Gekko, Emotion Engine and Intel PIII Architectures - Fighting for the Gamer

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Abstract. This communication addresses the current state of the art on electronic games consoles and the architecture behind them. The presented topics include both an overview and detailed analysis of the current top three gaming systems. It compares the technology and solutions used by the consoles manufactures, with emphasis on the consoles CPU, in the quest for the home entertainment market. It shows why these systems should not be considered the poor relative of mainstream computer systems. Finally it identifies some of the driving forces for the evolution of electronic games and gives some hints on what can be expected in the future.

1 Introduction

Video games today are no longer the simple X moving on the screen avoiding "falling" dots that a programmer could do in a weekend. Now you have upwards of 20 people, or more, working together for a year or more. They come from different professional disciplines, including writing, design, testing, programming, production management, art, 3-D modelling, sound, music and video production.

With its sophistication, today's video games demand a lot of computational power. They require plenty of parallelism, integer computation and are dominated by floating point computation required for graphics.

Sony, Nintendo and Microsoft are trying to make available that computational power through what can currently be stated as the "state of the art" in video games consoles: PlayStation 2 (Sony), GameCube (Nintendo), and Xbox (Microsoft).

But why would people prefer a game console instead of a PC? For several reasons:

- it is usually much cheaper; consoles manufactures tend to combine many functions onto a single chip keeping the chip count low, with limited expandability, reducing costs with extra hardware (extra sockets, power supply, cooling capacity, etc);
- there is no long wait for the game to load, just stick the game in and play; there are no installations to do;
- video game systems are designed to be part of an entertainment system: they are easy to connect to a TV and stereo, and there is no need for a special monitor; most game consoles are truly "plug and play";
- only one configuration; players do not need to configure the system every time they run a new game;
- game developers know exactly what components are in each system; the console does not change its functions or performance during its lifetime, and all components are fixed, so games are written to take full advantage of the hardware;
- there are no compatibility issues, such as operating system, drivers, correct audio card, supported game controller, screen resolution, and so on;
- most video game systems have games that allow multiple players; this tends to be a difficult process with a typical home computer.

This communications starts by examining the consoles architectures, their manufacturer design concepts and look at their main components with special emphasis on the CPU. Comparisons will be made in relation to software development approach, floating point performance, memory bus bandwidth and GPU performance. We will conclude pinpointing the overall strong points of the analysed consoles and evaluating some of the games and hardware evolution options and challenges consoles manufactures will face.

2 Going Deep Inside

2.1 Emotion Engine, PlayStation's 2 core

Sony's design concept behind PlayStation 2 (PS2) was to have a "High performance Graphics Synthesizer plus an Advanced CPU architecture with massive Floating Point capability"[1] to provide the highest performance. Sony wanted a system capable of creating what they have called the "Emotion Synthesis". The real time generation of: behaviours and character intelligence; complex real world dynamics simulation; algorithmic generation of content; complex geometry and images animation; skeletal physical modeling and inverse kinematics.

Sony decided to keep the PS2 backwards compatible, by integrating an I/O processor (IOP) with a 32-bit MIPS R3000 core identical to the original system. The IOP controls the sound processor (SPU2), CD/DVD and all the digital interfaces: FireWire (IEEE1394),

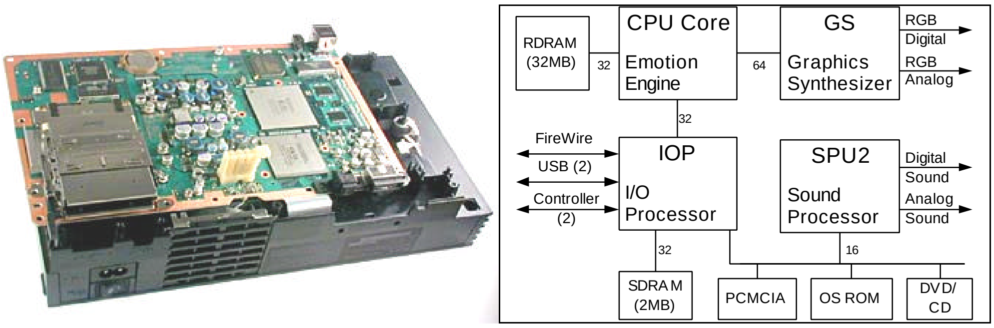

Fig. 1. PlayStation 2 interior (left) and system block diagram (right)

USB, PCMCIA, game controllers and eventually a hard disk. It communicates with the SPU2 through the 16-bit local bus and detects all the game controllers input which is sent to the Emotion Engine (EE) through the 32-bit bus.

