Evolution of Hardware in Nintendo Consoles

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***Abstract*— This work will examine the evolution of the hardware of Nintendo consoles. It will focus on three main components: processors, storage, and operating systems. It will explore these components of two handheld consoles, the Game Boy Advance and the DS, and two home consoles, the GameCube and the Wii, in-depth. By looking at each console type separately and avoiding analyzing outer changes, it will be easier to find the source of improvement between generations. When making these comparisons, memory seemed to be improved every console while either processors or operating systems seemed to be improved less often. Further, the new features of succeeding consoles will be examined, and investigation of the newest product, the Switch, will help predict Nintendo's future focuses regarding console development.**

I. BACKGROUND

Nintendo is a global consumer electronics and video game company that was founded in 1889 by Fusajiro Yamauchi. The founder died in 1940, and his great-grandson Hiroshi took over the business. Nintendo found its original success from selling playing cards, but it was Hiroshi who got the company into the gaming industry in the 1960s [1]. This is when Nintendo started making video games and eventually developing a variety of consoles. Nintendo released their first video game system in 1977. The corporation proceeded to find great success with their next console, the NES in 1983, which ended up selling 61 million units worldwide. Then, Nintendo created one of the first handheld gaming consoles, the Game Boy, reaching 118 million units sold [2]. With rapid success in the video game industry, Nintendo proceeded to launch further consoles including the GameCube, DS, and Wii. The company has not stopped improving their hardware with their newest product, the Nintendo Switch, being a unique combination of a handheld and home console.

II. INTRODUCTION

This work will explore the hardware of some of Nintendo's most popular consoles in depth. It will see how the components of the two categories of consoles have evolved over time. The results of each console distinguishing hardware features will be examined. For each, this work will be focusing on three categories. First, the main processor and other prominent processors such as the GPUs will be analyzed. Then, there will be an in-depth explanation of the memory architecture as well as a note of general quantities. The final component will be an investigation into the console's connection between hardware and software whether that be just a BIOS or an operating system. Since some of these systems may not have a complex operating system, the graphical interface of the main menus will also be taken into consideration. The significant improvements between generations of consoles of each category will be discussed. Since it would not be fair to compare a handheld console to an at home one, I will then be looking at the categories of hardware that were most improved and the company's general improvement trends over the years. This will be used to predict Nintendo's focus in the future and help understand the changes occurring to these consoles behind the scenes.

III. HANDHELD CONSOLES

A. Game Boy Advance

Nintendo released their first handheld console known as the Game Boy in 1989. It was an 8-bit console featuring interchangeable game cartridges. However, the display only supported four different shades of gray. It was durable and relatively inexpensive compared to competitors, since it optimized the power of AA batteries, this allowed the console to sell one million units in the United States in just a few weeks of its release [3]. This rapid success inspired the company to continue making variations of the Game Boy with improvements as needed.

One of the most notable follow-ups was the Game Boy Advance released in 2001 that was unique due to its landscape orientation with buttons on sides rather than below the screen. It now offered colored graphics like the Super Nintendo and up to 15 hours of battery life. The new console could run old Game Boy games and was now powerful enough to render basic 3D graphics of new games on the system. Additionally, the device just used a BIOS that showed the boot screen and some troubleshooting routines rather than an operating system. This powerful brain of the console made up for some of the common criticisms such as audio and failing to port Super NES titles due to the screen resolution.

To explain, it contained a powerful 32-bit, 16.8 MHz, ARM processor as the CPU that could run in either 32-bit ARM mode or 16-bit Thumb mode [4]. ARM mode utilized a three-stage pipeline in which execution of these 32-bit instructions were divided into three stages: fetching, decoding, and executing. This allowed multiple instructions to be executed concurrently and enabled maximum use of the CPU's resources [5]. While Thumb mode requires half the bus width, it can provide around 65% of the code size of ARM, but the mode has increased performance speeds [6]. Both modes can be used together in the same program allowing developers to optimize their resources.

