Identifying and Forecasting the Reverse Salient in Video Game Consoles: A Performance Gap Ratio Comparative Analysis

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Abstract

This study uses the reverse salient methodology to contrast subsystems in video game consoles in order to discover, characterize, and forecast the most significant technology gap. We build on the current methodologies (Performance Gap and Time Gap) for measuring the magnitude of Reverse Salience, by showing the effectiveness of Performance Gap Ratio (PGR). The three subject subsystems in this analysis are the CPU Score, GPU core frequency, and video memory bandwidth. CPU Score is a metric developed for this project, which is the product of the core frequency, number of parallel cores, and instruction size. We measure the Performance Gap of each subsystem against concurrently available PC hardware on the market. Using PGR, we normalize the evolution of these technologies for comparative analysis. The results indicate that while CPU performance has historically been the Reverse Salient, video memory bandwidth has taken over as the quickest growing technology gap in the current generation. Finally, we create a technology forecasting model that shows how much the video RAM bandwidth gap will grow through 2019 should the current trend continue. This analysis can assist console developers in assigning resources to the next generation of platforms, which will ultimately result in longer hardware life cycles.

Keywords

Reverse Salience; Performance Gap Ratio; Video Game Consoles; Video Ram Bandwidth

Introduction

Video game console manufacturers encounter a difficult strategic decision regarding timing when launching a new platform. In order to achieve wide adoption at a rapid pace, they must often market a new console at no profit or as a loss leader, with the expectation that revenues on software licensing through secondary sales throughout the life of the product will balance out and eventually produce increasingly profitable margins. Ideally, a console manufacturer would like to maximize the length of time between product generations in order to minimize the number of loss leaders and low-margin hardware introductions they have to absorb. On the other hand, if a competing console platform can launch a technically superior generation ahead of the opposition, it will likely cut into the market share of the incumbent system's software sales. Likewise, when no new consoles from any manufacturer appear on the market for a long period, consumers generally shift interactive software purchases to the always-evolving personal computer platform. The console manufacturer's dilemma ends up being that launching new platforms too often will lead to diminished margins, but letting a generation's technology lag too far behind the competition will lead to diminished market share. The objective of this research is to provide a forecasting methodology for interactive entertainment ecosystems to optimize the timing of incremental technological generations.

~~In our technological era of rapidly changing market conditions, and consumer-driven markets, it is crucial to understand how to forecast the rate of uncapped successive introductions, along with predicting the magnitude and diffusion of consumer adoption. One of the most fascinating industries that are multifaceted as well as filled with sequences of parallel diffusions of multiple generational products is the video game industry. While the video game industry is easily divisible between consoles and PC markets, those two markets have completely different characteristics. While it may seem simple to perceive a lag between consoles and PC hardware specifications, it may seem more difficult to gauge the magnitude of that lag. How should an analyst predict the optimum time to launch the next generational platform?~~ Over the life of a technological generation, users can perceive a growing gap between the game play experiences on a console compared to the same software titles running on an up-to-date PC. Measuring the growing lag between these experiences over time will provide a quantifiable metric for further analysis. Classical diffusion models [1] usually take into account independent, first-time~~-to-market~~ products and do not consider substitutes, complements and relationships between product categories and their specification requirements [2]. Studying technological systems evolution, we will use the reverse salience ~~a forecasting~~ methodology to ~~that would help us~~

analyze the performance gap between PCs and consoles that could potentially lead to a better understanding of when the manufacturer should launch the next generation and what specifications they should include. The causal relationship between reverse salience and the technological generation change of interactive entertainment consoles is that increasing performance gaps will lead to diminished market share, which one can only solve by launching the next generation. ~~We call such methodology reverse salience.~~

Reverse salience is the measure of the technological disparity between subsystems and the entire system's limited level of performance [3]. In other words, the sub-system that is hindering the full performance potential, the reverse salient, should be identified and corrected for the betterment and the progress of the whole system [4, 5]. In this study, we measure the performance gap and time gap as analytical measures of reverse salience magnitude. Performance gap measure reflects the dynamics of change in the evolution of the technological system through magnitude changes in reverse salience [6, 7]. While performance gap is the performance differential between the reverse salient subsystem and the most advanced subsystem, the time gap is the duration of time the reverse salient needs to improve to the performance of the most advanced subsystem [3]. ~~We focus our study on CPU core clock rates as a reverse salient sub-system in technological evolution of video game consoles.~~

Technology Forecasting in the Video Game Industry

The interactive entertainment industry's global market has been flourishing in the last few years. By 2007, United States video game revenues exceeded the sales of both the box office and music recording industries, becoming the third largest entertainment industry behind book publishing and DVDs[1]. According to PricewaterhouseCoopers' "Global Entertainment and Media Outlook: 2010-2014"[2], they expect the video game industry to expand at an annual rate of 10.6%, growing from $52.5 billion in 2009 to $86.8 billion by 2014. Notwithstanding the considerable popularity of video games, the scope of academic research in this field has not been as comprehensive. In his paper "The Ideology of Interactivity", Garite [8] says for example, that "Most of the work on video games published within the past two-and-a-half decades has been limited to either popular, journalistic accounts of the history of the game industry, or so-called 'empirical' studies of the effects of video game." In the literature, the authors of this paper have also found very few papers that have studied the forecasting of video games technical evolution. For instance, Wolfe [9] has used the Delphi technique to conduct a survey among US experts in order to predict how the future business of games may look. In the paper "Achieving Disruptive Innovation", Sun et al. [10] show how the adoption of ~~the~~ TRIZ theory (Theory of Inventive Problem Solving) is feasible to forecast the evolution of video game console systems as a distributive technology. On the other hand, Dedehayir [3] emphasizes that historical trends or temporal changes in reverse salience magnitude of any sub-system, in the video game system, could be used to forecast the future changes in the gaming performance on the holistic PC system.

When choosing between forecasting methodologies that can effectively characterize video game hardware evolution, matching the technology growth to a modeling scheme with a similar

[1] http://vgsales.wikia.com/wiki/Video_game_industry#Comparison_with_other_forms_of_entertainment
[2] http://www.pwc.com/gx/en/press-room/2010/E-and-M-players-seek-new-roles-digital-value-chain.jhtml

profile will result in the most accurate estimations [11]. Bowonder, Miyake, and Muralidharan [12] explain that technology progresses in a similar fashion as evolution in nature. We need to "anticipate surprises, convergence and divergence of technologies, as well as interactive events." One can see these concepts in video game evolution as hardware superiority is not the only factor in the survival of the fittest. Rather artificial selection [13] and chance events [14, 15] can favor and lock-in [16] an inferior but more accessible console. The progress of personal computers can be viewed similar to the constant recombination and mutation of genetics, whereas video game consoles evolve generationally with punctuated equilibrium.

Technology Cycle Time [17] has been shown to accurately assess technological progress through examination of patent reference ages. Bibliometrics and Patent Analysis [18] have been shown as reliable early indicators that the subject technology is evolving at a rapid pace. However, Rossel [19] warns that early detection and warning schemes using weak signals are often oversimplified and have costs that can outweigh the benefits, and can easily lead to poor resource management. Since console manufacturers have often chosen to protect their IP with trade secrets over patents, the profile for the early indicators cluster does not match well for this investigation.

The Technology Futures Analysis Methods Working Group [20] suggests exploring and integrating new methodologies to take advantage of data resources when analyzing complex systems. When dealing with a complex system containing multiple parameters, one can construct a composite model to develop a single measure of performance. While some systems can be analyzed by looking at a single parameter, other may require two or more parameters to be utilized in a composite score [21]. We are using Martino's perspective while we develop CPU score as a performance measure for our analysis. Martino [21] used this methodology along with regression modeling to characterize the progress of fighter jet subsystems. Inman, Lane, and Anderson [22] later re-analyzed Martino's data using TFDEA (Technology Forecasting Data Envelopment Analysis). They argue their approach exhibits improved predictive accuracy. Anderson, et al. [23] performed a similar study using TFDEA on a multiple parameter CPU model. This paper integrates Martino's regression methodology with Dedehayir's reverse salient approach in order to compare the technology gap between PC's and consoles. In the recommendations for future research, we discuss revisiting our data with TFDEA for a comparative analysis.

