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Examining the limits of Moore’s law

Possible influence of technological convergence on redefining the curriculum in ICT institutions

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Moore's law of exponential growth predicted the doubling of processor speed per unit of area on silicon microchips with a doubling period of 18 months. This has continued to be the case ever since Gordon Moore first postulated this notion in a publication in 1965. Some researchers have estimated Moore's law will reach its physical limits within the next 15-20 years. Notably, the rate of growth has already slowly begun its decay over the past decade and viable alternatives that provide equal to or superior processing speeds for computations are already in research and development stages.

The aim of the project was to determine whether or not the emergence of the nanotechnology and microelectronics industries could end up re-defining the next era in information and communication technology (ICT) as Moore's law approaches the end of its growth doubling pattern. Through a review of literature, articles were analyzed thematically as the research aimed to identify possible trends in microelectronics relating to various restrictions from Moore's law continuing indefinitely. The results of this report found that technological convergence is a future event. However, institutions have an opportunity to be leaders of change as the next big technological changes unfold. Recommendations were presented to help Helsinki Metropolia University of Applied Sciences tailor their future curriculum in the IT degree programme to future student groups in accordance with a potential merger of technology industries.

Keywords	Moore’s law, limits, future, microprocessors, curriculum

Contents

Glossary

Thematic analysis - to identify, analyze, and report patterns also called themes within a collection of given data corpus.

Data corpus - the sum of data collected.

Data set - the sum of data from within the corpus used for particular analysis.

Data item - each individual bit of data included as part of the collection of data.

Data extract - an individual bit of data that has been identified or classified and extracted from a particular item of data.

Parallelism - using more than a single central processing unit (CPU) or processor core at once in order to execute a program of multiple computational threads. The end goal of parallel processing is to make programs run faster because there are more engines (system resources) running different tasks simultaneously. The opposite case would be serial processing, running one string in a series of data at a time before moving onto the next computation.

Scaling / Scalability - how well changes can be handled in a given system in a positive way and how well something can become more and shrink down to less in order to accommodate those changes.

1 Introduction

In 1965, a paper published by Gordon E. Moore (co-founder of Intel) stated that every 18 months the number of transistors on an integrated circuit would roughly double [1]. Moore's prediction of a growth pattern that would double the number of transistors per equal unit area soldered onto silicon chips (past) or silicon microchips (present) meant these chips would yield exponentially faster processing speeds [1].

After 50 years of exponential growth of available processing speed coupled with the constant shrinking of silicon chip sizes, all the way down the scale to microchips, Moore's law has definitely been proven valid as well as stood the test of time. However, it is clear the time of continued exponential growth at the 18 month doubling rate will come to an end sooner or later and Moore's exponential growth law will inevitably reach maturity experiencing a noticeable stunt in growth along the way. Observing the SI units scale, at first, transistors were soldered onto square inch plates of silicone, then the transistors were soldered onto square centimetre sized processor chips, followed by square millimetre sized microchip processors reaching now billions of transistors per microchip found on modern era microprocessors. Eventually, it is not possible to shrink any further down the SI units scale in terms plate size.

Some researchers have projected Moore's law to hit its inevitable wall by as early as the year 2020 while others have concluded a more optimistic end to the doubling of a number of transistors on a single microchip suggesting that the exponential growth curve will continue until at least sometime in the year 2032.

As the limits of Moore's law are approaching, which one should not confuse with a law of nature that has to be obeyed, there is an open opportunity presented to explore the viability of alternatives to the most commonly implemented processor architecture of our time. Nanotechnology and microelectronics are two key industries related to information and communication technology that will likely play a major role in shaping the future of the semiconductor industry's design and implementation of microprocessors. It follows that these relationships may very well require the re-defining of job titles and professional roles at an industrial level as well as a re-classification of minor subjects and professional study areas at an academic institution level.

The objective of this project is in part an exploration of alternatives to traditional silicon microchips. Also, an aim is to show how the inevitable end of Moore's law will create the opportunity for engineers to develop superior computation performance using less net power albeit using more complicated multi-level circuit designs to achieve these performance results. To be presented in later sections of this report, there is a learning curve to overcome and as transition occurs from one convention to the next it will become evident; there are no shortcuts toward the future trends of new age processor implementations and yet the cut towards more efficient processing and lower power consumption is not that long because the research and development has been underway for a while now. It will be presented, that new microprocessor solutions are being developed and prototyped, the technologies are steadily improving, and viability will occur when the market is ready. In a global economy predicated on specialization, customization of processors for different applications should follow. These ideas should be explicitly made aware to engineering students during their studies to ensure students are prepared at the onset of their professional careers.

Through presentation of evidence, it is the aim of this project to show Moore's law reaching its limits will open many doors for innovations within the semiconductor industry and related sectors as students have a chance to be the first to benefit from the changes through their acquired knowledge at university. This report attempts to illustrate how the needs of many consumers worldwide will diversify processor architecture design practice and integrated circuits of the future can end up being shaped by engineering students who are aware of current trends and who are up to the many challenges the future will present.

This research project sets out to explore issues surrounding the following research questions:

- What are some of the factors and current trends that will influence the future of how microprocessors are designed and implemented?
- Does the current research and development of microprocessor technology indicate a potential merging of ICT and nanotechnology / microelectronics industries on some levels?
- Are there ways universities could implement changes into the curriculum in proactively prepare their engineering students for the inevitable end of Moore's law?

2 Theoretical Background

Gordon Moore originally predicted the doubling of components per processor chip to occur once a year but later revised those remarks in 1975 to indicate a doubling period of roughly two years about a decade later. There were a significant number of contributing factors for this prediction being realized among them Dr. Moore namely attributed the "...advances in photolithography, wafer size, process technology, as well as circuit and device cleverness, especially in semiconductor memory arrays..." [1] as having the most important roles during this initial growth of complexity. Moore's idea was such a visionary one because even back then he believed in the notion that large circuits of high complexity could be built on a single silicon wafer for minimal cost per component. As mentioned in the introduction section, small scales are to be considered when designing these integrated circuits. Moore had earned a Ph.D. from the University of California in physical chemistry and knew the required specifications that needed to be used for such isolated high-performance circuits. For example, a two-mil square could have some kilo-ohms value of resistance or a few diodes. This made it possible for a minimum of 500 components per linear inch (a quarter million per square inch). Meaning, 65,000 components could be fit into a space no greater than one-fourth a square inch. [2] Figure 1 shows the relative manufacturing cost per component over time from the 1960's to the 1970's.

Moore believed that "...there is a minimum cost at any given time in the evolution of the technology. At present, it is reached when 50 components are used per circuit. But the minimum is rising rapidly while the entire cost curve is falling..." [2] Ultimately, one cannot talk about Moore's law without factoring in economics as well.

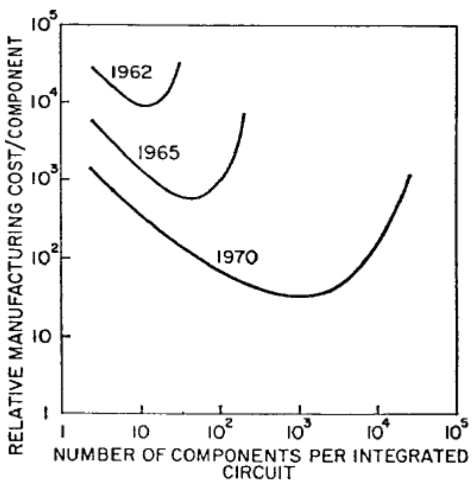


Figure 1. Cost per component over number of components per circuit. [2]

3 Methods and Materials

A review of literature was used as the research method to compile the corpus of data that was comprised for thematic analysis of this project. The collection of data was compiled from a wide range of online articles, which were then subsequently filtered down. Some of the searched articles were omitted from the data corpus prior to actual thematic analysis. Articles longer than 10 pages in length were omitted because of time management considerations and shorter articles were kept in favor of analysis from a more diverse range of authors and researchers. As a result, a greater number of short articles could be adequately analyzed in a comparable amount of time than one 25-page article from a single author.

The total number of online articles selected for the data corpus was greater than 60 from the search results. A variety of online search databases were used to find articles. All online search databases used had an online database of publications that allowed subscribers customizable search capability and access to full text versions of their listed articles in addition to a .pdf file download option. ACM Digital Library provided the majority of article hits offering a broad representation of articles from different industry and academic publication sources. Ebscohost is "the world's most-used reference resource" according to their website and some relevant articles were found from this information service. IEEE Explore is a digital library and provides content and publications that are specific to the technology sectors and the articles selected from this database were from reliable sources. ScienceDirect has a catalogue of roughly 2,500 journal articles and yet for this research project only a couple of hits were included as sources. Taylor and Francis online offers an outlet for research based publications from select press companies and yet only one article from their vast portfolio ended up relevant to this thematic analysis information search. Lastly, the Wiley Online Library also produced one article that hit on the keywords used during the extensive information search process.

Keywords used during the information search process were "Moore's law, limits of Moore's law, Moore's law end, and microelectronics trends." Early on in the process it became evident the first basic search phrase of 'Moore's law' produced the most results from the aforementioned search engines and information services. Adding more words in the search engines produced fewer hits or in some cases no results. This meant it was necessary to actively go through thousands of articles individually to determine potential candidates for inclusion into the data corpus prior to thematic analysis. The results ranged from online articles from current newly released publication to publications dating as far back as 2001. This range was selected so as to be inclusive of any relevant 21st century publications. The reason for this is because the focus of this research project is in part an exploration of future possibilities and to examine if there are notable current trends that will affect consumers of electronics, industries, as well as students of ICT. The focus was to look at literature in terms of a broader scope of microelectronics and microprocessors.

