The Exploration of IS and IT Architectural Improvements of Intel Microprocessors and Modern Implementation of the Intel Core i7 8th Generation

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Abstract

This project discusses the Intel microprocessor lines in terms of technological history in the personal computer market and details of the related technical aspects. This project first discusses the history of Intel Corporation and its early product and hardware history. The discussion then explores the technical features of the first Intel Pentium P5/P6 Processors, the Intel Pentium Dual-Core, and finally the Intel Core i7 8th Generation processor, while demonstrating the comparative CPU performance improvements and changes that have been implemented over time. Next, this project considers the modern implementation of the Intel Core i7 8th Generation processor and its demand by the IS and IT industry, computer gamers, and the personal computer market. Through logic and analysis based on IS and IT Architectures, this project concludes with the exploration of the Core i7 8th Generation and competitive improvements for future microprocessor performance considering defined limitations.

Keywords: Intel processor, microprocessor, architecture

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A microprocessor is a computer processor which incorporates the functions of a computer's central processing unit (CPU) on a single integrated circuit. Intel microprocessors have been a cornerstone of computer processing for over a half a century with its microprocessors found commercially in most desktop and mobile devices. IS and IT professionals like business professionals, developers, and programmers as well as computer enthusiasts have utilized machines from Dell, Lenovo, Hewlett-Packard, Apple, and many more all powered by the Intel microprocessor. According to computer journalist, Chris Finnamore, around 80% of new personal computers and over 90% of laptops have Intel processors (2017). Supported by this trend, it is easy to say that millions of computer users around the world rely on Intel microprocessors in their machines for various computational functions.

The chance of using an Intel microprocessor in your desktop or mobile device is incredibly high—but for good reason. The Intel Corporation has been in the semiconductor chip and microprocessor business for over half of a century due to its founders who pioneered and invented the integrated circuit, also known as the microchip. The invention of microchip first shifted users away from the supercomputer and allowed for the commercialization of personal computers. Today, Intel has built on its legacy of microprocessors through the Intel Core Series, which dominates the market, dealing with the wide range of computational demands among different users. Whether its compiling massive Big Data, playing a high FPS videogame, multitasking between work programs, or daily internet browsing, the Intel Core Series has got it covered. Through its advance microprocessors and supporting chip components, the Intel Core Series offers enough computational resources to get any job done.

The History of the Intel Corporation

Amidst a backdrop that includes space exploration, the first successful heart transplant, and the maiden flight of the Boeing 747, American engineers Robert Noyce and Gordon Moore started Intel inside their fabled garage in Silicon Valley, CA. After leaving their careers at Fairchild Semiconductor in July 1968, Noyce as general manager and co-inventor of the semiconductor integrated circuit and Moore as head of research and development, they created a company of their own. However, they could not do it alone and so they recruited other Fairchild employees to join them. One significant individual who joined them was the Hungarian-born businessman, chemical engineer, and driving force behind the success of the integrated circuit named Andrew Grove. Later Grove eventually went on to serve as chairman and CEO of Intel during the first three decades of the company (Langeneckert, 2017). Another individual who was critical to the start-up was venture capitalist, Arthur Rock, who arranged $2.5 million funding. Intel was then able to open its doors with experienced, reputable technologists, ensuring its future fame and success in the personal computer industry (Hall, 2013).

It is interesting to note that on naming the company, the founders first considered the name, Moore and Noyce, but ironically rejected the idea because it bore the resemblance to "more noise" which is undesirable in computers and is typically associated with electronic interference. Furthermore, they first founded the company as N.M. Electronics in mid-July 1968, but shortly thereafter settled on Intel which stood for Integrated Electronics – but only after buying the rights to the "Intel" trademark owned by Intelco hoteliers.

In 1970, Intel officially released their company to the public through their IPO at $23.50 per share and thereby raised an additional $6.8 million in funding. In contrast, the same year marked the Tech-Stock Crash with household names like Polaroid, Texas Instruments, and General Instruments falling well over 50% in value (Navellier, 2010). While the tech giant IBM lost 42%, this was the largest dollar amount lost in the crash equaling to $18 billion. According to the Nasdaq columnist and economist Louis Navellier, he posited that the crash occurred during a period when investors believed that the high growth rates of the sixties would continue for an extended period (2010). He called this pattern "the rapid growth myth" and believes that Intel was not affected partly due to its strategic entrance into a specialized computer market.

Intel's initial success was in largely due to its focus on computer components. Although the company only created one of the first microcomputers in 1972, the company had strongly distinguished itself from others in its ability to make semiconductors. Tech companies like IBM were challenged by federal litigation from the Justice Department for "bundling" hardware and software in violation of antitrust laws. Thus, Intel changed the competitive market by selling components individually. Through the 1980's, Intel's high quality and state of the art computer components were successfully sold to the consumer public and computer manufacturers. Intel also partnered with IBM as well as its competitors, becoming the main supplier of microprocessors for personal computers. Furthermore, Intel leveraged the growing personal computer market by launching the "Intel Inside" marketing campaign later in 1991 to create a sort of brand loyalty with its customers. During these early decades, Intel experienced historic growth and profitability as a household name and the top hardware supplier of the industry.

Discussion: The Exploration of Early Hardware and Product History

When Intel placed its first products on the personal computer market, they were not microprocessors. In fact, they were semiconductor memory chips. In 1969, Intel launched their 3101 Shottky TTL bipolar SRAM which featured a 64-bit static RAM that was twice as fast as its competitors. The same year Intel launched their 3301 Shottky bipolar 1024-bit ROM as well as the 1101 metal oxide semiconductor 256-bit static RAM. Then, Intel released their 1024-bit dynamic RAM chip called the 1103, which was by far the largest and most successful memory chip of the time. However, the success they initially had was only a small taste of what they would experience after focusing production on microprocessors for better opportunities and less competition.

The following sections of this project describe pivotal microprocessors that exhibit breakthroughs and advancements of design and architecture. While they focus on Intel microprocessors, they exhibit the key components of similarly identical competitor microprocessors of the time.

The Intel 4004 Microprocessor

After their failed attempt at entering the digital watch market and fierce competition by foreign semiconductor companies, Intel focused on microprocessors and introduced the first commercially available microprocessor in 1971, the Intel 4004 4-bit CPU. The Intel 4004 included a single core, a clock rate of 740kHz, an instruction cycle time of 10.8 microseconds, and a multiplexed 4-bit bus width. Despite these minimal configurations in comparison of what we have today, the Intel 4004 was important because it fully integrated the CPU on one chip, utilizing their patented semiconductor technology led by Ted Hoff, Federico Faggin, and Stan Mazor. Intel completed the 4004 under contract to the Japanese calculator manufacturer Nippon Calculating Machine Corporation, which let Intel retain all rights to the technology (Hall, 2013).

