Mooresches Gesetz (Exponentielle technologische Evolution)

Description

Das Mooresche Gesetz (englisch Moore’s law; deutsch „Gesetz“ im Sinne von „Gesetzmäßigkeit“) besagt, dass sich die Komplexität integrierter Schaltkreise mit minimalen Komponentenkosten regelmäßig verdoppelt; je nach Quelle werden 12, 18 oder 24 Monate als Zeitraum genannt.

Unter Komplexität verstand Gordon Moore, der das Gesetz 1965 formulierte, die Anzahl der Schaltkreiskomponenten auf einem integrierten Schaltkreis. Gelegentlich ist auch von einer Verdoppelung der Integrationsdichte die Rede, also der Anzahl an Transistoren pro Flächeneinheit. Diese technische Entwicklung bildet eine wesentliche Grundlage der „digitalen Revolution“.

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Mehr: [de.wikipedia.org/wiki/Mooresches_Gesetz]

Siehe auch:

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Shalf, J.. (2020). The future of computing beyond Moore’s Law. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences

Plain numerical DOI: 10.1098/rsta.2019.0061
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“Moore’s law is a techno-economic model that has enabled the information technology industry to double the performance and functionality of digital electronics roughly every 2 years within a fixed cost, power and area. advances in silicon lithography have enabled this exponential miniaturization of electronics, but, as transistors reach atomic scale and fabrication costs continue to rise, the classical technological driver that has underpinned moore’s law for 50 years is failing and is anticipated to flatten by 2025. this article provides an updated view of what a post-exascale system will look like and the challenges ahead, based on our most recent understanding of technology roadmaps. it also discusses the tapering of historical improvements, and how it affects options available to continue scaling of successors to the first exascale machine. lastly, this article covers the many different opportunities and strategies available to continue computing performance improvements in the absence of historical technology drivers. this article is part of a discussion meeting issue ‘numerical algorithms for high-performance computational science’.”
Chen, R., Li, Y. C., Cai, J. M., Cao, K., & Lee, H. B. R.. (2020). Atomic level deposition to extend Moore’s law and beyond. International Journal of Extreme Manufacturing

Plain numerical DOI: 10.1088/2631-7990/ab83e0
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“In the past decades, moore’s law drives the semiconductor industry to continuously shrink the critical size of transistors down to 7 nm. as transistors further downscaling to smaller sizes, the law reaches its limitation, and the increase of transistors density on the chip decelerates. up to now, extreme ultraviolet lithography has been used in some key steps, and it is facing alignment precision and high costs for high-volume manufacturing. meanwhile, the introduction of new materials and 3d complex structures brings serious challenges for top-down methods. thus, bottom-up schemes are believed to be necessary methods combined with the top-down processes. in this article, atomic level deposition methods are reviewed and categorized to extend moore’s law and beyond. firstly, the deposition brings lateral angstrom resolution to the vertical direction as well as top-down etching, such as double patterning, transfer of nanowires, deposition of nanotubes, and so on. secondly, various template-

assisted selective deposition methods including dielectric templates, inhibitors and correction steps have been utilized for the alignment of 3d complex structures. higher resolution can be achieved by inherently selective deposition, and the underlying selective mechanism is discussed. finally, the requirements for higher precision and efficiency manufacturing are also discussed, including the equipment, integration processes, scale-up issues, etc. the article reviews low dimensional manufacturing and integration of 3d complex structures for the extension of moore's law in semiconductor fields, and emerging fields including but not limited to energy, catalysis, sensor and biomedicals."
Chien, A. A., & Karamcheti, V.. (2013). Moore's law: The first ending and a new beginning. Computer

Plain numerical DOI: 10.1109/MC.2013.431
DOI URL
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"Moore's law has accurately predicted roughly biennial doubling of component capacity at minimal cost for almost 50 years. recent flash memory scaling exhibits increased density, but reduced write and read lifetimes effectively constitute an ending of moore's law. however, new resilience techniques, including adaptive management algorithms, and storage technologies based on information theory could maintain progress for a decade or more. © 2013 ieee."
Smit, M., van der Tol, J., & Hill, M.. (2012). Moore's law in photonics. Laser and Photonics Reviews