The keywords identified for thematic analysis included the following: Moore's law, nanotechnology, microelectronics, future, 3D, trends, limit, integration, and innovation. Accepted in the search were both the word itself as well as different versions of the root word. For example, when the word limit was highlighted different versions of the root such as the plural form limits, limited, or limitations would also be marked as keyword hits.

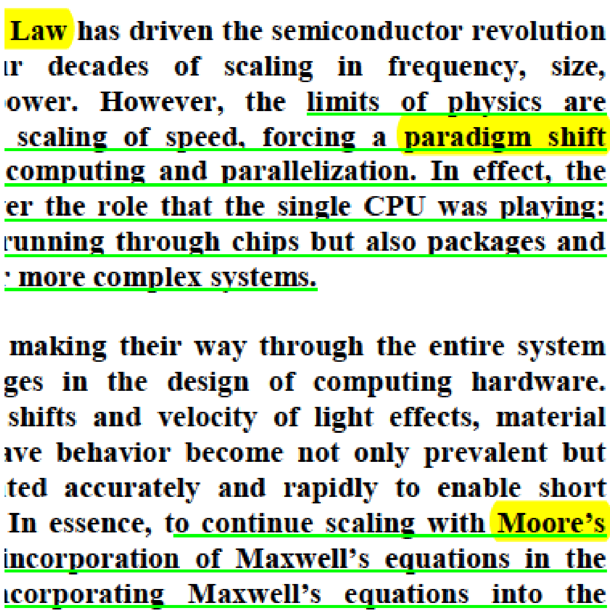
The research scope included the following: Looking for future solutions, discussion of trends in both speculative / anecdotal contexts, current production / design work, innovations, prototypes under development, overall exploration of alternatives to old paradigms and current semiconductor industry norms, mentions of and other laws of physics as they pertain to Moore's law.

Not included in the scope were the following: The mere mention of Moore's law without any kind of follow-up discussion or solutions given to mitigate the limitations of Moore's law, opinion pieces from authors who although writing for an otherwise credible publication, provided little substance to their publication, and any highly technical research articles that went into great detail regarding new implementations or possible methods that would arguably be more adequately discussed in a separate analysis about the same topic.

However, a large portion of the searched articles were from 10-30 pages. These articles were deemed as sources that were too dense to be included in the scope. The average number of pages in the articles was six. This report is intended to make constructive recommendations to an educational institution as opposed to a dissertation for industries.

Initially themes to explore in the data corpus included forecasting of the future direction of microprocessor implementation, paradigm shifts at an industrial scale in ICT, integration of current microprocessor design in combination with more experimental and forward-thinking ideas or concepts, innovative developments independent of Moore's law, and other alternative solutions that are hard to conceptualize unless they are explained in articles or presented through evidence.

Final thematic analysis is a deliberate process of reading and re-reading the articles included in the data corpus if necessary. Notes were made of the initial thoughts that came to mind that helped formulate the research questions outlined. Next, the coding of the data based on features was done in a systematic way across the entire data set, and the data was collated to each code. Once the codes were established (i.e. how to differentiate one bit of data from another), then collated codes were grouped by potential themes. Then, by review, the themes were checked in relation to the coded extracts followed by the entire data set. Upon more analysis, emerging themes were refined so the specifics of each particular theme, and the story the analysis explained started to take shape to produce clear definitions and made it possible to title each theme effectively. Ultimately, these five steps were necessary prior to the final analysis. The final phase was to select meaningful extract examples, final analysis of the selected extracts, and relating the thematic analysis back to the research questions and literature. Following these steps, the results will be compiled and explicated with a strong fundamental backbone to allow the data to be evaluated and further analyzed by the Helsinki Metropolia University of Applied Sciences faculty and board members.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running through chips but also packages and
more complex systems.

making their way through the entire system
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In essence, to continue scaling with Moore's
incorporation of Maxwell's equations in the
ıcorporating Maxwell's equations into the

Figure 2. Excerpt article highlighted, underlined and coded.

An excel sheet was created in order to catalogue articles in the scope and to score every keyword mentioned throughout each article (not including references). For example, in some articles Moore's law only appeared in the reference list and this was not counted as a keyword hit. However, this occurrence did not prevent the article from being included in the scope.

4 Results

Review of literature - 30 articles in scope for thematic analysis presented as excerpts

Article title: Be Absolute for death, life after Moore's Law

As mentioned in the introduction, current projections see Moore's law continuing to hold true for several years at the very least, which is significant when considering previous projections roughly 15 years ago; it was estimated in an article published in the Communications of the ACM magazine in March of 2001 that the curve of silicone density would hit a wall in either 2008 or 2010. At that time, the evidence presented was pointing towards problems with the process of photolithography, where the article mentioned "the lines etched onto the silicon wafers were becoming thinner than the wavelengths of light used to create them." [3] Although the slowing down of Moore's law has in fact begun it has been the combined efforts of microprocessor manufacturers such as Intel and AMD to keep the exponential growth continuing (i.e. maintaining the status quo or business as usual) for as long as possible which ended up ensuring growth well past 2010 as had been previously estimated. The article continues to postulate the possibility of technical innovation continuing even after the end of Moore's law. The example given was in reference to computing power relative to cost of materials and suggested perhaps the end of Moore's law will provide an opportunity for future designs to be built for a longer shelf life than only 18 months.

Article title: System's on a chip, what are the limits?

While reading an article from the Electronics & Communication Engineering Journal there was mention of a counter-part law to Moore's law known as 'Claasen’s law', which proposes that usefulness is a logarithmic function of technology. When Moore’s law and Claasen’s law are combined they make the perceived progression in systems a linear function of time. Thus, systems are subject to evolution as opposed to revolution: computers and other technology have become more complex exponentially, yet their main characteristic functions have improved solely in a linear fashion. [4] The article goes on to state that as we move towards increasingly complex designs in silicone technology economic factors will stipulate the need for the development costs to produce high yield results in the marketplace. This implies that companies will need to weigh the pros and cons of all projects that get the green light carefully. Meaning, companies cannot take unnecessary financial risks developing experimental processor technologies. The goal remains the same as it has been for 40 years, increased performance and faster computations at lower costs per operation. Engel Roza points out that "Moore’s law applies not only to silicon technology but also to information technology as a whole, since similar growth is also seen, for example, in magnetic and optical storage and in the use of embedded software." [4]

Article title: Carbon Nanotubes for Microelectronics?

The publication examined the overall exploration of alternatives to old paradigms and current semiconductor industry norms. It was surprising to learn that exploration of alternatives to traditional microelectronics were being written about as earlier as 2005 in a review article published in the Small Journal and written by Dr. Andrew P. Graham et al, titled 'Carbon Nanotubes for Microelectronics', where it was mentioned that there is learning curve and growth process happening as microelectronics aims to keep with Moore's law. Further development into the realm of nanotechnology what follows is dealing with things like Nano-structures and self-organization not to mention the integration of such aspects into reliable technologies. 3D incorporation might occur with regards to silicon technology and this might rectify the costly development of new lithographic exposure equipment. Therefore, carbon nanotubes are both better devices in terms of their potential as well as excellent counterpart for microelectronics moving in the direction of so called nano-electronics. [5] This was a claim made in reference to nanotechnology being still in the early stages at the time of the publication. Here it is suggested that in the future semiconductors for microelectronics might be a thing of the past and nanotubes made from carbon material could become a viable replacement as components parts inside of modern electronics. Since the ten years that have passed, semiconductors on silicon wafers are still the overwhelming processor design of choice for microelectronics manufacturers worldwide. While carbon nanotubes are not ready to replace semiconductors made under the Moore's law paradigm the applications are quite similar for what carbon nanotubes can be useful for. This article is a good example of researchers who were ahead of the curve in terms of their work and lab experiment because Dr. Graham and his colleagues were interested in the continued progression of microelectronics technologies using alternative materials to silicone in order to produce interconnects and transistors.

Article title: Moore's Law: Another Casualty of the Financial Meltdown

The publication mentioned a key point also shown by other articles, which is the realization that Moore's law is more so an economic notion as opposed to a physical law. The article is an excerpt from panel experts who explored some of the potential alternatives to more traditional microprocessor architectures - the driving force during the new millennium have been the development of innovative solutions taking us into an area known as "Moore than Moore", which applies to various packaging related 3D solutions namely SiP (Systems in Package) and PoP (Package on Package). It would be noted, neither one of these solutions was around a decade ago. Furthermore, there are many opportunities still yet to be capitalized on fully by engineers. Presently, designs exist that are 45/40 nanometers in scale and production is being ramped up to as small as 28 nanometer scale design kits that are being worked on by designers. [6] Ultimately, this article tended to focus on characterizing alternative approaches to Moore's law when it comes to microprocessor designs and 3D solutions that have only recently been developed.