This decision to include a processor that could run in different modes meant that the console would have to utilize a variety of bus sizes. The Game Boy Advance had 256 KB of 16-bit wide external RAM. Here, thumb instructions were stored and ran at full speed while 32-bit code was executed at half speed [4]. The Advance contained 32 KB of 32-bit of internal RAM used to store ARM instructions and run them at full speed [5]. For graphics, the system possessed 96 KB of Video RAM, and every cartridge's memory ranged from 2MB to 32MB [4]. Although the console was marketed as a 32-bit system, a lot of its memory was accessed through 16-bit buses (see Fig. 1, [5]).

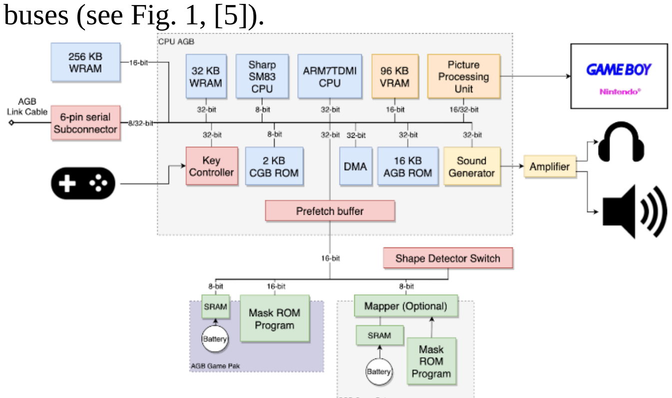

Fig. 1. Game Boy Advance main architecture.

To properly connect this memory and hardware to the software, the system used a BIOS in place of the operating systems that we are familiar with today. A BIOS is a pre-installed firmware that automatically boots up when a system is turned on and allows the hardware to initialize. So, when the Advance turns on, it will show the startup screen and decide if the game should be run, but most games ignore its existence once the game is properly functioning. This ROM that is connected to the BIOS, stores a variety of software routines that simplify operations such as arithmetic functions, an affine matrix calculation, decompression functions, memory copy functions, and a power interface [5]. Most of Nintendo's functionality is provided through software, but this allows the synchronization of all these components to run smoothly on the device.

B. Nintendo DS

Some of the most common complaints with the Game Boy Advance were sound problems, the graphical video interface of some of the games, physical screen problems, and power problems. Many of these were fixed by Nintendo's introduction of a new chargeable handheld console known as the DS in 2004. DS stood for dual screens which was the devices most distinguishable feature. It folded in half and had a display screen on the top as well as a new touch screen on the bottom which you could interact with via a stylus. The device still used game cartridges and only contained a few more buttons than the Advance, but it offered some new features such as Wi-Fi connection and a microphone.

In order to provide improved functionality from the Game Boy, the DS needed to contain new hardware. It contained two processors. The main processor was the ARM946E-S running at 67 MHz and the second was the ARM7TDMI running at 33 MHz [7]. The main CPU contained all the features of the ARM7, but it also included some additional features such as split-cache, higher clock frequencies, and a Harvard architecture. Also, rather than utilizing a three-stage pipeline, the ARM9 employed a five-stage pipeline consisting of the stages: fetching instructions, decoding instructions, executing shift and ALU, accessing memory, and writing to the register (see Fig. 2, [8]). Since the ARM9 was faster at executing instructions, this was the processor used by developers. The other processor, the ARM7TDMI, was the same CPU found in the Game Boy Advance, but it was set to run at double the speed in this console. For the DS, it was used to transfer data around to different components and often placed next to I/O ports to assist with I/O operations [9]. Both processors were important, but the ARM9 was often given more power than the ARM7.