Reverse Salience

The etymology of the term "Reverse Salient" goes back to World War I military jargon to describe a weak segment in a battlefront that is not advancing as quickly as the rest of the line [24]. A reverse salient, in any technological system, refers to any systematic component that hampers the evolution of the holistic structure [4]. This component fails to deliver the necessary level of performance needed for the optimal functionality of the entire technological system. As a result, any minor or major improvement of the reverse salient would certainly enhance the whole system performance. Dedehayir [3] uses the concept of reverse salient to develop quantifiable measures, which can be used to evaluate the magnitude of the reverse salience in technological systems. Primarily, he studies the PC technological system and analyzes the evolution of three technical sub-systems: ~~the~~ PC game software, the central processing unit (CPU), and the graphics-processing unit (GPU). He considers these three sub-systems as the crucial ones that are mainly delivering gaming performance to the whole PC system. By focusing on the PC game sub-system and the CPU, and then the PC game sub-system and the GPU, he measures the temporal behavior of the reverse salience and concludes that the PC game sub-system is the reverse salient.

Reverse salience has been used in many studies as a methodology to analyze the evolution of technological systems and to identify their weakest points. In the literature, we found some studies that show different technological systems, which have been hampered by a reverse salient. In his book, "*Networks of power: Electrification in western society"* Hughes [4] was the first in introducing the concept of reverse salience in the analysis of technological systems. He used the Edison's direct-current electric system generator as an example of a reverse salient that limited the supply of electricity within a defined region of distribution. Dedehayir and Hornsby [25] traced the historical evolution of digital broadcasting terrestrial (DVB-T) and handheld (DVB-H) technologies. They claimed that by identifying the current reverse salient and forecasting the future ones from available information such as standards and patent registries, DVB organizations can stay at the forefront of technological development. Takeishi and Lee [26] have discussed the role of music copyright management institutions in Japan and Korea as a social reverse salient. They consider that the copyright concept in this industry has impeded the evolution of mobile music preventing the technology from proliferating and reaching the end-user market. The polyvinyl chloride (PVC) industry is a unique example of a technological system that has been hindered by not only one, but many reverse salients. Mulder and Knot [27] have identified many fatal reverse salients that confronted the PVC plastic technology system: the difficulty of processing the PVC material, the quality of the final product, vinyl chloride concentration in the workplace and in products as well the VC emissions from factories that raised the health and environment hazard concerns. Moreover, Lehtonen and Nye [28] have analyzed the evolution of electricity network control in western Denmark and UK and concluded that lack of progress in network control would prevent the large technical systems (LTS) of electricity supply industry from further development and they considered it as the reverse salient of this technological system. Finally, Taylor [29] in his “Conclusion” derived that in ~~the~~ innovation theory, politics is the reverse salient.

Video Game Industry & Gaming Culture

The video game industry recently experienced substantial growth and is one of the most attractive investment categories in the entertainment business [30]. According to the Entertainment Software Association[3], 67% of American households play computer or video games with 34 years olds being the average game-player age and 40 years olds being the average game-purchaser age. In 2009, combined U.S. computer and video game sales equaled 10.5 billion dollars[4]. ~~The customers in the video game industry span a diverse culture: different tastes, performance needs, and social needs. While innovation plays a critical role in the buyer’s decision, it may be difficult to predict widely adopted trends. Probably not all gamers will push the limits of technology, but how much do they care about new technologies and advance performance characteristics?~~

[3] http://www.theesa.com/facts/pdfs/ESA_Essential_Facts_2010.PDF
[4] http://www.theesa.com/facts/pdfs/ESA_Essential_Facts_2010.PDF

Dietl and Royer [30] noted that customers are willing to invest in a system if they expect that it will survive in the market, emphasizing the importance of the long-term expectations of gaming consumers. They give several examples, like Nintendo creating a high reputation in the US market while reaching market shares of 90%. Meanwhile, Sega's first market entrant, the Master System, failed during the mid 1980s due to insufficient game variety. Sega quickly launched its 16-bit Genesis to help renew consumer interest. Since Nintendo at that time did not want to cannibalize its 8-bit system, it took until 1991 to market the 16-bit Super Nintendo Entertainment System. Various game console manufacturers have had challenges in pinpointing the right time for console introduction. After Sega exited the market in 2001, failing to achieve a large enough customer base for Dreamcast, the new era of video game consoles began with three major firms competing in the market: Sony, Nintendo and Microsoft. Their technical data started resembling the hardware specifications of personal computers. ~~From the point of view of the performance gap during this period, the perceived disparity narrowed compared to previous years.~~

The video game industry is interdependent: game developers and publishers depend on installed base of compatible consoles, while console manufacturers are dependent on the availability of games [30]. ~~High entry barriers protect console manufacturers in the industry.~~ While console manufacturers often sell hardware at a loss, they generate secondary profits from in-house game publishing along with royalties from third-party software sales. ~~With a well-established customer base, high switching costs shield the licensing profits. This also explains the argument that with~~ With equal factors such as console price and quality, a consumer would prefer to buy the console that offers a wider variety in game titles [31]. Once consumers adopt the consumer adopts a platform, they are to some extent captive to that ecosphere, thus driving up the demand and value of available games [31]. Game publishers acquire licenses from console manufacturers for the development, production, and sale of video games. Developers often deal with only one platform because of the consoles' technical differences between systems. With PC games being substitutes to video games, console manufacturers try to compete through quirky innovation and additional converged experiences (movie playback software, social media, wireless and motion controllers, etc).

Chanda and Bardhan Some authors [2] note that the periodic introduction of new products, video game consoles in our example, is one way that the companies increase the market presence and improve customers' perspectives about their organization. Chandra and Bardhan [2] They also state that when a technology starts approaching its its' natural limit of performance, a new technology takes over which would indicate a sequence of growth curves. Parallel diffusions of the multiple generational products emerge and influence consumers' adoptive decisions for a particular generation, based on its expected benefit, driven by the innovative power of the technology [2]. Hughes [4, 6] also indicates that through the phases of technological system evolution, invention and development, technological transfer and systems growth and expansion, the last phases developed are the ones where designers should identify and reinforce the reverse salient.

Since the late 1980s, system developers have satisfied the consumer desire for more powerful games by launching new platforms approximately every five years [31]. Console manufacturers stimulate market growth through aggressive price cuts. In November of 1993, Sony announced the formation of Sony Computer Entertainment to enter as a competitor in the market. They

~~focused their differentiation on the significance of hardware power, with the proposed machine representing the next wave in processor development, which doubled the power of existing units. In a way,~~ In 1993, Sony entered the market with PlayStation and leapfrogged the competition, by identifying ~~the~~ processor power as the ~~overall system's~~ reverse salient and correcting it, in order to compete in the ~~cutthroat~~ console-manufacturing environment [32, 33]. ~~Nintendo's 128-bit "GameCube" competed on performance while enlisting the help of IBM to design the chip architecture [32].~~ Technological leapfrogging is common in the videogame industry [33] and ~~required~~ requires substantial technological advantage that ~~could~~ can be achieved by properly managing the whole value system of components that provides an exceeding value to the existing standards in the industry. ~~Technological leapfrogging may take advantage of technological gaps and reverse salient in the system.~~

Disruptive Technologies

Performing reverse salience analysis can lead to ambiguous results when applied to the casual gaming market. ~~Over the past 15 years, the marketed attributes of system manufacturers fluctuate, with focus shifting between core performance, feature set, and games available.~~ Not all games push the limits of technology or require fast CPU and GPU performance. In order to adopt a Blue Ocean strategy, Nintendo has opted to pursue a tactic of releasing simpler games that appeal to a wider audience [34]. This software-centric approach leads to diminished focus on hardware specifications. When comparing the Xbox to the GameCube, Former Nintendo CEO, Hiroshi Yamauchi stated, "Microsoft is going after performance only, and does not understand that the game is played with software. . . it is just like trying to compare a sumo wrestler and a pro-wrestler; they play by totally different rules."[5] While the tastes of video game consumers are unique within different market segments, all consumers tend to desire more innovative game play. Whether it is social gaming and social networking while playing a game, motion detection systems, virtual reality or 3D gaming, the customer evaluates the gaming system based on the innovations it provides. ~~Technological leapfrogging in the video game industry requires harnessing rapid innovations, thus coming up with the console that is highly competitive in the market.~~

In the face of innovation, disruptive technologies often adversely affect a market leader's competitive leadership [35]. While some companies try to improve the performance specifications, like Microsoft Xbox 360, or Sony's Playstation 3, other companies have a high market share despite much lower, inferior specification (Nintendo's Wii). While innovation involves integration of technical and market information over time [35], innovation leaders might detect changes in technologies or detect changes in consumer needs or market condition to give them the innovative edge. Nintendo, while not innovating on performance characteristics of its console, invest in radical innovations that attribute to the components of the product with the focus on customer needs and wants. Nintendo also tends to saturate the market with Nintendo brand, ~~where Nintendo characters from the games jump from system to system (Mario, Donkey Kong, Pikachu, and Link),~~ which makes the console more desirable as a family-based entertainment system, and are placed on a wide variety of synergetic items ~~(T-shirts, magazines, lunchboxes etc)~~ [32]. Nintendo customer tends to value more the innovative features of the system (wireless and motion detection controllers, internet browsing) and the

[5] http://www.nintendoworldreport.com/news/5995

reputation of the Nintendo corporation and its' game library, rather than the CPU speed or the GPU performance characteristics.