Plain numerical DOI: 10.1002/lpor.201100001
DOI URL
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"A review of the complexity development of inp-based photonic ics is given. similarities and differences between photonic and microelectronic integration technology are discussed and a vision of the development of photonic integration in the coming decade is given. a review of the complexity development of inp-based photonic ics is given. similarities and differences between photonic and microelectronic integration technology are discussed and a vision of the development of photonic integration in the coming decade is given. © 2012 wiley-vch verlag gmbh & co. kgaa, weinheim."
Lecuyer, C.. (2022). Driving Semiconductor Innovation: Moore's Law at Fairchild and Intel. Enterprise and Society

Plain numerical DOI: 10.1017/eso.2020.38
DOI URL
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"Gordon moore designed moore's law as a multifunctional tool to drive process and product innovation, sell fairchild's and intel's microchips, and outcompete other semiconductor firms. because intel's ability

to stay on moore's law depended upon other corporations developing materials and manufacturing equipment for exponential scaling, moore and his closest associates heavily promoted moore's law in the microelectronics community. they also established the national and international technology roadmaps for semiconductors in order to set the direction and cadence of innovation in microelectronics at the national and, later, global scales. moore's and his successors' relentless pursuit of moore's law and their deft management of the roadmaps significantly reinforced intel's competitiveness and helped it to dominate semiconductor technology and industry until the mid-2010s."
Farmer, J. D., & Lafond, F.. (2016). How predictable is technological progress?. Research Policy

Plain numerical DOI: 10.1016/j.respol.2015.11.001
DOI URL
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"Recently it has become clear that many technologies follow a generalized version of moore's law, i.e. costs tend to drop exponentially, at different rates that depend on the technology. here we formulate moore's law as a correlated geometric random walk with drift, and apply it to historical data on 53 technologies. we derive a closed form expression approximating the distribution of forecast errors as a function of time. based on hind-casting experiments we show that this works well, making it possible to collapse the forecast errors for many different technologies at different time horizons onto the same universal distribution. this is valuable because it allows us to make forecasts for any given technology with a clear understanding of the quality of the forecasts. as a practical demonstration we make distributional forecasts at different time horizons for solar photovoltaic modules, and show how our method can be used to estimate the probability that a given technology will outperform another technology at a given point in the future."
Debenedictis, E. P., Badaroglu, M., Chen, A., Conte, T. M., & Gargini, P.. (2017). Sustaining Moore's Law with 3D Chips. Computer

Plain numerical DOI: 10.1109/MC.2017.3001236
DOI URL
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"Rather than continue the expensive and time-consuming quest for transistor replacement, the authors argue that 3d chips coupled with new computer architectures can keep moore's law on its traditional scaling path."
Reichardt, R.. (2006). Moore's Law and the pace of change. Internet Reference Services Quarterly

Plain numerical DOI: 10.1300/J136v11n03_09
DOI URL
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"In 1965, gordon e. moore, co-founder of intel, predicted that the number of transistors in an integrated circuit would double approximately every two years. his assertion became known as moore's law. the nature of reference and information service has changed dramatically over the past quarter century, as has literature searching. these changes are reviewed and examined in the context of moore's law. © 2006 by the haworth press, inc. all rights reserved."
Strawn, G., & Strawn, C.. (2015). Moore's Law at Fifty. IT Professional

Plain numerical DOI: 10.1109/MITP.2015.109
DOI URL
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"In 1965, gordon moore predicted that the number of transistors on a chip would double every year for the next 10 years. moore's law is still in effect today, with more than a billion transistors able to fit on a chip as of 2010. this article revisits moore's law and the rise of microelectronics."
Mollick, E.. (2006). Establishing Moore's law. IEEE Annals of the History of Computing

Plain numerical DOI: 10.1109/MAHC.2006.45
DOI URL
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"Every field has brief formulas or relationships that are useful for back-of-the-envelope calculations. rarely do these maxims become popular knowledge; even more rarely do they become as ubiquitous and influential as moore's law, the 40-year-old prediction that the speed of computers will double every year or two. here, a look at the way in which the legendary law evolved into a self-fulfilling prophecy. © 2006 ieee."
Theis, T. N., & Philip Wong, H. S.. (2017). The End of Moore's Law: A New Beginning for Information Technology. Computing in Science and Engineering

Plain numerical DOI: 10.1109/MCSE.2017.29
DOI URL
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"The insights contained in gordon moore's now famous 1965 and 1975 papers have broadly guided the development of semiconductor electronics for over 50 years. however, the field-effect transistor is approaching some physical limits to further miniaturization, and the associated rising costs and reduced return on investment appear to be slowing the pace of development. far from signaling an end to progress, this gradual 'end of moore's law' will open a new era in information technology as the

focus of research and development shifts from miniaturization of long-established technologies to the coordinated introduction of new devices, new integration technologies, and new architectures for computing."
Debenedictis, E. P.. (2017). It's Time to Redefine Moore's Law Again. Computer