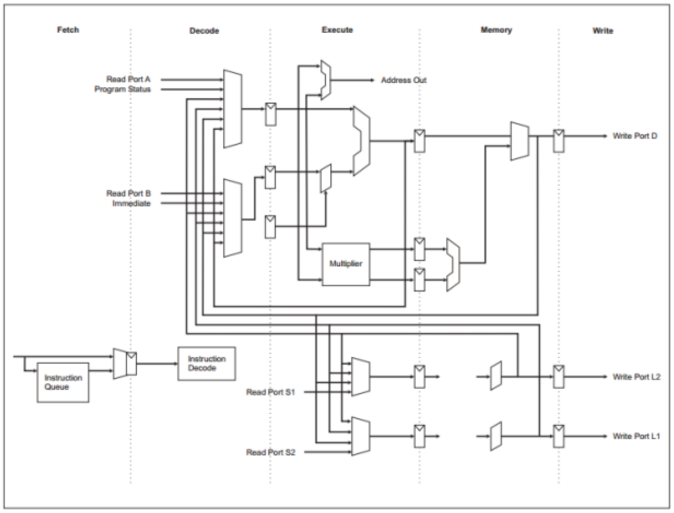

Fig. 2. Integer pipeline of ARM946E-S processor.

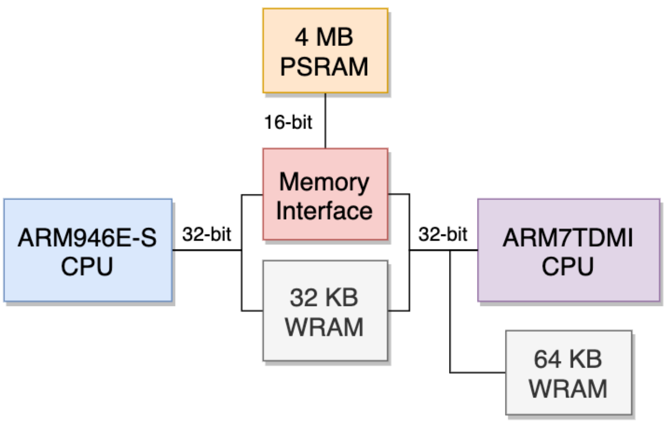

Fig. 3. RAM model of the DS.

The key to making sure both CPUs worked well together was in the memory setup. The main memory of the DS consisted of 4 MB PSRAM using a 16-bit bus and was shared between both processors [8]. However, only one CPU can access the same address at a time, so the ARM9 contained a register that controlled which processor took priority [7]. The DS also contained 64 KB of WRAM using a 32-bit bus and 32 KB of Work RAM using a 32-bit bus (see Fig. 3, [9]). The processors can work independently, but they require the use of a bidirectional FIFO unit with 16-bit channels as well as two shared 16 KB IRAM to communicate and synchronize. The ARM9 controls access to each IWRAM using a special register allowing data to be transferred back and forth between the processors while FIFO pipes can be used to interrupt when a new piece of information arrives on the queue allowing for synchronization [7]. Combining these two processors provided additional computation power and made backwards compatibility for a variety of games possible [8].

This dual-processor architecture causes the DS' "operating system" to be split among two chips as well. The device contains two ROMs each connecting a BIOS to one of the ARM buses. So, each CPU will boot from their respective ROM because their reset vectors point to different chips [9]. Both BIOS consist of stored boot code and interrupt call routines. Once a DS is properly booted up, the two processors will synchronize together and act as a single machine waiting for both to finish before starting to execute another task [9]. With this combination of software and hardware, the DS can improve from the Advance without the use of a PC operating system.

IV. HOME CONSOLES

A. GameCube

Nintendo also created a variety of home video game consoles. Rather than being battery powered and portable, these consoles connected to a display device such as a television and connected to external power sources. They often have more variety in controllers and allow for larger displays. However, superiority between handheld vs. at home consoles depends on your personal preference. In order to accurately compare the two categories, we must take a more in depth look at the hardware. In 2001, the same year that the Game Boy Advance was released, Nintendo released a compact home console known as the GameCube. Like with handheld consoles, Nintendo had a history of making home consoles as well. At a glance, the Game Cube was unique from the previous device, the NES, due to its use of optical disks rather than cartridges and new shape of controllers. Further, Nintendo partnered with IBM to make a very promising CPU known as the Gekko.