~~From the leapfrogging methodology point of view, incumbents (existing company in the market) could prevent technological gap by investments in continuous innovation, offering incentives to upgrade the newest platform and even willingly cannibalizing existing platforms with more advanced ones [33]. Additional services and peripherals could be provided to increase switching costs and tie the customer to the firm's technology. Companies like Nintendo might be excelling in reducing other reverse salients in videogame consoles that are not tied to performance gaps.~~

~~Paap & Katz [35] explain that moving to new technologies that can deliver performance, despite being below the company's technology performance level, may be necessary in addressing emerging drivers. Understanding the customer's mind and voice, along with gathering intelligence on the ever-changing market and its drivers are crucial elements in planning a framework that fosters innovation. This starting point may provide one with a competitive edge in the market despite the main performance characteristics of the product.~~

A Brief History of Video Game Console Architecture

Performing a quantitative comparison between different generations of video game consoles quickly becomes a daunting task. No specification in isolation accurately gauges the progress of technological evolution between platforms. For this reason, the inclusion of multiple specifications will more precisely measure the performance magnitude increase, by taking into account different subsystems within the hardware that may be developing at different paces. In order to construct a set of significant specifications, it is crucial to cover a brief review of the architectural changes over time.

The first commercially marketed home video game consoles began hitting retailer's shelves during the early 1970's. The killer app during this first generation was Pong, and its' tennis-like variants. In 1972, the Magnavox Odyssey was the first player in the market. This era pre-dates transistor-transistor logic (TTL) devices, so designers achieved digital processing through discrete logic components rather than a microprocessor. Several clones of the Odyssey began appearing in the mid 1970's such as Atari's Pong, Coleco's Telstar, and Nintendo's Color TV Game. Atari designed the first application specific integrated circuit for use in their consoles that combined all the game logic into a single package. General Instruments later introduced the AY-3-8500 chip, which included all the logic for Pong, along with other games such as Soccer, Squash, and Rifle (which implemented a reflective light gun peripheral). Several console manufacturers, including Tandy and Unisonic, integrated the third party off-the-shelf ASIC into incremental platform releases. Game cartridges in the first generation were merely jumpers to access games that were already present in the Application Specific Integrated Circuit (ASIC). Since console designers during the first generation had no microprocessors available to integrate, a reverse salient analysis based on CPU for this period is futile.

In 1976, Fairchild Semiconductor released the VES (later renamed Channel-F) console, which was the first home video game platform to feature a general-purpose microprocessor. Thus began the second generation of consoles, characterized by simple 8-bit CPU architectures. The

Atari VCS (later renamed 2600), Intellivision, Odyssey, and ColecoVision were the major consoles of this era. Another feature introduced in the second generation was ROM cartridges, which propelled the expandable games market. This quickly led to several startups for third-party game developers. Ultimately, the glut of market entrants in both hardware and software led to a saturation of inferior products that wore on consumers' fear, uncertainty, and doubt. By the end of 1983, the North American video game industry crashed, causing many designers and manufacturers to exit the market.

The Nintendo Entertainment System dominated the third generation market, which began in the mid-1980's. While architectures in this generation continue to use similar 8-bit general purpose CPUs, the major advancements came in the form of graphics hardware, increased RAM, and support for more ROM on game cartridges. This resulted in higher video resolutions, more simultaneous sprites and colors, and scrolling backgrounds. The Sega Master System uses nearly identical hardware as the ColecoVision, with the exception of eight times the memory and the updated Texas Instrument video display controller, based on TMS9918. Atari's 7800 had identical hardware to the 5200, with the exception of their new custom graphics IC, MARIA, and an extra chip for backwards compatibility with 2600 software.

In the fourth generation, which began in the late 1980's, all console manufacturers shifted to 16-bit general-purpose microprocessors. Although games continued to primarily use 2D-scrolling in this generation, software continued to become more complex, requiring faster components and more processing and graphics resources. Designers implemented incremental hardware changes to support 16-bit gaming, rather than revolutionary architecture adjustments. The primary market leaders of this generation were the Super Nintendo and Sega

Genesis. A unique architecture introduced in this generation was SNK's Neo Geo. It featured the same hardware that users would find at the arcade, a Motorola 68000 primary CPU, along with a Zilog Z-80A for co-processing tasks. The software on this platform efficiently took advantage of the dual CPU resources resulting in a high-end user experience, but with a premium price tag.

The first 32-bit and 64-bit general purpose CPUs began showing up in the fifth generation of video game consoles during the mid-1990s. Sony Playstation, along with the Nintendo 64 and Sega Saturn, dominated the market during this generation. The revolutionary change in software for this generation was the implementation of 3D graphics. Console designers replaced video processing units with hardware accelerators to calculate 3D spaces and render corresponding 2D images. This new suite of spatial algorithms and pipelines required a hefty enlargement of video memory along with substantial bandwidth increases. The Sega Saturn was the first console to feature dual primary CPU's, but few titles on the platform used the extra resources effectively.

The sixth generation of video game consoles, which launched at the end of the millennium, contained four primary market competitors: Sega's Dreamcast, Sony's PlayStation 2, Nintendo's GameCube, and Microsoft's Xbox. While core CPU clock frequencies in this generation continued to increase, gaming software was reaching a point where it could no longer take advantage of increased CPU instruction sizes. While the Dreamcast and PS2 moved to 64-bit processors, the Xbox and GameCube implemented 32-bit. Designers garnered the largest performance gains through increased GPU bandwidth, as 3D gaming worlds continued to grow in size and detail. The Xbox architecture used components similar to personal computers, including the slightly modified Pentium 3 CPU and an iterative release of nVidia's GeForce 4 GPU. Sony collaborated with Toshiba to design the Emotion Engine chip, which included the CPU along with seven other functional units on the same die. For increased graphics performance, the processing architectures of this generation began including embedded DRAM circuits in the GPU package. One such example is PlayStation 2's Reality Synthesizer, which includes 4 MB of eDRAM.

By the end of 2005, the seventh generation of video game consoles began arriving at retailers. Only three primary competitors remained in the market: Microsoft's Xbox 360, Sony's PlayStation 3, and Nintendo's Wii. Microsoft collaborated with IBM to design a tri-core PowerPC-based CPU for the 360. Sony worked with Toshiba and IBM to develop the Cell architecture-based Broadband Engine. The Broadband Engine contains a primary core and eight support processors in the PS3 configuration. Sony designed the Cell architecture to handle decoding functions for high efficiency media codecs to converge the gaming and home theater experience. This strategy enabled Sony to port the Cell architecture to other consumer electronics devices. The hardware budget in the original PS3 had become so expensive that platform managers removed some functionality, such as PS2 software backwards compatibility, to realign with cost goals. Conversely, Nintendo's Wii features technically inferior specifications, but became the top selling console of the generation. The Wii introduced an innovative motion controlled interface device, which appealed to non-traditional gamers. The graphics chips in this generation began embedding large amounts of eDRAM into the same package as the GPU.

The seventh generation of video game consoles has already enjoyed a longer life cycle than most previous generations. Only Nintendo has announced their plans on releasing a next generation console as of this writing (Wii U). While specifications will be available soon, a reverse salient analysis can provide an analytical forecast today for what the new console might look like in a year.