Figure 1. Architecture of Intel 4004

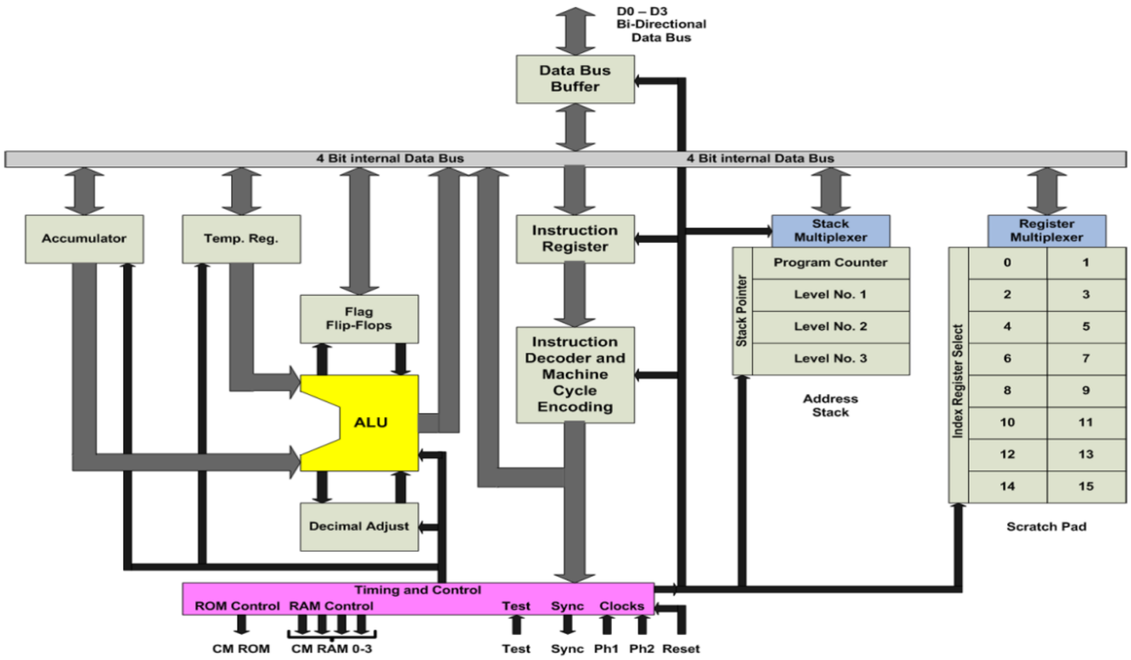

Figure 1. Architectural Functional Diagram of Intel 4004. This figure illustrates technical architecture of the Intel single-chip 4-bit 4004 CPU. It also highlights the 16 4-bit registers to the right in grey, the tracking and control unit in purple, the ALU in yellow, and the 4-bit data bus in light grey. (Paluvadi, 2009).

The Intel 8008 Processor

In 1972, Intel introduced one the first microcomputers and also the successor to the Intel 4004, the Intel 8008. The Intel 8008 had an 8-bit CPU and importantly marked the early byte oriented microprocessor design. It featured a single core, a clock rate of .5/.8MHz, 7 8-bit register scratchpad, 14-bit program counter, and an external 14-bit memory address bus that could address 16KB of memory. In terms of instructions per second, compared to the Intel 4004, the Intel 8008 performed slower by 36,000 to 80,000 at .8MHz. However, the Intel 8008 could process data 8-bits at a time due to increased word size and access more RAM, giving it a significant speed advantage over the Intel 4004 in most applications. Intel went on to create the successive lines of numbered microprocessors which expanded on the Intel 8008 architecture. These include the Intel 16-bit 8088 found in the first mass produced personal computer from IBM and the Intel 16-bit 8086 which most importantly gave rise to the x86 architecture of backwards compatibility. The x86 architecture meant that newer CPU's could use software and applications from older machines. Intel continued this expansion of the Intel 8008 and the x86 architecture throughout the 1980's and early 1990's as a commitment to retrograde compatibility in its future lines of microprocessors (Hall, 2013).

Figure 2. Architecture of the Intel 8008

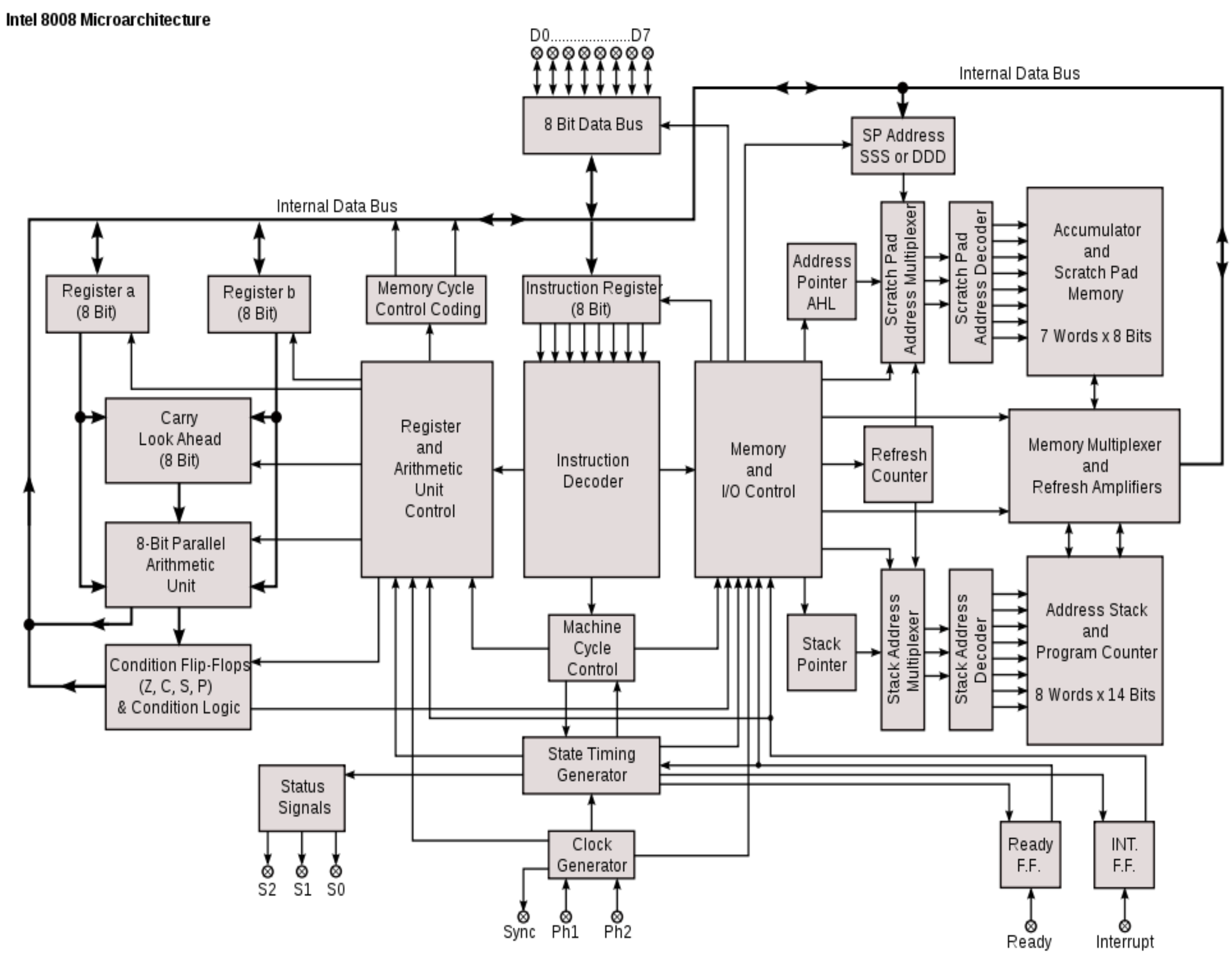

Figure 2. Architecture of the Intel 8008. This figure illustrates the technical architecture of the Intel 8008 chip which provides the framework for its numbered model successors. Among the complex