The GameCube needed a processor that would be powerful enough to smoothly run the latest games as well as cheap and small enough to fit in a compact enclosure. IBM started with a past processor design, the PowerPC 750CXe, that was successfully used on the iMac G3 and added new capabilities suitable for game development [10]. These alterations resulted in the PowerPC Gekko that would be run at 486 MHz. The PowerPC aspect meant that it was a part of the family of reduced instruction set microprocessors that had extensions to improve floating performance. Gekko implemented 32-bit PowerPC architecture that provided "integer data types of 8, 16, and 32 bits, and floating-point data types" of both single- and double-precision as well as offering new instruction sets [11, pg. 21]. Additionally, the Gekko featured a 4-stage basic integer pipeline responsible for low clock speeds and a 7-stage floating point pipeline optimal for gaming performance [12]. Since this was a general-purpose CPU, it was not the best processor or perfect for the GameCube. Nevertheless, its ability to handle game logic and successful ability to implement the graphics pipeline resulted in satisfactory performance.

The GameCube utilized a combination of CPU memory, card memory, and disk game memory. It's main memory consisted of a 24 MB MoSys 1T-SRAM with 3MB embedded a 1T-SRAM within a Flipper [13]. This 1T-SRAM was made up of DRAM that was popular, slow, and cheap, but it could also behave like faster SRAM allowing it to provide a steady bandwidth between the CPU and main memory [10]. The system also contained 16 MB of 81 MHz DRAM that was used as a buffer for the game disk drive and audio [13]. The console also featured a DVD rather than cartridges to change games and two memory card slots to save the game memory similar to SD cards. Further, the disks were capped at a capacity of 1.5 GB to prevent illegally copying Nintendo's content leading some games to be launched on a series of disks. This annoyed consumers, so Nintendo later fixed this problem by returning to cartridges. Conversely, the memory cartridges were offered in a variety of sizes ranging from 4 MB to 16 MB. With this combination of main memory, compact disks, and cartridges, Nintendo was able to come up with a unique and successful memory architecture (see Fig. 4, [12]).

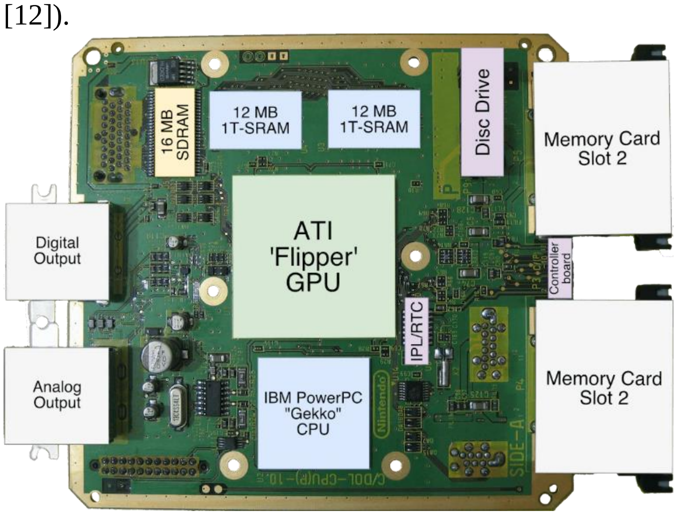

Fig. 4. GameCube marked motherboard.

Subsequently, the GameCube finally featured a more visible operating system than just a classic BIOS running in the background. Once the console was turned on, it launched an operating system known as the Dolphin OS that initialized the hardware, provided system calls and global variables to be used in games [10]. Once booted, you would see the startup screen that plays the GameCube logo animation. The system also contained a well-developed main menu that would be displayed if you pressed A during a game or started the console without a disk. This allows you to pick between a variety of settings such as changing the date and time, changing the sound and screen position, or managing your memory cards. This feature was one of Nintendo's most advanced and user-friendly menus at the time.