Data Collection and Methodology

The goal of this study is to identify, characterize, and measure the historical performance gap between video game hardware subsystems and their personal computing counterparts. Video game consoles share many of the same sub-systems as the PC: Software, CPU, Memory, GPU, Storage, and Removable Media. While the PC's hardware handles many types of applications, console hardware traditionally serves a single purpose, playing video games (although convergence over time has added many other entertainment applications). While video games can be the most resource-intensive type of software, the PC's hardware must also be able to handle multitasking, OS management, and many other demanding functions. The software needs of the two types of systems continue to converge over time, such that the main difference is that PCs continually evolve, while video game consoles only progress on a generational basis.

Two primary hardware subsystems characterize technological progress during the evolution of video game consoles: CPU and Graphics hardware. While benchmarking utilities can conveniently compare different iterations of hardware on a personal computer, developers may not have the resources to modify them to run on a video game console. This study involved finding pertinent specifications for these comparisons. The CPU subsystem contains three relevant specifications that marketers have used to differentiate each console: Core Frequency, Instruction Size, and Number of Cores. Our original approach only used the CPU's core frequency, but we will show later in the paper why this methodology fell apart during the mid-2000's. One could measure the benefits of these parameters with a benchmarking tool, but we were unable to find any standard performance measure or CPU scoring model that covers the history of x86 as well as console CPUs. Realizing we had to account for computing complexity and parallelism, we derived our own CPU score by calculating the product of these three parameters. We suggest further research to discover a more accurate CPU scoring model, such as determining the weight of these three parameters. However, creating a highly precise CPU scoring model was not a major objective for this project.

$$\boxed{CPU\_SCORE = CORE\_CLK(MHz) * DATA\_SIZE(Bytes) * CORES}$$

CPU Score[6]

For graphics hardware, manufacturers have documented two specifications that one can reference to see the progress of evolution: GPU Frequency and Video Memory Bandwidth. Since 3D graphics software drove these hardware needs, the range of the data collected begins with the launch of generation five during the mid-1990s.

Our investigation requires three sets of data for the comparison. For video game consoles, we created a list of thirty systems. We included the ~~biggest commercial successes~~ top selling as well as the most notorious flops of all time. There are multiple consoles from each generation

[6] For data busses listed in bits, divide by eight to derive the size in bytes

capturing representative specifications from available systems in their given era. The consoles of the first generation did not contain general-purpose microprocessors, so we included none of these systems in this study.

While this study selects a general cross-section of different console types, some researchers may be more interested in a target market such as hardcore or casual game systems. They could repeat this methodology using only the consoles that fit the desired purpose. For example, if one only wants to analyze game systems for technologically immersive experiences, they would want to omit some of the more recent Nintendo consoles from the analysis. After compiling the list of thirty of the most historically popular consoles for the investigation, we scoured multiple sources for the technical data and specifications included in each platform. Some of these sources included manufacturer's websites and data sheets, internet databases such as consoledatabase.com[7], and Wikipedia articles. Ultimately, we found the data between these sources to correlate identically. In some cases, a single platform could have multiple releases with minor specification improvements. We disregarded these extended data points because the improved releases often occurred late in a product's life cycle and long after sales of the platform have tapered off. Table 1 lists the video game console specifications we used in this study.

The Cell architecture in the PS3 provided a challenge in determining core count. Although there are nine cores on the die, they are not all equal in performance. This presents a problem with our CPU scoring model that we will discuss further in our analysis and recommendations for

[7] http://www.consoledatabase.com/consoleinfo/

further research. For the sake of this analysis, we specified Sony's Broadband Engine as having three cores to match the performance of its' contemporary, Xbox 360.

To derive the specifications for any given year, we first analyzed which major consoles were on the market for that year. When a manufacturer releases a next generation console, the specifications for the new console would replace the older model. After identifying the major consoles in a given year, we averaged the specifications for those consoles. Given the target market for a particular console, the specifications can vary drastically. For example, Sony's PlayStation 3 includes a 3.2 GHz processor to render realistic graphics for games tailored toward more mature audiences (first person shooters, driving simulators, etc.). Whereas, Nintendo's Wii only needs a 729 MHz processor to handle a game library that targets a younger audience with ~~cute cartoonish characters and~~ less resource-intensive game design. If we chose to use only the peak performer, it would undermine the hardware needs of the market share leader. In order to obtain a more representative result of the overall market, a detailed approach would be to collect the sales figures on each system in a given year and calculate a weighted average of the specifications based on unit volume. Without the annual sales figures, we opted for a simpler model of averaging the specifications of all competitors on the market for any given year. If an analyst is more concerned with the hardcore market rather than the casual ecosphere, they should perform these calculations using only the peak performer in lieu of this democratizing averaging methodology.

Table 1: Console Specifications

One of the comparison data sets focuses on Personal Computer CPU specifications. The Intel x86 architecture saw several generations of Pentium processors released during the same period as our console data set. Over the past fifteen years, AMD has been the only other CPU manufacturer with significant market share. However, AMD's earlier processor models were licensed clones of Intel CPUs, and they continued to produce units with similar specifications throughout this time-period. Due to time constraints and the belief that AMD's inclusion would not affect our results, we only included Intel's products. The initial plan only included the analysis of core frequencies, so we excluded multi-core processors from our data, due to the inability of the original metric to capture the performance increase. After realizing that core frequencies would tail off in 2006, we added multi-core Pentiums (Pentium D, Pentium Dual-Core), and processors with Intel's Core architecture (Core 2 Duo, Core 2 Quad, i3, i5, and i7). We omitted the Celeron family of processors from our data set, as Intel markets this as a budget alternative for PCs running applications less resource intensive than gaming.

Through Intel's internet database and Wikipedia, we identified exactly 200 processor models that matched this criterion. The products range from the 8086, released in 1978, through the 2000-series iCores, released in 2011. Within each model, there were several categories of chips clocked at different rates. For any given year, we averaged our derived CPU Score for all the processors Intel released in that period to represent the field of choices, rather than the peak performer.

The two main players in the graphics hardware market since the mid-1990s have been nVidia and ATI. The competition between these two parties has resulted in similar specifications over the past fifteen years. For the graphics hardware data, we only used nVidia's specifications as a comparison. We omitted the collection of ATI data for time reasons, but would expect this exclusion has an insignificant effect on the results. Data begins in 1995 with pre-GeForce units such as the Vanta and Riva families, and continues through each successive generation of the GeForce line (through GeForce 500-series in 2011). This study uses the specifications of 184 models of nVidia GPUs.

Data Analysis: Identifying the Reverse Salient

Our first attempt at identifying a specification for reverse salient analysis involved the CPU's core clock frequency. Figure 1 shows the historical rates of evolution for both Intel CPUs and video game consoles. The Performance Gap plot is the difference between the two subjects. The graph's vertical axis is on a linear scale to emphasize the phenomenon that begins to occur around 2002. While the Performance Gap grows exponentially between 1976 and 2002, it begins to tail off and then decline by 2005. At first glance, it may appear that console specifications are closing the gap, but this does not tell the whole story. Around 2002, the x86 processors began reaching the architectural limitations for their core clock frequencies[8] (which is around 3.8 GHz). One can see this behavior in the chart as the Intel plot begins leveling off in 2002, and the console plot levels off in 2006. Intel and other manufacturers looked to other CPU parameters such as architectural efficiency, multi-core die, and increased instruction size. Concurrently, Intel released the first processors with hyper-threading in 2003. Their first dual-core processor, the Pentium D, began shipping in 2005. This time-span also saw an increased

[8] http://spectrum.ieee.org/computing/hardware/why-cpu-frequency-stalled

adoption of 64-bit processors as Microsoft launched their first version of Windows to support the x86-64 extensions in 2005. Using CPU clock rate as the only parameter for comparison clearly falls apart after 2002. For this reason, we developed the previously described CPU score to analyze technological growth beyond this frequency limit.

Figure 1: Performance Gap of CPU Core Frequency

We devised the CPU Score to fashion a more accurate model of architectural evolution by including parallelism and instruction size in the measurement parameters. Figure 2 shows the CPU Score on a logarithmic scale from 1976 through 2011. With the CPU Score, there is no longer the leveling off problem that we previous saw using only the core frequency. Exponential technology growth continues throughout all generations.