The Graphics Synthesizer (GS), incorporates a parallel rendering processor with an internal 2560 bit wide data bus (1024 read, 1024 write, and 512 for texture). This bus allows a 48Gb/s bandwidth when communicating with the 4MB embedded DRAM.

The Sound Processor (SPU2) has a local 2 MB of memory and uses 48 sound channels plus definable, software programmable voices for producing the 3D sound.

The Emotion Engine, a 13.5-million-transistor microprocessor developed by Sony and Toshiba, incorporates a 128bit RISC CPU core (based on the MIPS III and a MIPS IV subset) with a clock frequency of 300MHz. It has a floating point unit with 10 floating-point multiply-accumulators [2] and 4 floating-point dividers (Co-processor 1) and two independent floating point vector processor units, VPU0 (Co-processor 2) and VPU1, an MPEG 2 decoder circuit (Image Processing Unit/IPU), a 10-channel DMA controller, and a Graphics Interface Unit (GIF) and interfaces for the RDRAM and I/O processor.

The communication with the Direct Rambus DRAM is through two channels at 800MHz, achieving a 3.2GB/s bus bandwidth.

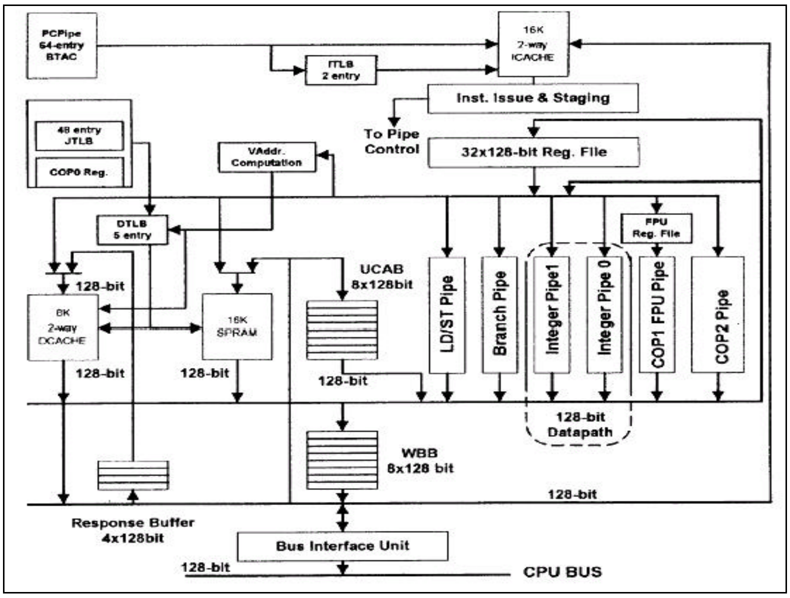

Fig. 3. Sony's MIPS based CPU core [3]

The CPU core (figure 3) has a 2-way Superscalar 64-bit integer unit with a 128-bit SIMD multi-media command unit, a 16KB (2-way) instruction cache, a 8KB (2-way) data cache and a dual port 16KB Scratch Pad RAM.

Instead of the standard MIPS 64- bit SIMD integer instructions, Sony defined new 107 128-bit multimedia instructions. They were implemented doubling the width of the 32 general-purpose registers to 128 bits and using the two 64-bit integer units in parallel. Working together these two units can execute four 32-bit, eight 16-bit, or sixteen 8-bit integer arithmetic operations per cycle.