Article title: Three Steps to Thermal Noise Death of Moore's Law

The article excerpt introduced another law theorized by physicist Rolf Landauer known as the Landauer limit, which needs to be factored in when calculating the end of certain technological progress as it relates to Moore's law implementations - in terms of the limit of energy that can be spent on processing a single bit of data of a CMOS logic it is calculated that one bit of data is equal to Landauer's limit (according to estimation using the proposed model from the article). The energy limiting is not obtainable unless there is sophisticated coding of the processed data. In order to avoid processing of the coded data, a lot more energy must be used to process one bit of data. This paper detailed the estimation of three limiting energies from the proposed model of a logic gate. The results of the study found "the limiting energies can be used, with Moore's law, to predict time after which development of CMOS technology is no longer possible." [7]

Article title: Moore's Law and energy and operations savings in the evolution of optical transport platforms

The article differentiated two ideas in terms of the original 1965 research as well as more recent continued research from a different discipline in relation to the optics platforms - Moore's law as it was defined in its original form there was change in number of transistors, the space was physical size of the integrated circuit chip and the period of change versus space was roughly one year and six months. Likewise, these three elements can be applied to the computing speed of a processor where the change would be the clock speed or frequency of the processor (dominating the computation of each micro step during execution of a machine instruction), the space would still be the processor chip, and the period would remain the same at 18 months. For this example, the change element in Moore's law would be extended from the number of transistors (original form) to now the exponential growth of processing speed. [8] In other words, Moore's law originally used to be concerned about the number of transistors per wafer in particular. Whereas, today chip manufacturers are more concerned with exponentially greater clock speeds per chip. Thus, even Moore's law has been reframed over time to stay relevant with the current paradigm of technological developments throughout each era Moore's law has been followed by industry. Once the scales shrunk down small enough, there has been a switch from the saving of raw materials to energy and operations savings as seen here in the optics and photonics industry.

Article title: Analysis of Universal Logic Gates Using Carbon Nanotube Field Effect Transistor

The article outlined how carbon nanotubes appear to be a leading candidate as a viable alternative to current microprocessor designs - "Due to extraordinary physical and electrical properties, carbon nanotubes have become one of the most promising technologies that might someday pick up where conventional CMOS devices leave off ... The unique properties of carbon nanotubes due to their one dimensional character and the peculiar electronic structure of graphite and the fact that, its diameter can be controlled by chemistry and not by conventional fabrication techniques may make them the natural successor to silicon microelectronics." [9] The article goes on to propose that the adoption of new materials or technologies is obligatory as these will conserve much of what is beneficial about the current silicon technology and be able to endure with the problems pertaining to physical limits persisting improvement trends into the future. Alternative materials namely Ge (Germanium), SiGe (Silicon Germanium) compound semiconductors as well as different devices such as ultra-thin body fully depleted SOI MOSFETs (Silicon On Insulator Metal Oxide Semiconductor Field-Effect Transistors) present a host of new challenges. In the end, the superior solution would be carbon nanotube technology. [9] It seems convergence between new and old paradigms might be indicative of a future trend in the semiconductor industry regarding microprocessor implementations as evidence of the silicon germanium alternative to pure silicon.

Article title: Scaling: More than Moore's law

The article outlined how Moore's law will ultimately have to branch out and diversify its efforts across other technologies in order to prevent slowing down more than it already has the past ten years. - The limits of circuits will continue to be driven by technologists. Circuits in terms of "sub-threshold and near-threshold design, multi-radio smarts and interfaces), systems (spatially adaptive ultra-low duty-cycled), and processing (driven by applications that can be made parallel)." Although typical photolithography-driven scaling down to 20 nanometers is uncertain, equivalent scaling will be made possible via software, stacking, architecture, and other 'More than Moore' technologies. [10] If one redefines the rules of Moore's law and allows other contributing factors for scaling to continue then arguably the curve will still continue for some time in the future. However, perhaps then, this should be considered or named another law completely? In this article 'More than Moore' appears once again as a topic of discussion when exploring alternatives in the third dimension. The goal is to get a better density and electrical performance out of each chip in this new 3D approach. More innovation will be required to achieve these lofty goals but this might be possible considering the research is being worked simultaneously at different institutions so the efforts could presumably be combined at some point. If not, the competitive approach of keeping intellectual property and research results private from competitors also has its merits.

Article title: Design-Aware Lithography

The article continued to explain in more technical detail the limitations of lithography as an approach to Moore's law designing in the 21st century. As the study showed, the foremost obstacle in terms of manufacturing borders on the process of lithography. Lithographic tools have not succeeded in run alongside of Moore's law. Most notably, the wavelength of light used for lithography has been constant at 193 nanometers for a considerable amount of time, while feature sizes being printed are a small portion of that. Even usage techniques like immersion lithography, the lithographic k1 factor has regularly been comparable to its theoretical single exposure limit of 0.25. As technology scaling moves ahead with limited lithographic capabilities remaining, there exists a tendency to move in the direction of heightened co-optimization of design and process. A leading enabler is to strengthen the design-manufacturing interface to grant additional information yield compared to typical layout shapes to propagate to lithography. [11]

Article title: Surviving the end of frequency scaling with reconfigurable dataflow computing

The article provided a brief review of the history of popular microchip manufacturer Intel - For the past decade the x86 processor architecture has cemented a place at the core of the majority of supercomputers in the world today. Presently, approximately four fifths of the supercomputers listed in the TOP 500 are comprised of one variation of another of Intel's processor architecture. Embracing the x86 architecture has been fueled by in large by economic factors and formidable economies of scale on the backs of both consumer and low end server x86 markets have brought down the per unit costs leading many to construct larger and more complex computer systems. Furthermore, clock frequencies of cores started to stagnate back in 2004 and as a consequence conventional processors have been impelled to adopt multi-core architectures. Thus, the dawn of multiple-core chips using multiple identical cores have aimed to achieve enhanced performance through what is known in the industry as parallelism. [12] The implications here are that parallelism are going to be at the forefront of future Intel releases into the marketplace in order to maintain a competitive advantage.

Article title: System-Level Design Exploration for 3-D Stacked Memory Architectures

The article explored another dimension of scaling, whereas the old Moore's law looking to shrink down in scale this article examines the possibilities of growing up in scale - Over the years, classical technology scaling of semiconductor chips ensued Moore's law. Nonetheless, the improvements seen on transistor performance are limited and doubling of frequency every 24 months is not going to happen. Lately, three dimensional integrated circuits (3D ICs) employing the vertically through-silicon vias or TSVs as a way of connecting each of the dies has been presented. 3D is an alternative solution to existent Package-on-Package (PoP) and System-in-Package (SiP) processes. Generally, the continued increasing of complexity of modern Systems on Chip (SoC) or embedded system design can be said to be acute. In order to accomplish the requisite design productivity when bearing in mind time-to-market pressure, an accepted solution is to use electronic system-level design methodology to design the system in the distinctive level of abstraction. Among the group, an important technology within ESL solutions would be to build the hardware / software co-simulation platform by implementing virtual prototyping concepts. [13] A combination of technology might be an ideal solution to keep up with demand. For the past 50 years, consumers have come to expect new releases every 18 months and for this reason there is pressure to continue offering products on a set schedule that match that expectation. Economics also play a role as manufacturers want to continue to grow their quarterly profit margins.

Article title: Moore meets Maxwell

The article was an important part of the scope because it explains the physical laws that need to be factored in while also introducing new hurdles if industry is intent on keeping pace with past deadlines - the laws of physics standing in the way of continued speed scaling and this will necessitate a paradigm shift in the direction of computing executed via multiple cores (and parallelization). Essentially, the system as a whole is behaving as a single central processing unit would being asked to do more. Signals will run at high speeds through the chips as well as packages and boards will be connected across more and more complex systems. In addition, the continuation of scaling in terms of Moore's law would necessitate the inclusion of Maxwell's equations into the process of design. "Incorporating Maxwell’s equations into the design flow is only possible through the combined power that new algorithms, parallelization and high-speed computing provide. At the same time, incorporation of Maxwell-based models into circuit and system-level simulation presents a massive accuracy, passivity, and scalability challenge." [14]

Article title: Impact of nanotechnology advances in ICT on sustainability and energy efficiency

The article explored alternatives from a different perspective, outlining the benefits of nanotechnology based circuit implementation. Here the research showed - within the optical-communication industry there is a lot of talk surrounding the ongoing research of photonic crystals because photonic crystals hold the potential to provide scientists the a lot more control over photons that would allow superior affability over such properties relative to say the lesser control of flow of electrons, which has effectively been what has powered the evolution of semiconductor technology to where it is today at least within the realm of information technology. Having said that, with the goal of fitting a higher number of total transistors per chip (resulting in smaller and faster integrated circuits) more shrinking is still required. By shrinking down the physical chip size what happens is you get increased resistance and greater dissipation of energy and these contributing factors place limitations onto Moore's law.

