An Analysis of the CELL Broadband Engine Architecture and its Implications on the Difficulty of Emulating the PlayStation 3 Console

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ABSTRACT

This paper presents a comprehensive analysis of the hardware architecture of Sony's PlayStation 3 (PS3), with a specific focus on the Cell Broadband Engine Architecture (CBEA). The CBEA is a unique architecture that employs two instruction set architectures, the PowerPC and Synergistic Processor Unit (SPU), for system management, control, and compute-intensive processing. The PS3's CBEA comprises a PowerPC Processor Element (PPE) and a Synergistic Processor Element (SPE), which are responsible for data processing. The CBEA supports simultaneous memory access with Direct Memory Access (DMA) engines and includes a Resource Allocation Management (RAM) facility to address latency and bandwidth issues.

In addition to discussing the hardware components of the PS3, this paper also delves into the challenges of programming for the PS3's architecture, specifically the complexities of code partitioning, vectorization, synchronization, scheduling algorithms, and space and time multiplexing of computation on cores, all of which are required to achieve efficient execution and to fully utilize the potential of the processor. Furthermore, this paper highlights the difficulties of emulating the PS3 due to its sophisticated architecture and the involvement of DMA in transferring data between components. Overall, this paper aims to provide a detailed overview of the PS3's hardware architecture, its significance in the gaming industry, and the challenges associated with programming and emulating its unique CBEA architecture.

CCS Concepts

• Computer systems organization → Architectures → Parallel architectures → Multicore architectures

• Applied computing → Computers in other domains → Personal computers and PC applications → Computer games

Keywords

CELL Broadband Engine Architecture; PlayStation 3; emulation; parallelism; console; gaming; RPCS3

1. BACKGROUND OF THE STUDY

In the past, video games were only available as prototypes and designs running on machines used by scientists in their research labs, which were understandably limited in their functions, features, and accessibility. As time went by, efforts made on the advancement of various technologies pushed the development of video games to further evolve to different computing platforms and devices. Gradually, the popularity of video games increased over the past few years, where video games are now played on different computing devices accessible to gamers, such as a personal computer, gaming console or mobile phone. With the rising popularity, debates on which gaming device is better have emerged highlighting the difference between personal computers and gaming consoles [8][9][10][17]. However, despite the significance of personal computers to the mass in terms of its accessibility, affordability, and efficiency, gaming consoles remains to be patronized by most gamers with Sony's PlayStation 2 reigning as the best-selling video game console of all time among the rest of consoles produced by Microsoft, Nintendo, and Sony itself in the gaming console market [21].

1.1 History of Emulation

Significantly, the popularity of gaming consoles attracted gaming enthusiasts to preserve old video games essentially through the process of emulation, which was coined by IBM in 1963. Emulation of video game consoles historically began in the mid-1990s after it became feasible for the current technology to replicate the hardware and software components of gaming consoles into a software platform that allows host systems to run software or use peripheral devices designed for the original system. Apparently, most of the first unauthorized and non-commercial console emulators were often incomplete and defective due to deduction of the consoles by programmers through reverse engineering, yet still, Nintendo Entertainment System (NES) was the first recognized gaming console that was emulated having emerged into SNES9X in 1996 [6].

With regards to popular consoles, Microsoft's XBOX, Nintendo's Switch and Wii, and some of Sony's Playstation consoles have been successfully emulated as most video games from these consoles can now be effectively run on personal computers. Yet, despite having almost the entire line of Sony's PlayStation consoles emulated, PlayStation 3 remained a challenge to programmers.

1.2 PlayStation 3 Console

Figure 1. Sony's PlayStation 3

Sony's PlayStation 3 was first released on November 11, 2006, in Japan [2], November 17, 2006, in North America, and March 23, 2007, in Europe and Australia [19][22][23]. It was another console marketed by Sony Interactive Entertainment succeeding its previous console, PlayStation 2, and was primarily competing against Microsoft's Xbox 360. It had a large library of games that catered to a wide range of players and genres, including action-adventure, first-person shooter, role-playing, and sports games. Some of the most famous games played on the PlayStation 3 include: The Last of Us Part 1, Uncharted 2: Among Thieves, Red Dead Redemption, Dark Souls, and Grand Theft Auto V [11]. Apparently, it was the most powerful video game system ever designed at the time of its release [1]. It used CD ROM-based 3-D graphics and had a Cell Processor that was so powerful that the unit wouldn't even need a dedicated graphics processor [1].