Figure 2: Historical CPU Scores for Intel and Console

The beginning of the seventh generation (2005) marks the only time where console performance has exceeded PC performance, thus the CPU Score Performance Gap has gone negative (see Figure 3). The specifications of the Xbox 360 and PS3 CPUs were ahead of the average Intel CPU you could buy at that time. There could be two explanations for this technological leapfrogging. The first explanation is that our CPU Score does not account for processing efficiency. We did not discover a reliable benchmark that could compare the MIPS of a video game console to the MIPS of a PC processor. Such a benchmark would have to be application specific to video game performance and other converged tasks, such as video playback. It is possible that the inclusion of processing efficiency could swing the CPU Score back into the favor of PC CPUs. The other explanation for the leapfrog is that Sony and Microsoft saw a long-term economic advantage to investing in a hardware platform that would last longer than the usual generational life cycle. This strategy weighs losing more upfront costs, while enjoying a longer period of positive revenue flow in the future. The Performance Gap plot in Figure 3 shows the short-term effects of this strategy, but due to the exponential pace of technological progress, the gap is currently back to its' highest values ever.

Figure 3: Performance Gap for CPU Score

Within the graphics subsystem, two specifications have characterized technological evolution over the past fifteen years: GPU Core Rate and Video RAM Bandwidth. The GPU Core Rate indicates how fast the processor can handle the graphics instruction set. Video RAM Bandwidth is the flow rate between the GPU and dedicated video memory. These specifications both play a part in how quickly a large and detailed 3D world can be updated and redrawn. This ultimately leads to a more realistic gaming experience.

Figure 4 shows the historical growth of the GPU core clock rate since consoles first implemented the architecture in the fifth generation. Since this time, nVidia's GPUs have been linearly progressing at about 45 MHz per year. This is a much slower pace of progress than the exponential growth we witnessed with CPU clock speeds. The difference is that GPUs have evolved through parallelism and bus sizes rather than drastic speed increases. It is logical that GPUs will run into frequency limits similar to what we previously saw with CPUs, but this threshold may occur at a different frequency.

Figure 4: Performance Gap of GPU Core Frequency

Figure 5 shows the evolution of video memory bandwidth since the infancy of 3D implementation in the mid-1990s. The growth has been exponential throughout this era. Since the adoption of 3D graphics, the speed of memory has been a significant bottleneck. The need for faster memory has resulted in the development of several generations of double data-rate (DDR) memory, and more recently Graphics DDR (GDDR), which handles power more efficiently and generates less heat. The GPUs in Xbox 360 and PS3 also contain small amounts of embedded DDR (eDDR) integrated on the GPU die. The advantage of eDDR is that it can contain much larger data buses, which can run at faster speeds without the need for an external memory controller.

Figure 5: Performance Gap of Video Memory Bandwidth

We have now seen the individual Performance Gaps for our three subject specifications. The Performance Gap for each specification behaves in a different manner: the CPU Score gap has experienced some fluctuations between growth and decay, the GPU Core Frequency gap is growing at a linear pace, and the VRAM Bandwidth gap is growing at an exponential pace. Furthermore, each of these gaps represents different units. In order to perform a comparative analysis between these specifications, one must normalize them. One option is to use the Time Gap methodology to normalize specifications into how many years behind the technology is lagging. Another convenient way to achieve this means is to use the ratio of performance utilized to performance available. We call this the Performance Gap Ratio (PGR). When a technology is experiencing exponential performance increases, the Performance and Time Gaps can be moving in opposite directions, making it difficult to determine whether the true technology gap is increasing or decreasing. PGR can reveal greater variance on a linear scale to help determine underlying trends. Equation 1 displays the proposed formula as it applies to this study.

$$PGR(t) = \frac{Performance\_Available(t)}{Performance\_Utilized(t)}$$

Equation 1: Performance Gap Ratio

Charting the PGR over time can help characterize generational growth. One of the main differences between personal computers and video game consoles is the rate of change in technology. For the PC, this advancement is incremental and nearly continuous. Hardware manufacturers and integrators are constantly launching new products with specifications that are slightly better than currently available products. Conversely, video game consoles traditionally experience generational growth. Although there may be minor upgrades on a given platform, such as increased storage or peripheral interface, the specifications do not make a significant jump until the manufacturer launches the next generation. In a perfectly aligned scenario, we would expect the PGR chart to appear like a ramping waveform. At the beginning of each generation, the ratio would begin at some minimum value. Throughout the generation, the PGR would grow to some maximum value and then jump back down to a minimized value when the next generation launches.

Figure 6 shows the PGR of the three subject parameters from the second generation until present. The first generation consoles are not CPU-based and thus not included in this analysis. We have added shaded regions to represent the time spans for each generation of console, starting with the second generation. The dates of each region begin with the first year a manufacturer launched a console in that generation. The CPU Score PGR spike during the third generation stands out as a time when video game consoles displayed the highest magnitude of inferiority to personal computers. The major cause of this spike was that Intel released their first 32-bit processors (i386) during this era when consoles were still using 8-bit processors. The technology gap over the past three generations pales in comparison to the performance lag consoles experienced prior to the fifth generation.

Within each generation, trends begin to form. For the first couple of years of each generation, the PGR drops to some minimal value and then increases for the rest of the generation. The pattern is not a perfect ramping waveform, because the launch of each next generation platform generally spreads throughout a two or three year period.

Figure 6: PGR Comparison

Figure 7 scales the timeline of the PGR comparison to focus on the seventh generation. The chart shows the ratio for CPU Score going below 1 for the first half of the generation. The GPU Core Rate has evolved at a linear pace, so neither it nor the CPU Score have reached a PGR of 2.0 as of 2011. In every previous generation, the CPU Score PGR has reached at least 4.33 before the next generation launched. This graph clearly shows Video memory bandwidth as the specification that is falling behind at the most rapid pace. The results of this analysis indicate that VRAM bandwidth is a more significant reverse salient at this point than either CPU Score or GPU Core Rate.

Figure 7: PGR during Gen 7

Data Analysis: Forecasting the Reverse Salient

Now that we have identified that VRAM bandwidth is the current reverse salient in video game consoles, we will characterize the trend to assist in forecasting the future. Figure 8 revisits the

Performance Gap for VRAM Bandwidth. The trend line was found using exponential non-linear regression. According to Robert Colwell, uses of extrapolation include informed future allocation of limited time resources, analysis of historical data with no possible further sampling or statistically enlarging smaller sample sets [36]. Extrapolation should be viewed as the generation of estimates for missing observations outside the sample timeframe or period [37]. Martino (2003) justifies forecasting by extrapolation from a forecaster's perspective through the assumption that the past of a time series contains all the information needed to forecast the future of that time series [38] An appropriate model could then fitted to the historical data and the projection of that becomes a forecast. [38]. Equation 1 shows the Performance Gap formula for the trend-line, where the argument is the year and the result is the Performance Gap. The trend line was developed using MS Excel's trend line algorithm, where the gap shows exponential growth. The data appears to fit the model well, where $R^2 = 0.944$.

Figure 8: VRAM Bandwidth Performance Gap Trend

$$\mathrm{Pr}\,edicted\_VRAM\_Gap(t) = 0.3184e^{0.3253(t-1995)}$$

Equation 2: Predicted VRAM Bandwidth Performance Gap

With the VRAM Bandwidth model, we can now predict how big the Performance Gap will be in the future as long as the current trend continues. The Predicted Performance Gap accounts for future console releases.   We can also predict future PGR values if no improvements occur in current consoles. The predicted PGR uses the VRAM Bandwidth of consoles in 2011 and the Predicted Performance Gap for that given year (Equation 3). Table 2 shows that in the absence of any new console releases, the PGR will likely reach 20 in 2016 and reach 50 by 2019. If any new consoles were to release, we would need to update the PGR predictions based on the new specifications.

$$\Pr edicted\_VRAM\_PGR(t) = \frac{\Pr edicted\_VRAM\_Gap(t) - Console\_Spec(2011)}{Console\_Spec(2011)}$$

Equation 3: Predicted VRAM Bandwidth PGR

Table 2: VRAM Bandwidth Performance Gap and PGR Predictions through 2019

Conclusion and Recommendations for Further Research

This investigation has shown that the Technology Gap in the CPU subsystem of video game consoles has been shrinking for three generations. Within our three subject parameters, we have identified the VRAM interface as the fastest growing gap using the Performance Gap Ratio methodology. Based on these results, we have developed technology-forecasting equations to assist video game industry analysts with predicting future technology needs. Several parameters factor into the decision of when to launch the next generation platform and what specifications it should contain. On one hand, the console is a low-margin or loss leader necessity for collecting on future software royalties. The manufacturer wants to keep that console on the market as long as possible to maximize licensing profits and avoid eroding their indirect network. On the other hand, consumers always yearn for a more realistic experience, requiring improved graphics and processing power. Software subsystems evolve rapidly, enabled by the uncapped growth in hardware technology. Competition between console manufacturers drives new generations of platforms to meet these customer demands. The forecasting equations derived from this reverse salient analysis provide insight to assist manufacturers in choosing the correct project timelines and specifications based on known available hardware.