diagram, you can find the 7 word 8-bit memory scratchpad on the top right, 8-bit data bus on the top middle, and ALU/CU in the center (Wikichip, 2014).

The Intel Pentium P5 and P6 Processors

The Intel Pentium P5 Processor was the first non-numbered microprocessor from Intel because the company wanted to avoid competitors like AMD launching microchips with similar names and already similar microprocessor architecture. The name Pentium was coined in reference to the fifth generation of the x86 architecture chip. In terms of technical CPU performance, the Intel Pentium P5 had a 66 MHz clock rate, 64-bit expanded external data bus, and was the first Intel chip to use superscalar processing. In Intel's superscalar processing, the microprocessor takes separate arithmetic logic units (ALU) execution units for different types of instructions. This innovation allowed the computer to execute instructions in parallel with simply ALU's. Note this is to be differentiated by future multicore microprocessors that incorporate fully functional CPU's on the same chip. While other microprocessors only executed one instruction per clock cycle, the Pentium could execute more than multiple instructions per clock cycle. Furthermore, Intel achieved higher speeds in the Pentium P5 by increasing the number of transistors. Roughly following the cofounder Moore's Law that the number of transistors on a chip will double every one to two years, Intel went from 1.2 million transistors in the Intel 80486 to 3.1 million transistors on the Pentium P5. However, while the speed of the Pentium was a significant improvement on its predecessors, Intel engineers unfortunately found that an obscure segment in the 3.1 million transistors that caused the chip to perform division incorrectly after its release in 1993 resulting in a $475 million loss. This incident was called the "Pentium flaw", which was initially hidden by Intel until they were uncovered and incurred heavy remanufacturing losses (Hall, 2013).

Figure 3. Architecture of the Intel Pentium P5

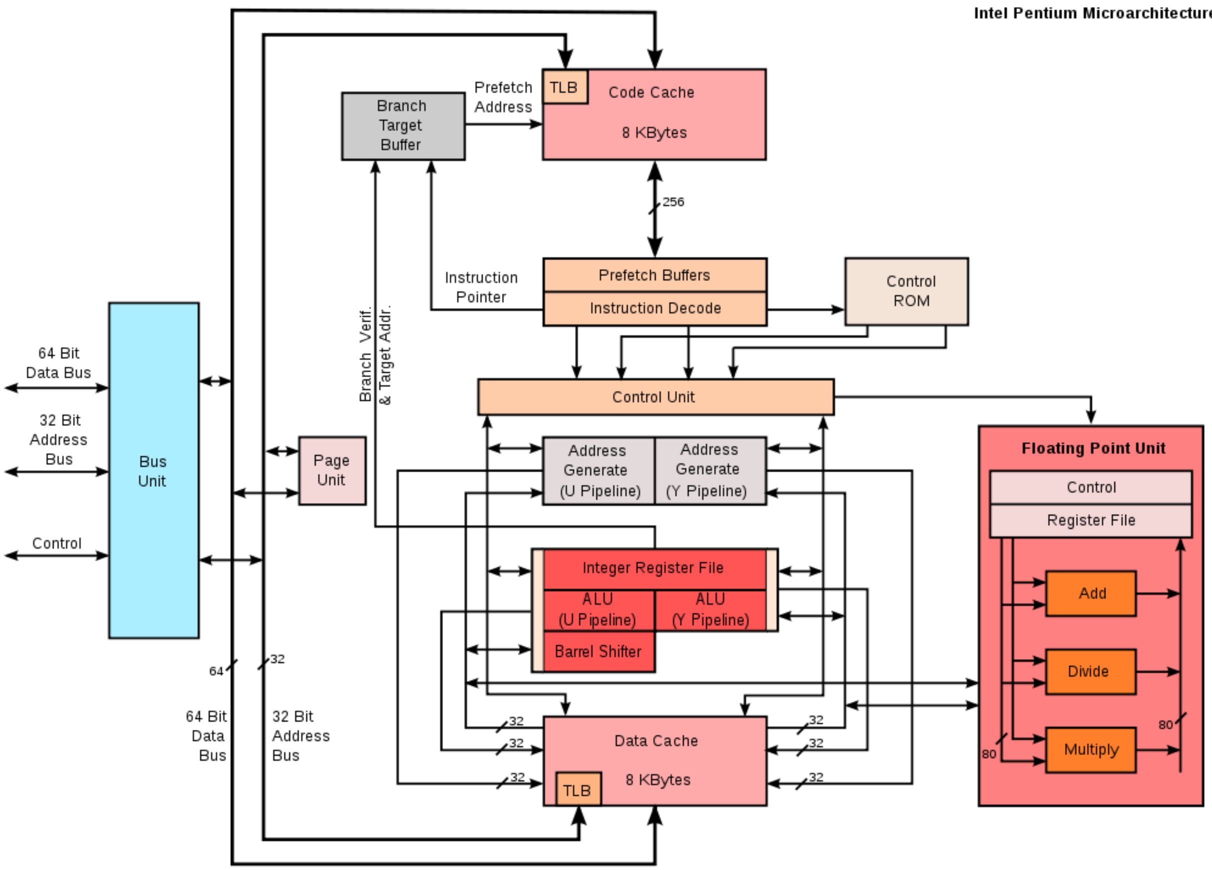

Figure 3. Architecture of the Intel Pentium P5. The figure illustrates the technical diagram of the P5. It also shows the expanded 64-bit data bus, the control unit, and most importantly the multiple ALU components for superscalar processing (Wikichip, 2014).

Intel launched the Pentium P6 in 1995, which ran in parallel to the Pentium for the high-end personal computer market. Marketed as the Pentium Pro, it featured a second level cache and superscalar, reduced instruction set computer (RISC) processor on a dual-chip processor. Essentially, this meant that CPU instructions were fixed and simplified for faster parallel processing. The second generation P6 architecture ultimately replaced the P5 through the release of the low to high-end tiered Pentium II and Pentium II Xeon and also later again for the third generation Pentium III/III Xeon. While Intel continued to manufacture the P6 architecture in successor models like the Pentium M and also in dual-core versions of the Pentium M, the Pentium brand of the P6 series eventually fell to low-end models between Celeron and Core brand lines. As opposed to the future dual-core chip, the dual-chip processor was much slower because it had lacked the more efficient communication and synchronization between processing units located nearby on the same chip. However, this dual-chip architecture eventually paved the way for the dual-core processors of the mid-2000's.

