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Abstract
Roughly stated, Moore's Law observes that the processing power of computers doubles approximately every two years, and has retained striking accuracy over the past five decades. Since it was first observed by Intel Corporation co-founder Gordon Moore in 1965, Moore's Law has been something of an enigma to the semiconductor industry. Although originally made to project the industry's capacity to innovate, Moore’s Law came to dictate the pace of the semiconductor industry’s growth. Many industry experts continue to insist on its impending doom, despite numerous incorrect examples of such forecasts during the last 30 years. I discuss the ever-evolving meaning of Moore's Law that has allowed it to persist in surprising ways. However, the eventual demise of Moore's Law, if not pre-empted by economic factors, is all but guaranteed by the laws of physics. I explore the sustainability of an industry founded on a model of exponential growth and suggest an alternative model of logistic growth. Ultimately, I connect the progress of the semiconductor industry to the progress of the global economy, and anticipate ways to weather the change in growth signaled by the end of Moore's Law.

Moore's Law or Moore's Flaw?

Sustainability of an Industry Built on Exponential Growth

According to a report by market analyst firm Kantar Worldpanel, Americans upgraded their smartphones in 2016 after holding onto them for an average of 23 months. This two-year upgrade cycle is so well established in the smartphone industry that Verizon Wireless used a long-running promotional slogan: "New Every Two". On the surface, the idea of "New Every Two" may seem like a clever ploy to ensure a steady income stream for the smartphone industry; instead, "New Every Two" reveals an underlying law that has guided the manufacturing of electronic devices for the past 50 years. This law was first observed by Intel Corporation co-founder Gordon Moore in 1965 and has since come to be known as Moore's Law. Roughly stated, Moore's Law observes that the processing power of computers doubles approximately every two years. Smartphones, which are little more than handheld personal computers, have been manufactured to follow design roadmaps based on Moore's Law, with new flagship components appearing roughly every two years. All electronic devices use components made from special materials called semiconductors. Manufacturers of semiconductor-based goods are known collectively as the semiconductor industry. The semiconductor industry’s ability to sustain Moore’s Law has allowed the “New Every Two” business model to be viable, with consumers enthusiastically buying new smartphones every two years, provided they pack faster speed and more appealing features into a sexier package. Would consumers be willing to buy smartphones every two years if they were just new, and no longer faster and better? Such may be the case if the semiconductor industry was suddenly no longer able to sustain Moore’s Law. Industry experts are increasingly forecasting the imminent demise of Moore’s Law. The question is whether Moore’s Law will end due to natural constraints of current technology, as governed by the laws of physics, or die prematurely due to economic reasons. Prevailing trends in the global economy—under-regulated free trade, rampant globalization, and rising monopolies—threaten the financial sustainability of existing business models. The semiconductor industry must adopt alternative business models that promote sustainability or brace for the upheaval accompanying an abrupt end to Moore's Law.

Technological Progress and Moore's Law

While the average consumer might never notice it, nearly every sector of the global economy has come under the jurisdiction of Moore's Law. Moore's Law is most easily understood as a modern representative for technological progress. Technological progress is easier to understand when it is broken down into technological eras. The technological era of particular interest is the First Industrial Revolution, which spans from roughly 1760 to 1830. During this time, the production of goods was revolutionized starting in Great Britain, and spread worldwide thanks to European colonization that ranged from the Americas, though Africa and Asia, to as far west as modern Indonesia (Lucas 109). Robert Lucas Jr., Professor Emeritus in Economics at the University of Chicago and recipient of the 1995 Nobel Prize in Economics, argues that the First Industrial Revolution marked a major turning point in history, with the average person's standard of living consistently improving for the first time (110). In this way, the First Industrial Revolution influenced nearly every aspect of daily life. The value of the world's total production of goods and services can be used to evaluate global economic performance and is known as the global gross domestic product [GDP]. J. Bradford De Long, Professor of Economics at the University of California, Berkeley and former Deputy Assistant Secretary of the U.S. Department of the Treasury, points out that global GDP grew at a fairly steady pace in proportion with global population until 1800 (2-3). The global economy was transformed by the innovations from the First Industrial Revolution, which allowed goods and services to be produced at an unprecedented rate. Starting around 1800, the global GDP took on a new trend of exponential growth that has continued to present day (see figure 1).