Plain numerical DOI: 10.1109/MC.2017.34
DOI URL
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"The familiar story of moore's law is actually inaccurate. this article corrects the story, leading to different projections for the future. moore's law is a fluid idea whose definition changes over time. it thus doesn't have the ability to 'end,' as is popularly reported, but merely takes different forms as the semiconductor and computer industries evolve."
Eeckhout, L.. (2017). Is Moore's Law Slowing Down? What's Next?. IEEE Micro

Plain numerical DOI: 10.1109/MM.2017.3211123
DOI URL
directSciHub download

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"This column discusses the current state of moore's law, potential solutions to the slowdown, and how crucial it is that technology continue to innovate."
Lundstrom, M. S., & Alam, M. A.. (2022). Moore's law: The journey ahead. Science

Plain numerical DOI: 10.1126/science.ade2191
DOI URL
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"High-performance electronics will focus on increasing the rate of computation the transistor was invented 75 years ago, and the integrated circuit (ic) soon thereafter. the progress in making transistors smaller also led to them becoming cheaper, which was famously noted as moore's law (1). today's sophisticated processor chips contain more than 100 billion transistors, but the pace of downsizing ('scaling') has slowed and it is no longer the only or even main design goal for improving performance in particular applications. how can moore's law continue on a path forward? new approaches include three-dimensional (3d) integration that will focus on increasing the rate of information processing, rather than on increasing the density of transistors on a chip. "
Peper, F.. (2017). The End of Moore's Law: Opportunities for Natural Computing?. New Generation Computing

Plain numerical DOI: 10.1007/s00354-017-0020-4
[DOI URL]
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“The impending end of moore’s law has started a rethinking of the way computers are built and computation is done. this paper discusses two directions that are currently attracting much attention as future computation paradigms: the merging of logic and memory, and brain-inspired computing. natural computing has been known for its innovative methods to conduct computation, and as such may play an important role in the shaping of the post-moore era.”

Lu, C. P.. (2017). AI, native supercomputing and the revival of Moore’s Law. APSIPA Transactions on Signal and Information Processing

Plain numerical DOI: 10.1017/ATSIP.2017.9
[DOI URL]
[directSciHub download]

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“Artificial intelligence (ai) was the inspiration that shaped computing as we know it today. in this article, i explore why and how ai would continue to inspire computing and reinvent it when moore’s law is running out of steam. at the dawn of computing, alan turing proposed that instead of comprising many different specific machines, the computing machinery for ai should be a universal digital computer, modeled after human computers, which carry out calculations with pencil on paper. based on the belief that a digital computer would be significantly faster, more diligent and patient than a human, he anticipated that ai would be advanced as software. in modern terminology, a universal computer would be designed to understand a language known as an instruction set architecture (isa), and software would be translated into the isa. since then, universal computers have become exponentially faster and more energy efficient through moore’s law, while software has grown more sophisticated. even though software has not yet made a machine think, it has been changing how we live fundamentally. the computing revolution started when the software was decoupled from the computing machinery. since the slowdown of moore’s law in 2005, the universal computer is no longer improving exponentially in terms of speed and energy efficiency. it has to carry isa legacy, and cannot be aggressively modified to save energy. turing’s proposition of ai as software is challenged, and the temptation of making many domain-specific ai machines emerges. thanks to deep learning, software can stay decoupled from the computing machinery in the language of linear algebra, which it has in common with supercomputing. a new universal computer for ai understands such language natively to then become a native supercomputer. ai has been and will still be the inspiration for computing. the quest to make machines think continues amid the slowdown of moore’s law. ai might not only maximize the remaining benefits of moore’s law, but also revive moore’s law beyond current technology.”