Markovic et al stated: "Researchers are considering using light and photonic crystals (in alternative to electrons traveling in wires) for the new generation of integrated circuits. Light can travel much faster in a dielectric medium than an electron in a wire, and it can carry a larger amount of information per second. Given the impact that semiconductor materials have had on every sector of society, photonic crystals could play an even greater role in the 21st century]." [15]

Article title: CPU DB: Recording Microprocessor History

The article reviewed microprocessors of the past and speculated on the possible reasons why Moore's law has begun to slow down over the past ten years noting that - spanning a twenty year period (1985 to 2005) the increase in metal layers and sizable cache structures (that had high transistor densities) resulting in shrinking down the average size of one transistor by a factor of four. Moreover, dating back to the year 2005, transistor density has gone down by two times (more or less). The data collected does not pinpoint a reason as to the change in density. However, the reason might be due to both more stringent design rules for sub-wavelength lithography that use more powerful logic styles in the processor as well as a decreased overall size of the processor area used for cache in chip multiprocessors. Dating back to the mid-1970s, very large scale integration or VLSI designers have relied upon a significant degree of expertise from the field of engineering to generate and advance modern microprocessors. In the end, improved performance and better energy over output has gone down by many orders of magnitude which has caused microprocessors to be engines that drive the infrastructure of information technology. [16] Once more, the theme of energy efficiency is presented and discussed as something of a trend dating back to many years ago.

Article title: Near-Threshold Voltage (NTV) Design-Opportunities and Challenges

The article showed further exploration of alternative approaches to current microprocessor standards. It was outlined that in the golden days of Moore's law scaling and performance there were impressive advancements in transistor density, speed, and energy consumption seeing in some instances up to one thousand fold performance advancements. Progress is ongoing, however, further progress will not be easy to sustain and the reasons are twofold. On the one hand, technology scaling yields continued advancements for greater transistor density. Whereas, on the other hand, similarly little advancement is seen in terms of both transistor speed per capita and energy consumption per transistor. It follows that, moving forward in time, the frequency of operation will rise deliberately; and energy consumption will end up being the main thing hindering better performance. Moore's law will still offer a wealth of transistors for integration, but increased energy consumption per transistor will still be the price one has to pay. Near threshold voltage (NTV) operation of logic is able to advance the energy efficiency curve by an order of magnitude. [17]

Article title: What to do About the End of Moore's Law, Probably!

The article proposed new implementations for microprocessors as the limits of Moore's law are approaching through inexact design techniques. The researcher explains that - by considering the implementation of unreliable circuits and computing blocks from unreliable elements, as opposed to working to build reliable switches, circuits and computing hardware from potentially unreliable components then the end result would be an imaginably more robust domain of switches available. Thus, there would be less restriction given these conditions as previously when there was a greater emphasis on reliability than emphasis more on a broader selection of switches. Palem and Ligamneni proved this idea was more than just a concept and its feasibility was shown through various mathematical models namely 'random access machine' and also representative circuits where probabilities of the switches determine error. Furthermore, Palem and Ligamneni state "this idea is in stark contrast to conventional computing systems and hardware design wherein the hardware is expected to operate correctly all the time. In this context, automatic algorithmic methods are used widely across the layers of abstraction to achieve gains, to great effect." [18]

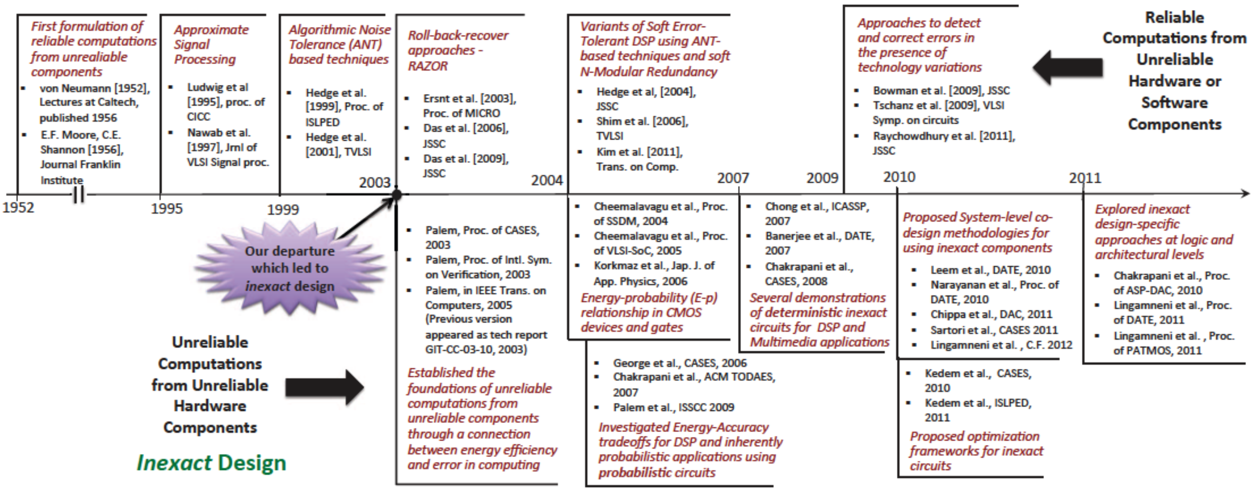

Figure 3. Timeline of research and innovations of inexact circuit design. [18]

Figure 3 showed it was over a decade ago (2003). Palem and Ligamneni began their mathematical experimentation of inexact circuit design, which was roughly seven years prior to the first reliable computations resulting from unreliable hardware of software components being achieved in 2010.

Article title: Past performance of assisted reproduction technologies as a model to predict future progress: a proposed addendum to Moore’s law

The article documented examples from the biomedical field of study and relates back to make recommendations the Moore's law as it is currently defined. Also, the article keys in on other laws of applied physics that have been discovered as a result of Moore's law - the atom transistor is where the theoretical limit between the relationship of memory expansion versus processor speed can be seen. In February of 2012, the first experimental atom transistor was reported. An atom transistor meant that transistors were spaced one atom apart from one another. Beyond this maximum density Moore's law can no longer expand. Moore's law has shown that computer hard drives and computational speed double every year and a half and speed actually expands at rate of 60% from year to year. Notably, there are a few other laws in applied physics which have borrowed from Moore's law. Namely, Nielsen's law predicts an annual doubling of internet bandwidth speed. Moreover, Metcalfe's law states that network value is proportional to the square of the total number of nodules. [19] It appears in terms of information technology and microelectronics there are similar patterns appearing and parallels can be drawn as far as the density of data being processed of transmitted across wires and through the air.

Article title: Chips Go Upscale

The article explained how although 3D are not a new idea there are still some chips that are being innovated in some areas of electronics that offer improvement over past designs, mentioning how - flips chips are a primitive form of 3D packaging that have been around for a while. To build a flip chip one must place two chips face to face joining them together via solder bump technique. A more advanced idea then flip chips would be to stack traditional 2D chips on top of one another to create layers according to required specifications of the application and finally to bond and electrically connect the edges together. Following this approach is both a practical and cost effective method while still using traditional semiconductor methods. The final outcome from the design perspective is a device that takes up a lot of real estate and so the application should be chosen accordingly (i.e. not ideal for tiny mobile electronics. Lastly, there is some performance loss traded off in exchange of more total chips as signals must flow between the different layer stacks. [20]

Article title: Spintronics for Low-Power Computing

The publication presented for discussion the research findings of Yue et al on spintronics as they relate to economic power in terms of low power consumption methods - "Yue et al addressed seven spintronic technologies and six computing systems or logic circuits that integrate the spin degree of freedom of electrons. Non-volatility provided by spintronics is a favorable alternative to overcome the power efficiency bottlenecks of microelectronics and spintronic devices are suitable to build up the computing logic blocks. Hybrid circuits are currently more mature than the other technologies. All spin logic and nano-magnet logic can provide the most efficiency for both power and scalability performances. However, there are still many challenges before practical applications of hybrid circuits will prove reliable." [21] Basically, these spintronics are nano-devices offer benefits reduced power, better reliability, and or provide a space for new functionalities to be introduced into circuits. The use of such technology in circuit design would help microprocessors steer clear of many undesirable characteristics of classical silicon microchips namely high consumption of power, heat dissipation, and issues regarding the reliability of computations.

Article title: ICE: Inline Calibration for Memristor Crossbar-based Computing Engine

The article introduced a computing engine for the future and test results demonstrate a power economical approach. The research shows that - a memristor is a device that offers ultra-high integration density that enables a high amount of signal connections inside of a small sized circuit. Such a device shows signs of promise that help propel Moore's law past the current silicon road map boundaries. In addition, crossbar structure of memristors, which is based on the variable resistance states allows for very high execution efficiency of the matrix vector multiplication. Matrix vector multiplication is a major part of artificial neural networks. Furthermore, the memristor crossbar-based computing engine or MCE can be utilized to achieve a low power approximate computing system. [22] Such a technology could prove to be revolutionary as a solution to alternative computing architecture. However, the researchers also mentioned their technology experiences a loss of precision over time the way it is currently set up. Most likely, more work and testing is required before this technology is truly ready for commercialization and yet it is important ground level work being conducted at participating Universities through joint research and development (Tsinghua University and University of Pittsburgh).