As dramatic as the First Industrial Revolution was, it is not solely responsible for the continued exponential growth that the global economy has enjoyed since 1800. The Second Industrial Revolution picked up where the First left off, spanning from the mid-1800s to the early 1900s. The Second Industrial Revolution introduced new innovations that again influenced nearly every aspect of daily life. These innovations allowed people, goods, and new ideas to spread across the globe with unprecedented ease, sustaining the exponential growth in global GDP. Starting in the mid-1900s, advances in technology ushered in the Atomic, Jet, and Space Ages and further fueled the exponential growth in global GDP, a continuation of the economic progress started by the First and Second Industrial Revolutions. During the 1960s, the start of the Digital Age marked a unique change in technological progress. While all previous innovations were centered around mechanical devices and analog electronics, innovations of the Digital Age

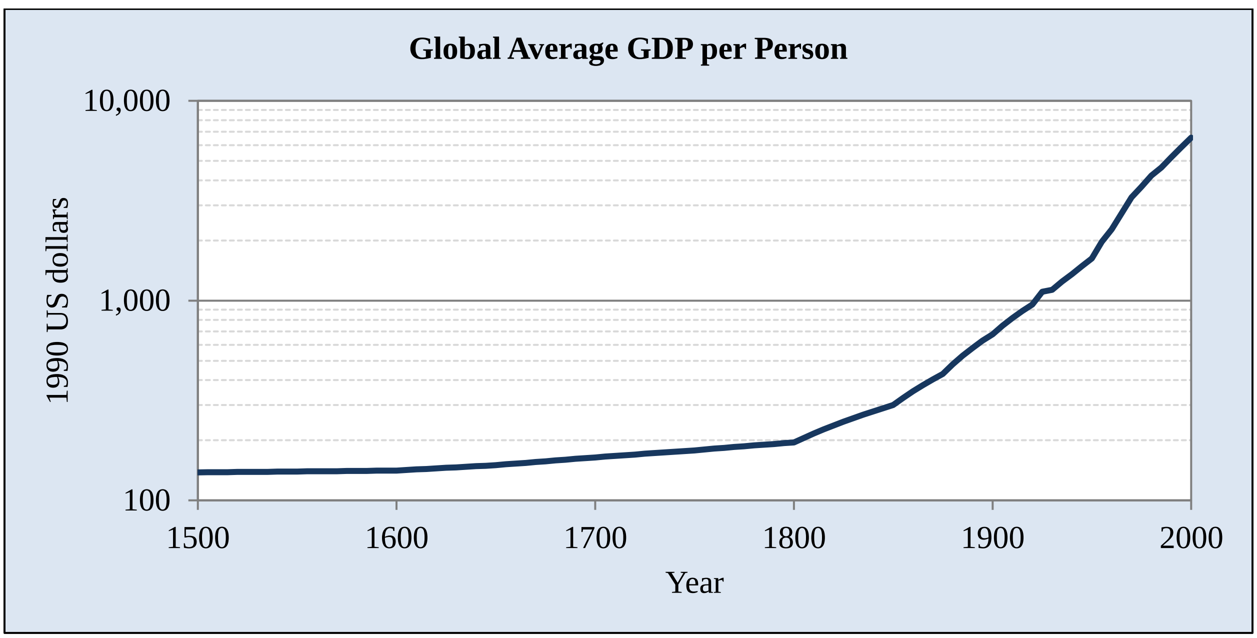

Figure 1. This graph is based on estimated global GDP divided by estimated population for 1500 to 2000, adjusted for inflation to 1990 US dollars (De Long 5-6).

saw the recording and exchange of information switch to the digital realm—meaning that information could be encoded as simply 0s and 1s. Accompanying the Digital Age was the rapid adoption of computers to process and store digital information. From the exponential growth observed in the development of computers arose Moore's Law. In the Digital Age, computers are used in practically every sector of the global economy to innovate and increase efficiency, influencing nearly every aspect of daily life like the technological eras before it. Together, the technological eras have sustained the exponential economic growth that was first experienced during the First Industrial Revolution. Since this crucial turning point in history, we have enjoyed an ever-increasing standard of living thanks to technological progress. As the modern representative for technological progress, Moore's Law has become the global economy's main driver of continued exponential growth.

What Is at Risk If Moore's Law Ends?

The average person might be unconcerned with the fate of Moore's Law, deeming it merely a matter of academic self-indulgence. Consider the extent to which Moore's Law pervades our entire global economy. In terms of global GDP, Lee Graham of industry analyst giant IHS Markit reports that the pace of innovation predicted by Moore's Law has contributed an estimated $12 trillion of additional value. That represents a full percentage point of global GDP growth from 1995 to 2011—37 percent of the global economic growth. Graham continues, "If the cadence of Moore’s Law had slowed to every three years, rather than two years, technology would have only advanced to 1998 levels: smart phones would be nine years away, the commercial Internet in its infancy (five years old) and social media would not yet have skyrocketed." If the pace of innovation observed by Moore's Law were only marginally slower, doubling our computing power every three years instead of two, we would not yet know so many devices that we have come to rely on daily. Graham goes on to detail the impact of Moore's Law on everyday quality of life: while only 0.1 percent of the world's households had high-speed internet connections in 1991, 40 percent now have a high-speed internet connection as of June, 2015. Graham explains that 150 billion new barrels of extractable oil have been discovered thanks to the technological innovations allowed by Moore's Law. Finally, Graham argues that Moore's Law has allowed researchers to perform 1.5 million high-speed screening tests per week for new materials in bio-fuels and feedstock, up from 180 per week in 1997. Moore's Law has guided innovation extending to nearly every sector of the global economy: agriculture, biotech, communication, electricity, materials science, medicine, energy, and transportation.