Figure 4. Architecture of the Intel Pentium Pro

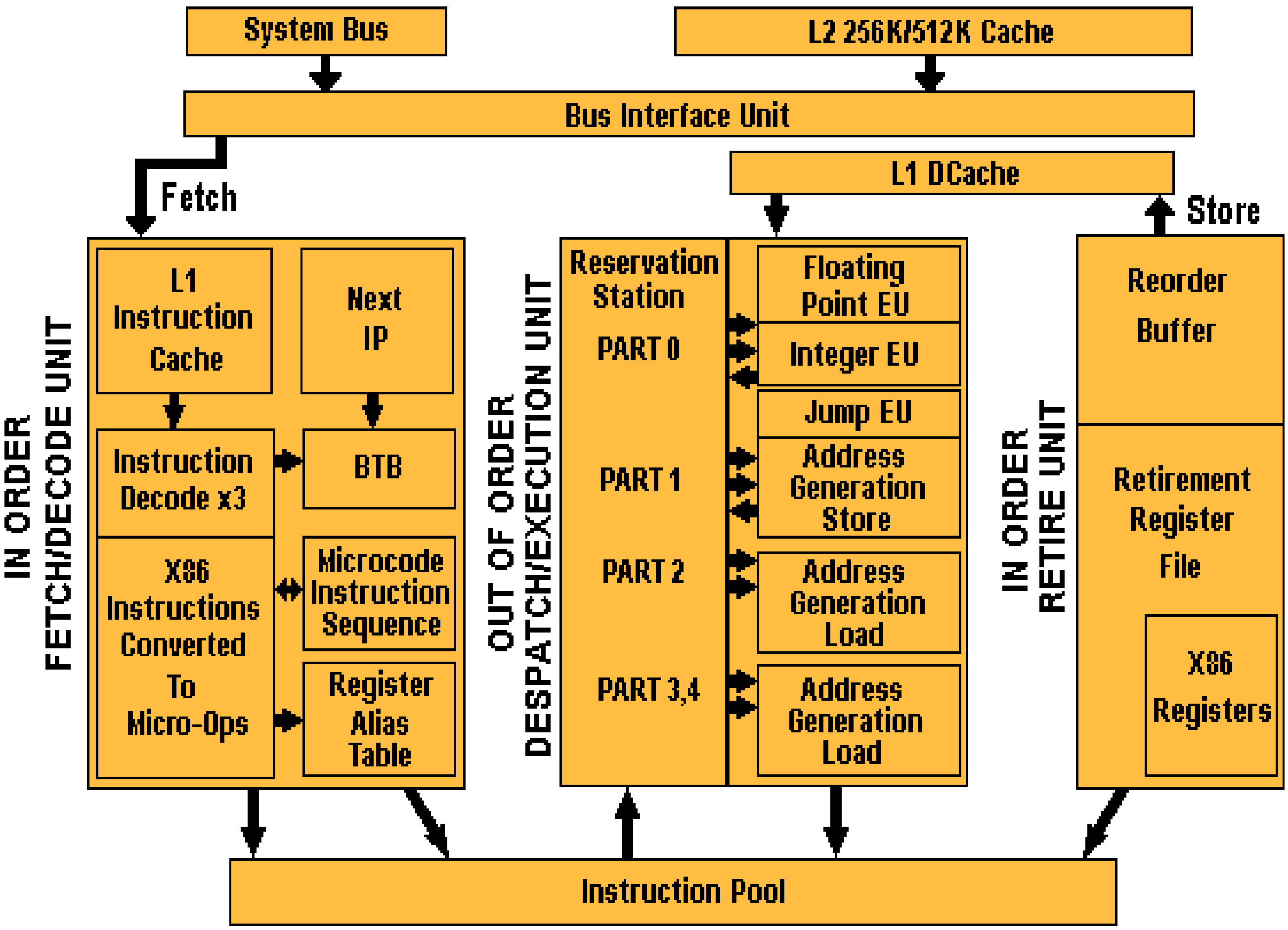

Figure 4. Architecture of the Intel Pentium P6. This figure illustrates the functional architecture of the P6. It also clearly the second level cache L2 separated from the L1 Cache by the bus. The L2 cache is the distinguishing upgrade of the P6 from the P5 processor, establishing a key performance improvement for future processors (Wikichip, 2014).

The Intel Pentium Dual-Core Processor

In 2006, Intel announced the re-release of the Pentium brand. Initially, they sought out to release the Pentium on a single core with 1MB cache but realized that it was not strong enough to distinguish itself from the Celeron brand line. Therefore, Intel released the Pentium with two cores instead of one and branded it as the Pentium Dual-Core. The Intel Pentium Dual-Core was Intel's first dual-core CPU released in mobile and desktop computers because manufacturing technology finally significantly allowed for a larger amount of transistors on the same chip. The dual processor configuration of the Pentium Dual-Core meant that it had two individual processors on the same processor die unlike the Pentium Pro or Pentium D which was also released but as two dies each with a single-core in 2005. This improvement meant for better communication and synchronization of execution between CPUs for parallel processing. The Pentium Dual-Core featured 1.3 to 3.4 GHz clock rate for the 32-bit "Yonah" or 64-bit "Merom" CPU configurations. Like its predecessors since the Intel 8086, it also complied with the x86 architecture and works with older software.

Dual-core configurations similar to the Pentium Dual-Core were well employed in future CPU models among the different brand lines of Intel including Celeron, Core, Core "I" series, and Pentium. The logic behind the two slower clock rate and lower power processors on the same chip was to increase performance while reducing current leakage and incurring less thermal consumption on the CPU for an affordable price (Fisco, 2005). Furthermore, Intel exhibited consideration of the mobile revolution and the shift away from desktop devices. Power consumption was not a significant issue in desktop plug-in computers whereas mobile phones and laptops relied heavily on a single charge. Through the Intel Dual- Core architecture, Intel efficiently shrunk the size of the processor, increased CPU clock rate, and reduced energy consumption. In terms of user implementation, the dual processor demonstrated increased performance in multithreaded applications and multitasking. This allowed users to run multiple programs in the background. In high computational cases such as running multimedia, playing a videogame, application development, and all of the above, the more powerful multithreading dual-core processor was the effective solution. However, in cases of single-tasking and single-threaded applications, the slower dual-cores inside of the Pentium Dual-Core fundamentally performed the same as any other single-core processor with comparative clock rate.

