Digital Innovations & Contemporary Research in SCIENCE, ENGINEERING & TECHNOLOGY
Vol. 6. No. 1, March, 2018

Article Citation Format
Chiadika Mario & Nwabudike Austine (2018). Moore's Law and Future Technology
Journal of Digital Innovations & Contemp Res. In Sc., Eng & Tech. Vol. 6, No. 1. Pp 145-154

Article Progress Time Stamps

Article Type: Research Article
Manuscript Received: iSTEAMS Extended paper
Review Type: Blind
Final Acceptance:: 29th March, 2018
DOI Prefix: 10.22624

Moore's Law and Future Technology

[1]Chiadika Mario & [2]Nwabudike Austine
[1]Computer Engineering Department
[2]Computer Science Department
Delta State Polytechnic
Ogwashi-Uku, Delta State, Nigeria.

[1]Correspondence E-mail: anwumario@yahoo.com

ABSTRACT

The expression "Moore's' Law" is used to describe several predictions about the speed of computers, it show that a form of these laws along with some simple number theory, explains why the rate at which the log of the number of digits in the largest known prime has grown linearly Moore extrapolated that computing would dramatically increase in power, and decrease in relative cost, at an exponential pace that the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented. Moore predicted that this trend would continue for the foreseeable future. In subsequent years, the pace slowed down a bit, but data density has doubled approximately every 18 months, and this is the current definition of Moore's Law, which Moore himself has blessed. Most experts, including Moore himself, expect Moore's Law to hold for at least another two decades.

Keywords — Moore, Future, Technology, Evolution, Digital Age & , Integrated Circuits

---

1. INTRODUCTION

Back in 1965, a rising young Engineer called Gordon Moore (who went to co-found Intel) noted that computer had a habit of doubling in power every eighteen (18) months or so. His observation came to be enshrined as Moore's law and remarkably still holds true today. Moore anticipated that 18month doubling trend based on what he had seen in early year of computer chip manufacture. In his 1965 paper he plotted the number of transistor that fit on a chip since 1959 and saw a pattern of yearly doubling that he then extrapolated for more decades. (Kyle, 2003). Moore's law is the observation that the number of transistors in a dense integrated circuit doubles approximately every two years. The observation is named after Gordon E. Moore, the co-founder of Intel and Fairchild Semiconductor, whose 1965 paper described a doubling every year in the number of components per integrated circuit and projected this rate of growth would continue for at least another decade. (Moore, 2015).

According to Peter Denning ,a computer scientist at the naval postgraduate school in California, his doubling prediction was turned down into an industry objective for computing companies " it might be a self-fulfilling law" science has mysteries and in some ways this one of those mysteries. Denning adds also that certainly, if the rate could have gone faster, someone would have done it, notes computer scientist Calvin Lin of the University of Texas at Austin. The computer industry is moving ahead like no other, the primary driving force is the ability of chip manufacture to pack more and more transistors per chips every year. More transistors, which are tiny electronic switches, means larges memories and more powerful processors. Since each new generation had four times as much memory as its predecessor, he realized that the number of transistors on a chip was increasing at a constant rate and predicted this growth would continue for decades to come. (Andrew 2010).

Moore law's is an empirical observation about how fast solid state physicists and process Engineers are advancing the state of art and prediction that they will continue at the same rate in the future. Some industry observers expect Moore's law to continue for at least another decade, at that point transistors will consist of too few atoms to be reliable although advances in quantum computing may conceivable change that. (Oskin et al 2002). Moore's law is not really a law like those describing gravity or the conservation of energy. It is a prediction that the number of transistors (a computer's electrical switches used to represent 0s and 1s) that can fit on a silicon chip will double every two years as technology advances. This leads to incredibly fast growth in computing power without a concomitant expense and has led to laptops and pocket-size gadgets with enormous processing ability at fairly low prices. Advances under Moore's law have also enabled smart phone verbal search technologies such as Siri, It takes enormous computing power to analyze spoken words, turn them into digital representations of sound and then interpret them to give a spoken answer in a matter of seconds.(Annie,2015).