The growth of the global economy can be measured in the growth of productivity, which is the output per unit input. An economy producing two tables per tree is twice as productive as an economy only producing one table per tree. Moore's Law has been the primary driver of economic productivity over the course of the Digital Age. Every two years, the semiconductor industry has been able to produce computers that offer twice the computing power for effectively the same cost of production. Kenneth Flamm, Professor of Public Affairs at the University of Texas at Austin, perfectly captures the consequences we are already experiencing from a slowing-down of Moore's Law:

> Economic impact from a winding down of Moore's law has already started rippling through the semiconductor industry, downstream to the computer and communications equipment industries, out to information technology-using industries, and may be contributing to the current slowdown in labor productivity growth visible across much of the global economy. (29)

If Moore's Law collapsed, the global economy would not suddenly come to a screeching halt. Instead, the waves of influence would first hit the computer industries directly tied to the semiconductor industry and ripple down through the global economy over a period of time. At some point, productivity growth would cease to be exponential, mirroring the end of exponential growth accompanying the death of Moore's Law. This would result in a second great turning point in history—when global GDP breaks from the exponential trend that started in 1800 with the First Industrial Revolution. Analysts have yet to forecast the next technological era that would follow the Digital Age, because we have yet to discover a next generation of innovations that would enable continued exponential growth. As such, the preservation of Moore's Law represents the only currently-known means of sustaining an exponentially growing economy.

By relying on exponential growth for sustainable profits, the semiconductor industry has put itself on a perilous path. The semiconductor industry's profit center has been the computer chip, the component that acts as the computer's brain. Each new generation of chips are so microscopic and intricate now that they require billions of dollars of highly specialized manufacturing equipment—billions of dollars of highly specialized manufacturing equipment that will be obsolete in just a few years. Flamm demonstrates that chip manufacturing equipment costs are 22 to 40 times higher than in 2001 (37). The intricacies require billions of dollars of investment into research and development for each new generation of chips. Apek Mulay, a senior semiconductor industry analyst, estimated in 2013 that a new generation chip would require an investment of over $10 billion (29). The businesses making these investments need strong consumer demand to allow for an adequate return on investment. Consumers expect new devices to be faster, better-featured, and sexier, so the semiconductor industry has come to rely on exponential growth to meet consumer expectations and drive demand.

The Ever-Changing Definition of Moore's Law

In order to understand how Moore's Law has retained such striking accuracy over the past five decades, one must first understand the fluid nature of how Moore's Law has been defined throughout its history. While Moore's Law is commonly stated as a doubling of computer processing power every two years, this is a simplification of a much more complicated idea. The eponymous law was first observed by Intel Corporation co-founder Gordon Moore in 1965: the components per chip doubles every year. The definition of Moore's Law shifted in 1975, as Moore realized his original definition was off roughly by a factor of two and revised his original observation to every 18 months.

Though the original definition included resistor and capacitor components, Moore's Law quickly underwent a second transition in its understanding. Instead of doubling the components per chip every 18 months, Moore's Law came to be understood as the doubling of a single type of component, transistors, every 18 months. Transistors are made from semiconductors and are the basic components at the heart of every computer chip. General readers do not need to understand exactly what a transistor does, which is a very complicated matter. Instead, think of transistors like an electronic switch. They are able to switch on or off based on an input, so they act as the smallest decision-making component of a computer chip. A large network of these decision-making transistors on a chip are together able to perform complex computations, like taking a picture from a camera lens, converting that image to pixel-by-pixel color data, and storing that data as a single picture file. Practically speaking, doubling the number of transistors on a chip doubles the processing power of that chip.

Chips would be impractically large if the number of transistors continually doubled without shrinking their size. Every stride made in increasing the number of transistors has been in lockstep with a shrinking of transistor size. Moore's Law was refined again to a doubling of transistor density, as opposed to just doubling the number of transistors. The 2,300 transistors on the first commercially available computer chip measured about half the width of a human hair (see figure 2). Fifty years of Moore's Law has transformed the chip from these humble beginnings, with the latest generation smartphone chip packing 3,000,000,000 transistors small enough that 2000 fit within the width of a human hair. This smartphone chip would be the size of half a basketball court if its transistors were the same size as the first chip's transistors. It is unlikely that we would be willing to lug around smartphones the size of half a basketball court.