But how do the CPU, VPU0 and VPU1 work together? An example of the roles [4][5] VU0 and VU1 play in an ice-skating racing game is a scene that consists of main characters competing against each other and background objects such a cheering audience and a forest landscape. The main characters need to move and change their shapes in real time for a player's input. VPU0 can process these needs. On the other hand, VPU1 processes the background objects, with many polygons. VPU1 works independently for fixed, simple geometry operations that generate display lists to be sent to graphics synthesizer.

In the EE's serial operation mode (figure 2) VPU0 works as a coprocessor to the CPU core for complex procedures such as physical simulations - in our ice-skating race it could be the skate's friction to the ice. The result may be a display lists or front-end data as a result of their collaborative work to VPU1. In EE's parallel mode you have a situation where the CPU and VPU0 work together and VPU1 works independently. As a result, multiple display lists are generated asynchronously. The graphics interface system (GIF) is responsible for arbitrating and switching the display lists to send to the Graphics Synthesizer releasing the microprocessor for other tasks.

The CPU's scratchpad RAM (SPR) can be used as a hub storing the data produced both by the CPU and VPU0. Alternatively, the same scratchpad can be used to store information brought from the main memory by the DMA controller while the CPU is still busy with other operations. When finished the CPU will have this data immediately available for use.

2.2 Gekko, Nintendo's 'Moonlight'

Nintendo design goals for GameCube were: simplicity of architecture; focus on game developer time to market; maximize achievable sustained performance and efficient board design [6]. Nintendo states "Instead of going for the highest possible performance, which does not contribute to software development, our idea was to create a developer-friendly next generation TV game machine that maintained above-standard capabilities.” [7]

GameCube’s Gekko, or "moonlight" in Japanese, is a RISC CPU, clocked at 485MHz, developed by IBM based on the Power PC 750 architecture, with extensions to support higher floating point throughput and higher bus bandwidth. Gekko is a superscalar processor with 32-bit address bus and 64-bit data bus. There is an abundance of operating registers in Gekko. It features 32 General Purpose Registers (GPRs) and they can store the data for the two 32-bit integer ALUs. IBM changed the original PowerPC floating-point unit (FPU), it cut the 64-bit FPU in half, allowing it to do one double precision (DP) 64-bit floating-point or two single precision (SP) 32-bit floating-point operations every cycle. In the same way each of the 32 floating-point registers can hold one DP 64-bit operand or SP 32-bit operand. This feature allows Gekko to execute SIMD floating point operations. A pipelined multiply-add yields four floating-point operations per cycle for a throughput of 1.9 GFLOPS. It could be said that some of Gekko’s 38 new instructions would be for dealing with this new floating point capabilities not available in the original PowerPC 750.

There are two separate 32K (8-way) L1 caches for data and instructions. While there is a unified L2 cache of only 256K (2-way) the original PowerPC 750 had up to 1MB L2