The implications of Moore's Law are quite obvious and profound. It is increasingly referred to as a ruler, gauge, benchmark barometer, or some other form of definitive measurement of innovation and progress within the semiconductor industry. As one industry watcher has recently put it:

> "Moore's Law is important because it is the only stable ruler we have today, It's a sort of technological barometer. It very clearly tells you that if you take the information processing power you have today and multiply by two, that will be what your competition will be doing 18 months from now. And that is where you too will have to be." (Malone 1996)

Moore's Law is that it has become an almost universal guide for an entire industry that has not broken stride in exponential growth rates for almost four decades now. The repeated predictability and regularity of Moore's Law are characteristics of the elusive perpetuum mobile for this industry. Some have referred to Moore's Law as self-reinforcing or a "self-fulfilling prophecy." Moore himself recently stated:

> "More than anything, once something like this gets established, it becomes more or less a self-fulfilling prophecy. The Semiconductor Industry Association puts out a technology road map, which continues this generation every three years. Everyone in the industry recognizes that if you don't stay on essentially that curve they will fall behind. So it sort of drives itself." (Moore 1996)

The primary driving force of economic growth is the growth of productivity, and Moore's law factors into productivity. Moore (1995) expected that "the rate of technological progress is going to be controlled from financial realities." The reverse could and did occur around the late-1990s, however, with economists reporting that "Productivity growth is the key economic indicator of innovation. (Jorgenson, et al 2014).

2. MOORE'S SECOND LAW

As the cost of computer power to the consumer falls, the cost for producers to fulfill Moore's law follows an opposite trend: R&D, manufacturing, and test costs have increased steadily with each new generation of chips. Rising manufacturing costs are an important consideration for the sustaining of Moore's law. This had led to the formulation of Moore's second law, also called Rock's law, which is that the capital cost of a semiconductor chip fabrication plant also increases exponentially over time. (Schaller 1996).

In 1977, Robert Noyce, then Chairman of the Board at Intel, wrote:

> "Today, with circuits containing 2^{18} (262,144) elements available, we have not yet seen any significant departure from Moore's law. Nor are there any signs that the process is slowing down, although a deviation from exponential growth is ultimately inevitable. The technology is still far from the fundamental laws of physics: further miniaturization is less likely to be limited by the laws of physics than by the laws of economics."

Almost two decades later, Noyce's foresight of economic limitations has brought about what has been referred to Moore's Second Law. (Ross 1995)

3. CENTRAL PROCESSING UNIT

A central processing unit (CPU) is the electronic circuitry within a computer that carries out the instructions of a computer program by performing the basic arithmetic, logical, control and input/output (I/O) operations specified by the instructions. The term has been used in the computer industry at least since the early 1960s.Traditionally, the term "CPU" refers to a processor, more specifically to its processing unit and control unit (CU), distinguishing these core elements of a computer from external components such as main memory and I/O circuitry. (Kuck.1978). The form, design and implementation of CPUs have changed over the course of their history, but their fundamental operation remains almost unchanged. Principal components of a CPU include the arithmetic logic unit (ALU) that performs arithmetic and logic operations, processor registers that supply operands to the ALU and store the results of ALU operations, and a control unit that fetches instructions from memory and "executes" them by directing the coordinated operations of the ALU, registers and other components.

Most modern CPUs are microprocessors, meaning they are contained on a single integrated circuit (IC) chip. An IC that contains a CPU may also contain memory, peripheral interfaces, and other components of a computer; such integrated devices are variously called microcontrollers or systems on a chip (SoC). Some computers employ a multi-core processor, which is a single chip containing two or more CPUs called "cores"; in that context, single chips are sometimes referred to as "sockets". Array processors or vector processors have multiple processors that operate in parallel, with no unit considered central. Thomas.2014).