Figure 5. Microarchitecture of the Intel Pentium Dual-Core

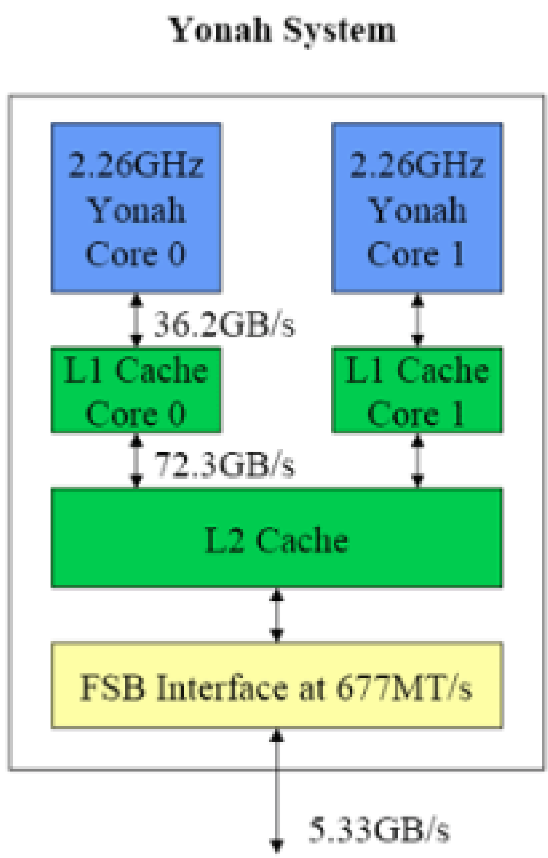

Figure 5. Architecture of the Intel Pentium Dual-Core. The figure illustrates the Pentium Dual-Core 32-bit Yonah microarchitecture. This is the configuration of the two cores and it illustrates the

2.26GHz core with dedicated L1 cache and shared L2 cache between the two cores. It also shows the FSB at 677MT/s or 5.33 GB/s (Kanter, 2006).

The Intel Core i7 8th Generation Processor

The all-new Core i7 8th Generation processor exhibits the latest in microprocessor technology and design. It exhibits the newest technology and most up to date features of CPU microprocessor architecture. Whereas the Intel Core i7 8th Generation "U" series for laptop was launched August 21, 2017, the Intel Core i7 8th Generation codenamed, Coffee Lake, was launched on October 5th, 2017, showcasing the latest upgrades of the previous Skylake and Kaby Lake 7th generation processors. Furthermore, the Core i7 belongs to the Core series family as a high-end model for today's developers, gamers, and overclocking computer users. The Core i7 8th Generation Coffee Lake is a refinement of the 7th generation microarchitecture, featuring quad-core and hex-core configurations with x86-16, x86-32, and x86-64 instruction set architectures.

Figure 6. Skylake Architecture for High-End Quad-Core

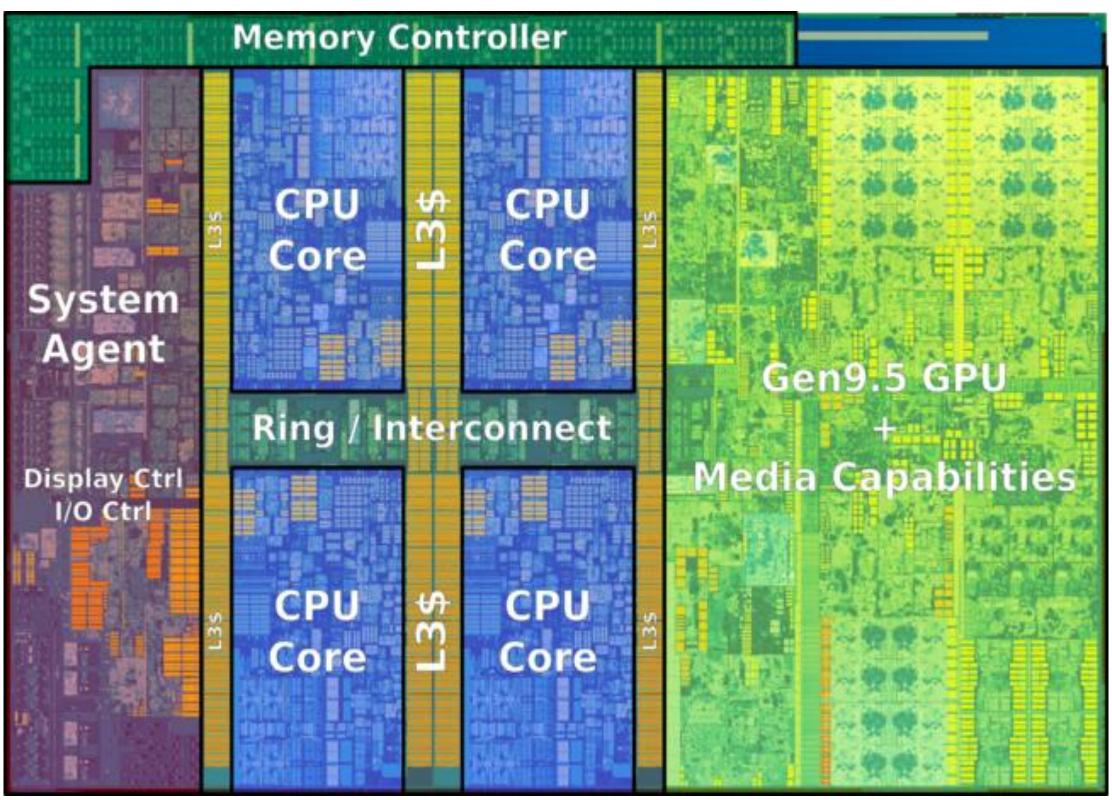

Figure 6. Skylake Architecture for High-End Quad-Core. The diagram illustrates the architecture for the Core i7 Skylake as well as the Kaby Lake. While the Core i7 8th Generation for desktop and laptop is also based on this architecture, this chipset more closely embodies the Core i7 8th Generation quad-core for laptop computers. The diagram can be compared to the Coffe Lake chipset later in this section (Wikichip, 2017).

The Intel Core i7 8th Generation for Laptop

The Core i7 8th Generation comes in either 8550U or 8650U laptop versions. In comparison to the previous Kaby Lake generation, the 8th Generation "U" series processor is a refinement of former using the same underlying technology. The newer 8550U and 8650U both include 8MB CPU dedicated cache and four-core processors with hyperthreading technology so that each of the four physical cores emulates two core for parallel processing. The versions respectively feature a 1.8-4GHz clock rate for the 8550U and a 1.9-4.2GHz clock rate for the more powerful 8650U. In addition, during periods of high computational use, Intel Turbo Boost Technology effectively increases each core's clock rate to 4-4.2GHz. Intel strategized production of the multi-core laptop microprocessors to handle single and multi-threading applications while efficiently considering size and energy consumption. According to editor Gregory Bryant at Intel, he states that the company promises a performance boost of 40% over the previous generation due to the new quad-core configuration, power-efficient microarchitecture, advance process technology, and a huge range of silicon optimizations (2017).