1.3 CELL Broadband Engine Architecture

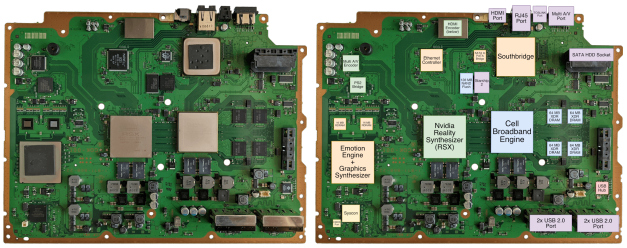

Figure 2. PlayStation 3 Motherboard

Historically, PlayStation 3's hardware architecture is based on a unique design called the Cell Broadband Engine [1], which was a revolutionary microprocessor created by the STI (Sony Group-Toshiba-IBM) Design Center as a composition of new unconventional multi-core architectures for Sony Interactive Entertainment's PlayStation 3 that is beyond performance and efficiency [12]. Within the PS3 is the notorious CELL processor which consists of one PowerPC Processor Element (PPE) clocked at 3.2 Ghz and eight Synergistic Processor Elements (SPEs). Additionally, it contains the Reality Synthesizer or RSX, the graphics card for the PS3, which was developed by NVIDIA and has a memory size of 256MB. Lastly, the console also has 256MB of Extreme Data Rate Dynamic Random-Access Memory or XDR DRAM [5].

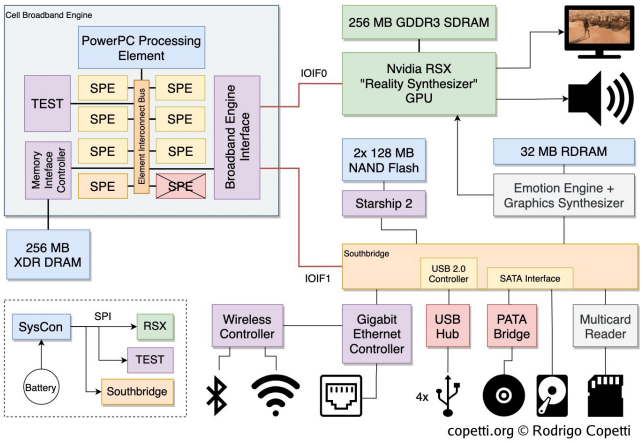

Figure 3. PlayStation 3 Architecture Diagram

The Power Processing Element (PPE) of the CELL processor is a novel core that differs from any previous PowerPC core produced by IBM. It functions as a general-purpose microprocessor and is responsible for running the operating system. The eight Synergistic Processor Elements (SPEs), on the other hand, are specifically designed to perform high-speed calculations. Unlike conventional processors that rely on hardware caches to automatically bring data and instructions closer to the processor, the Cell Broadband Engine requires programmers to create a "shopping list" of the data needed by the program. While this places a greater burden on the programmer, who must specify the required data in advance of execution, it also reduces the area needed for hardware caches. This allows the Cell Broadband Engine to accommodate eight SPEs and one conventional core in a technology that would otherwise only support two conventional high-performance cores.

With these, the authors desire to provide an analysis of the hardware architecture of Sony Interactive Entertainment's PlayStation 3 by discussing extensively the components of the hardware and comparing the architectures of PlayStation consoles. In addition, the study attempts to identify the implication of the architecture of PlayStation 3 in the emulation of the console.

2. RELATED LITERATURE

The Cell Broadband Engine Architecture marks its distinction from other processors through its use of two instruction set architectures, which are namely: PowerPC and the Synergistic Processor Unit or SPU. Thus, a processor can only be considered as CBEA compliant if it has one or more PowerPC Processor Elements (PPEs) and one or more Synergistic Processor Elements or SPEs. The PPE follows the IBM PowerPC Architecture and is used for system management and application control. Unlike other architectures that use extensions like vector or SIMD multimedia extension, the CBEA uses an independent SPU that follows the SPU instruction set architecture for compute-intensive processing. This separates data processing and control functions, allowing for more parallelism in applications [14].