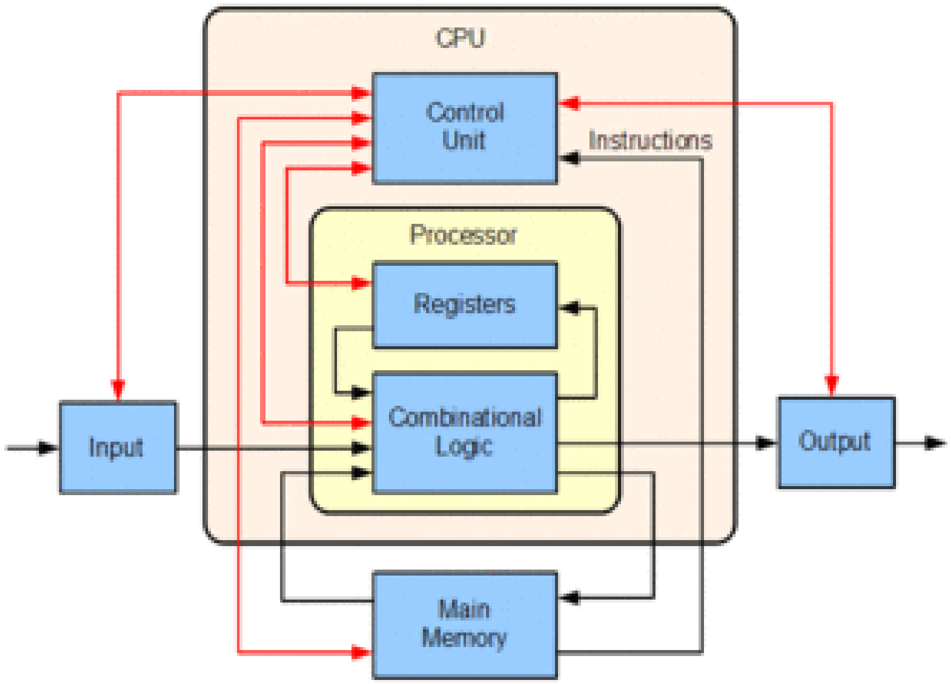

Fig 1: Typical diagram of a Central Processing Unit.

4. HISTORY OF MOORE'S LAW

In 1959, Douglas Engelbart discussed the projected downscaling of integrated circuit size in the article "Microelectronics, and the Art of Similitude Engelbart presented his ideas at the 1960 International Solid-State Circuits Conference, where Moore was present in the audience. For the thirty-fifth anniversary issue of Electronics magazine, which was published on April 19, 1965, Gordon E. Moore, who was working as the director of research and development at Fairchild Semiconductor at the time, was asked to predict what was going to happen in the semiconductor components industry over the next ten years. His response was a brief article entitled, "Cramming more components onto integrated circuits". Within his editorial, he speculated that by 1975 it would be possible to contain as many as 65,000 components on a single quarter-inch semiconductor (Evans, 2014).

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. His reasoning was a log-linear relationship between device complexity (higher circuit density at reduced cost) and time .(Schaller, 1996). At the 1975 IEEE International Electron Devices Meeting, Moore revised the forecast rate. Semiconductor complexity would continue to double annually until about 1980 after which it would decrease to a rate of doubling approximately every two years.

He outlined several contributing factors for this exponential behavior

- ✓ Die sizes were increasing at an exponential rate and as defective densities decreased, chip manufacturers could work with larger areas without losing reduction yields;
- ✓ Simultaneous evolution to finer minimum dimensions;
- ✓ And what Moore called "circuit and device cleverness".

Shortly after 1975, Caltech professor Carver Mead popularized the term "Moore's law". Despite a popular misconception, Moore is adamant that he did not predict a doubling "every 18 months." Rather, David House, an Intel colleague, had factored in the increasing performance of transistors to conclude that integrated circuits would double in performance every 18 month (Kanellos, 2005)

5. ENABLING FACTORS AND FUTURE TRENDS

Numerous innovations by scientists and Engineers have sustained Moore's law since the beginning of the integrated circuit (IC) era. A few innovations are listed below, as examples of breakthroughs that have advanced integrated circuit technology by more than seven orders of magnitude in less than five decades:

- ✓ The foremost contribution, which is the raison d'être for Moore's law, is the invention of the integrated circuit, credited contemporaneously to Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor.
- ✓ The invention of the complementary metal–oxide–semiconductor (CMOS) process by Frank Wanlass in 1963, and a number of advances in CMOS technology by many workers in the semiconductor field since the work of Wanlass have enabled the extremely dense and high-performance IC's that the industry makes today.
- ✓ The invention of the dynamic random access memory (DRAM) technology by Robert Dennard at I.B.M. in 1967, made it possible to fabricate single-transistor memory cells, and the invention of flash memory by Fujio Masuoka at Toshiba in the 1980s, leading to low-cost, high-capacity memory in diverse electronic products.
- ✓ The invention of chemically-amplified photo resistor by C. Grant Willson, Hiroshi Ito and J.M.J. Fréchet at IBM c.1980, that was 10–100 times more sensitive to ultraviolet light. IBM introduced chemically amplified photo resistor for DRAM production in the mid-1980s.
- ✓ The invention of deep UV excimer laser (exciplex laser) photolithography by Kanti Jain at IBM in 1980, has enabled the smallest features in IC's to shrink from 800 nanometers in 1990 to as low as 22 nanometers in 2012. This was built on the invention of the excimer laser in 1970, by Nikolai Basov, V. A. Danilychev and Yu. M. Popov, at the Lebedev Physical Institute. From a broader scientific perspective, the invention of excimer laser lithography has been highlighted as one of the major milestones in the 50-year history of the laser.
- ✓ The interconnect innovations of the late 1990s include that IBM developed CMP or chemical mechanical planarization in 1980, based on the centuries-old polishing process for making telescope lenses. CMP smooth's the chip surface. Intel used chemical-mechanical polishing to enable additional layers of metal wires in 1990; higher transistor density (tighter spacing) via trench isolation, local poly silicon (wires connecting nearby transistors), and improved wafer yield (all in 1995). Higher yield, the fraction of working chips on a wafer, reduces manufacturing cost. IBM with assistance from Motorola used CMP for lower electrical resistance copper interconnect instead of aluminum in 1997.

6. MOORE'S LAW AND THE FUTURE OF TECHNOLOGY

Computer industry technology road maps predict (as of 2001) that Moore's law will continue for several generations of semiconductor chips. Depending on 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. Intel was reported in 2005 as stating that the downsizing of silicon chips with good economics can continue during the next decade, and in 2008 as predicting the trend through 2029.

Given the engineering challenges, a little pessimism hardly seems out of place.

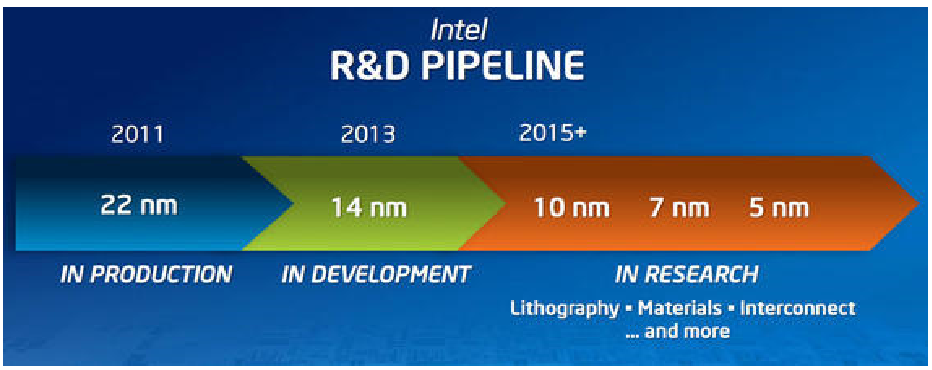

Fig 2 : Intel's current chip manufacturing road map extends to the 5nm process "node," scheduled to arrive in chips in 2019.

Gordon Moore's idea was to give people a sense of what was possible. His idea was to make electronics so cheap that we could put them into tiny computers that everybody could use. He wanted to show people that very, very rapidly this technology would get very, very cheap, but then, in 1970, a man named Carver Mead, who worked with Gordon Moore, took a deeper dive into the actual physics of transistors. He named them Moore's Law in around 1970 and showed that this trend could continue for probably another 20 to 50 years from now.

7. SOME OF THE NEW DIRECTIONS IN RESEARCH THAT MAY ALLOW MOORE'S LAW TO CONTINUE ARE:

At the same time, Moore recognizes that history has proven him and mostly everyone else wrong about past predictions. His closing remarks at a Microlithography Symposium in February 1995 challenged the participants to continue to "think smaller":

> "Semiconductor technology made its great strides as a result of ever increasing complexity of the products exploiting higher and higher density to a considerable extent the result of progress in lithography. As you leave this meeting I want to encourage each of you to think smaller. The barriers to staying on our exponential are really formidable, but I continue to be amazed that we can either design or build the products we producing today. I expect you to continue to amaze me for several years to come." (Moore 1995)