Chip manufacturers eventually discovered ways to design new chips that double their processing power without having to the double transistor density. Consequently, the definition of Moore's Law shifted over time from the doubling of transistors density to the doubling of processing power density. Chris Mack, a semiconductor industry expert, points out that there were two additional factors driving the doubling every 18 months: increases in chip area and design cleverness, which eliminated the nonfunctional chip area (203). The revised 18-month doubling period proved remarkably accurate until very recently (see figure 3). In 2016, Intel Corporation revised their immediate roadmap to doubling every two and half years instead of every 18 months. Already, it is apparent that Moore's Law can no longer be maintained at the previous pace, demonstrating yet another shift in the fluid nature of the understanding of Moore's

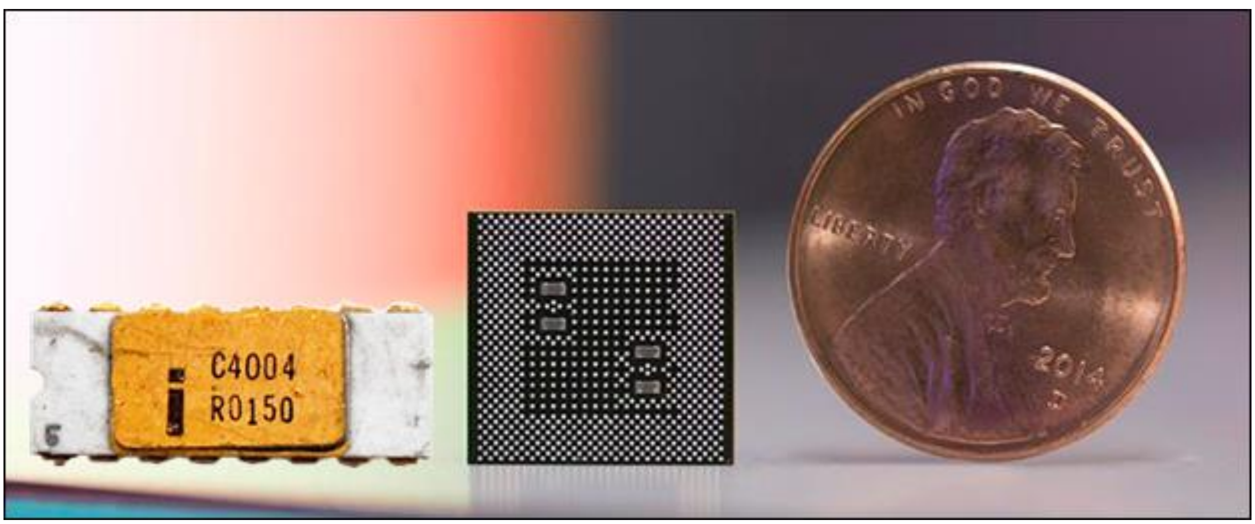

Figure 2. This picture shows the first commercially available computer chip (the Intel 4004, left) alongside the latest generation smartphone chip (the Qualcomm Snapdragon 835, center) that will power the upcoming Samsung Galaxy S8, Samsung Galaxy Note 8, and Google Pixel 2.

Law. This ever-changing understanding of Moore's Law shows that it is not a natural law, like Newton's law of gravity. Moore's Law has morphed in response to the industry's ability to sustain it, serving as a roadmap for the semiconductor industry to plan its growth.