During the boot-up process, one of these SPEs is disabled to increase chip yield. This disabled SPE is not used for handling computations and processing data. It merely serves as a spare SPE. This is intended so that when one of the SPEs is defective after the chip was manufactured, the entire chip is not discarded

since there is a spare. However, that spare will always be deactivated, regardless of whether it is functional or not [7].

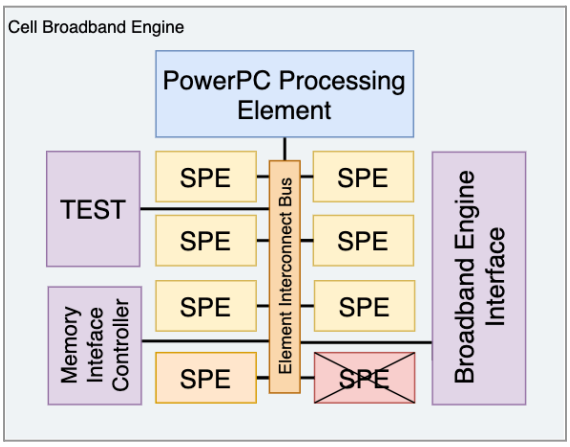

Figure 4. Cell Broadband Engine

According to Steve Bush, the author of "Consortium Discloses Cell Processor Specification," the SPEs are dependent on the PPE to run the operating system as well as the top-level control thread of an application. Meanwhile, the PPE is dependent on the SPEs to deliver a satisfactory level of application performance. As such, the SPEs are designed to be programmed in high-level languages [5]. The CBEA also provides support for simultaneous memory access made possible by the Direct Memory Access (DMA) engines. The purpose of these engines is to move data with the assistance of the coprocessors [4].

2.1 PowerPC Processor Elements

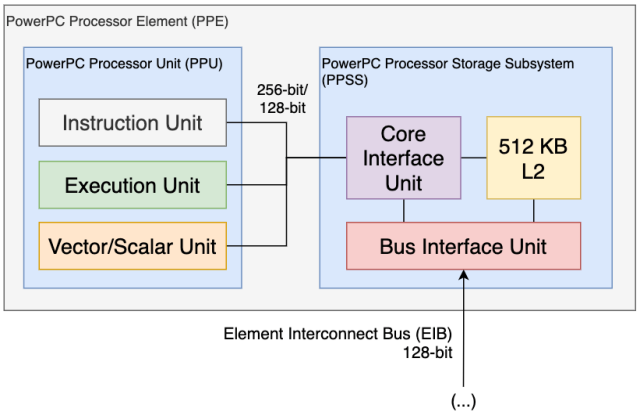

Figure 5. PowerPC Processor Element

The PPE performs control plane functions that typically require the more general-purpose computing capabilities provided by the PPE. It is a 64-bit processor based on Version 2.02 of the PowerPC Architecture, which offers many features suitable for the application spaces targeted by the CBEA [2]. Even though the CBEA has offload processors for handling vector and streaming media processes, the vector/SIMD extension was also included in the PPE. The extension was used to make it easier to develop and port applications to the SPE, as well as to enable parallelization across the PPEs and SPEs for various applications. Since the SPUs also have this extension, the extension provided to the PPE strictly follows the rounding modes specified in the SPU instruction set architecture to ensure compatibility [14].

2.2 Synergistic Processor Units

As for the SPU, a single core or unit contains exactly 128 registers which are all 128-bit single instruction multiple data or SIMD registers. Having these many registers allows for more efficient instruction scheduling and also enables the capability for more optimization techniques such as loop unrolling. Each SIMD operation or SPU instruction processes data in sixteen 8-bit integers, eight 16-bit integers, four 32-bit integers or single-precision floating-point numbers, or two 64-bit double-precision floating-point numbers [14]. These are the granules, or the sizes and types of data, that can be processed by a single SPU instruction. A granule of sixteen 8-bit integers means that one instruction can operate on 16 numbers which all have a size of 8 bits or 1 byte. A granule of two 64-bit doubles means that one instruction can operate on 2 numbers which both have a size of 64 bits and are both double data types.