> "We have become addicted to speed. Gordon Moore is our pusher. Moore's law, which states that processing power will double every year and a half, has thus far held true. CPU designers, always in search of a better fix, drain every possible ounce of fat from processor cores, squeeze clock cycles, and cram components into smaller and smaller dies." (Joch 1996)

In 2008, researchers at HP Labs announced a working memristor, a fourth basic passive circuit element whose existence only had been theorized previously. The memristor's unique properties permit the creation of smaller and better-performing electronic devices. In 2010, researchers at the Tyndall National Institute in Cork, Ireland announced a junctionless transistor. A control gate wrapped around a silicon nanowire can control the passage of electrons without the use of junctions or doping. They claim these may be produced at 10-nanometer scale using existing fabrication techniques.

In 2011, researchers at the University of Pittsburgh announced the development of a single-electron transistor, 1.5 nanometers in diameter, made out of oxide based materials. Three "wires" converge on a central "island" that can house one or two electrons. Electrons tunnel from one wire to another through the island. Conditions on the third wire result in distinct conductive properties including the ability of the transistor to act as a solid state memory. Nanowire transistors could spur the creation of microscopic computers.

8. MATHEMATICAL EQUATION ON MOORE'S LAW

According to Carver Mead, our equation here is one way to mathematically render what came to be known as Moore's law. If P_0 is the current performance of something (say the number of electronic element that can be squeezed into one square centimeter on a chip) the equation predicts that the future performance n years later P_n rises exponential, the future performance is the case, equal to the current performance times two raised to the Nth power. The exponent n in the equation indicates that the performance doubles every years, other leaves have stated that the performance of electronic every year, other leaves have stated that the performance doubles every year, other have stated the performance of electronic devices is doubling more slowly then, that perhaps every 18 month and thus ,perhaps the exponent should be a little smaller, In 1975, Moore revised his 1965 prediction to a doubling of performance every two years, In the case ,our equation below will become

$$P_n = P_0 \cdot 2^{n/2} \qquad (1)$$

In any event ,the prediction of Moore's law have been eerily accurate ,as such each succeeding generation of computer chips has been shown to roughly follow Moore's original prediction, the prediction itself has been extended into the future . In 2008, Intel suggested that Moore's law would continue to hold until 2029, some prognosticators have been more optimistic other less so, the technology currently used to manufacture computer chips will eventually run into fundamental limits as transistors approach the size of individual atom, other technology, however may mature in the time to allow the improvement predicted by Moore's law to extend for into the future.