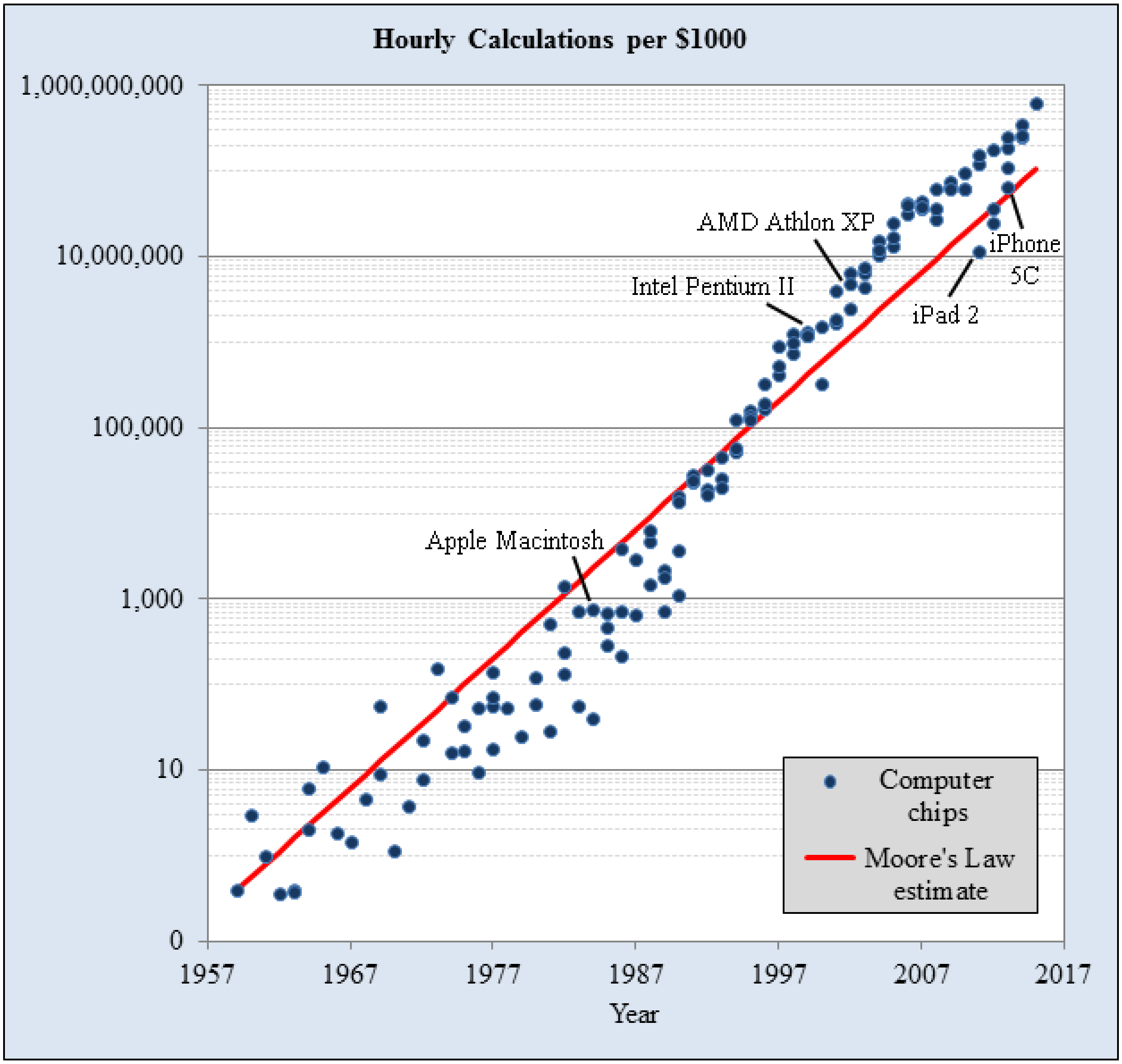

Figure 3. This graph is based on data of the processing powers and prices of various computer chips, adjusted for inflation to 2000 US dollars (Brunner). Moore's Law estimate is based on taking the first chip's processing power and doubling it every two years through 2015.

The End of Moore's Law Due to Laws of Physics

In an ideal world, there would be no limit to Moore's Law. The semiconductor industry would be able to pump out better chips until the end of time. Sadly, there are several laws of physics that serve as natural limits to exponential growth. The prevailing notion among experts is that the semiconductor industry is already bumping up on many of these natural limits. Mack describes the lower limit of chip voltage scaling as a key issue. Shrinking transistor size had always relied on a scaling down of voltage to give smaller, faster transistors that consumed less power (204). However, unavoidable voltage fluctuations from thermal noise prevent voltage from being scaled down with transistor size (204). This means that the industry's ability to shrink transistors will no longer give transistors that can achieve faster speed while consuming less power. Mack goes on to explain that the industry is reaching an upper limit of practical production yield. The production yield is the percent of the manufactured devices that function properly, so a process with a 50% yield will spend twice as much to make a finished, saleable device as a process with a 100% yield (206). Chip makers have gone from average yields of 20% to 40% in the 1970s, to 50% to 70% in the 1980s, to 80% to 90% in the 1990s, and over 90% in recent times (206). It is easy to see 100% as a natural limit for production yield, so the semiconductor industry will no longer be able to see cost benefits from improved production yields. Mack concludes that it is unlikely that there are many years of Moore's Law left (207). This viewpoint represents the predominant notion among industry experts.

Even if all manufacturing limits were overcome, the quantum limit would undeniably limit the progress of Moore's Law. All electrical devices utilize the flow of electrons. Thus, a practical transistor could never be smaller than the size of an electron. James Powell used a famous law of physics, the Heisenberg uncertainty principle, to calculate a smallest possible size for transistors. He then extrapolates the current trend of transistor size reduction using this calculation, ultimately arriving at 2036 as a reasonable year when the quantum limit would be reached (1248). Without the ability to shrink the size of transistors, chips would no longer be able to double in processing power every two years, or over any timeline for that matter. *Breaking Bad*'s Walter White would agree: the Heisenberg uncertainty principle dictates that Moore's Law has an inevitable end in the quantum limit.