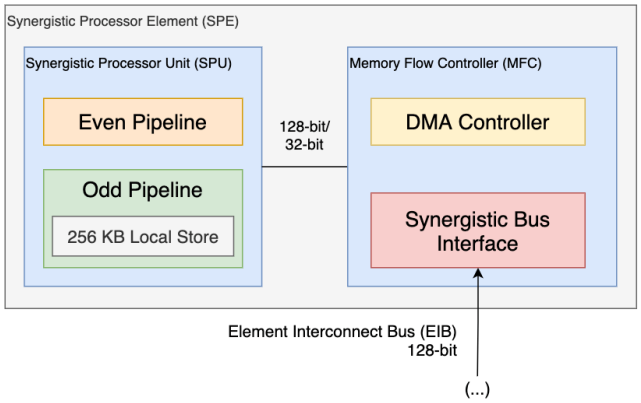

Figure 6. Synergistic Processor Element

Unlike the separate set of registers in the PowerPC architecture, the SIMD registers in the SPU are unified which means it can be an operand of either an integer instruction or a floating-point instruction. Maximizing the performance of an SPU involves tuning the data structures of the program to be defined around the SIMD data flow, since we are working with SIMD registers. New techniques such as double buffering should also be implemented in order to efficiently overlap the computation processes with the movement of data within the processor. In doing so, this makes the SPU immune from memory latency, specifically the system memory accesses. Despite being SIMD operations, scalar operations can still be performed using the preferred slot of the SIMD register [14].

2.3 Memory and Resource Allocation

There is a local storage space dedicated for each SPU that holds the instructions and data, and it is the only way through which an SPU can address memory. As a way to maintain synchronization with other coprocessors, the SPUs and each of their corresponding local storage comes with a Memory Flow Controller or MFC. This component, together with the SPU itself and the associated local storage, make up the whole of the SPE. All data movement is handled by the MFC, which is capable of moving data between storage domains. However, MFC commands are only initiated by the SPU or PPE. Additionally, the specific component in the MFC

that performs the data movement is the Direct Memory Access or DMA [14].

Since CBEA is a multiprocessor system, this means multiple processors are constantly requesting resources at the same time. This can sometimes lead to problems with latency and bandwidth. To address this issue, the CBEA includes a Resource Allocation Management (RAM) facility that ensures critical resources like system memory aren't being used up by just a few devices. Enabling RAM will execute the assignment of a Resource Allocation Group (RAG) to each device that attempts to request resources, and a portion of each critical resource is allocated to each RAG. How these resources are controlled by the RAM varies depending on the implementation. In a Cell BE processor, RAM handles the system memory and I/O interfaces using a token-based control mechanism, which allocates a percentage of the managed resources to each RAG. This prevents resources from being wasted or underutilized [14].

Taking the aforementioned functions of RAM into account, the RAM facility would appear to be a bandwidth management system, but its bandwidth and latency depend on the access size and pattern. To avoid problems with lower bandwidth when accessing the same physical memory bank, RAM requires a token for each bank. The token manager distributes the memory allocation equally among all banks, resulting in higher achievable memory bandwidth if the access pattern is evenly distributed. Small accesses can cause poor utilization of system memory, but this is addressed in a CBEA-compliant processor by defining each token as the transfer of a full cache line, or 128 bytes, and requiring two tokens for transfers that require a read-modify-write of system memory to update the error -correction code or ECC [14].

2.4 Legacy

The main goal of Sony, Toshiba, and IBM with the CBEA is to make it powerful to perform computationally demanding operations or tasks by heavily utilizing the concept of parallelism. More specifically, the computations involved were geared towards multimedia processing and 3D video game engines. To achieve this, code simplicity has to be traded for faster computations. This is why the PlayStation 3 is considered an inferior console when compared to Microsoft's Xbox 360 at the time. Nevertheless, when optimizations are done right, the PS3 was able to outperform any gaming console in the past market. Due to its high processing power, the CBEA was also used in other areas and sectors aside from the console market, such as military and private sectors, cybersecurity, neuromorphic computing, protein folding, and medical research [5].

In the past, improving the performance of sequential programs was done through technology scaling, but this approach is gradually becoming obsolete. Now, the new method for increasing program performance is by using multicore parallelism. The PS3 demonstrated this technique perfectly through its intensive use of multiple core processes. As such, it is considered more than just a gaming console as it can also be used as a platform for academic and research purposes by installing other operating systems and booting into a programmable environment using popular Linux distributions. This makes the PS3 a viable platform for learning and experimenting with programming models and patterns for parallel execution [18].

