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The Logarithmic Law of Usefulness

The amount of information storable on a given amount of silicon doubles every year.

Dr. Theo Claesen, Philips Semiconductors -- Semiconductor International, 7/1/1998

During the past 25 years, we have witnessed a rate of progress in information technology that seems beyond comprehension. An increase in the characteristic parameters by a factor of between 1000 and 1 million has been the rule rather than the exception.

For instance, progress in the field of transportation took centuries before a factor of 1000 was accomplished: A horse cart, an early automobile and a supersonic airplane cover the distance of 30 km in one day, one hour and one minute, respectively. A factor of 1000 in only 10-15 years thus means a real revolution.

Why can we apparently cope so easily with this exponential growth? How can we so easily absorb and implement such progress without being confused by its implications? One answer is that the perceived progress, the increase in usefulness, is not exponential, but linear. In other words, usefulness is a logarithmic function of technology.

In the electronics industry, Moore's Law describing the developments in microelectronics is a well-known and widely accepted hypothesis. Gordon Moore, who later founded Intel, formulated it in 1964, as follows:

The amount of information storable on a given amount of silicon doubles every year.

Since 1970, the doubling period has increased to about 18 months (Fig. 1). Moore's Law can alternatively be formulated as the following:

The size of the details that are carved in the semiconductor material decreases by a factor of two every 18 months.

It is interesting to see that this also causes the transmission speed of signals between elements to increase and the heat dissipation to decrease. All well-known information, and even though it is expected to be limited by hard physical or economic boundaries, it still holds, and will hold for a number of years to come. What is equally interesting is that Moore's Law not only holds for progress in microelectronics per se, but also holds for progress in related areas such as storage and software. There even exists a twin law to Moore's Law, called Parkinson's Law, that reads: "Memory usage of evolving systems tends to double every 18 months."

Generalized Moore's Law

A generalized form of Moore's Law reads as follows:

All performance indicators applicable to the field of information technology improve by a factor of two in a period of one-and-a-half to three years.

This will be illustrated with examples for three fields in information technology: microelectronics, storage and software.

First, in microelectronics microprocessors, dynamic and static random-access memories (DRAMs and SRAMs), digital signal processors (DSPs) and application-specific integrated circuits (ASICs) have evolved during the past decade in such a way that the performance indicators (such as the number of transistors per chip and the memory size) have increased, and the geometric feature size and the gate delay (related to the operational speed of the chips) have decreased. This resulted in exponential changes in the computing power (Fig. 2), the memory capacity and the speed of the chips, i.e., the functional or the "secondary parameters." The factors indicating this exponential growth are different for the different qualities, but all are positive, relatively large and result in substantial growth.

Then there are the storage systems. The digital storage media -- magnetic and optical discs and tapes -- and the systems to read and write the data on these media have shown enormous progress. The performance indicators (such as the number of bits per carrier, the price per megabit and the number of bits that can be stored or retrieved per second) for hard-disk drives (HDDs), digital tapes and compact discs and their derivatives (CD-ROM and CD-i) have obeyed the generalized form of Moore's Law without failure (Figs. 3-5). This has resulted in the

At a Glance

While technology has advanced in the past 25 years at an enormous rate, the usefulness of that technology has been slower -- linear, actually. This has lead the author to postulate a new law that states that usefulness is a logarithmic function of technology.

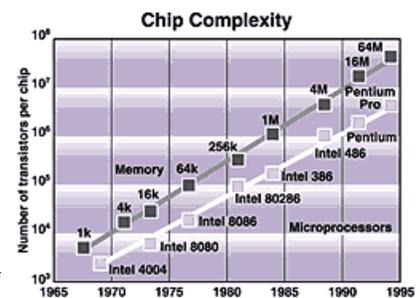


Fig. 1. Moore's Law states that the amount of information storable on a given amount of silicon doubles every year. Since 1970, the doubling period has increased to about 18 months .