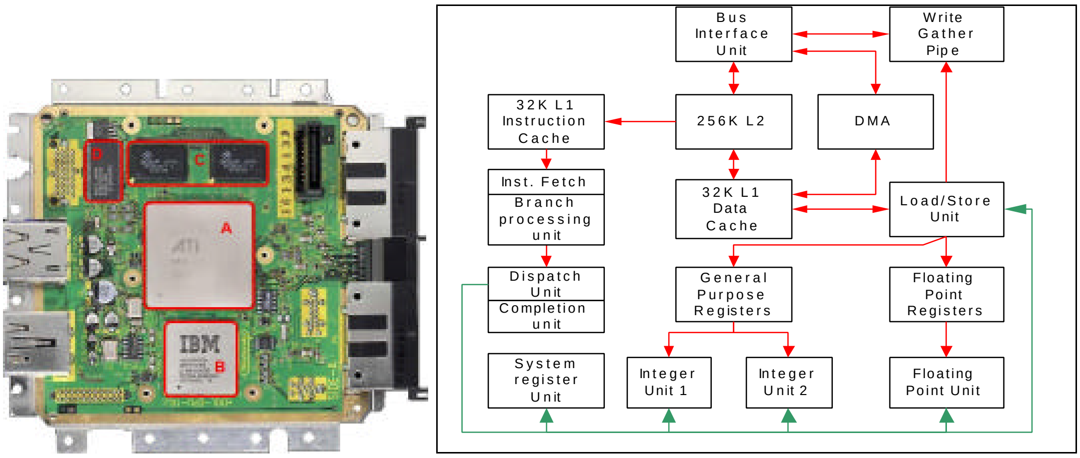

Fig. 4. On GameCube’s motherboard (left) we can see GameCube’s main components: the ATI Flipper chip *(A)*, IBM’s Gekko processor *(B)*, MoSys 24 MB 1T-SRAM *(C)* and 16MB DRAM *(D)*. On the right we can see Gekko’s block diagram [6]

cache [8]. To improve the internal data flow, IBM tried to eliminate "cache trashing", or wasting cache space on transient data [6]. Half (16K) of Level-1 data cache can be locked down so that it retains only the data that needs to be reused. The transient data does not displace reusable L2 data or unlocked L1 data cache. The locked data in L1 data cache can be transferred to the Bus Interface Unit (BIU) through the DMA while allowing the device to process in parallel a different instruction.

Data can be compressed/decompressed in the Load/Store Unit (LSU) with ratios of 2:1 and 4:1 so when transferring it across the external bus to Flipper chip from a peak of 1.3Gb/s its possible to get a 2.6GB/s or 5.2GB/s effective bus bandwidth. Just before this the Write Gather Pipe (WGP) is used to optimise this transfer. It gathers sequential non-cacheable information from the LSU in its 128-byte FIFO and transfers it across to Flipper in blocks of 36 bytes. This transfer can be parallel with other instructions execution.

Gekko connects only to one other chip, the Flipper chip. With 51 million transistors Flipper includes the Graphics Processor, Audio Processor and I/O Processor. It also includes what typically is called north and south-bridge functionality in the x86 architectures. All the system logic including CPU interface, Video Interface, Memory Controller, I/O Interface are there. The I/O Processor controls the optical disc drive, game controllers, memory cards and serial and parallel ports.

Gekko main tasks are the game scripting and control of the intelligence of the game, physics and collision detection, design custom effects and geometry and close up lighting [6]. The Graphics Processor was designed to perform almost all of the 3-D rendering tasks, including lighting and geometry, and can produce something between 6 to 12 million polygons per second. There are 3MB of embedded 1T-SRAM (6.2ns latency) in Flipper that can be used by developers to cache information close to the graphics chip without having to access outside memory and improve in this way the graphics performance.

Flipper's 128-bit memory interface runs at the same speed as the Flipper core, 162MHz, and it yields a 2.6GB/sec peak bandwidth when communication with the 24MB (10ns latency) of 1T-SRAM.

The Audio Processor, running at 81Mhz, is a custom Macronix 16-bit DSP core with 64 channels with a 48-kHz sampling rate processing. Its instruction memory as well as the data memory are split onto 8KB RAM plus 8KB ROM each. On the motherboard there is also 16 MB of Audio DRAM. This memory is used not only for audio processing but also for lower-priority system operations that do not require graphics' voracious bandwidth appetite. It could be used for caching data from the optical disk for a faster use avoiding in this way the disks access latencies.

2.3 Pentium III & Company, Microsoft’s Brut Force Attack

When first announced, Microsoft aimed to build Xbox as a “dedicated video game console” [9]. Their goal was to develop a high-performance, easy-to-use platform that would

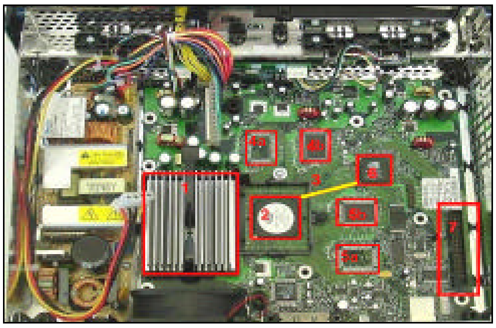

Fig. 5. Xbox’s interior: the Pentium processor with its big heat dissipater, nVidia’s XGPU chip without the fan, 64 DDR-RAM and 16MB memory chips are on the other side of the board. nVidia’s MCPX chip and the bus that links both nVidia’s chips. On the right side there is the EIDE connector for the DVD drive.

enable developers to create better games, faster and offer “game enthusiasts an incredible experience”. In terms of hardware they went into the field they new better: PC technology.