Table 1: Processor Chronology By Date Of Introduction

	Chip	Date	Speed	No Of Transistors
1	4004	NOV 1971	400 KHZ	2,300
2	8008	APRIL 1972	500-800 KHZ	3500
3	8080	APRIL 1974	2MHZ	4500
4	8085	MARCH 1976	5MHZ	6500
5	8086	JUNE 8, 1978	10MHZ,8 MHZ,5MHZ	9000
6	8088	JUNE 1979	8MHZ,6MHZ	29000
7	80286	FEB 1982	12MHZ,10MHZ, 6MHZ	55,000
8	INTEL 386 DX PROCESSOR	OCT 1985		
9	INTEL 386 SX PROCESSOR	JUNE 1998		
10	INTEL 386 SL PROCESSOR	OCT 1990		
11	INTEL 486 SX PROCESSOR	APRIL 1991		
12	INTEL 486 SL PROCESSOR	NOV 1992		
13	INTEL PENTIUM PROCESSOR	MARCH 1993		
14	INTEL DX4 PROCESSOR	MARCH 1994		
15	INTEL PENTIUM PRO PROCESSOR	NOV 1995		
16	INTEL PENTIUM II PROCESSOR	MAY 1997		
17	INTEL PENTIUM II XEON PROCESSOR	JUNE 1998	400 MHZ	22,000,000
18	INTEL PENTIUM III PROCESSOR	FEB 1999	500,400 MHZ	28,000,000
19	INTEL PENTIUM IV PROCESSOR	NOV 2000	1,5 GHZ, 1.4 GHZ	42,000,000
20	PENTIUM 4 PROCESSOR	APRIL 2001	1.7 GHZ	55,000,000
21	MOBILE INTEL PENTIUM 4 PROCESSOR-M	JUNE 24,2002	2GHZ,1.90 GHZ	220,000,000
22	MOBILE INTEL PENTIUM 4 PROCESSOR-M SUPPORTING HT TECHNOLOGY	SEPT 2003	3.20,3.06,2.80,2.66 GHZ (533 MHZ SYSTEM BUS)	410,000,000
23	INTEL CELERON PROCESSOR 360 AND 350	AUGUST 2004	1.4 GHZ, 1.3 GHZ	592,000,000
24	MOBILE INTEL PENTIUM 4 PROCESSOR SUPPORTING TECHNOLOGY 552	JAN 2005	3.46 GHZ	
25	INTEL PENTIUM PROCESSOR EXTREME EDITION 965	JAN 2006	3.73 GHZ	291,000,000,000
26	INTEL CORE 2EXTREME PROCESSOR QX9770	DEC 2007	3.20 GHZ	
27	CORE I3 MOBILE PROCESSOR	JAN 2010	4M CACHE, 2.93 GHZ, 1333 Mhz FSB) And I3-540(4M CACHE, 3.06 Ghz, 1333mhz FS)	2,000,000,000
28	CORE I5 PROCESSOR WITH 4 CORE	JAN 2011	6M CACHE, 2.3 Ghz TO 3.3 Ghz	
29	DESKTOP PROCESSOR IN THEIR A10 LINE, THE A10-5700	OCT 2012	4M L2 CACHE, 3.4 Ghz OR 4.0 Ghz IN TURBO MODE, 1866 Mhz FSB AND THE A10-5800K (4M L2 CACHE, 3.8 Ghz OR 3.8 Ghz IN TURBO MODE, 1866 Mhz FSB)	5,000,000,000

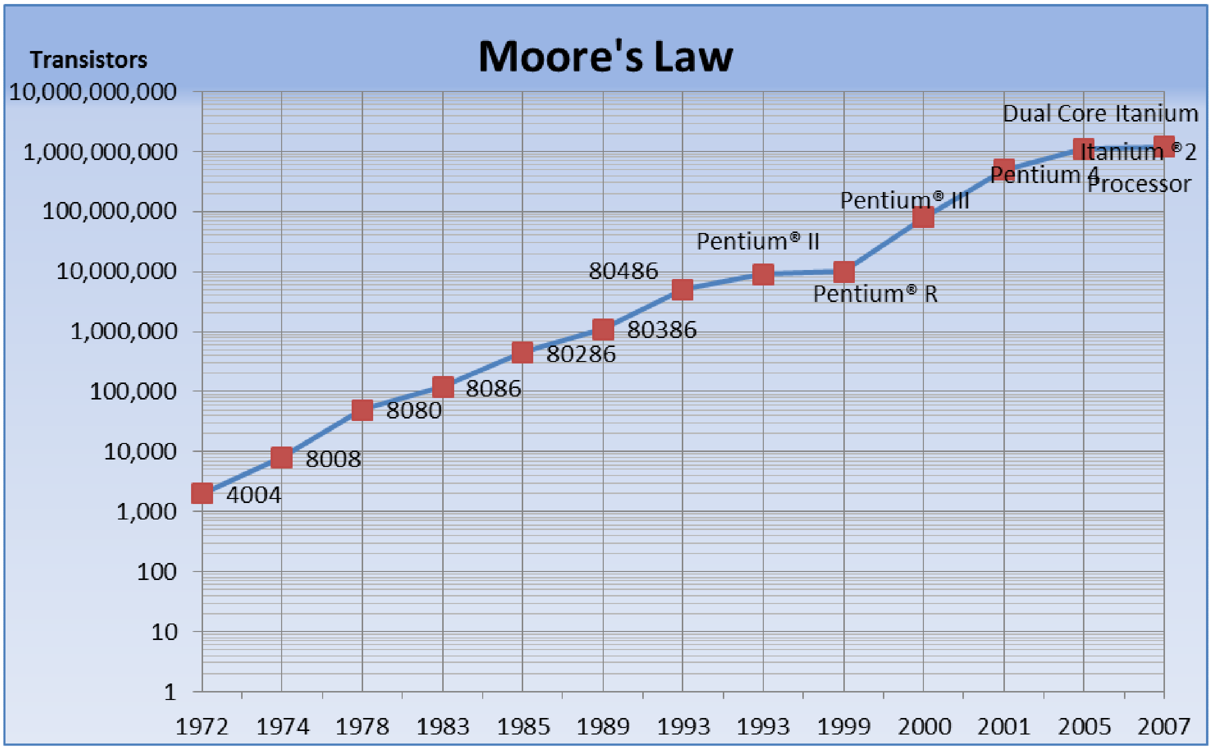

Fig 3: Production Progression from 1971 when 4004 was designed to 2007 when Dual core Itanium was released to the market