Earlier in the paper, we discussed how the CPU Scoring model fails to factor in processing efficiency. Further research may help to discover a benchmark that one could use on both video game consoles and personal computers that specifically measures gaming and multi-media performance. Power efficiency in the CPU is an additional parameter that would warrant a similar investigation. Another area for further research would include emerging processor and memory architectures. We mentioned in the paper our difficulties with categorizing the Cell architecture and eDRAM. With technologies on the horizon such as SoC and GPGPU, architectures will only continue to become more complex, making historical comparisons more difficult. Technology Forecasting Data Envelopment Analysis (TFDEA) might be another methodology one could use to improve on the accuracy of our non-linear regression models. It would be interesting to see if the trends identified in this paper continue through Generation 8 and beyond. Further research might include fitting logistic curves to pin-point shifts in the videogame industry where particular disruptions will off-set growth in some factors and facilitate launch of new consoles. Other variables, either tangible or intangible could be used to predict future behavior in this industry. Factor analysis and structural equation modeling might produce interesting results in terms of significance of factors influencing the changes in the industry.

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Platform	Gen	Years	Cores	Bus (bits)	CPU MHz	CPU Score	GPU MHz	VRAM MB/s
Channel F	2	76-79	1	8	1.79	1.79		
Atari VCS	2	77-82	1	8	1.19	1.19		
Astrocade	2	77-80	1	8	1.79	1.79		
Odyssey2	2	78-83	1	8	1.79	1.79		
Intellivision	2	80-83	1	16	0.86	1.73		
Atari 5200	2	82-84	1	8	1.79	1.79		
Vectrex	2	82-84	1	8	1.5	1.50		
ColecoVision	2	82-84	1	8	3.58	3.58		
Arcadia 2001	2	82-84	1	8	3.58	3.58		
SG-1000	2	83-85	1	8	3.58	3.58		
PV-1000	3	83-84	1	8	3.58	3.58		
NES	3	83-89	1	8	1.79	1.79		
Sega MS	3	86-88	1	8	3.58	3.58		
Atari 7800	3	86-92	1	8	1.79	1.79		
TurboGrafx	4	87-90	1	16	7.16	14.32		
Genesis	4	89-93	1	16	7.61	15.22		
SNES	4	90-93	1	16	3.5	7.00		
Neo Geo	4	90-93	1	16	12	24.00		
Jaguar	5	93-96	1	32	13.3	53.20	26.59	53.18
3DO	5	93-95	1	32	12.5	50.00	25	50
Saturn	5	94-97	2	32	28.63	229.04	28.63	115
PlayStation	5	94-99	1	32	33.87	135.48	33.87	132
N64	5	96-00	1	64	93.75	750	62.5	562.5
Dreamcast	6	98-00	1	64	200	1,600	100	800
PS2	6	00-05	1	64	294.91	2,359	147.46	3,200
Xbox	6	01-04	1	32	733	2,932	233	6,400
GameCube	6	01-05	1	32	485	1,940	162	2,200
Xbox 360	7	05-11	3	64	3200	76,800	500	21,600
Wii	7	06-11	1	32	729	2,916	243	3,900
PS3	7	06-11	3	64	3200	76,800	500	22,400

Table 3: Console Specifications

Year	Predicted Performance Gap (GB/s)	Predicted PGR
2012	80.3	6.0
2013	111.2	8.0
2014	153.9	10.6
2015	213.1	14.3
2016	295.0	19.5
2017	408.4	26.6
2018	565.4	36.4
2019	782.7	50.0