3. DISCUSSION AND FINDINGS

The PS3's Cell BE architecture differs from other multi-core offerings in that its eight synergistic processing elements or SPEs must explicitly fetch data from main memory to perform computations. This presents many challenges for research purposes as programs running on the Cell BE require the coordination of computation and communication. The added trouble of partitioning code across the SPEs is required to achieve efficient execution and to fully utilize the power of the processor. It is also done to increase parallelism [18].

3.1 Code Partitioning

up image processing:

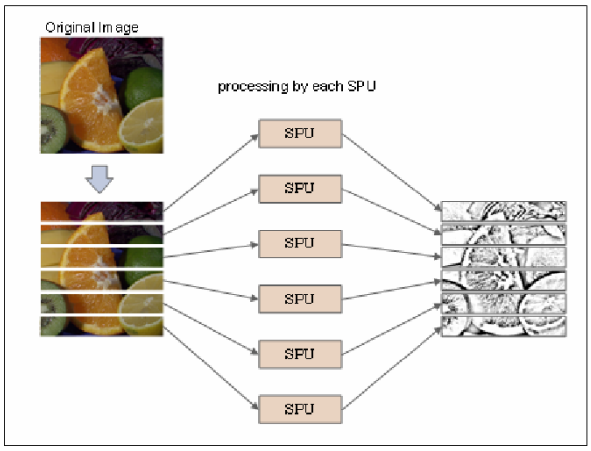

Figure 7. SPU Utilization Using Parallelism

Code partitioning is a way to distribute the workload of an application across different processing units. It is different from multithreading in that the latter is the execution of multiple tasks within a single process. Partitioning is only possible when a processor uses more than one core, but a multi-threaded software has the ability to run on just a single core. Between the two, code partitioning is the most efficient in terms of optimization since it improves the performance and scalability of an application, but it is more difficult to implement. Nevertheless, the two can be utilized together to fully maximize the capabilities of a processor [15].

Other than partitioning code into different parts for the SPEs, the code also needs to perform vectorization since each SPE is a short vector processor. If that wasn't challenging enough, the programmer must also make sure that the cores are synchronized when there is overlapping communication and computations to be done. Additionally, there is the implementation of a scheduling algorithm and the decision of whether static or dynamic scheduling of computation should be used. Lastly, we have space and time multiplexing of computation on cores [18].

3.2 Programming

In terms of development, the PS3 seems to be troublesome especially for programmers. As of currently, the PS5 is only backward compatible with the PS4. PlayStation 3 games, on the other hand, are only available for stream play through the PlayStation Now service, which is quite demanding for individuals who don't have a reliable internet connection. The main problem is in the PS3's hardware, particularly its CELL

processor. The console was a huge deviation from its predecessors and even its successors. Its seven floating co-processors or the synergistic processing units (SPUs) are difficult for developers to work with. Even though the PS3's CPU runs at 3.2 Ghz, it became infamously known for its complexity and sophisticated architecture rather than its huge power advantage [3].

The processor works by allowing the central PowerPC processor element to offload intensive computations to the co-processors. These extra cores are excellent in doing parallel operations such as mathematical computations and allow the console to perfectly simulate intricate physics including collisions, clothing, and particles. Moreover, the PS3's floating speed was forty times faster than its predecessor. However, harnessing the potential of the CELL processor is easier said than done since the process isn't automatically handled. The developers have to partition their code themselves [3].

This resulted in a steep learning curve for PlayStation 3 game programming, to the extent that developers would regularly ignore the SPUs completely and just use the PPE [3]. This wouldn't be an issue if the game developers are targeting a single platform only, but when it comes to developing for multiple platforms, the process becomes cumbersome since the game has to be fine-tuned to the PS3's hardware in order for it to utilize the SPUs properly. Furthermore, the source code could possibly be rewritten entirely.

3.3 Direct Memory Access

Sharing data around each of the SPUs would require the involvement of a Direct Memory Access or DMA. A DMA transfer can be initiated from any of the CELL processor's components. This can be from one of the SPUs, the PPU, or even the graphics processor. Once data reaches the SPUs, data processing can be done in a rather quick manner. Therefore, it is important to keep the SPUs supplied with data and each core running. For example, if we want to write a single byte from the SPU's local storage to main memory using a simple SPU program, we must first set up a DMA transfer. Then, we must initiate the transfer and wait for it to complete before loading 16 bytes or 128 bits from the local memory [16].