The Intel Core i7 8th Generation Coffee Lake

The new Core i7 8th Gen Coffee Lake comes in either 8700 or the "K" series 8700K desktop versions. Both versions include 12MB L3 shared cache and six high-speed cores—the 8700's clock rate speed is 3.2GHz and the 8700K's clock rate speed is 3.7GHz. On top of that, the versions include hyperthreading, bringing the core total up to twelve functional cores for parallel processing.

Intel's Turbo Boost Technology 2.0 also improves on multi-threaded as well as single-threaded applications. The Turbo Boost Technology 2.0 makes it possible for a single core to run a frequency of 4.7-4.7GHz or 4.3GHz if Turbo Boost Technology runs on all cores, demonstrating its flexibility and superiority over the archetypal single-core processors in most applications. The unlocked "K" series processors will also offer configuration flexibility with up to forty platform PCIe 3.0 lanes for system expandability on graphics, storage, and I/O. In terms of memory and chipset, the 8th Gen desktop chip will require the new Z370 instead of the older Z270 and will also support the memory speed of the DDR4-2666 (Ludlow, 2017). Therefore, users looking to upgrade their CPU will also have to upgrade their chipset. In addition, the new Z370 will support USB 3.1 Generation 1 or 2 based on OEM motherboard manufacturer specifications.

Figure 7. Intel Core i7 8th Gen Coffee Lake Architecture

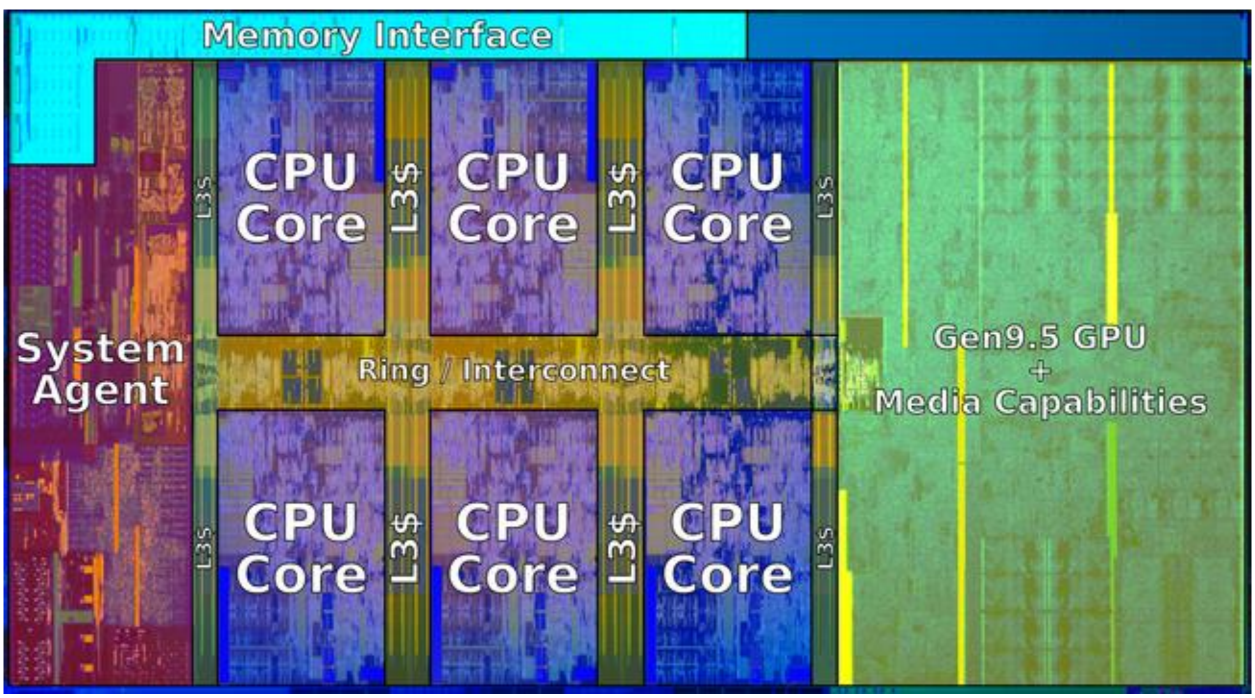

Figure 7. Intel Core i7 8th Gen Coffee Lake Architecture. This is the functional architecture of the Core i7 Coffee Lake. The diagram illustrates the six cores of the 8700 and 8700K found in desktop versions. The green section labeled Gen 9.5 GPU and Media Capabilities includes the PCIe 3.0, DDR storage, and I/O interfaces (Wikichip, 2017).

The Modern Implementation of the Intel Core i7 8th Generation Processor

Intel claims that the Intel Core i7 8th Gen processor will not only get the job done but get it done faster. Aside from the increase performance, the new processor also boasts flexibility and scalability for a variety of users and applications. According to Intel's online survey containing 2,552 Americans in March 2017, 63% want to multitask more on pc productivity, 62% prefer pc for entertainment, 49% prefer pc for content creation, 66% prefer pc for shopping, and significant percentages preferring pc for gaming, storage, communication, and general browsing (Bryant, 2017).

Intel designed the Core i7 8th Gen for businesspeople, developers, gamers, and the everyday users who need a computer that gets the job done. For business professionals who simultaneously run multiple applications for bookkeeping, accounting, finance, and security, Intel's hyperthreading and Turbo Boost Technology 2.0 ensure speedy computations and smooth operation. Considering workstations in offices everywhere, Intel measures that performance for the 8th Gen is 40% faster while multitasking versus the 7th Gen and 2.3x while multitasking versus five-year-old models. Intel also considered creative developers and measured the performance improvements of video and photo editing. Intel claims that 4K video editing is 32% faster versus the 7th Gen and 14.7x faster versus five-year-old models, taking only three minutes compared to forty-five minutes. In addition, when organizing and editing photos for a slideshow, Intel demonstrates that the 8th Gen is 48% faster versus the 7th Gen and 2.3x faster versus five-year-old models when mass editing on Adobe Lightroom. For gamers, the new processor is designed with the same GPU in the Kaby Lake that is rebranded as the UHD 620. However, gamers can expect better performance with increased clock rate and optimized drivers. Intel markets that gamers will experience 25% more FPS and up to 45% better mega-tasking versus the 7th Gen. Finally, the everyday user will benefit from having up to three 4K video displays simultaneously, 1.9x increased performance for web browsing, and up to ten hours of battery life on a single charge for laptops (Bryant, 2017).

Intel markets that the new 8th Gen microprocessors will be on more than 145 designs. The faster clock rate will also allow for the seamless integration of optimized touch, voice, and stylus applications without compromising performance. In addition, other features will include the Intel SGX and Intel Online Connect Built-in security as well as extensive I/O for USB, display, and Thunderbolt applications. Offering different performance points at varying price points for the new Core i7 8th Generation as well as the other Intel processor brands, consumers will should not have a problem finding an Intel based computer that suits their needs at the price that they can afford.

Conclusion: Improvements and Limitations to Microprocessor Architecture

With each performance improvements to microprocessor architecture, it is important to discuss the limitation factors and problems. Computer engineers deal with all of these limitations when optimizing CPU performance and building microprocessors.