Table 4: VRAM Bandwidth Performance Gap and PGR Predictions through 2019

Figure 9: Performance Gap of CPU Core Frequency

Figure 10: Historical CPU Scores for Intel and Console

Figure 11: Performance Gap for CPU Score

Figure 12: Performance Gap of GPU Core Frequency

Figure 13: Performance Gap of Video Memory Bandwidth

Figure 14: PGR Comparison

Figure 15: PGR during Gen 7

Figure 16: VRAM Bandwidth Performance Gap Trend

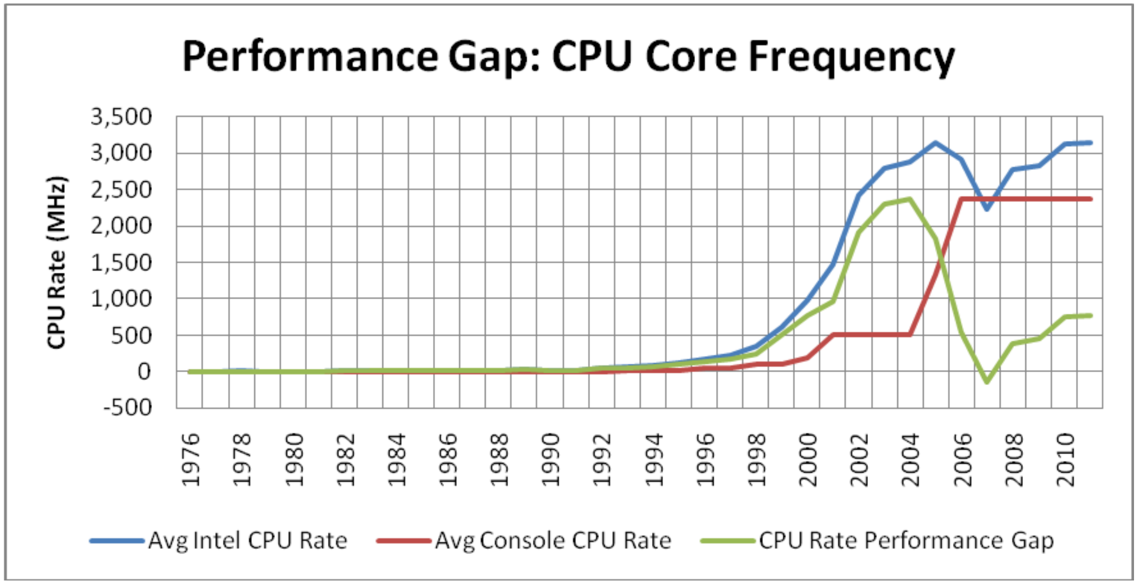

Figure 17: Performance Gap of CPU Core Frequency

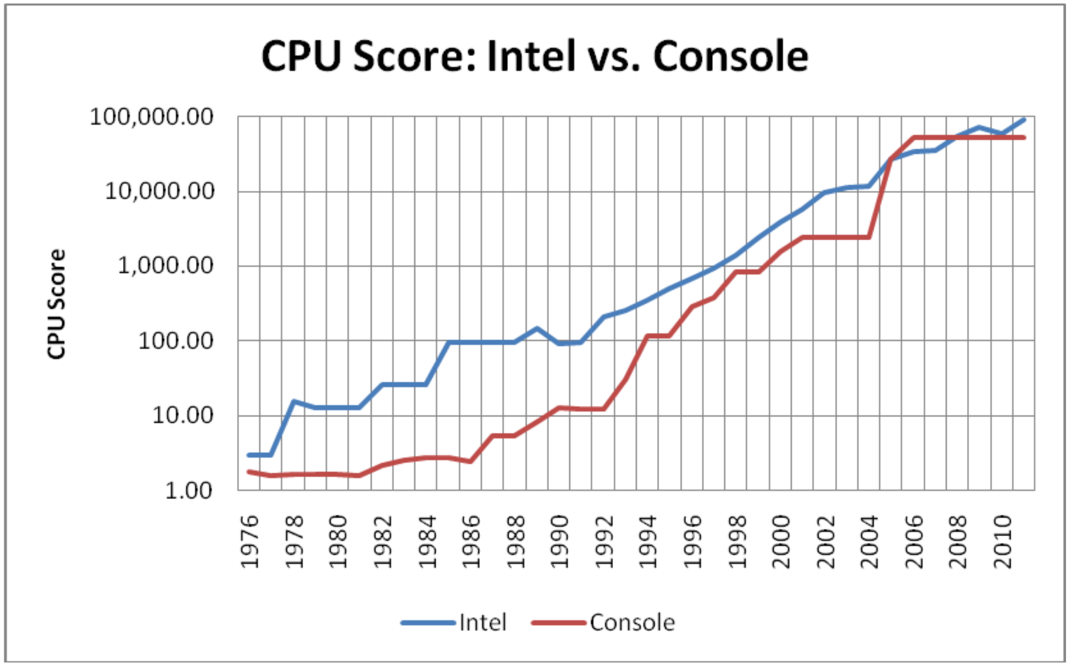