MacK, C.. (2015). The Multiple Lives of Moore’s Law. IEEE Spectrum

Plain numerical DOI: 10.1109/MSPEC.2015.7065415
[DOI URL]

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“A half century ago, a young engineer named gordon e. moore took a look at his fledgling industry and predicted big things to come in the decade ahead. in a four-page article in the trade magazine electronics, he foresaw a future with home computers, mobile phones, and automatic control systems for cars. all these wonders, he wrote, would be driven by a steady doubling, year after year, in the number of circuit components that could be economically packed on an integrated chip. a decade later, the exponential progress of the integrated circuit-later dubbed ‘moore’s law’ – showed no signs of stopping. and today it describes a remarkable, 50-year-long winning streak that has given us countless forms of computers, personal electronics, and sensors. the impact of moore’s law on modern life can’t be overstated. we can’t take a plane ride, make a call, or even turn on our dishwashers without encountering its effects. without it, we would not have found the higgs boson or created the internet. but what exactly is moore’s law, and why has it been so successful? is it evidence of technology’s inevitable and unstoppable march? or does it simply reflect a unique time in engineering history, when the special properties of silicon and a steady series of engineering innovations conspired to give us a few decades of staggering computational progress?”
Track, E., Forbes, N., & Strawn, G.. (2017). The End of Moore’s Law. Computing in Science and Engineering

Plain numerical DOI: 10.1109/MCSE.2017.25
DOI URL
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“The guest editors of this special issue provide readers with a unique mix of perspectives to develop a deeper understanding of the issues surrounding moore’s law and the prospects for continued exponential growth in the coming era of computing. the field is indeed too large for a thorough treatment of all its aspects within one special issue. nevertheless, they believe that the insights that can be gained by including different perspectives on technology, science, engineering, and economics from those who are recognized leaders in their disciplines should complement and possibly even extend other treatments of the subject.”
Waldrop, M. M.. (2016). The chips are down for Moore’s law. Nature

Plain numerical DOI: 10.1038/530144a
DOI URL
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“The semiconductor industry will soon abandon its pursuit of moore’s law. now things could get a lot more interesting.”

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Dean, J., Patterson, D., & Young, C.. (2018). A New Golden Age in Computer Architecture: Empowering the Machine-Learning Revolution. IEEE Micro

Plain numerical DOI: 10.1109/MM.2018.112130030
[DOI URL]
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“The end of moores law and dennard scaling has led to the end of rapid improvement in general-purpose program performance. machine learning (ml), and in particular deep learning, is an attractive alternative for architects to explore. it has recently revolutionized vision, speech, language understanding, and many other fields, and it promises to help with the grand challenges facing our society. the computation at its core is low-precision linear algebra. thus, ml is both broad enough to apply to many domains and narrow enough to benefit from domain-specific architectures, such as googles tensor processing unit (tpu). moreover, the growth in demand for ml computing exceeds moores law at its peak, just as it is fading. hence, ml experts and computer architects must work together to design the computing systems required to deliver on the potential of ml. this article offers motivation, suggestions, and warnings to computer architects on how to best contribute to the ml revolution.”
Fuchs, A., & Wentzlaff, D.. (2019). The Accelerator Wall : Limits of Chip Specialization Transistor Performance. 5th Annual IEEE International Symposium on High-Performance Computer Architecture (HPCA)

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“Specializing chips using hardware accelerators has become the prime means to alleviate the gap between the growing computational demands and the stagnating transistor budgets caused by the slowdown of cmos scaling. much of the benefits of chip specialization stems from optimizing a computational problem within a given chip’s transistor budget. unfortunately, the stagnation of the number of transistors available on a chip will limit the accelerator design optimization space, leading to diminishing specialization returns, ultimately hitting an accelerator wall. in this work, we tackle the question of what are the limits of future accelerators and chip specialization? we do this by characterizing how current accelerators depend on cmos scaling, based on a physical modeling tool that we constructed using datasheets of thousands of chips. we identify key concepts used in chip specialization, and explore case studies to understand how specialization has progressed over time in different applications and chip platforms (e.g., gpus, fpgas, asics). utilizing these insights, we build a model which projects forward to see what future gains can and cannot be enabled from chip specialization. a quantitative analysis of specialization returns and technological boundaries is critical to help researchers understand the limits of accelerators and develop methods to surmount them.”
CAO, G., GUO, G.-P., LI, H.-O., ZHANG, X., & WANG, K.. (2017). Quantum computation based on semiconductor quantum dots. SCIENTIA SINICA Informationis