The CPU that powers the Xbox is a Coppermine based Pentium III running at 733MHz with only 128KB L2 non-blocking cache instead of the original 256KB. Xbox's Pentium core was left with an 8-way set associative L2 cache instead of the 4-way set associative cache of the Celeron. Xbox’s 733 MHz Pentium would be in terms of performance in-between the Celeron (Coppermine 128) and the original Pentium III (Coppermine).

The other aspects of the CPU, as far as we can tell, remain unchanged. The on-chip L2 cache runs at full clock speed and has a 256 bits wide bus. It still includes two separate non-blocking 16Kb L1 caches, one for data and one for instructions.

There are eight 32-bit general-purpose registers. The eight floating-point/MMX registers are capable of storing two 32-bit values (SP), one 64 (DP) or ten 8-bit values. These 8 bit values can be used for representing for instance a screen pixel. Pentium III SIMD extensions provide eight 128-bit general-purpose registers, each of which can be directly addressed [10]. They can hold 128-bit data and can be used to enhance floating point and 3-D application performance.

Although using an Intel processor, Xbox does not have an Intel chipset. The north-bridge, which connects the processor with the system memory and the graphics hardware, is integrated in the Graphics Processing Unit, nVidia's XGPU. Although similar to Nintendo's GameCube where the north-bridge is also included in graphics chip the similarities end there. NVidia's XGPU is a fully programmable 3D processor running at 233Mhz, although in earlier stages frequencies of 250MHz and even 300MHz were discussed, with resolution of up to 1920x1080 pixels, contains more than 60 million transistors (Intel's Coppermine PIII has round about 28 million transistors). It can process more than 1 trillion operations per second and produce, in theory, up to 125 million polygons per second.

The role of the south-bridge is done by Nvidia's Media and Communications Processor (MCPX) chip. With two DSPs at its core, performs the processing networking functions, peripherals control, and it is a sophisticated 3D audio processor. The MCPX will enable Xbox to process 256 channels of 2D audio and 64 channels of positional Dolby Digital 3D audio. The connection between the north and south bridge is done with AMD's Hyper-Transport interface at 800Mbytes/s, which offers a much higher bandwidth than the traditionally PCI bus used in a PC.

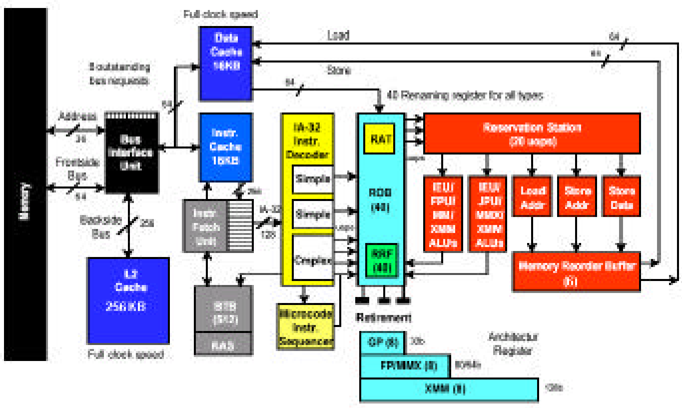

Fig 6. Original 733MHZ PIII (Coppermine)

The CPU and Xbox Graphics Processor Unit (XGPU) share the same chunk of 64MB of 200MHz double-data rate (DDR) memory made up of four 16Mb DDR SDRAM chips. With this Unified Memory Architecture (UMA) the memory can be allocated to graphics, audio, textures or any other function as needed. The memory used on the Xbox is very fast by PC memory standards but only decent by video memory standards. It runs at 200MHz DDR offering the effective bandwidth of a 400MHz solution. When combined with NVIDIA's 128-bit TwinBank memory architecture this offers a total of 6.4GB/s of memory bandwidth that is to be shared between the XGPU and the CPU. The 133MHz Front side bus path to the CPU limits the maximum amount that the CPU can ever use of that bandwidth to 1.06GB/s, leaving a minimum of 5.34GB/s to be used by the rest of the system.