In the event of writing a byte to the main memory, it is first necessary to organize it as a 16-byte value and store it in the local memory of the SPU. Subsequently, a DMA transfer must be initiated and monitored until completion. Indeed, the process of transferring a single byte between the main memory and the SPUs can be complex. When considering the presence of five additional SPUs and a PPU potentially executing their own processes, the complexity increases significantly. Factors such as synchronization, memory mapping, and inter-unit communication must be taken into account to facilitate data sharing [16].

3.4 Emulation

The most popular emulator today for the PS3 is the RPCS3. Currently, it can run 68% of the PS3 game library, but it has been growing at a rather steady pace for a while now. According to one of RPCS3's developers, codenamed 'Whatcookie', the primary culprit for the PlayStation 3's difficulty in terms of emulation is its 128 byte read/write operation or cache lines and the floating-point format that the SPUs support. This explains why the PlayStation 5 is backward compatible with the PS4, since both run on an x86 CPU like most computers and both have 64 bytes cache lines. Additionally, since the PS3 operates on 128 bytes of data, a single event for the PS3 would appear as two events on a system with 64-byte cache lines [3].

3.4.1 Cache Lines

Each data transfer is called a token in a CBEA-compliant processor, which is always a full cache line or 128 bytes. This means that every event or operation would take 128 bytes at a time. A processor that is operating with 64-byte cache lines would not be able to execute or imitate a full transfer as a CBEA-compliant processor in one single complete operation, since that would require two cache lines to be accessed. It would have to split the data transfer into two 64-byte chunks and perform them separately. Apparently, this presents a problem with emulating the PS3 console because the transfer has to be divided into two separate transfers. Moreover, for transfers that initiate both a read and write operation, two tokens are required, making it more difficult to implement.

3.4.2 Floating-Point Format of SPU

Moving on, it was also mentioned that the floating-point format that the SPUs support poses a problem with PS3 emulation. This is because the SPUs deviated from the IEEE standard for floating-point calculations. Specifically, the single-precision floating-point instructions are not compliant with the IEEE 754 Standard when it comes to calculating results. Nonetheless, the format used for representing floating-point numbers does comply with the aforementioned standard, and this applies for both single-precision and double-precision. Additionally, the range of normalized numbers is extended for single-precision operations, but the full range as specified by the IEEE standard is not implemented [13].

A base-10 zero number has two representations: positive zero, which is when all bits are zero, and negative zero - which is when one bit (the sign) equals one. Both representations are viable as inputs, but zero results will always equate to a positive zero. As for the characteristics of single-precision operations in the SPU, the following is not supported: Not a Number (NaN), Infinity (Inf), and denorms since they are treated as zero. The SPU also does not support any rounding mode except truncation towards zero [13].

Fortunately, for double-precision operations, the usual conventions used by the IEEE 754 standard are retained. However, there are still some minor differences. For instance, double-precision operations in the SPU support only a subset of the operations required by the IEEE standard. Denorms are also only partially supported depending on the implementation. Those who do support it treat the denormal operands as zeros. Nevertheless, all four rounding modes specified by the standard are supported, as well as the two kinds of NaNs and the very strict rules on the propagation of NaNs [13].

Table 1. Differences between SPU and IEEE Standard

Aspect	SPU Standard	IEEE Standard
Formats	Single precision (extended-range mode) and double precision (IEEE mode)	Single precision (binary32), double precision (binary64), quad precision (binary128), half-precision (binary16), and bfloat16

Operations	Floating add, subtract, multiply, multiply and add, reciprocal estimate, reciprocal square root estimate, interpolate, convert to/from integer	Floating add, subtract, multiply, divide, square root, remainder, round to integer, compare, classify, convert to/from integer
Exceptions	Invalid operation (I), divide by zero (Z), denormal operand (D), inexact (X)	Invalid operation (I), divide by zero (Z), overflow (O), underflow (U), inexact (X)

3.5 Existing Hardware Features

Furthermore, the RPCS3 development team stated that the primary obstacle for Sony in emulating the PlayStation 3 on the PlayStation 5 is utilizing the Synergistic Processing Units. Effective emulation necessitates some form of hardware support. While porting RPCS3 may provide some assistance, the lack of hardware synchronization to emulate atomic memory access presents a significant challenge to performance. Ideally, Sony would want to incorporate SPU hardware directly onto the motherboard to facilitate emulation. Mark Cerny, the lead architect of the PlayStation 4 and PlayStation 5, did mention that the Tempest Engine contains an SPU-like cluster for audio processing. While this may provide some potential for leveraging existing hardware, there remain additional challenges related to the use of AMD architecture on Intel processors [16].