Figure 18: Historical CPU Scores for Intel and Console

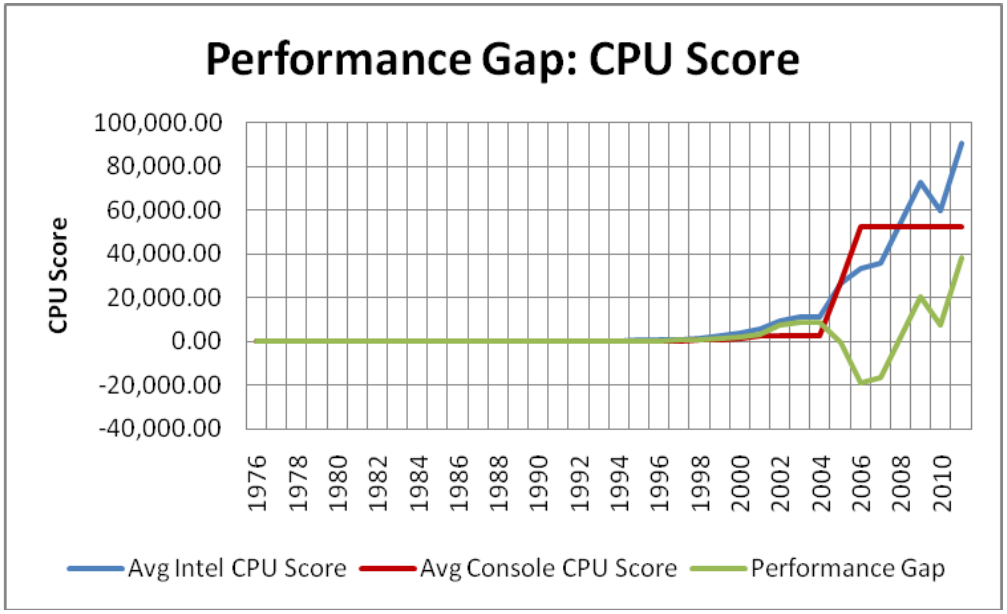

Figure 19: Performance Gap for CPU Score

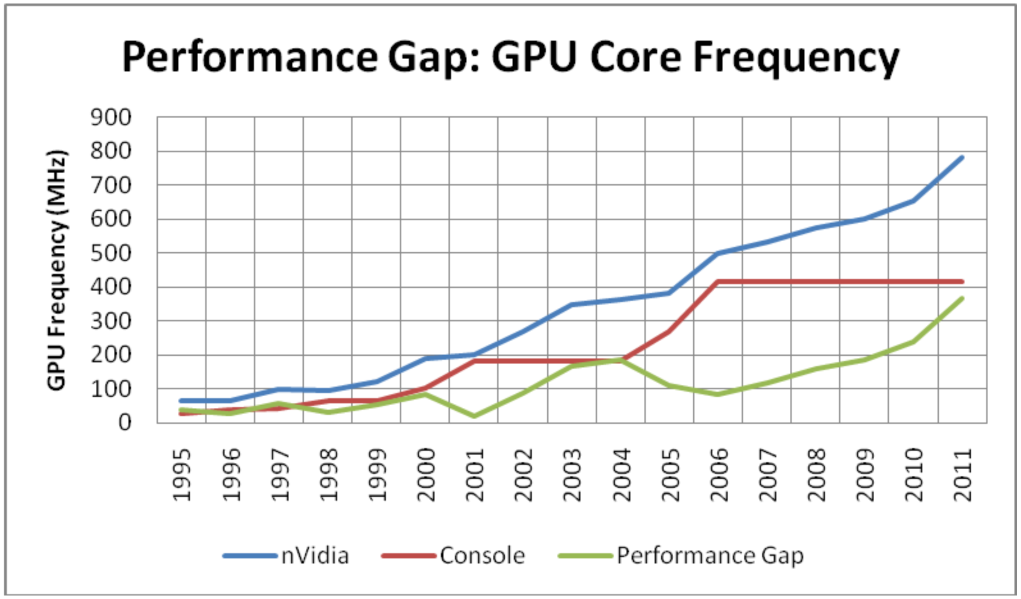

Figure 20: Performance Gap of GPU Core Frequency

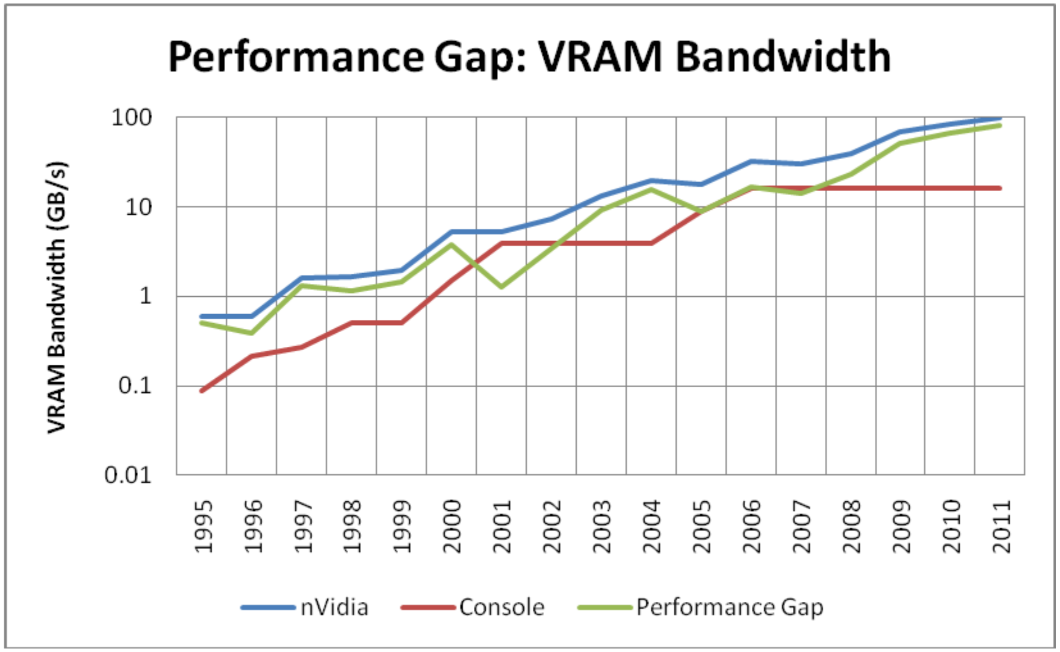

Figure 21: Performance Gap of Video Memory Bandwidth

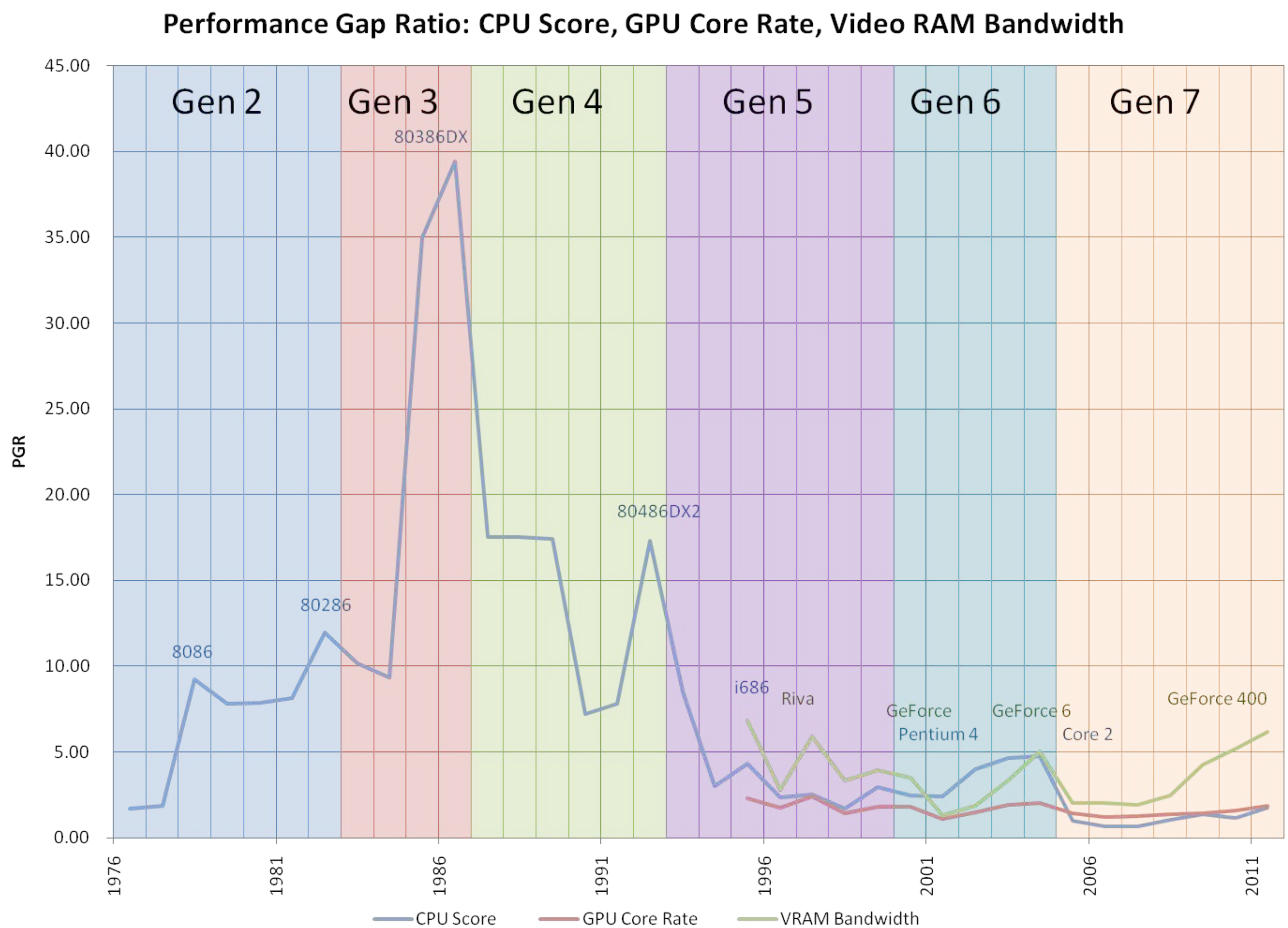

Figure 22: PGR Comparison

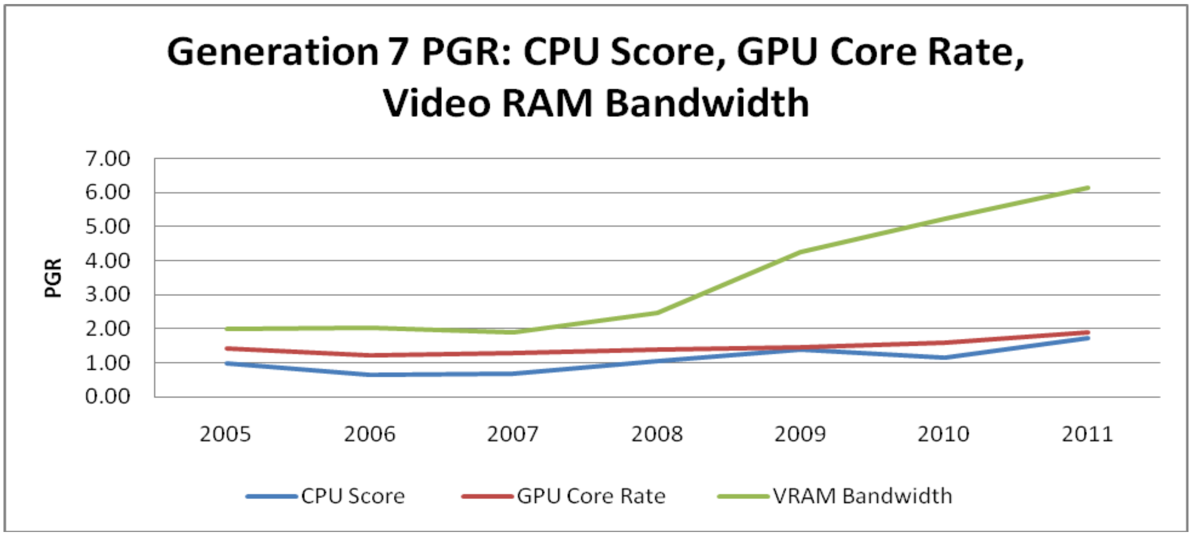

Figure 23: PGR during Gen 7

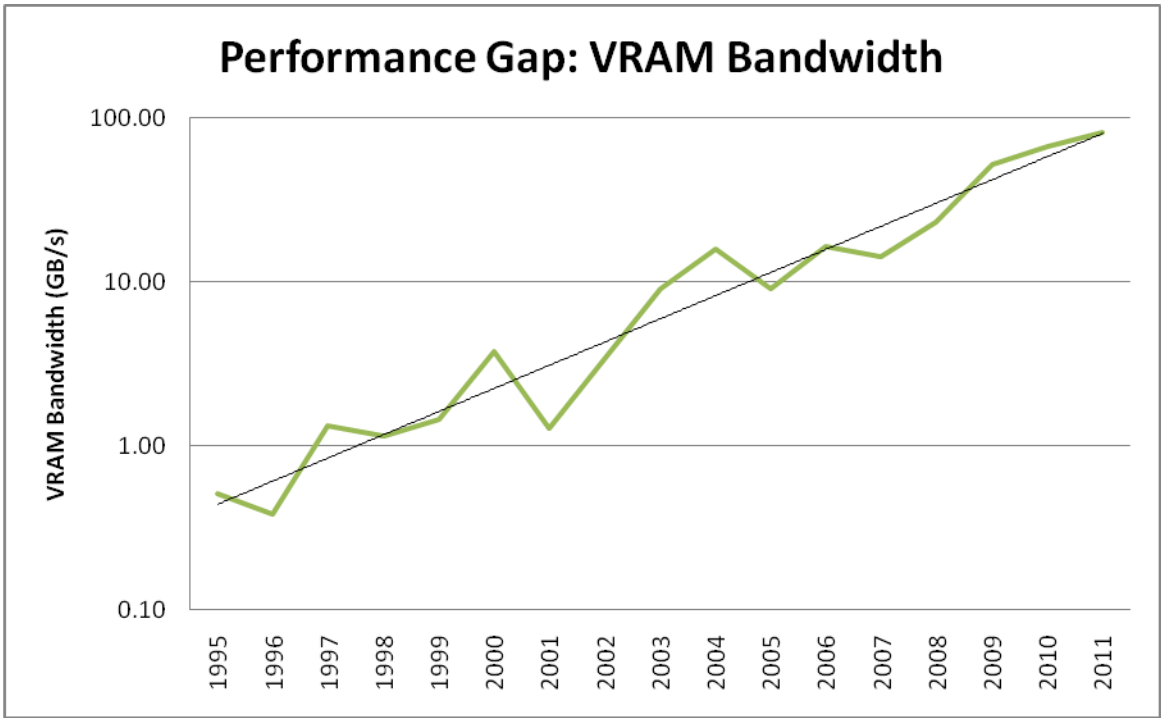

Figure 24: VRAM Bandwidth Performance Gap Trend