Transistor Heat Interference

To begin with limitations, high power consumption and overclocking frequently leads to increased wear and tear on CPU's without the proper cooling of billions of ultra-tiny electron gates called transistors. The heat produced during cycles of on and off electron states leads to radio interference especially if the transistors are spaced very close together. This limitation of the spacing and number of transistors challenges Moore's Law. Radio interference from the heat compromises the integrity of accurate computation and can lead to problems with the executing instructions. Reducing energy consumption through multicore processors and larger cooling fans can alleviate some of this issue.

Transistor Delays

Transmission delays within the CPU deal with the amount of time that it takes for circuits and transistors to charge up or drain electrons. While the size of chips have gotten smaller not only for their fitment inside of mobile devices, this smaller size also decreases the length of circuits and transistors in a chain so that electrons have less distance to travel, increasing clock speed. This limitation also deals with the "switching frequency", describing the amount of time it takes for a circuit and transistor to flip states.

Transistor Size and Count

Transistor count and size is another limitation to the clock speed of CPUs. As defined by Intel co-founder himself, Moore's Law states the number of transistors will doubles every two years. Important to note, another observation called Dennard scaling also claims that the amount of power required to run transistors in a specific volume will remain constant despite increasing the number. However, this observation has been debunked. As transistors become increasingly small in order to fit more on the same size computer chip, the scaling ratio of voltage and power to volume has nearly reached its limit due to the structural integrity and resultant current leaking of transistors (Mattsson, 2014).

Figure 9. Moore's Law Over Time

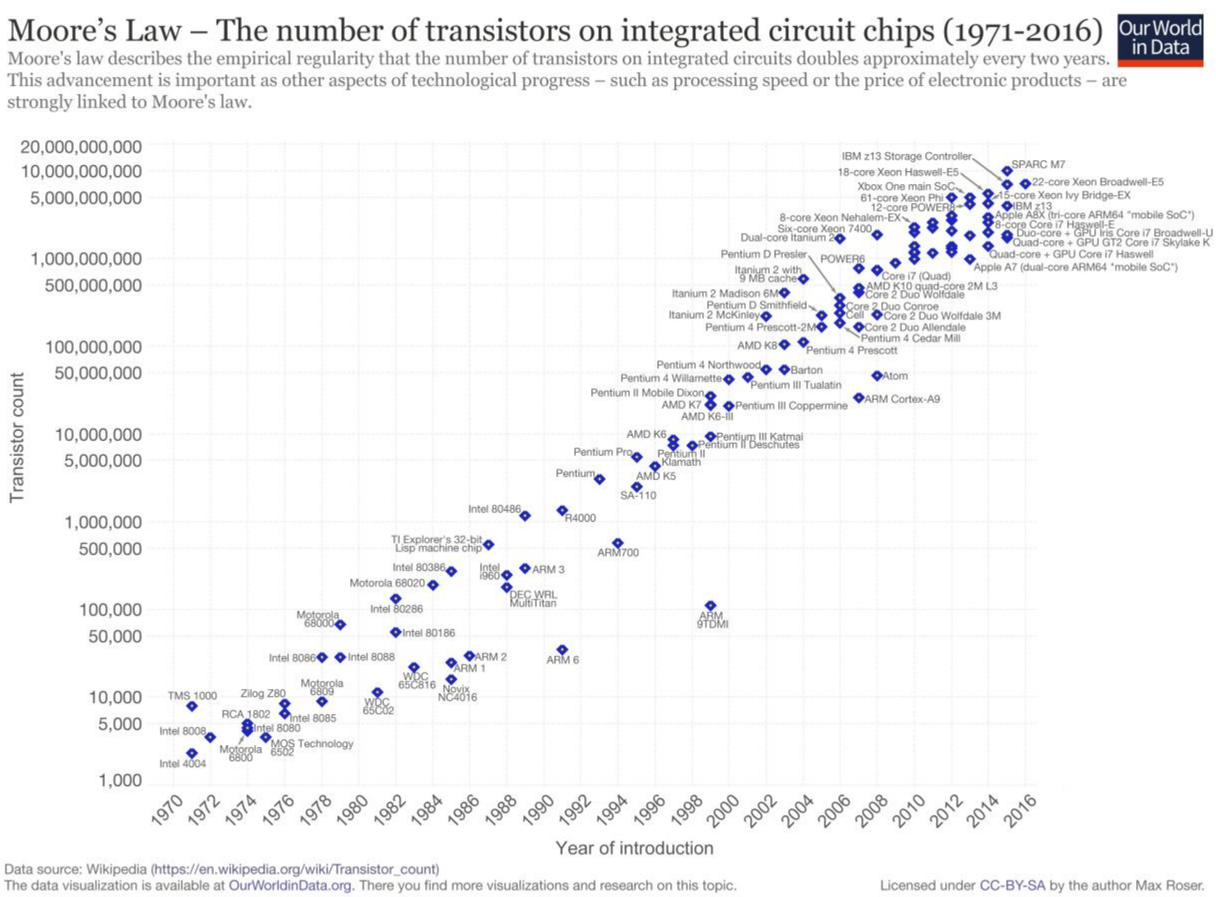

Figure 9. Moore's Law Over Time. This plot graph shows the doubling count of transistors every one to two years known as Moore's Law. Considering the plateau limitation of transistor count, this can still be used to roughly predict the progress of clock rate, transistor implementation, and price of chips in the future. The graph trends from 1970 to 2016 (Roser 2017).

Especially at Intel, computer engineers continue to push for greater performance on their microprocessors. Realizing at 22nm that simply shrinking transistors was not resulting in the benefits that they desire in accordance with Moore's Law, they have attempted to solve the problem of plateauing clock rates by moving away from 2-D, planar, transistors to 3-D, tri-gate, transistors (Bohr, 2011). According to Intel's head Mark Bohr, tri-gate transistors work by wrapping the transistor switch around three of the sides of a current flowing on raised silicon fins versus one side on the planar architecture. This maximizes current flow in on states for performance, optimizes reduction of current flow to zero in off states for power efficiency, and maximizes switching between states again for performance. As a result, tri-gate transistors create more than 50% power reduction at constant performance and 37% performance increase at low voltage, increasing efficiency and performance (Bohr, 2011).