Plain numerical DOI: 10.1360/n112017-00118
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“Quantum computing is the outcome of the size of semiconductor chips breaking the limits of classical physics, and is a landmark technology in the post-moores law era. making use of the quantum properties of electrons in semiconductor quantum dots is believed to be one of the most promising candidates for the realization of quantum computing. in recent years, a series of breakthroughs have been made, including the preparation and readout of qubits, and the manipulation of quantum logic gates. this paper first introduces the background and significance of research on semiconductor quantum dot-based quantum computing and then provides an overview of the developments regarding spin-, charge-, and few-electron-based qubits, as well as the long distance coherent coupling of qubits. finally, we discuss future trends in semiconductor-based quantum computing.”
Chien, C. F., Wu, C. H., & Chiang, Y. S.. (2012). Coordinated capacity migration and expansion planning for semiconductor manufacturing under demand uncertainties. International Journal of Production Economics

Plain numerical DOI: 10.1016/j.ijpe.2011.10.024
DOI URL
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“Semiconductor industry is very capital intensive in which capacity utilization significantly affect the capital effectiveness and profitability of semiconductor manufacturing companies. due to constant technology advance driven by moores law in semiconductor industry, multiple production technologies generally co-exist in a wafer fabrication facility with utilization of a pool of common tools for multiple technologies and critical tools dedicated for a specific technology. because part of the equipment is common for products of different technologies, production managers have limited flexibility to dynamically allocate the capacity among the technologies via capacity migration. the possibility of capacity migration and interrelationship among different technologies make capacity planning difficult under demand and product-mix uncertainties. this paper aims to develop a dynamic optimization method that captures the unique characteristics of rolling demand forecast mechanism to solve capacity expansion and migration planning problems in semiconductor industry. in semiconductor industry, demand forecasts are rolling and updated when the latest market and demand information is available. this demand forecast mechanism makes forecast errors in different time periods correlated. we estimate the validity and robustness of the proposed dynamic optimization method in an empirical study in a semiconductor manufacturing company in taiwan. the results showed practical viability of this approach and the findings can provide useful guidelines for capacity planning process under rolling forecast mechanism. © 2011 elsevier b.v. all rights reserved.”
Dwivedi, A., & Dwivedi, A.. (2008). Emerging Trends in Nano Technology for Modern Industries. Certified International Journal of Engineering and Innovative Technology (IJEIT

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“Whenever we go for a morning walk in the mughal garden, we see peacocks dancing with their colourful feathers. when we look at the deep and beautiful colours on the feathers of the peacock, we have often wondered how even after many years, the colour of the peacock feather does not fade away. even we keep peacock feathers in our books. this phenomenon of long lasting original colour to the peacock has come from god’s own creation of nano materials coated in a peacock’s feather; and they diffract light, which gives us the rich colours everything in this universe-from giant stars to our bodies work on a molecular scale. our hearts and lungs are big objects but all the processes take place at the molecular level. therefore, everything in our body and in the physical universe is already based on nanotechnology. observation of nature and the role of science in understanding it from our research in nano sciences can be converted into a technological product by using the same or similar nano materials which gave the natural colour to the peacock’s feathers, as part of our shirts, sarees, fabric and apparels. it is a welcome destination for science to mature into technology and become a product of utility for society. nanotechnology has transformed and modernized the materials industry by empowering scientists to manipulate materials at the atomic level. nanotechnology, is the ability to work with matter at a nanoscale, measured in the length of approximately one-to-100 nanometers (a nanometer being one billionth of a meter)-which changes the fundamental properties of matter. one nanometer being equivalent to the width of three or four atoms. ‘it is more restrictive than most definitions, but contains critical distinctions that help guide people to true applications of nanotechnology, such as the specification that there must be novel features due specifically to the smaller size.’-greg schmergel in this paper we have discussed the use of nanotechnology in various areas industry. today, rfid is used in enterprise supply chain management to improve the efficiency of inventory tracking and management. however, growth and adoption in the enterprise supply chain market is limited because current commercial technology does not link the indoor tracking to the overall end-to-end supply chain visibility. rfid (radio frequency identification) is new emerging area, work on radio frequency & used for material tracking. the product identification & tracking is today’s majo…”
Thylén, L.. (2006). A Moores law for photonics. In Proceedings of International Symposium on Biophotonics, Nanophotonics and Metamaterials, Metamaterials 2006

Plain numerical DOI: 10.1109/METAMAT.2006.335053
DOI URL
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“We formulate a ‘moore’s law’ for photonic integrated circuits, based on breaking down the diverse photonics device types in photonics circuits into equivalent basic elements or functions, making a comparison with the generic elements of electronic integrated circuits more meaningful. the results serve as a benchmark of the evolution of photonic integrated circuits. © 2006 ieee.”