Article title: Moore's Law and the Sand-Heap Paradox

The article explained how Moore's law is not only about physics but also the financial side cannot be ignored. The editor of this article Moshe Y. Vardi chronicled that - economic factors are burdening the semiconductor industry while at the same time industry is having issues dealing with transistor density to allow better performance. Keep in mind, Moore's law has never only been about providing advanced performance rather there has been a prerequisite of getting better cost-performance, meaning Moore's law should also provide greater performance at a set price as well as less expense to silicon chip manufacturers. Robert Colwell, presently affiliated with DARPA the Defense Advanced Research Projects Agency and former chief architect at Intel Corp. of the IA-32 chip affirmed that he expects the death of Moore's law to come around the year 2020. Notably, Andrew A. Chien and Vijay Karamcheti contend that in terms of flash memories the exponential growth curve of Moore's law is over as of now. Furthermore, Chien and Karamcheti state that "increases in capacity will be accompanied by reduced reliability and performance." [23] With organizations like DARPA having calculated the end of Moore's law to come in the next five year window, I imagine plans are already underway as to an action plan that can be follow leading up to that fatal date, in terms of what technology to development would be a good investment for the next 50 years. Having said that, now is not the time to be thinking all doom and gloom because as has often been the case the end of an era has been followed swiftly be a new paradigm where perhaps Moore's law is no longer required to flourish exponentially. This editorial also mentions a repeating theme about the business side of ICT as the implications are inescapable; alternative approaches to Moore's law will have to help maintain profits companies have worked so hard to achieve over the years.

Article title: The Electronic Design Automation Challenges in the Dark Silicon Era

As found by Shaique et al - the power consumption of transistors does not scale proportionately in terms of integration density and as a consequence projections suggest that technology nodes in the future will only be conceivable to simultaneously power on a portion of cores on a multiple core chip to be able to still operate inside of the power budget. The powered off portion of the chip is also known as dark silicon and presents new obstacles to overcome. At the same time, there are opportunities for designers, especially with considering the reciprocal action of dark silicon and thermal, reliability, and variability concerns to be aware of. [24] Here there is evidence shown of another common theme established in the articles, in that, any solution under the sun comes packaged with inherent downsides and so the pros and cons must be weighted through calm and careful consideration of both sides of the equation before committing to develop alternatives further. The path towards innovation takes its own time and therefore cannot be rushed.

Article title: Efficient Code to Counter Dying Moore's Law

Software is another component to consider when pondering the future of Moore's law. Also, software might not be first that comes to mind when thinking about the production of silicon microchips and the expenses that companies must factor into their production budget if they want to maximize their investment into new solutions and innovative ideas. David Hemsath writes - "Developing resilient, secure, efficient software requires more skills, time, and money, along with a different mind-set, from what we see in the commercial software industry today. Software researchers and engineers alike (and the organizations funding them) must reset their expectations vis-à-vis hardware advances. New algorithms and new systems and better use of existing resources through virtualization and software parallelism can help mitigate the slowdown in hardware advances." [25] It turns out companies are well aware about effective ways of cutting costs on the raw materials and hardware side of their business. However, it may be that in the coming years companies should become just as aware about software efficiency as means to get more out of their hardware. This was a theme I thought would have been more prevalent going into this research project. In 2014, it came to mind that sometimes imagination or more likely re-imagination would be a good tool to use during times of change and when industries are in a state of flux. Sometimes industry professionals get comfortable in their jobs and stand back on their heels waiting for the next wave of technological change. Yet, sometimes all that is required is a rethink of technology that is already in place but is not being used as effectively as it could be such as the case with software parallelization opportunities that only require a different mind-set.

Article title: The Software behind Moore's Law

Software has also played a role in the shrinking of processors - it is not possible to optimize hardware to be faultless at nanometer scales. As a result, algorithms used for software control must correct hardware glitches on the basis of mathematical models that stipulate the inverted behavior. Technical challenges aside, production of chips has to account for both manufacturing and cost of ownership. Moore's law requires that the cost per gate correspondingly goes down. To accomplish this, a Dutch company ASML provides scanners that are fully automated and manufactured in high-speed factories. [26] 45 Million lines of code are running for the scanning technology at its current release. A scanner is basically an inverse microscope that prints the layout onto the integrated circuit chip (silicon wafer) what will eventually be etched on in later steps. After the pattern is exposed to the wafer the process of lithography continues to the next step.

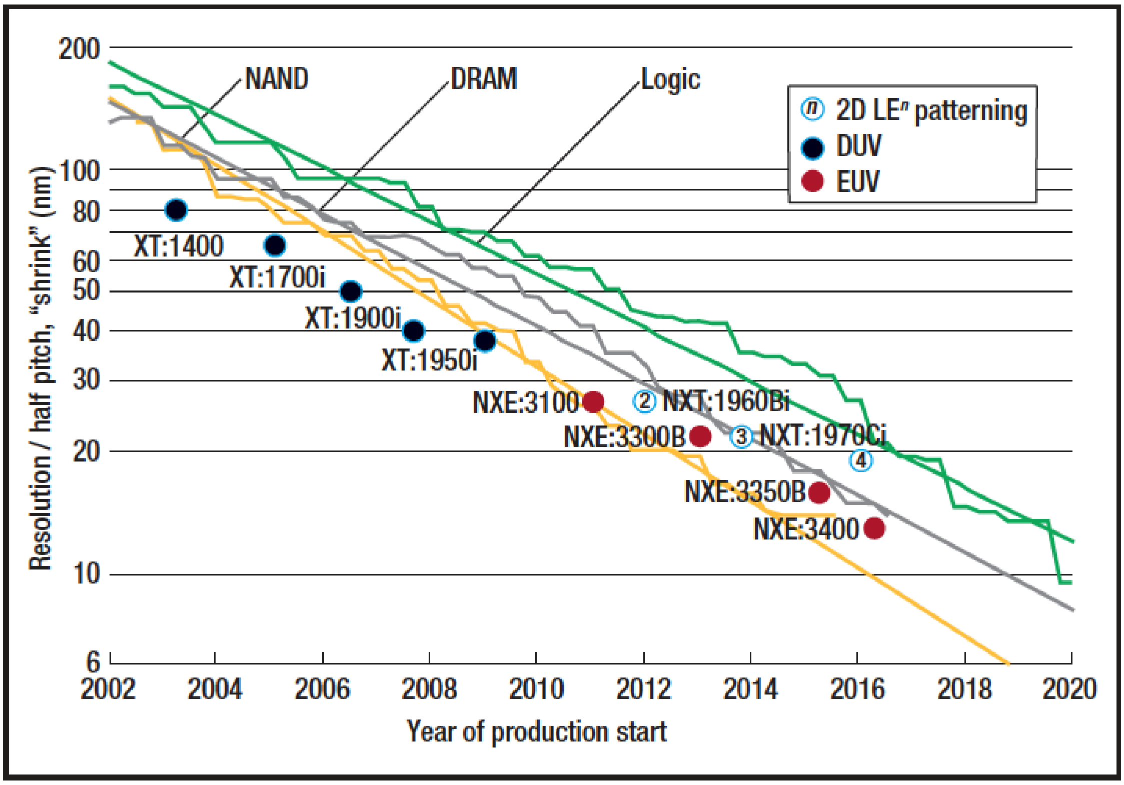

Figure 4. ASML plot of shrinking wafers over time. [26]

Without such improved resolution through increased complexity software code (from one release to the next) available and running at the manufacturing level of chips it would be hard to see Moore's law continuing for very much longer. Figure 4 shows basically an inverse curve than would be seen for Moore's law of exponential growth (which trends up, approaching infinity). ASML is one of the many companies that serves as a backbone to Moore's law especially the newer version of Moore's law that really emphasizes decreased size to keep costs per chip low.

Article title: Multicore Education, Pieces of the parallel puzzle

The article introduced yet another related law to Moore's law known as Moore's Dividend. This publication also suggests educators should help future professionals become more aware of the concept of parallelism in processors moving forward. It was chronicled that - presently, Moore's law continues to endure. Yet, Moore's Dividend that enabled software developers to expect progressively higher speed central processing unit speeds to allow for faster software is elapsed. Meaning, in order to achieve better performance on current and future hardware platforms applications have to be designed and programs coded that can run concurrently on different cores. In the best cast scenario, "performance of parallel applications should scale as the number of available cores increases." According to observations, for synchronous core processes and parallelism to be brought to the mainstream educators should re-frame parallelism into simpler concepts, ideally concepts students can first surmise and then hopefully gain an understanding about them in an organic sense that sticks with them. [27] The ICT industry is undergoing constant change and when change occurs the gap between professionals and students gets smaller instead of wider because it levels the playing field through democratization of information. All current and aspiring members of the community must adapt to change equally be prepared to learn as new concepts are introduced or become more a part of the workflow than they previously have been.

Article title: A Domain Model to Improve IT Course Design

The publication focused on some of the causes in information technology that drive change. The article characterized design problems in academia as the reason some courses lag slightly behind when it was outlined that - Information Technology (IT) is an academic discipline subject to rapid change. The cause is because of a number of factors namely Moore's law, the application-oriented nature of the discipline as well as the relative adolescence of IT as a discipline. Currently, there is a design problem when creating IT courses that aim to both appease constant change as well as meet the given quality criterion. The design problem is not being able to invest an adequate amount of time structuring the courses. Instructional design and evolving design models from other fields have been refined that help address this design problem in IT. In conclusion, it is important to recognize that an IT course is a subsystem within a larger system and similar to other systems should be responsive to better design strategies and practices that can lead the way. [28]

Based on this situation, related fields should have a greater influence in shaping ICT degree programme courses in the future. Adequate time needs to be spent planning what courses are offered. Whereas, unfortunately, the current trend in many institutions worldwide is that adequate time is spent on planning what courses will be cut from the budget to save on costs.