B. Wii

Following the GameCube, Nintendo released their version of the next generation of home consoles, the Wii, in 2006. The company's success with interchange disk games prompted them to keep the same mechanism as long as they held more. This console had similar graphics to the GameCube only supporting standard definition resolutions and used SD cards rather than memory cartridges. One of the most distinguishable features of the Wii was its new wireless controller that could detect rotation and three dimensional motion utilizing a mix of internal sensors and infrared positioning. This console was marketed to more casual users since you could now play online, connect a variety of sensors, and new game varieties were possible with the controllers. Similar to many other Nintendo developments, the company began with previously successful hardware and enhanced it to fit their customers needs and improve performance.

Specifically, the Wii used the IBM PowerPC 750CL codenamed Broadway, which was a slight modification of the Gekko processor used as the GameCube's CPU. The Broadway ran at 729 MHz, twice the speed as the Gekko was run in the GameCube [14]. There didn't seem to be too many modifications within the CPU which allowed developers to be familiar with their environment and focus on creating faster games with new features. For Graphics, the system used a 3 MB ATI Hollywood GPU clocked at 243 MHz that allowed for more geometry and effects [15]. The device also contained an I/O controller to handle communication between the GPU and the system, and a processor called

Starlet to handle the external I/O and WiiConnect24 while the console was asleep [16].

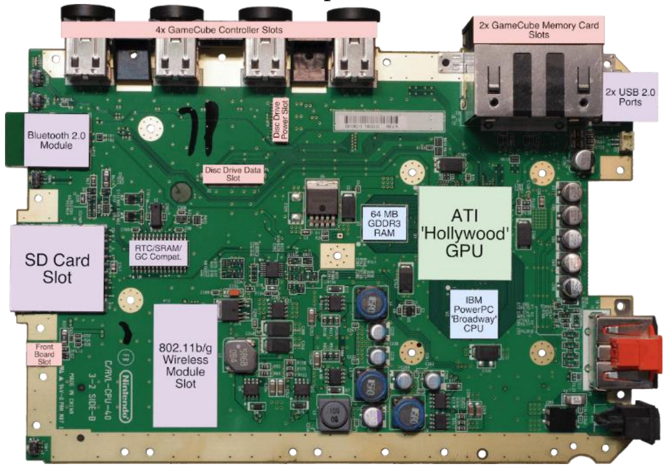

Fig. 5. Labeled motherboard of the Wii.

For memory, the Wii used the basis of the GameCube layout, but it was rearranged, and some enhancements were added. There was 24 MB of 1TB-SRAM that was now located in the GPU package (see Fig. 5, [14]), so it was accessible for graphical textures and video data usage. There was also 64 MB GDDR3 SDRAM for more general purposes and 512 MB of internal flash memory [15]. You could also add up to 32 GB of memory to store games from the online shop with the insertion of an SD. Most of the games were still played on discs though. Nintendo now made this able to support up to 8.5 GB over 5 times the storage of the GameCube, and still used a non-proprietary format to avoid licensing fees [16]. The first models of the Wii were also backwards compatible allowing you to play old GameCube Games with the right controllers.

Nevertheless, the issue of the connection between hardware and software became more complex for Nintendo when it came to the new controllers. Their gaming system now had to have one operate on the main CPU, Broadway, and one operate on Starlet for the I/O operations [14]. Starlet is an Input/Output Operating System meaning it transfers information between the computer's main memory and external devices such as the controller. These systems are composed of peripherals, I/O control units, and software to carry out the I/O transactions through a sequence of I/O operations [17]. Therefore, Starlet takes some of the work of the main CPU and the two are able to communicate with each other using IPC protocol in which the CPUs share two registers each. They are able to write on the other's register and the CPU can perform a function in response. Further, Broadway's operating system runs on the main CPu and is commonly known as the system menu [14]. Once the console turns on, you are greeted with a main menu, similar to the GameCube, one is able to adjust the system settings without a disc inserted. However, the Wii offers some new features such as a variety of downloadable applications as well as a messaging service that you can run without a game. If you decide to put in a game, then the mix of these two operating systems helps everything run smoothly.