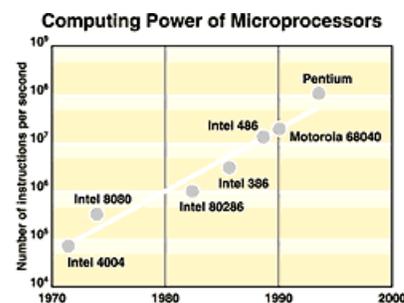


Fig. 2. Computing power has increased exponentially because of increases in the number of transistors per chip and the memory size and decreases in geometric feature size and gate delay.

improvement of the secondary parameters, which are formulated, once again, as the memory size, the speed of data storage and the price per bit. The first two increase, and the last one decreases.

In the field of software, we can think of a telephone switch (now completely built in software), the user interface of a television set, the set-top box for digital television and databases accessible through new web browsers. The growth these systems have gone through is enormous (Figs. 6,7). The program size, the number of lines of code that are necessary to realize their functions and the amount of data needed for this in huge databases show exponential growth. Developments in these fields have not occurred independently of each other.

The increase in the number of transistors on a chip design could not be managed without the use of computer-aided design software. Software could not have had such an impact if there had not been hardware systems with chips on which it could be run. This again would not have been possible if there had not been huge and fast storage systems available. Whichever way you look at it, it is indisputable that enormous progress has been made in these fields over the past 25 years. What will happen in the next 25?

Hard limits

Even when Moore first formulated his law, one was more than aware of the limits to the growth described it. You could not shrink dimensions endlessly without meeting physical limits. However, limits are found not only in physics, but also in other areas. There are physical, economic and "design" limits.

In the next 10-15 years, we will have enough room to move on in the direction we are now going.

The following examples are randomly chosen, and many more can be thought of without effort. I will start with the hard physical limits. If you look at, for example, the size of a bit in a magnetic medium, it is evident that you cannot reduce it below the size of the magnetic domains themselves. The very properties that allow you to store a bit in a small area on the medium disappear if the dimensions shrink too much. An area of about 1 pm^2 is needed to store one bit. Such an area contains a number of grains that have the magnetic properties necessary to be able to read and write a bit. The size of a magnetic grain is 0.0007 pm^2 and since we need -- because of signal/noise requirements -- about 100 grains in one bit, there is still room for improvement here. Extrapolating today's course of events, we can diminish the size per magnetic bit to 0.07 pm^2 . This leaves room for another 10-12 years of improvement in this field. A lot of research work into the reading and writing mechanisms will have to be done before this can be applied in a working device, however.

In solid-state memories, a similar argument leads to this conclusion: Moving from the 1 million electrons per cell that we have now, down to the minimum of 100, leaves plenty of room for improvement.

However, IC process technology may be the limiting factor for progress. The smallest features resolved in lithography determine the smallest details made in the IC. Therefore, the limiting factors are the optical properties of wafer steppers and the wavelength of the light used. By using a wavelength in the DUV region, together with improvements of the optical system in wafer steppers, it is possible for the semiconductor industry to advance in the chosen direction for the next 10-20 years.

In optical recording, the wavelength of the light that is employed to write and read limits the bit size. In principle, we can reduce the wavelength of the lasers used in optical recording, provided that we can produce working lasers with smaller wavelengths. Visible light should not limit us, however.

Real limits?

I now come to economic factors. When Moore formulated his law, estimates indicated that the costs of starting a new IC factory would be \$1 billion by the year 2000 (Fig. 8). At that time, this was a large and unacceptable amount of money, especially when compared to the \$4 million such a factory cost at the time. However, today, about 20 new IC factories are being built worldwide, each costing around \$1 billion. Profits in this sector have risen so high, apparently, that the height of this number is no longer a real limit, at least for now.

Are there no real limits then? Will they all shift further away as we near them?