Article title: An Assessment Framework for Identifying Information Technology Bachelor Programs

This article suggests a new assessment strategy for ICT institutions that take into consideration different levels of subject matter that change and need to be actively kept up to date. The article proposed that - a problem exists when surveying the landscape of a leading edge IT program and the zero-sum-game approach of universities design their curriculum does not help matters in the least. The vast majority of universities enforce policies that limit the total number of credit hours required for a degree. When a new topic is brought in it means another topic needs to be depreciated or perhaps even be rid of completely. Furthermore, key research in regards to this ongoing epidemic is the realization that different facets of the body of knowledge used to identify IT programs age at different rates. In particular, the body of knowledge keys in on three levels of IT subject matter identified as knowledge areas, units, and topics. Aging occurs in reverse order meaning that topics change the fastest. It is both possible and likely when during IT program evaluation that programs would adopt new topics but less likely that a program will change units, and highly unlikely that knowledge areas will change. [29] Note, this article was written pertaining to the Universities in America. However, European institutions were also mentioned for the sake of comparison. I think this article really hits home on so many fronts affecting course offerings at universities today.

As this applies to reaching the end Moore's law, I think of challenges that could potentially be faced when trying to introduce a topic that is so far off in the horizon and yet still so important in terms of the industrial change it will bring about in the years to come. The only course at Metropolia that comes to mind which specifically mentions Moore's law was a three ECTS computer architectures course offered as a professional study to the night group students. There were not any further opportunities to attend credit courses on the subject. Given that resources are limited and funding is seemingly being cut each year, then perhaps more of the computer programming language credit courses could be moved exclusively to virtual classrooms and the computer labs could be used to introduce lecturers on more of the embedded engineering courses that cannot be conducted as effectively through remote teaching. Too many times, as a student have I sat in a room filled computers and I have posed a question to the teacher and I was asked to search for it on google. In that case, the answer to my question could have been found while at home or even on the subway or at the cottage via Wi-Fi. Time in the classroom needs to be valued, kept sacred, and maximized.

Article title: A Corporate / University Partnership for IT Professional Development

The article was written as a proposal to encourage participation between the private sector and schools in America. Such a link would be beneficial to each respective organization's best interests because of common interests. The paper chronicles that - "much has been written in the past decade about the importance of innovation, agility, and change in creating and sustaining successful organizations. Agility is an organization's ability to sense changes and to respond efficiently and effectively to them. The remarkable advances in computer hardware performance captured in Moore's Law are indicative of the astounding rate of change that has been systemic to the entire information and communications technology field over the past four decades." [30]

The gap between professionals and aspiring professionals is actually not that wide. The ideas presented in this paper suggest there is measurable need in cooperative efforts that would bridge the gap even closer together and goes on to say IT companies have a real opportunity to gain a strategic advantage by becoming "learning organizations." The main link here is to show university faculty members possess specialties that are vital to the running of a good company. In turn, what this does is it translates into an unexpected alternative way of teachers to be able to (upon their return from the job placement program) actively engage their home university students with what the teacher learned while they were at the company.

Article title: Legacy Job Titles in IT: The Search for Clarity

Over the years there has been a significant amount of redefinition and reclassification of jobs in the information technology industry as outlined by Donohue and Power "as technology developed and methodologies changed, the roles of IT staff expanded. This coupled with the adoption of the Object-Oriented paradigm and the advent of the Internet changed and expanded the role of the IT developer considerably. The number of programming languages and software development methodologies grew to capitalize on these advances. Tools became cheaper; in many cases they were free and some methodologies became automated to a certain extent." [31] On the contrary, I do not believe clarity is something that should be expected in the information technology industry any time soon. A broader title suites workers in this industry just fine provided that there is a broad range and at least some depth of knowledge across many fields to add weight to all in compassing title such as information and communication technology engineer for instance.

Article title: The Profession of IT Avalanches Are Coming

The article documented tendencies of individuals to become set in their beliefs and victims of change. Furthermore, the article suggests that even in the face of uncertainty it is important to remain aware and not lose sight of the future of the industry. After all, change is the only constant when forecasting the future of information technology and it was stated that - traditions in scientific and technological knowhow might tend to suggest incorrectly that "things follow laws, have predictable paths, and can be controlled." However, as technology is embedded in human social systems, and the use of technology depends on human ingenuity, the path of technology becomes difficult to forecast in it of itself. It is true that gross trends exist in technology such as Moore's law but still uncertainty remains in terms of exactly which of an entire multitude of possibilities will end up as true. It also turns out that some of the possibilities can be quite unruly and sudden. [32] It would be wise to follow the wisdom of this article and intend to be proactively as an institution in covering all bases of information technology and not relying too heavily on any one subsection to be relevant in the next five years or even next couple of years. I believe Eric Hoffer said it best when he said "In times of change learners inherit the earth; while the learned find themselves beautifully equipped to deal with a world that no longer exists."

In summary, 30 articles were not included in the scope and 30 articles were included in the scope for thematic analysis. From a sample size of 60 articles the results were evenly split 50/50. Figure 4 below illustrates each of the keywords identified at the beginning of this research project. Within the 30 articles here were eight occurrences of keywords being mentioned greater than ten times (double digits), which is significant considering the relatively short length in articles (less than ten pages). The least mentioned keywords were '*trends*' and '*microelectronics*.' In the other hand, the most mentioned keywords were '*Moore's law*' and variations of the words '*limit*' (i.e. limits, limitation, limited, etc.).

Upon further analysis, the highest number of individual keyword hits from any one article was '*limit*' which was mentioned 31 times in the article "Three steps to thermal noise death of Moore's law" from an IEEE publication. The most total keywords hits from any of the articles in the scope was 59 total mentions in the article "Impact of nanotechnology in ICT on sustainability and energy efficiency found from the Ebscohost database. The least total keywords hits from an article was 2 total mentions from the article "Multicore Education: Pieces of the Parallel puzzle" that was found from the ACM Digital database.

The following themes were extracted from the literature: a) we are in a transition period for information and communication technology as Moore's law will continue for a number of years even in the most pessimistic estimations, b) most of the exploration of alternatives are in their infancy or experimental phases even though results may be encouraging, economic factors place limitations and restrictions of the type of research that actually receives funding, c) Moore's law ending is a future event there is more value as an IT professional to focus on the present, and d) the articles proved long term innovation goals are often placed aside for more short term gains.

Table 1. Keywords extracted from 30 articles included in the research scope.

Keywords	**Number of times mentioned**
Moore’s law	114
limit	111
3D	66
integration	52
future	47
innovation	38
nanotechnology	32
microelectronics	19
trends	18

The length of the articles did not appear to limit the number of keyword mentions. Meaning, there was a mix of high volume keywords in one or two page articles as well as articles longer in length that did not produce significantly higher scores. It might be the number of keywords mentioned has more to do with the writing style of the authors. Evidence to support this claim comes from analysis of the EDA challenges in the Dark Silicon Era publication, were issues surrounding the limits of Moore's law are discussed at great length without specifically mentioning the words Moore's law even once throughout the article.

5 Discussion

Moore's law as a keyword during this literature review was mentioned 114 times and only slightly more than limit at 111. This is not a coincidence since after reading through 60 articles the topic of this report does seem to be on trend when looking at the evolution of Moore's law over the past 50 years. It is encouraging to find so many research papers and individuals within academia who are more experienced in the disciplines of physics, computer science, and business also discussing these issues. The research questions set out to explore at the beginning of this thematic analysis have found some answers. On the other hand, a number of concepts and challenges were introduced that were simply not taken into consideration prior to the information search.

The implications of the studies conducted in the articles are such that the slowing and eventual end of Moore's law will not hinder future innovative applications from providing equal or superior processing speeds that make use of alternative processor architecture such as for example 3-D processing architecture designs. For this reason, Moore's law ending is symbolic of an end of an era as opposed to an absolute end in improving high speed processor performance. Some developers of the traditional processors may remark the end of the growth curve for Moore's law with negative connotations. Conversely, developers who are leading the innovation of new processor architectures will be proponents for the multitude of benefits displayed by new technologies in nanotechnology and microelectronics.

Further study in the coming years will be able to determine if the alternatives can hold up to the same performance standards over a longer period of time consistently. The fact designers and developers are conceptualizing and building prototypes is encouraging and yet alternatives cannot necessarily be declared substitutes. Thus, there are both users and developers who will continue their work using typical processor architectures, which have been used in the implementation schema for the past 50 years.

The biggest surprise from the statistics of keyword hits was that going into the process it was assumed nanotechnology would be a common thread among the research based articles. On the contrary, nanotechnology in relation to the limits of Moore's law was only a minor theme in the majority of articles in the scope. In fact, the large majority (90%) of the mentions of nanotechnology as a keyword came from one article in particular. Similarly, with microelectronics as a keyword roughly 74% of the total mentions came from again one research paper. I think this implies convergence of nanotechnology and microelectronics caused by Moore's law limitations is not a current trend, at least not as of yet anyway.

6 Conclusions

Moore's law has experienced exponential growth in several ways including decreased chip size by miniaturization, increased speed by a greater number of transistors per chip, and in some ways importantly because silicon microchips are presently the most cost-effective implementation method for semiconductor manufacturers to produce the chips as their usage on a global scale. Electronics and technology companies who demand the production of the chips do so in such great volumes that chip manufacturers can generate revenue in the billions of dollars every year worldwide. From a consumer perspective, there are a variety of applications for these silicon microchips when they are integrated into larger sequential circuits and devices. However, from a product development and raw materials point of view the same end is achieved during production regardless of new innovations in the production pipeline that are waiting to be adopted by industry. Bearing all of this in mind, economic factors have played a measurable role in the research and development of alternatives to silicon microchips that have fueled Moore's law for the past 50 years. Although current research has shown that further exploration of alternatives is warranted for the most part, the old paradigm still remains in abundance of supply and only time can tell what exactly the future holds.