Figure 10. 22nm Tri-Gate Transistor

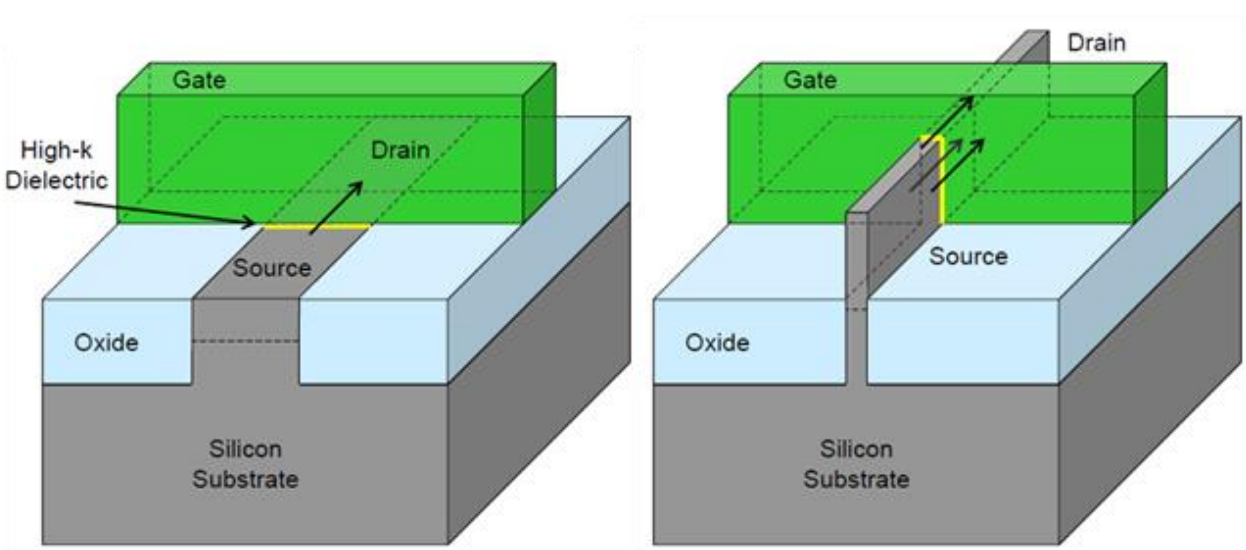

Figure 10. 22nm Tri-Gate Transistor. Here is a comparison of the old 2-D transistor design to the new tri-gate transistor design. The new design increases performance and efficiency due to the three-sided control that the gate holds over the current. The enhanced control of the tri-gate design allows for optimization during on and off states (Kanter 2011).

Word Size and Bus

The larger word size means that CPU can process more bits of data at one through its buses and eventually into its registers. It can be used to described the width of bus components. Buses include the Front Side Bus connected to the North Bridge and the Back Side Bus connected to the cache structure. However, increasing word size is increases CPU efficiency to a point because of complexities with wait states related to other devices connected to the CPU on the motherboard. Increasing bus widths can also improve communication lines between devices on the motherboard. This also generally implies that more bits can be carried between computer components at a time. Serial buses typically are cheaper to implement and faster for high rate transmission compared to parallel buses that require more complex synchronization. Therefore, serial buses are significant improvements when considering bus speed.

Cache Size and Structure

Caches are used to avoid the slow memory access times of the CPU to main memory and hard disk which are often located off the chip. Intel engineers increase the cache size and count through multi-level caching in order to reduce these CPU wait states incurred by slow access times. Cache is a small, high-speed SRAM between the CPU and primary storage that predicts and prioritizes frequently access memory. When the CPU executes a read, it first goes to the cache before moving on to primary storage through a hit, miss, or swap process. The cache controller determines if the memory is stored in the cache and predicts what data will be requested in the future and pre-loads that data to cache in advance. Caches exploit spatial locality and temporal locality. Spatial locality is when the cache brings in more data than has been requested by storing nearby memory in a block. Temporal locality is when the cache removes memory than has not been recently accessed. In addition, the cache reduces wait states during write executions when one write access must be confirmed before another can begin. While larger caches have higher hit rates, they also have slower access time. As seen first in architecture of the Intel Pentium P6 and successor models up until the Core i7 8th Gen, Intel engineers deal with this problem by implementing multiple levels of caches also with processor dedicated cache levels. Further, split caches between data and instructions further increase execution efficiency because they can be access simultaneously and increase CPU-memory bandwidth, altogether improving execution speed by over 50% with typically a hit rate of over 90% (Xing, 2017).

Figure 11. Cache Level Hierarchy

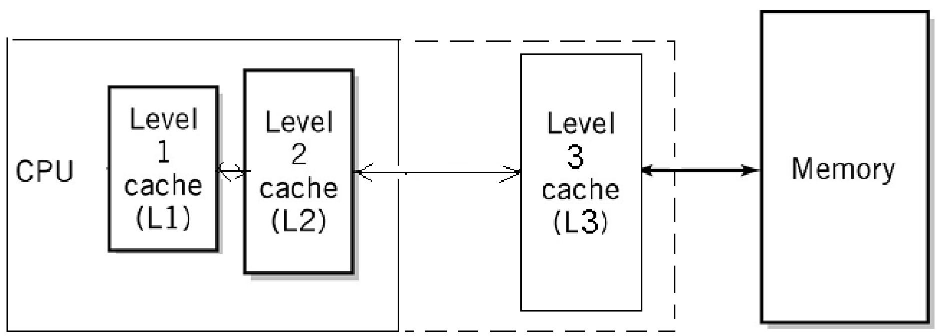

Figure 11. Cache Level Hierarchy. Illustrating the tiers of cache, L1 cache is the smallest and fastest, L2 is the next largest and less fast, and L3 is the largest and least fast cache. The arrows provide the flow of the hit and miss process. (Xing 2017).

Multi-Core Processors

The utilization of multi-core processors will continue to be improved through hardware and software in the future for increased CPU performance. Naval officer and PHD of mathematics at Yale, Admiral Grace Hopper, eloquently stated the basis of multi-core solution in her analogy:

> In pioneer days, they used oxen for heavy pulling, and when one ox couldn't budge a log, they didn't try to grow a larger ox. We shouldn't be trying for bigger computers, but for more systems of computers (Schieber, 1987).

Intel engineers have focused on the development of the multicore processor instead of single-core processors since 2005. Multicore processors rely on optimizing the division and synchronization of computations or parallelism in order to improve overall computer performance as well as reduce heat, power consumption, and stress within various internal components. Examples of the configuration of multicore processor systems include asymmetrical multiprocessing, symmetrical multiprocessing, and multi-threading. Since the execution speed of a CPU is directly related to the clock speed of the CPU, equivalent processing power can be achieved at much lower clock speeds, reducing power consumption, heat, and stress within the various computer components. Currently Intel uses their brand of symmetrical multiprocessing and multi-threading called Hyperthreading which allows parallel execution of instructions within a single core and between cores, while synchronizing across multiple cores through the operating system. Today, engineers are increasingly invested in parallel computing for design improvements in both hardware and software—continuing to develop ways to make microprocessors faster, stronger, and more efficient.

Future Study of Microprocessor Architecture

Examining the modern history, design, and implementation of Intel microprocessors, this project warrants future study into the technical elements of improving microprocessors and overall computer performance. This research focuses on Intel architecture as similarly identical architectures are easily seen in competitor microprocessors throughout the same periods of time. The results of this research reveal the limitations and improvements of hardware and software design for use in the entire computer community. Furthermore, it creates a basis for understanding the architecture of microprocessors, beckoning others to learn and understand more about the topic in order to contribute to the greater knowledge and advancement of computer science, information systems, and information technology.

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