3.5.1 Transactional Synchronization Extension

There is an x86 extension known as TSX or Transactional Synchronization Extension which provides a feature set for handling transactional memory. RPCS3 utilizes a TSX feature known as RTM or Restricted Transactional Memory, which grants exclusive access to a memory block. If another thread attempts to access the same block of memory, the calling application determines the outcome. This TSX extension feature aligns well with the transactional and atomic memory behavior of SPUs. Unfortunately, TSX extensions are exclusive to Intel and are not available on AMD processors [16].

In the absence of TSX support, a custom software solution must be developed to manage the locking and copying of memory in order to determine if any memory block has been altered. This can become increasingly complex when dealing with multiple SPUs, resulting in compromised performance. However, it is worth noting that the RPCS3 team has successfully developed a workaround for Ryzen processors, utilizing a clever cache line emulation mechanism that emulates contention problems with minimal locking [16].

3.6 Main Challenges

Rob Wyatt, who worked on the engine architecture of Insomniac for PlayStation 3 development, made some remarks regarding the intricacies of the SPUs of the CELL processor. He is also formerly a member of the Sony ICE Team and has a solid understanding of the underlying architecture of the PS3 processor. On top of that, he had written thousands of lines of SPU code. When asked about emulating the PS3, he responded by stating that the SPUs continue to be a class of their own. He said that writing SPU code is like writing code for two programs at once. One manages the data, which seems to be a reference to the PPE, and the other one for managing math operations, which is what the SPU is responsible for [16].

In his terms, sustained single core performance on an SPU is still higher than almost all other alternatives in the market. Aside from writing code for the SPU and PPE, one must also make sure that parallelism is enabled by default. Thus, emulating them on any modern CPU would be near impossible. Nonetheless, a modern PC does run at a similar clock speed as the coprocessors of the CBEA. However, it cannot sustain data. In addition, there are a variety of challenges such as loading from memory with cache misses, dealing with branching, not having enough registers, and the complexity of the DMA [16].

4. CONCLUSION

The Cell Broadband Engine Architecture (CBEA) of the PlayStation 3 is a remarkable feat of engineering. However, its sophisticated architecture presents unique challenges for game programming and emulation. The CBEA's utilization of multiple Synergistic Processing Elements (SPEs) and a PowerPC Processor Element (PPE) requires explicit coordination of computation and communication, as well as the implementation of code partitioning, vectorization, synchronization, scheduling algorithms, and space and time multiplexing of computation on cores to achieve efficient execution.

The utilization of Direct Memory Access (DMA) for data transfer between components presents a significant challenge due to its intricate and labor-intensive nature, requiring numerous steps to execute. Additionally, the advent of the CBEA necessitated the implementation of various programming techniques such as bulk synchronous parallelization, DMA traffic scheduling, and the overlapping of computation and transfers, which were relatively unfamiliar at the time [20]. Moreover, the PS3's unconventional features such as a 128-byte cache line and SPUs that support a non-standard floating point format further heightens the complexity associated with development and emulation. These factors, in conjunction with one another, significantly contributed to the intricacy of the PS3.

5. RECOMMENDATIONS

Based on the findings presented in this paper, future researchers studying the PlayStation 3's hardware architecture should consider the following recommendations:

1. Include other components of the PlayStation 3 console. To fully understand how emulation works, it is imperative to not only limit the study to the CELL processor of the PS3, but also take into account the rest of its components. In this case, we have the Reality Synthesizer which is the graphics processing unit of the PS3, and the Extreme Data Rate Dynamic Random-Access Memory, among others.
2. Explore the potential of using existing hardware features on modern platforms, such as the Tempest Engine on the PS5 or the TSX extension on Intel processors, to facilitate emulation of the PS3's SPUs and their atomic memory access behavior.
3. Further investigate the trade-offs and challenges of using software solutions, such as cache line emulation or custom locking mechanisms, to emulate the PS3's 128-byte read/write operations and floating-point format on systems with 64-byte cache lines and IEEE standard compliance.

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