V. COMPARISSON BETWEEN CONSOLES

A. Handheld Systems

Nintendo has been successfully integrating new combinations of hardware in both their handheld and home consoles and altering them for improvements over generations. It is easy to visually see the new designs and software between consoles, but the hardware behind the scenes makes a significant difference. The Game Boy Advance differs visually from the original Game Boy released in 1989 with its new horizontal appearance. However, its true evolution was contained within its ARM processor that could either run in either 32-bit ARM mode or 16-bit Thumb mode. Using these modes together allowed the developers to have sufficient resources while still having acceptable game performance speeds. This decision meant that using a variety of bus sizes in the system's memory would be necessary to run both varieties of instructions at full speeds. Further, the operating system for the Advance was not very visually appealing, but the BIO was a pre-installed firmware that contained a variety of software routines in order to make sure every game booted properly.

The follow-up console, the Nintendo DS, varied visually from the Advance due to its new dual screens including one touch screen, Wi-Fi connectivity, microphone, and additional buttons. Within the inside, the DS contained double the processors as the Game Boy. The DS possessed the ARM946E-S running at 67 MHz and the ARM7TDMI running at 33 MHz, these were both significantly higher speeds compared to the Advance's process running at 16.8 MHz. Similar to how the Advance's processor ran in two different modes, the DS split tasks by using one processor, the ARM7, to focus on

I/O operations while it gave the other processor, ARM 9, often more power to help developers prioritize tasks. Additionally, the DS contained a lot more memory than its predecessor. It had 4 MB of RAM compared to 256 KB of RAM, and 656 KB of Video RAM compared to 96 KB. The DS's game cartridge's memory could also go up to 256 MB whereas the Advance's could only go up to 32 MB. Due to its dual processor setup, the DS's memory architecture had to be more complex. The console also featured two ROMs each connecting a BIOS to one of the ARM buses. Although each CPU had to boot from their respective ROM, the BIOS was used to store similar boot code and interrupt routine calls to ensure that the games would run properly. The DS indeed had significant upgrades from the Game Boy Advance on the inside of the system as well as the outside.

B. Home Systems

Nintendo began releasing home gaming with the Color-TV game around 1977. The NES became a popular 8-bit gaming console around the world shortly after its release in 1983. It became so successful that Nintendo released similar follow-up consoles such as the Super Nintendo and the Nintendo 64, but the GameCube differed from the others by interchanging the games through discs rather than cartridges. It's successor, the Wii released five years later, continued to use this disc system. However, it used new wireless motion controllers, which caused its hardware to vary greatly from the GameCube's.

Since Nintendo wanted to make sure this console was up to their customers' standards, they contracted IBM to create the 486 MHz PowerPC 750CXe processor known as the Gekko. It was a 32-bit processor that featured both a 4-stage integer pipeline and a 7-stage floating point pipeline making it optimal for gaming performance. It worked so well that IBM used it as the basis of Wii's processor, the PowerPC 750CL, and there seemed to be few modifications besides running at twice the speed of the Gekko. One key to the Wii's success was using the Hollywood GPU clocked at 243 MHz rather than the GameCube's 162 MHz "Flipper" which allowed for more geometry and visual effects. For memory, the Wii once again began with the basis of the GameCube's architecture, but it was able to hold much more and had slight alterations. The same 24 MB of 1TB-SRAM was now located in the GPU package and its DRAM was increased from 16 MB to 64 MB. Additionally, the Wii now used SD cards of up to 32 GB of storage rather than memory cards maxing at 16 MB, and the game discs could hold up to 8.5 GB instead of 1.5 GB.