I am not so sure about that. There is one field that may present us with insurmountable problems, and that is the third factor: "design." When we in Philips Research started the IC Design Centre, back in 1985, I spoke to a plant manager of an IC factory in, I think it was, Southampton. In his development department, the average design efficiency of his projects was 5000 transistors per man per year. It is not so hard to understand that now that chips with 1,000,000 transistors are possible, these cannot be designed by one person, since it would take 200 years. It would even take 100 cooperating people two years, which is too long and not manageable. From experience, we know that we can do it faster. Nowadays, teams made up of a

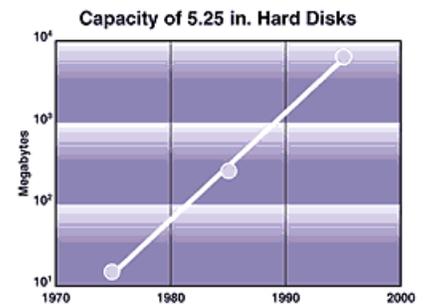


Fig. 3. Magnetic storage media has obeyed the generalized form of Moore's Law without failure.

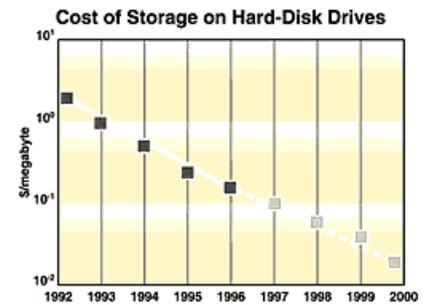


Fig. 4. The cost per bit of storage on hard-disk drives has been exponentially decreasing.

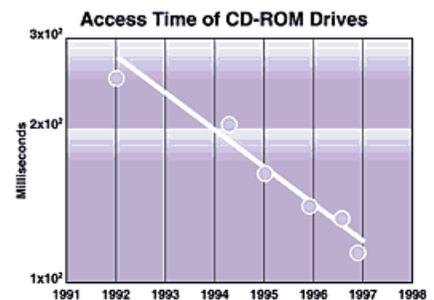


Fig. 5. The ability to quickly read data from CD-ROM drives has helped speed information access.

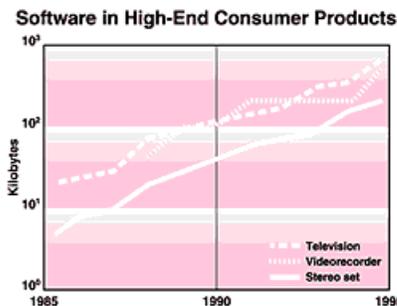


Fig. 6. The growth of software -- the program size, the number of lines of code, etc. -- in high-end consumer products is enormous.

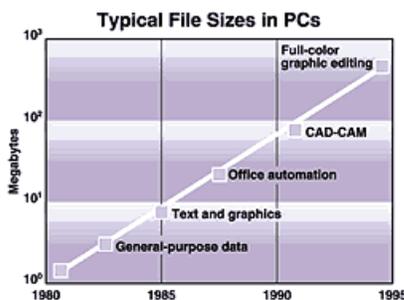


Fig. 7. As software complexity increases, so too does the size of the files used in PCs.

few people design chips containing a million transistors in half a year. Indeed, again, this is an exponential increase. However, we could not have done this without the help of automated design tools and methods. I am confident that we will manage chips with 10 or even 50 million transistors in the same period and with the same number of people in the coming years. It will be hard work, but I have a feeling that we will succeed.

However, I am not so confident about design progress in another field: software. We are passing an abyss, as it were. In software design, a complete transformation of the culture has to take place to be able to cope.

I know of more failures of software projects -- failures in particular with respect to timing -- than IC design projects dealing with the same amount of complexity. Why is that? One important aspect is this: In software design, one is hindered by the inherently useful opportunity of being able to change things up to the last minute. Again, compared with IC design, where every change means a new processing cycle of about three months, this looks like an advantage, but may actually be a disadvantage. In consumer products, for instance, there is not much reusable software in existence, and where it does exist, it is not reused. Given the complexity and the extent to which software is playing a role in today's progress in technology, software designers should and can learn a lot from IC designers. Formal methods and techniques will have to play a larger role than they do today.

None of the foreseen limits will really prevent us from advancing further in the direction that we have been going the past 25 years.

Moore's Law, and the generalized Moore's Law, will hold for at least another 10-15 years.