The creation of innovative processor architectures can further the development curve of processor performance conceding in some cases slower overall computational speed yet yielding improved efficiency. Furthermore, hybrid technologies can incorporate both tried and tested technologies as well as pushing the envelope with more innovative implementations that will ultimately help create the blueprint for potential predecessors to the traditional mass produced microprocessors which have been estimated to reach a critical mass by 2032 or sooner.

ICT institutions have an opportunity to be leaders during times of technological change and to revolutionize the way ICT programmes are structured through innovative evaluation methods of current course by way of three proposed levels 'knowledge areas, units, and topics' [29].

A quantitative analysis of trends regarding where the end of Moore's law might lead the semiconductor industry to in the future is much too cumbersome of an undertaking given limited resources and such a small sample size of data. In general, it does not look like nanotechnology / microelectronics and ICT are close to merging. However, time will as this is a difficult to thing forecast.

In the end, through active thematic analysis of 60 articles the most compelling themes extracted from the literature were that this is still a transition period for information and communication technology as Moore's law will continue for a number of years even in the most pessimistic estimations. Secondly, most of the exploration of alternatives are in their infancy or experimental phases even though results may be encouraging. Third, economic factors place limitations and restrictions of the type of research that actually receives funding. Also, as Moore's law ending is a future event there is more value as an IT professional in operating under the old paradigms of scaling. Last but not least, the long term innovation goals are often placed aside for more short term gains as the economic forces outweigh the benefits or inventing a better solution.

Ultimately, Moore's law is the most readily available and obvious example for academic institutions to be mindful of the need to actively update their curriculum to account for 21st century technology. The learning curve will be long before measurable results can be seen in student performance and more importantly understanding. Therefore, it would be best to keep an open mind when considering changes to diploma programmes. There are inherit problems when proposing this outlook since there are few textbooks being written on the end of Moore's law. Currently, a lot more conjecture remains among researchers and industry about what exactly the future of ICT will look like. In addition, it is too early to tell if ICT will look a lot more like nanotechnology programmes in the coming years or if silicone will simply be replaced by another raw material so as to continue the status quo.

7 Recommendations

It is critical that pioneering work is done at schools in the laboratory setting by building prototypes with forward-thinking architecture in order to push the boundaries, encourage creativity among students, and hopefully to optimize the transition period between Moore's law ending and the beginning of the next era in processors. Students who one day wish to become developers in the silicone microprocessor industry should take heed of the fact that technology is cyclical in nature and constant exponential growth of anything is simply not sustainable indefinitely, much less the speed of microprocessors relative to their size and raw materials needed for manufacturing in this case.

In a world of specialization, application-based implementations of microprocessors are delivering promising results through research and development aimed towards specific industries. It would be a good idea to implement either intensive courses, summer school courses, or even professional studies courses for students to take that would prepare them for the challenges they might face as either software engineers or embedded engineers. Too often, when we think of Moore's law, only the hardware side is taken into consideration.

As mentioned earlier, software actually serves as the key design element that has driven the miniaturization of chips through scanners and millions of lines of code (referring to Figure 3). I think this would definitely be a worthwhile investment of the annual budget to introduce courses over these topics for willing participants. Understandably, software scanners in their own right might be relevant enough as a core subject. Which is something I have not seen being offered to students as of yet.

Research and development of innovative energy-efficient prototypes must also be practiced at top technical colleges and universities of applied sciences worldwide. This research and development should be used as a vehicle to drive toward a paradigm shift in the semiconductor manufacturing industry. In the distance, with the predicted end date of Moore's law is still relatively far on the technological horizon before maturity occurs there is arguably a window of opportunity that by taking a proactive approach now within educational institutions towards searching out creative ideas and encouraging development of never before seen architectures it will advent the next rising wave in the cycle of technological prosperity.

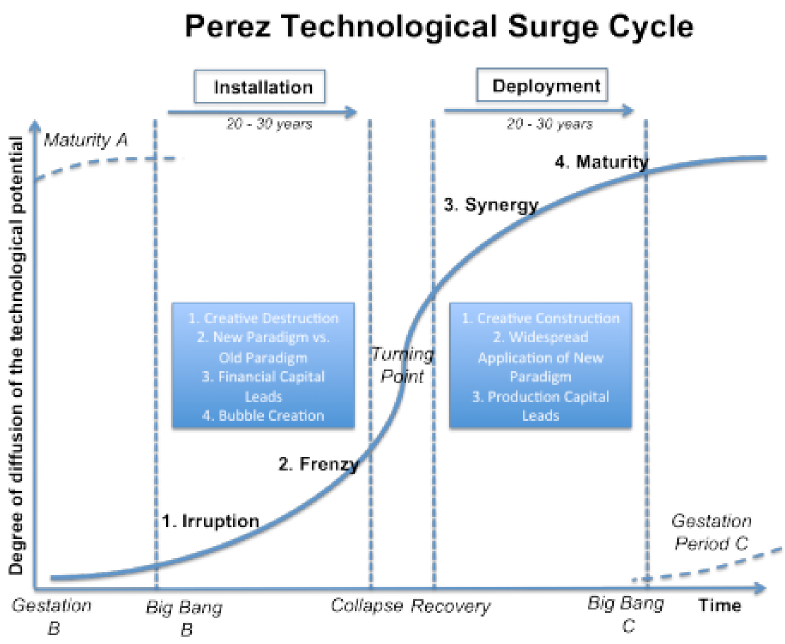

Figure 5. Four stages of technological growth cycle. [33]

It is important to learn from the examples of history and understand that technological growth happens in cycles; “Age of Information and Telecommunications (1971-current): Beginning in the 1970s with innovations in micro-electronics and the emergence of computing technology, the age of information merged previously isolated global information networks into a unified system, increasingly accessible digitally through sophisticated computers and application software.” [33]

Moore's law was originally right on the cusp of this information age technological surge and now before the peak hits as maturity is about to be reached the time has come to revert back to the drawing board and give way to the next gestation period while microprocessor architects and designers rejuvenate the semiconductor industry with their untrodden ideas and ingenious vision of where technology is going as opposed to where it has been. Figure 5 shows the four stage progression that technologies such as Moore’s law cycle through over time. Given these points, in order for the semiconductor industry to evolve as the end Moore's law fast approaches, it is essential to maintain foresight during times of change especially at the academic level prior to many students entering the workforce and technology industry for the first time. Also, it is not possible to evaluate the potential value of innovation without being aware of the socio-economic factors that are at work. Typically, industries tend to forecast growth indicators in terms of segments that are in one quarter at a time intervals (one quarter is equal to three months of a fiscal year). At the point when microprocessor performance / size growth rate reaches its limits, subsequently, the gestation period of the next growth cycle will have begun to show itself (growth indicators in terms of different variables such as energy efficiency for instance).

The forecast timeline should now be reframed where the word quarter should meaning quarter of a century. Patiently surveying how innovation will happen in the next 25 years as each stage in the life cycle of technological change takes shape will be the superior forecasting measure. I think this lends itself to valuable information ICT institutions should consider when planning their next changes in curriculum.

In the final analysis, what have up until now been the winning dominant microprocessor designs of the past should look to invite external forms of competition in order to encourage growth and positive change in the semiconductor industry; the path of which should be started on at the academic Bachelor of Engineering level in my opinion. It appears likely it is through the vessel of change technological paradigms can be challenged as innovation trajectories will tend to shift in the process. The forces that help the experimental process are vital for emergence of the next technological revolution and for articulation of a new paradigm and new growth cycle [34, 106].

I think schools like Helsinki Metropolia University of Applied Sciences would be an ideal place for students to learn on the cutting edge of industrial changes, as is already done in providing a positive learning environment. At the same time, Metropolia also has an opportunity to look to expand its horizons if there is interest in looking into the future of ICT landscapes for the next ideas. The next ideas will indeed shape the technological world around us whether we like it or not and when they do perhaps that will be the appropriate time to garner some more attention to the ideas presented throughout this project.

References

1 Computer History Museum – The Silicon Engine, 1965 - "Moore's Law" Predicts the Future of Integrated Circuits.
URL: http://www.computerhistory.org/semiconductor/timeline/1965-Moore.html
[Online] Accessed 11.3.2014

2 Moore G. Life Fellow. Proceedings of the IEEE, vol. 86, no. 1. IEEE. January 1998.

3 Cringely R. Be Absolute for death, life after Moore's Law. Communications in the ACM Vol.44, No. 3. 2001.

4 Roza E. System's on Chip, what are the limits?. Electronics & Communication Engineering Journal. 2001.

5 Graham A.,Duesberg G., Seidel R., Liebau M., Unger E., Pamler W., Kreupl F., and Hoenlein W. Carbon Nanotubes for Microelectronics?. Small Journal. 2005.

6 Cong J., Nagaraj N.S., Puri R., Joyner W., Burns J., Gavreilov M., Radojcic R., Rickert P., Stork H. Moore's Law: Another Casualty of the Financial Meltdown? San Francisco, California. July 2009.