Moore's Law should not be depicted as exponential growth, given the certainty that Moore's Law as we know it will eventually end. True exponential growth is able to perpetuate without end. Instead, Moore's Law would be more appropriately modeled as logistic growth (see figure 4). Logistic growth appears exponential at first, then flattens out, gradually becoming less exponential and more linear in the middle. Finally, the growth flattens almost completely, approaching a brick-wall limit at an ever-slowing rate. For Moore's Law, the first phase of logistic growth would be the semiconductor industry's exponential growth over the past 50 years. The semiconductor industry is now entering the middle phase, as evidenced by the slowing of

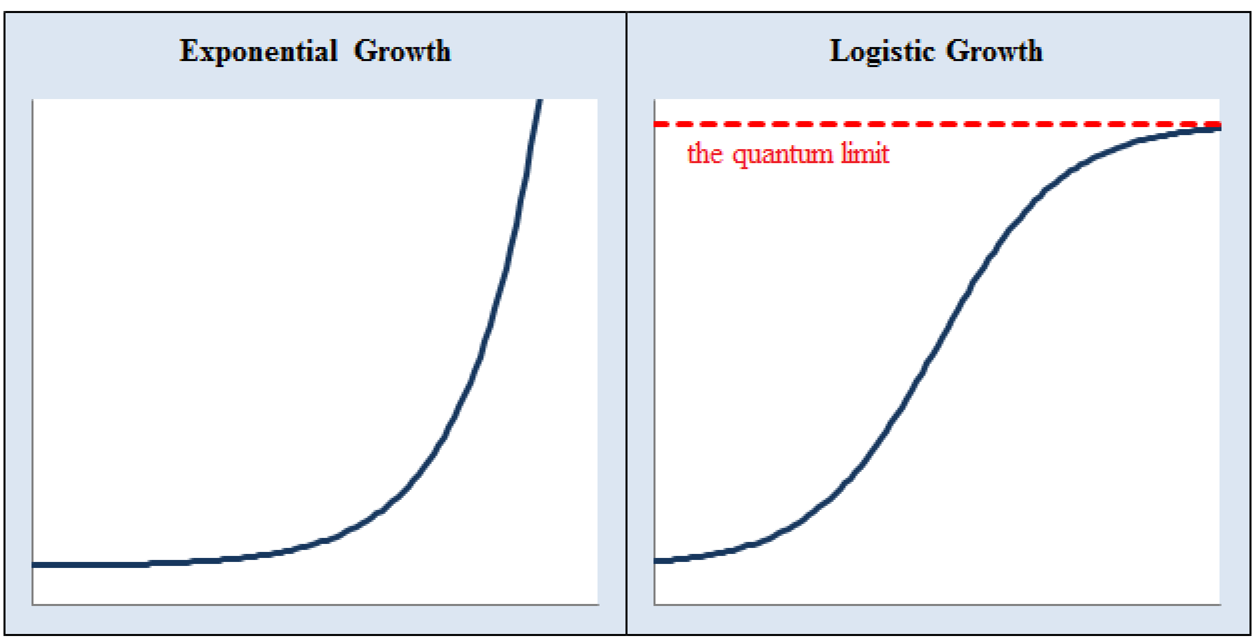

Figure 4. These two graphs illustrate the differences between exponential and logistic growth.

Moore's Law from doubling every 18 months to every two and half years. As the semiconductor industry's pace of growth continues to slow, it will flatten out as it approaches the brick-wall quantum limit. Logistic growth provides a much more sensible model for understanding Moore's Law, however appealing an ideal world's endless exponential growth may be.

Economic Factors May Preempt the End of Moore's Law

As undeniable as it is that Moore's Law will come to an end, it is debatable how soon the semiconductor industry will reach it. It seems unlikely that the semiconductor industry would be able to navigate the maze of physical limitations to reach the ultimate quantum limit. Before that point, the semiconductor industry will be fighting to squeeze the last few percentage points of improvement out of limits like the lower limit of chip voltage scaling and the upper limit of production yield. These last few percentage points of improvement can only come through exponentially increased research and development costs. Instead of reaching an end to Moore's Law due to laws of physics, it is more likely to be preempted due to economic reasons. Herein lies the debate as to how soon the end of Moore's Law will be reached.

Industry experts can be roughly divided into two circles of thought, the first being that end of Moore’s Law is nigh. Earlier, Mack provided an example from this circle of thought, finding Moore's Law as unlikely to have many years left. Flamm provides another example, concluding that "[t]he design of a new partnership capable of successfully creating the technological foundations of the 21st century successor to Moore's famous law deserves urgent attention" (39). Mulay contributes another strong voice to this circle, positing a well-reasoned argument against the semiconductor industry's current business models. He describes Moore's Law as the *de facto* business model for the semiconductor industry and a major deflationary force in the global economy (2). This deflationary power is a direct consequence of the core idea behind Moore's Law: that transistor density will double approximately every two years. Because transistors constitute the logic circuits in electronic devices, increasing the density of transistors increases the device's functionality for approximately the same manufacturing cost. The deflationary power of Moore's Law means it has allowed consumers to enjoy a greater purchasing power (5). Mulay points the finger at globalization for threatening the progress of Moore's Law. American chip-makers have chosen to combat exponentially-rising research and development costs by exporting chip manufacturing to cheap overseas labor, leading to a large trade deficit, idle domestic manufacturing facilities, job losses, and stagnant wages (12). He then criticizes "monopoly capitalism". Figure 5 demonstrates his argument: as profits have flowed disproportionately to the richest 1% of the population, the gap between wages and productivity has widened. If productivity continues to outpace wage growth, then the average consumer will not be able to afford expensive, cutting-edge devices. Without consumer demand, companies will not have a sustainable return on investment, which could halt Moore's Law in its tracks (6).