This figure about was done with the help of Microsoft excel moving from 1971 when 4004 was designed to 2007 when Dual core Itanium was released to the market. The analysis shows the increment in transistors infused in a processor for over the years as predicted by Gordon Moore

9. CONCLUSION

To keep up with Moore's Law, Engineers must keep shrinking the size of transistors. Intel, the leader in the race, currently uses a manufacturing process with 22-nanometer features. That's 22 billionths of a meter, or roughly a 4,000th the width of a human hair. For contrast, Intel's first chip, the 4004 from 1971, was built with a 10-micron (10,000-nanometer) process. That's about a tenth the width of a human hair. Today, mobile device is becoming smaller and lighter to meet the users' requirements and the most advanced logic technology node in production is 22 nm in 2012 and the target for 2013 will be 14 nm. With feature sizes below 100 nm, silicon technology has entered the realm of nanotechnology and continuing true Moore's Law becomes more and more difficult and requires new structures, materials, and technology The three important factors to reduce size are lithography, scalability of the planar CMOS transistor, and performance degradation due to pitch scaling, We have estimated that the potential future nanotechnologies will enhance the current known barriers for Moore's Law. Based on our estimations on the scale of these nanotechnologies, we further forecast the major milestones and key technologies that confront us in the near future. The computing industry and the world population have enjoyed five remarkable decades of Moore's Law and still continue in years to come.

REFERENCES

1. Moore, Gordon E. (1965-04-19). "Cramming more components onto integrated circuits" (PDF). Electronics magazine. Retrieved 2011-08-22.
2. Moore, Gordon E. (1965). "Cramming more components onto integrated circuits" (PDF). Electronics magazine. p. 4. Retrieved 2006-11-11.
3. Moore, Gordon. "Progress In Digital Integrated Electronics" (PDF). Retrieved July 15, 2015.
4. Jorgenson, Dale W.; Ho, Mun S.; Samuels, Jon D. (2014). "Long-term Estimates of U.S. Productivity and Growth" (PDF). World KLEMS Conference. Retrieved 2014-05-27.
5. "Overall Technology Roadmap Characteristics". International Technology Roadmap for Semiconductors. 2010. Retrieved 2015-10-08
6. Aizcorbe, Ana; Oliner, Stephen D.; Sichel, Daniel E. (2006). "Shifting Trends in Semiconductor Prices and
7. The pace of Technological progress". The Federal Reserve Board Finance and Economics Discussion Series. Retrieved 2014-05-15.
8. Moore, Gordon (March 30, 2015). Gordon Moore: The Man Whose Name Means Progress, The visionary Engineer reflects on 50 years of Moore's Law
9. Weik, Martin H. (1961). "A Third Survey of Domestic Electronic Digital Computing Systems". Ballistic Research Laboratory.
10. Kuck, David (1978). Computers and Computations, Vol 1. John Wiley & Sons, Inc. p. 12. ISBN 0471027162.
11. Thomas Willhalm; Roman Dementiev; Patrick Fay (December 18, 2014). "Intel Performance Counter Monitor – A better way to measure CPU utilization". software.intel.com. Retrieved 2015-02-17.
12. Schaller, Bob (1996-09-26). "The Origin, Nature, and Implications of "Moore's Law"".Research.microsoft.com. Retrieved 2011-08-22.
13. Kanellos, Michael (2005-04-11). "Intel offers $10,000 for Moore's Law magazine". ZDNET News.com. Retrieved 2013-06-21.
14. Schaller, Bob (September 26, 1996). "The Origin, Nature, and Implications of "MOORE'S LAW"". Microsoft. Retrieved September 10, 2014.