New law

This brings us back to the original question. If growth is exponential in so many areas, it is surprising that it can be absorbed by society. Imagine a philosopher coming from a far away galaxy, not yet exposed to microelectronics. What would that person have predicted given the sustained sharp exponential growth of technology over the past 25 years? Perhaps chaos, social disorder or, in any case, an unrecognizable society. We all know that we have coped.

We have been able to absorb this technology and use it to increase our comfort.

Why is that?

Let us go back 25 years. We had a home, a car, a television with six channels, a telephone, a tuner, a gramophone and a newspaper. We lived comfortably with all that. We did not have things that we have now in 1998 such as a TV set with up to a hundred channels and a remote control, a cellular phone, a fax, an answering machine, a PC with CD-ROM, a CD player, a CD-i, a VCR and the Internet. Apparently, new products have readily absorbed and exploited the possibilities that technology offered. The exponential growth in technology has made this possible. Although the change is significant, when you look at it from the users' point of view, this change is not so extreme, and more so when you consider the changes brought about in society. Nowhere is the exponential growth explicitly visible.

I would now like to postulate a new law, i.e., the "logarithmic law of usefulness." By usefulness, I mean something like the impact of technology on our daily lives. The law I state holds that the following is true:

Usefulness is a logarithmic function of technology.

In turn, technology is only a linear function of computing power, operating speed, memory capacity and perhaps a few other parameters. These parameters increase exponentially. So, technology increases exponentially. In combination with the law I stated, this means that usefulness increases linearly, to an extent that we can grasp. I have not derived this new law analytically, but neither did Moore his law. I will, however, give some examples and some observations from which you can get a feeling that the law is valid.

- A telephone handset containing 10 preset numbers is helpful enough for most calls; a base station with some hundred represents the next step in usefulness. A telephone book with 100,000 numbers will help you further; while for all possible phone calls, a world base with hundreds of millions of subscriber numbers is needed. The technology needed to provide these numbers increases exponentially, while the usefulness increases only stepwise.
- If you compare the early PCs with a 8086 processor and the operating system MS-DOS with today's Pentium and Windows 95, you must admit that the exponential growth in the arithmetic and memory capacity, and in the number of code lines of the applications, have indeed made computers more useful. But not so much more as an exponential function would suggest.
- In speech recognition, a database of 10 words and a system trained for one speaker make hands-free dialing possible: Simply speaking the numbers is sufficient to make the connection. You can access the 10 preset numbers in your handset with Peter, Mary, etc. A 1000-word vocabulary that can be recognized as coming from more than one speaker could make your electronic products in the home react to commands from all members of the family. However, a true dialogue or a dictation system requires recognition of all possible speakers and of all possible words and thus requires an order of magnitude more operating and storage capacity. In usefulness, it is, in my view, just one step farther.
- In data retrieval, you find the same hierarchy for a simple dictionary, an encyclopedia and the Internet.
- In data communication, the steps from telex via fax to E-mail required a huge increase in technological power to make incremental steps in usefulness possible.
- The software in television sets went from 0 bytes and 20 push buttons to 30 Kbytes for simple sets to 1 Mbyte for high-end television sets, with only a modest increase in the actual user benefit.
- Videocassettes of 180 min allow you to store one movie plus a bit of a second. Tapes with twice as much storage capacity are not twice as useful, as it is more convenient to keep one movie on one separate tape.
- You may find it useful to have a thousand books, but if you are looking for something special you will soon revert to the town library of 100,000 books. If you do not find the answer there, you might revert to the Library of Congress containing all books ever printed.
- A particularly interesting example of exponential growth is the evolution in communication technology. When depicted on a logarithmic scale, the traffic intensity shows an exponential increase over time, a double exponential increase as it were (Fig. 9). Looking at the increase in comfort or the possibilities for

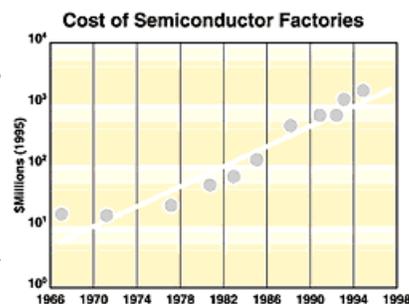


Fig. 8. Semiconductor fabrication facilities now cost more than \$1 billion to construct and equip.