Ultimately, voices in this first circle of thought call for action—to consider what changes the semiconductor industry should make to combat the winding down of Moore's Law. Mulay calls for a shift in the semiconductor industry to a sustainable business model in which wages are tied to productivity. With higher wages, employees would enjoy great purchasing power. Combined with the growth of consumer purchasing power from the deflationary force of Moore's Law, consumers would drive demand for new innovations (31). In turn, this would allow companies to achieve an adequate return on investment, providing the driving force to sustain Moore's Law until the laws of physics dictate its demise. Mulay contends that this business model's sustainability would outlive Moore's Law due to the tethering of wages to productivity, which leads to a natural regulation of supply, demand, and economic growth (33). Mulay's economic principles would sacrifice the raw pace of exponential innovation from a capitalistic free market. However, they are much more likely to be sustainable in the absence of Moore's

Law, once logistic growth is embraced. Voices such as Mack, Flamm, and Mulay forewarn of the impending death of Moore's Law, and call for changes in the semiconductor to promote long-term sustainability before, during, and after the end of Moore's Law.

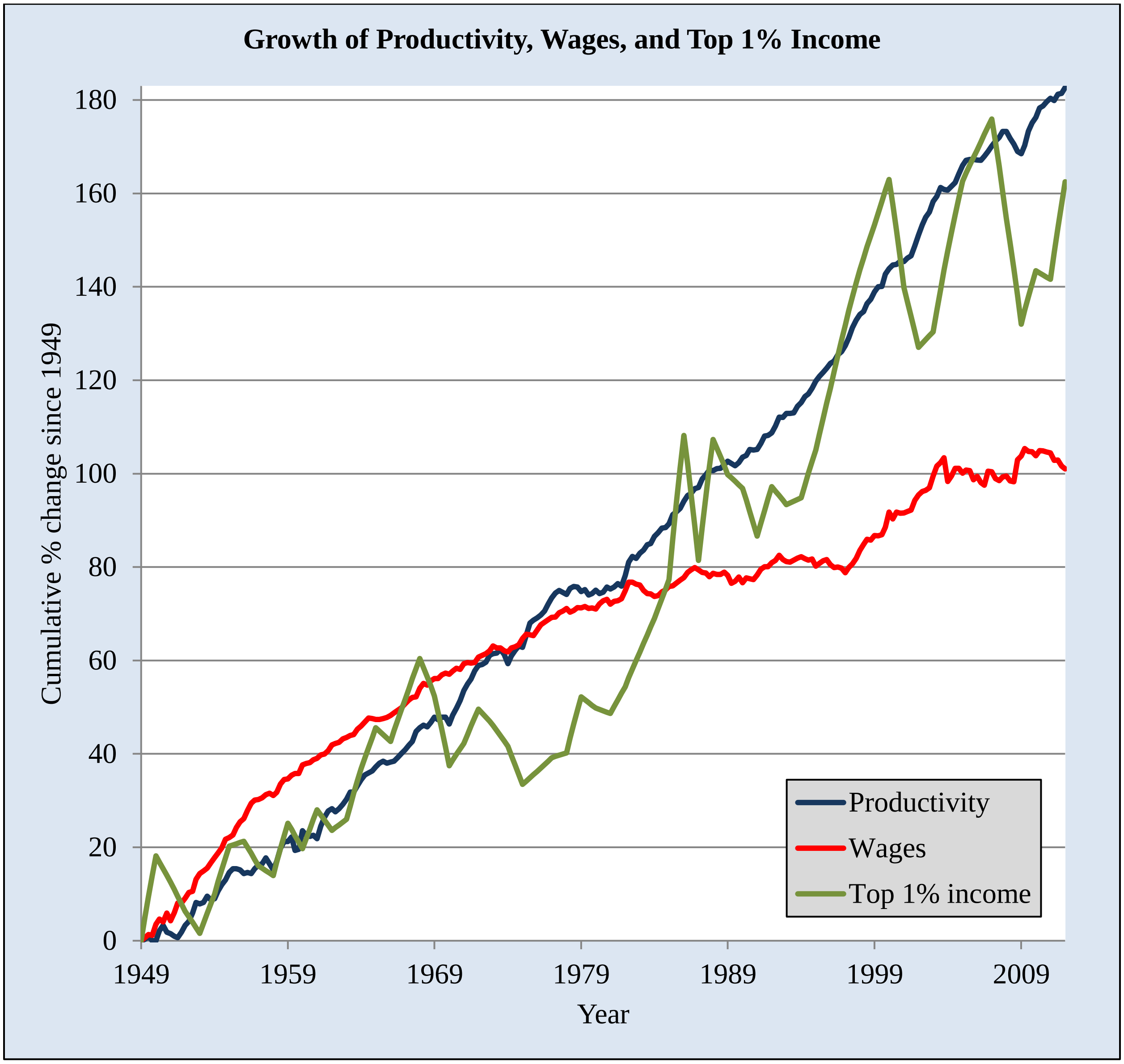

Figure 5. Productivity and wage data is derived from statistics for the manufacturing sector from the Bureau of Labor Statistics (Fleck, chart 6). Top 1% income growth is derived from annual real income levels for the top 1% earners in the United States (Piketty, table 1).