7 Izydorczyk J. Three Steps to Thermal Noise Death of Moore's Law. IEEE Transactions On Very Large Scale Integration (VLSI) Systems, Vol. 18, N. 1. January 2010.

8 Han S. Moore's Law and energy and operations savings in the evolution of optical transport platforms. IEEE Communications Magazine. February 2010.

9 Gajarushi A., Sarwade N. Analysis of Universal Logic Gates Using Carbon Nanotube Field Effect Transistor. International Conference and Workshop on Emerging Trends in Technology. Mumbai, India. February 2010.

10 Kahng A. Scaling: More than Moore's law. IEEE Design & Test of Computers. May 2010.

11 Banerjee S., Agarwal K., Nassif S. Design-Aware Lithography. Napa, California. February 2011.

12 Pell O., Mencer O. Surviving the end of frequency scaling with reconfigurable dataflow computing. ACM SIGARCH Computer Architecture News 60 Vol. 39, No. 4. September 2011.

13 Chi-Hung L., Wen-Tsan H., Hsien-Ching H., Chun-Nan L., Jen-Chieh Y. System-Level Design Exploration for 3-D Stacked Memory Architectures. Taipei, Taiwan. October 2011.

14 Camposano R., Gope D., Grivet-Talocia S., Jandhyala V. Moore meets Maxwell. EDAA. 2012.

15 Markovic D., Zivkovik D., Cvetkovik D., Popovik R. Impact of nanotechnology advances in ICT on sustainability and energy efficiency. Renewable and Sustainable Energy Reviews. 2012.

16 Danowitz A., Kelley K., Mao J., Stevenson J., Horowitz M. CPU DB: Recording Microprocessor History. Communications of the ACM Vol. 55, No. 4. April 2012.

17 Kaul H., Anders M., Hsu S., Agarwal A., Krishnamurthy R., Borkar S. Near-Threshold Voltage (NTV) Design-Opportunities and Challenges. Design Automation Conference. San Francisco, California. June 2012.

18 Palem K., Lingamneni A. What to Do About the End of Moore’s Law, Probably! Design Automation Conference. San Francisco, California. June 2012.

19 Cohen J., Alikani M., Bisignano A. Past performance of assisted reproduction technologies as a model to predict future progress: a proposed addendum to Moore’s law. Reproductive Biomedicine Online. August 2012.

20 Anthes G. Chips Go Upscale. Communications of the ACM Vol. 55, No. 9. September 2012.

21 Yue Z., Weisheng Z., Klein J., Wang K., Querlioz D., Youguang Z., Ravelosona D., Chappert C. Spintronics for Low-Power Computing. EDAA. 2014.

22 Boxun L., Yu W., Yiran C., Hai H., Huazhong Y. ICE: Inline Calibration for Memristor Crossbar-based Computing Engine. EDAA. 2014.

23 Vardi M. Moore's Law and the Sand-Heap Paradox. Communications of the ACM Vol. 57, No. 5. May 2014.

24 Shafique M., Garg S., Henkel J., Marculescu D. The EDA Challenges in the Dark Silicon Era (Temperature, Reliability, and Variability Perspectives). Design Automation Conference. San Francisco, California. June 2014.

25 Hemsath D. Efficient Code to Counter Dying Moore's Law. Communications of the ACM Vol. 57, No. 6. June 2014.

26 Wester R., Koster J. The Software behind Moore's Law. IEEE Software. April 2015.

27 Ernst D., Murphy T., Ortiz A. Multicore Education, Pieces of the parallel puzzle. Milwaukee, Wisconsin. March 2010.

28 Helps R. A Domain Model to Improve IT Course Design. West Point, New York. October 2011.

29 Rowe D., Lunt B., Helps R. An Assessment Framework for Identifying Information Technology Bachelor Programs. West Point, New York. October 2011.

30 Abernethy K. A Corporate / University Partnership for IT Professional Development. Consortium for Computing Sciences in Colleges. January 2012.

31 Donohue P., Power N. Legacy Job Titles in IT: The Search for Clarity. Milwaukee, Wisconsin. June 2012.

32 Denning P. The Profession of IT Avalanches Are Coming. Communications of the ACM Vol. 57, No. 6. June 2014.

33 Sherman Alex. The Cyclical Nature of Technology Revolutions.
URL: http://thefirstpart.com/2011/04/26/the-cyclical-nature-of-technology-revolutions/ [Online] Accessed: 24.4.2014

34 Carlota P. Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Cheltenham, UK: Edward Elgar Publishing Limited; 2002.

35 Parallel processing - Wikipedia, the free encyclopedia.
URL: http://en.wikipedia.org/wiki/Parallel_processing [Online] Accessed: 25.4.2015

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Keyword hits from articles in scope

Row	Article	# of pag	Moore's la	nanotechnol	microelectr	futur	3D	trend	limi	integrati	innovation
5	Be absolute for death, life after Moore's Law (ACM Digital)	2	8	0	0	1	0	0	1	0	1
6	Efficient Code to Counter Dying Moore's Law (ACM Digital)	1	5	0	0	0	0	0	0	0	0
7	Moore meets Maxwell (ACM Digital)	2	3	0	0	1	3	0	0	2	0
8	Moore's Law and the Sand-Heap Paradox (ACM Digital)	1	14	0	0	1	0	0	0	0	1
9	Moore's Law: Another Casualty of the Financial Meltdown? (ACM Digital)	2	8	0	0	1	7	1	2	7	3
10	System-Level Design Exploration for 3-D Stacked Memory Architectures (ACM Digita	1	1	0	0	0	17	0	1	3	0
11	ICE: Inline Calibration for Memristor Crossbar-based Computing Engine (ACM Digital)	4	3	0	0	1	0	0	1	1	1
12	Chips Go Upscale (ACM Digital)	3	3	1	1	1	27	0	4	3	0
13	Analysis of Universal Logic Gates Using Carbon Nanotube FET (ACM Digital)	5	1	0	0	0	0	1	1	1	0
14	CPU DB: Recording Microprocessor History (ACM Digital)	9	1	0	0	1	0	3	2	0	0
15	Design-Aware Lithography (ACM Digital)	6	1	0	0	0	0	0	8	0	0
16	Near-Threshold Voltage Design - Opportunities & Challenges (ACM Digital)	6	3	0	0	3	0	0	9	2	1
17	Spintronics for Low-Power Computing (ACM Digital)	6	2	0	4	2	8	0	4	7	0
18	Surviving the end of frequency scaling with reconfigurable dataflow computing (ACM D	6	1	0	0	1	1	0	7	0	0
19	The EDA Challenges in the Dark Silicon Era (ACM Digital)	6	0	0	0	1	0	1	4	2	1
20	What to Do About the End of Moore's Law, Probably! (ACM Digital)	6	6	0	0	2	0	0	2	2	1
21	Scaling: More than Moore's law (IEEE)	2	5	0	0	1	3	1	0	9	6
22	Systems-on-chip: what are the limits? (IEEE)	7	4	0	0	1	0	0	5	1	0
23	3 Steps to Thermal Noise Death of Moore's Law (IEEE)	5	7	1	0	3	0	0	31	1	0
24	The Software behind Moore's Law (IEEE)	4	6	0	0	1	0	0	3	3	4
25	Moore's Law & Energy & Operations Savings in the Evolution of OTP (IEEE)	4	21	0	0	1	0	0	0	0	0
26	Carbon Nanotubes for Microelectronics?.pdf (Wiley Online Library)	9	0	1	14	1	0	0	3	4	2
27	P.P.A.R.T.M.P.F.P: a proposed addendum to Moore's Law.pdf (Science Direct)	6	5	0	0	5	0	4	5	0	0
28	Impact of NT advances in ICT on sustainability & energy efficiency (EBSCOHOST)	7	1	29	0	8	0	3	6	0	12
29	A corporate / University Partnership for IT Professional Development (ACM Digital)	6	1	0	0	0	0	0	0	1	2
30	A Domain Model to Improve IT course Design (ACM Digital)	2	1	0	0	0	0	0	2	0	0
31	An Assessment Framework for Identifying IT Bachelor Programs (ACM Digital)	6	0	0	0	4	0	0	7	3	0
32	Legacy Job Titles in IT: The Search for Clarity (ACM Digital)	6	1	0	0	0	0	1	3	0	0
33	Multicore Education: Pieces of the Parallel Puzzle (ACM Digital)	2	1	0	0	1	0	0	0	0	0
34	The Profession of IT Avalanches Are Coming (ACM Digital)	3	1	0	0	5	0	3	0	0	3
35		Total hits:	114	32	19	47	66	18	111	52	38

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innovation	9
integration	8
limit	7
trends	6
3D	5
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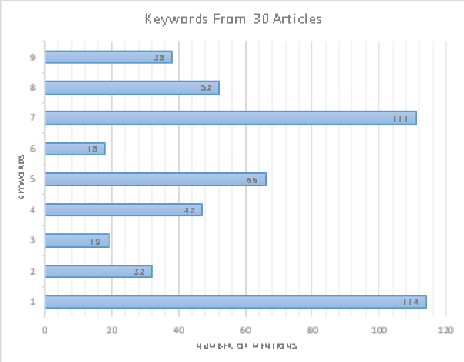
nanotechnology	2
Moore's law	1



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