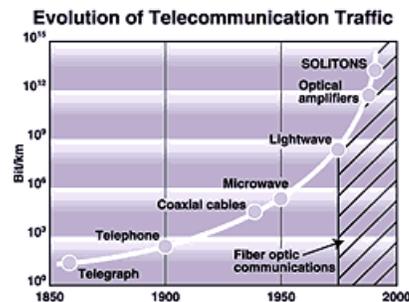


Fig. 9. When depicted on a logarithmic scale, telecommunication traffic intensity shows an exponential increase over time -- in a sense, a double exponential increase.

use that this technology has brought us, it indeed is the one with the greatest impact on our lives.

Figure 10 summarizes the progress in microelectronics, storage and software technology and shows how the end result of this progress is a linear increase of usefulness with time.

Progress in Information Technology			
Field of information technology	Parameter	Time dependence	Coefficient value
Microelectronics	Computing power	$\exp(c_1 t)$	c_1 : approx 0.33/year
	Solid-state memory	$\exp(m_1 t)$	m_1 : approx 0.28/year
	Speed	$\exp(s_1 t)$	s_1 : approx 0.75/year
Storage	Memory	$\exp(m_2 t)$	m_2 : approx 0.32/year
	Speed	$\exp(s_2 t)$	s_2 : approx 0.75/year
	Price/Mb	$\exp(-p t)$	p : approx 0.70/year
Software	Software size	$\exp(c_2 t)$	c_2 : approx 0.31/year

Technology is a function of a number of parameters that all vary exponentially with time. Coefficients are large and roughly vary between 0.25 and 0.75. This implies that technology has advanced in the past 25 years by a factor between 518 and 139×10^6 . A large increase indeed. The usefulness has not increased with such a large factor, which brings us to the logarithmic law of usefulness:

$$\text{usefulness} = \log(\text{technology})$$

with $\text{technology} = f(\text{computing power, speed, memory, etc.})$ and given the exponential increase of the parameters, this results in a linear increase of usefulness with time.

Fig. 10. Progress in microelectronics, storage and software technology and how the end result of this progress is a linear increase of usefulness with time is shown. This is the logarithmic law of usefulness.

Apart from these examples, there are a few other observations that support my law. First, seeing and hearing, as examples of human perceptions, are also logarithmic functions of the provided input. Usefulness is also a perceived quality. Even when the sensors cannot be located and tested for their transfer functions, why should this quality not also depend logarithmically on input? Second, a large number of the solutions that information technology provides fall into the class of the combinatorial optimization problems (see sidebar on "Traveling Salesman"). Characteristically, the number of solutions to be investigated, i.e., the complexity, grows exponentially with the number of variables, while the answer only brings you one step further. Third, we are all familiar with the human nature of collecting things until we run out of room for storing things. Only seldom do we stop collecting things because it is no longer useful. The advances in technology provide us with exponentially growing cellars and attics. We load them with information, only occasionally taking out something that we perceive as useful at that moment.

So far is my expose about this new law. What can we conclude from it? What do we learn? How will it influence our decisions? In my opinion, there are a few things we can learn from it. The first is that society can accommodate exponential growth of technology without pain.

We do not have to be afraid that technology will take over, because we can handle it.

The second is if a society wants substantial improvements, for instance, to solve such things as the traffic jams or improve the educational system technologically, fortunes have to be spent on R&D to get there.

Finally, we in industrial electronics research can still continue our work, while society eagerly adopts all of our results.

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Traveling Salesman

The traveling salesman problem is a well-known example of the class of combinatorial optimization problems. Given a set of cities and the distances between them, what is the shortest route a sales representative can take to visit each city once? A route through six cities presents 60 possible pathways, but a route through 12 cities presents almost 20 million possible pathways. A route through "n" cities presents $n!/12n$ possible routes. With the exponentially increasing capacity of the computers used to solve this problem for a large number of cities, the optimal solution is approached in ever smaller steps. The problem of the traveling salesman is also a problem in the design of VLSI IC design, where economizing on the length of the interconnect is the goal.