The other circle of thought is that the semiconductor industry will continue to find unexpected innovations and methods to sustain Moore’s Law for the foreseeable future. The history of Moore's Law shows that the semiconductor industry has maintained a fluid understanding of Moore's Law. Surprising innovations have allowed it to be sustained amongst increasing forecasts of its imminent demise over the last decade. These innovations have instead sparked the semiconductor industry to reevaluate its definition of Moore's Law several times. Erik DeBenedictis, scientist at Sandia National Laboratories, argues that upcoming shifts in chip architecture, programming, and manufacturing processes, will again necessitate a shift in the definition of Moore's Law (74). This shift might divorce Moore's Law from the requirement of ever-improving chip density. Struggles to continue improving chip density have already slowed the cadence of Moore's Law from 18 months to two and a half years. Instead, Moore's Law could be married to the idea of improving processing power per dollar spent in manufacturing. Processing power per dollar could continue improving even after reaching the quantum limit, breathing new life into the sustainability of a redefined Moore's Law.

Voices from this second circle of thought argue for maintaining the *status quo*, insisting on confidence in the free market's self-regulating qualities. Bret Swanson, president of technology research firm Entropy Economics and venture capital firm Entropy Capital, writes on behalf of the American Enterprise Institute, a well-known conservative public policy think tank. Swanson argues that although Moore’s Law is unlikely to continue to be valid going forward, when measured in terms of conventional metrics, we will continue to experience exponential growth in computation, storage, and communication (7). He bases this on a prediction that the industry will innovate a variety of new materials, devices, and parallel architectures. He argues that this continued exponential growth will help transform a number of lagging industries, such as education and health care (16). He has high praise for the economic policies that have so far allowed for Moore’s Law to be realized. Stacy Smith, group president of Manufacturing, Operations and Sales at Intel Corporation and former Intel CFO, takes a defensive posture towards Intel’s use of Moore’s Law as a roadmap for their business strategy. More importantly, he defends Moore’s Law itself as a democratizing force, allowing for more people to access computers, due to exponential growth in computing power lowering the cost of any business model that uses computing. Smith certainly favors a capitalistic free market, where the raw pace of exponential innovation has a trickle-down benefit to consumers and other businesses. Smith’s ultimate point is that Intel’s position as an industry leader will parallel Moore’s Law—neither is ending any time soon. Voices like DeBenedictis, Swanson, and Smith argue that the end to Moore's Law is far down the road, though it will likely need to be redefined once again to maintain its validity.

Conclusions

While it is a matter of debate how soon Moore's Law will end, the quantum limit convincingly demonstrates a brick-wall limit. The semiconductor industry might once again find unexpected innovations to extend the exponential growth that has fueled the industry. Even so, if the *status quo* business models in the semiconductor industry are maintained, the global economy must brace for the upheaval accompanying the inevitable end to Moore's Law. The entire industry is predicated on the idea of exponential growth, so it is hard to imagine that the industry is prepared for life after exponential growth. The stock markets have the historical trend of exponential growth built into the pricing, expecting future gains to follow the same trend. Implicit in this expectation is a reliance on Moore's Law to continue driving innovation across every sector of the global economy. When this changes, the global economy could see a collapse of its stock markets as it adjusts to life after Moore's Law, unless an unforeseen new technological era is ushered in. An economic recession, if not a full-blown economic depression, would almost certainly follow. If one takes the view that the prevailing global economic principles are putting Moore's Law in imminent peril, the industry must shift to sustainable business models that tie wages to economic productivity. Moore's Law was born out of capitalistic trends that started during the First Industrial Revolution and continued with the rise of globalization since the Second Industrial Revolution. As the modern representative for technological progress, Moore's Law has maintained the pace of exponential economic growth. The semiconductor industry depends on the exponential growth dictated by Moore's Law, which might instead be seen as Moore's flaw in the future. If we have learned anything from observing life on Earth, it is that no exponential growth can carry on forever. Instead, Moore's Law can be modeled more appropriately as logistic growth. Doing so would guide stock markets to temper future expectations, reducing the risk of a crash when Moore's Law collapses. For the past 50 years, Moore's Law has enabled the semiconductor industry to enjoy unwavering exponential growth without a second thought as to its ultimate sustainability. It is high time for the semiconductor industry to begin considering what happens when Moore's Law meets its inevitable demise, instead of continuing to bury their collective head in the sand.

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