Besides this increase in memory, the Wii also had to now contain two operating systems since it had new controllers. The GameCube utilized Dolphin OS which was able to initialize hardware, store system calls, and provide global variables. It also provided a more visually appealing menu allowing you to change system settings than its comparable handheld console the Game Boy Advance. If everything was running smoothly, you would see a satisfying animation of the GameCube logo being built and then be brought to the menu and the game would begin if a disk was inserted. The Wii had a similar main CPU operating system, that greeted you with a main menu and allowed you to adjust system settings if there was no game. Conversely, the Wii's main menu now had more features including downloadable applications and messaging services. The Wii also had Starlet's operating system which was responsible for the I/O operations made heavy by the new controllers. Since the two operations systems could effectively communicate via IPC protocol, this took a significant amount of work off the main CPU allowing the console to run smoothly.

VI. EVOLUTION OF NINTENDO

The company has continued to develop new consoles every few years that keep up to date with the latest technology; however, they have just been alternating old systems rather than creating whole new ones. To explain, Nintedo has released many versions of the DS including the DSi and the 3DS. Its main new features included two digital cameras, the DS online shop, and a new slot for SD cards. The next variation, the 3DS, was released in 2011. It had two noticeably visible changes: a top screen displaying 3D graphics without the use of graphics and a new button that you could move in any direction without holding down. These improved visuals and faster performance were attributed to the hardware of the CPU and GPU, but there does not seem to be a significant amount of changes considering the number of years passed between modifications.

Nintendo has focused even less on developing new home consoles with the only modification of the Wii being the Wii U back in 2012. It's main distinguishable feature was a wireless, tablet-like, GamePad that featured its own screen and toggle buttons similar to the GameCube. Once again, Nintendo started with a familiar start of the Wii's Broadway chip, increased its' speed to 1.24 GHz, and came up with the IBM PowerPC 7xx. It contained a new GPU clocked at double the speed of the Wii's and featured a significant upgrade in flash storage ranging from 8 GB to 32 GB depending on the model [18]. Subsequently, Nintendo's most recent console seems to be a combination of both handheld and home consoles.

This new product, the Switch, consists of two main modes. In one, you can connect controllers to the screen of the device and play on the go like the GameCube Advance with new DS technology. In the other, you can put the screen in a docking station, remove your controllers, and play on a television like the Wii. The device contains the success of both types of previous consoles. It uses game cartridges and a microSD card slot similar to the DS, but it also only contains one CPU and wireless controllers like the Wii. In Addition, the Switch automatically contains 32 GB of internal storage that can be easily expanded to 2TB [19]. This a significant improvement from any previous consoles. Unfortunately, Nintedo doesn't release much information about the operating system, but we can only assume that it has gotten more complex after investigating the Wii.

VII. CONCLUSION

All these consoles have made significant developments in at least one of the following areas: processors, memory, or operating systems. For example, the Game Boy advance used a processor that could run in either 32-bit ARM mode or 16-bit thumb mode allowing both to be synchronized together for optimal game performance and resource utilization. Then, the DS contained two processors, an ARM7 and an ARM9, to balance the execution of different instruction sets. This also forced the DS to have to use a combination of 16-bit and 32-bit addressing schemes. All the consoles saw improvements in storage, but the home consoles featured more visually appealing main menus due to their operating systems. The GameCube had a unique startup animation as well as a user-friendly settings menu. The Wii was the first Nintendo system to feature two operating systems and had a main menu with messaging services and downloadable apps. Every console has contained many improvements behind the service.

Many of Nintendo's original consoles did not have operating systems that we know today but improved their hardware. The handheld consoles focused on developing faster and more powerful CPUs, while the home consoles focused more on developing graphical menus. All the consoles have seen significant upgrades in storage capabilities. It seems that this trend of improving memory and creating new CPUs will continue to. Operating systems will likely get more complex when trying to combine the two categories into one with the creation of the Switch. It seems that Nintendo will continue to make modifications of this console in the future, and the company's video game systems contain operating systems very different from personal computers.

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