next, the law of diminishing returns dictates that as each machine becomes more and more advanced, further advances will become more and more complicated; the advantage of the new advancement would not be worth the effort put into the new machine. Next, in lots of areas of science and engineering, there are hard upper limits. For modern-day processors and computational machines based on registers and arithmetic logic units the laws of physics will soon certainly limit further improvements in speed and reduction in component size. The speed of computation will obviously be a factor in achieving artificial intelligence, and this computational speed is predicted by Moore's Law.

Consciousness

One key aspect to consider is consciousness. Consciousness, or the point when the machines "wake up", or the "awareness" of the being or machine may not be as "simple" as more and more powerful processors. Intelligence from the human aspect may not simply be the natural result of a collection of billions and billions of neurons firing. Consciousness may be something larger and more complicated than anyone can imagine.

Just like dark matter and dark energy that permeates the universe hides a great majority of the universe, consciousness or awareness may also be below the surface of the human neural network. Without dark matter and dark energy, the universe would not hold together or have evolved just it has. Similarly, consciousness or awareness may be the "dark matter and dark energy" of our existence. Just because we cannot see something, does not mean there is a deeper mechanism or meaning.

Therefore, super intelligent conscious machines may in the distant future if even possible at all.

Ray Kurzweil stated that an analysis of history shows that technological progress follows a pattern of exponential growth. He calls this exponential growth the "Law of Accelerating Returns". He explains that whenever technology approaches a barrier, new technologies will eventually surmount the barrier.

> *An analysis of the history of technology shows that technological change is exponential, contrary to the common-sense “intuitive linear” view. So we won’t experience 100 years of progress in the 21st century — it will be more like 20,000 years of progress (at today’s rate). The “returns,” such as chip speed and cost-effectiveness, also increase exponentially. There’s even exponential growth in the rate of exponential growth. Within a few decades, machine intelligence will surpass human intelligence, leading to The Singularity — technological change so rapid and profound it represents a rupture in the fabric of human history.*

The Collapse of Moore's Law

According to theoretical physicist Michio Kaku, Moore's Law is beginning to break down. According to Kaku:

> *...in about ten years of so, we will see the collapse of Moore's Law. In fact, already, we see a slowing down of Moore's Law. Computer*

> *power simply cannot maintain its rapid exponential rise using standard silicon technology. Intel Corporation has admitted this.*

Kaku argues that the collapse will be due to heat and leakage issues.

There is an ultimate limit set by the laws of thermodynamics and quantum mechanics as to how much computing power is possible with silicon. This hints at the notion that the age of silicon will eventually come to a close, and a Kaku argues that Moore's Law could eventually flatten out completely by 2022.

However, Moore's Law may get another boost with the development of three-dimensional silicon chips and further improvements in parallel processing.

Silicon will eventually have to be abandoned for the trend in processing power and memory capacity to increase further. This breakthrough, whether through quantum computing or molecular computing or probably some currently unknown technology, will undoubtedly be revolutionary for the computer industry, and possibly even for the human race.

Even Gordon Moore himself, on the 40th anniversary of the publication of his visionary law, has stated that Moore's Law probably only has 10 to 20 years left.

> *Nothing like this can continue forever. The dimensions are small enough now that we are approaching the size of atoms... We have 10 to 20 years before we reach a fundamental limit.*

Summary

Moore's Law is a term used to describe the increase in computing power over time. Moore's Law was introduced in 1965 by Gordon Moore. Moore's Law is gauged by the maximum number of transistors on a microprocessor or memory chip at any given point in time. He stated that the number of transistors on an integrated circuit will double approximately every two years. Whether held up by the accuracy of Moore's visionary prediction or driven by industry’s thirst to keep up with the trend in technology, Moore's prediction has proven to be true for almost five decades.

This exponential computing trend has affected all avenues of life including (by not limited to) the following: personal computers, communications, transportation, navigation, agriculture, medical, world finance, education, and social media. Some industry experts believe Moore's Law will reach a fundamental limit within the next few decades, while others expect a revolution in the microprocessor technology to maintain the trend.

Many visionaries feel that we humans will soon reach a point in our existence that can be described as unpredictable and maybe even unsettling. This point in history (if the predictions are true) will be the result of an intelligence explosion caused by a technological singularity. A technological singularity is the point in human history where life or even existence after the event which is based on technological progress is unpredictable or incomprehensible.

These are only predictions though. The fact of the matter is this: we don't know. We don't know enough about consciousness to apply the concept to a machine (yet) if it is even possible...

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