Just a small note on the Operating System (OS), although Microsoft is including a 8GB hard drive in the X-Box the OS, based on Windows 2000 core, will actually be put on each DVD game instead of the hard-drive itself. Why? Well if the OS needs to be patched to fix bugs and such, the only thing Microsoft needs to do is to send the game developers a new version of the OS. So a game will have on the DVD everything it needs to run. And there is no worries about the size of the OS since will be around 500K and that loads in a no time. The gamer, will not have to worry about running Windows Update every other week.

3 How Do They Compare?

3D requires a lot of floating point calculations and PS2 has in total 10 Floating Point Units across the CPU, VPU0 and VPU1 for doing it. The help of small-embedded memory and caches is also available. The problem here is how to control the data flow. When used effectively PS2's vector units dramatically improve the system's performance. The goal here is to take advantage of Emotion Engine's full parallelism capacity but this requires extensive and talented programming. If a software developer wants to port a PC game to the PS2 he has to rewrite most of the programming code to take advantage of the parallelism available.

Gekko is based on the PowerPC 750 and there is already a long history of graphics routines development for that CPU. Apple's G3 had the PowerPC 750 at its core. Regarding the x86 architecture, it has probably the highest number of software developers working with it. If a PC developer wants to port a PC game to the XBox he just has to make some modifications in the programming code.

Game programmers will have to get used to the GameCube and Xbox's CPU differences but the learning curve will be much smoother and quicker than with the PS2's Emotion Engine. Nevertheless one event can change this: a Linux version is now available for PlayStation 2; anyone who really wants to get to grips with the inner workings of the machine can do so. Incidentally, that also means that PlayStation 2 is now the only true open source console on the market and that can attract many more game programmers.

Table 1. Technical specifications at a glance

	PlayStation 2	GameCube	Xbox
CPU	300 MHz Emotion Engine, Mips based	485 MHz IBM Gekko, PowerPC based	733 MHz Intel PIII
Graphics Processor	Graphics Synthesiser 150MHz	ATI Flipper 162MHz	NVidia XGPU 233MHz
Polygon peak performance	66 Millions/s	12 Millions/s	125 Millions/s
CPU GFLOPS	6.2	1.9	3
Memory	Main memory: 32MB RDRAM (part of it for VideoRAM); 4 MB GS embedded DRAM; sound: 2 MB	Main Memory: 24MB MoSys 1T-SRAM, Graphics: 3MB embedded 1T-SRAM in Flipper, 16Mb Audio DRAM	64 MB DDR-SDRAM, unified memory architecture
Memory bus bandwidth to CPU	3.2 GB/sec	2.6 GB/sec	1.06 GB/sec
Storage Medium	8 MB memory card, DVD	Propriety 8 cm optical disk, 1.5GB capacity, 2 Memory Cards	8Gb Hard Disk, 8MB memory card per controller, DVD
I/O Ports	2 game Controller ports, 2 USB, Firewire (IEEE1394), PCMCIA	4 Game controller ports, 2 serial port (27Mbps), parallel port (81Mbps)	4 Game controller ports, Ethernet 10/100
Operating system	Closed, Sony Proprietary	Closed, Nintendo proprietary	Windows 2000 Kernel
Audio Channels	48	64	256, 64 for 3D sound

In terms of raw performance, the Pentium III 733MHz (SPECint95: 35.6, SPECfp95: 30.4) will outperform the PowerPC 750 (SPECint95: 23.9, SPECfp95: 14.6) running at 500MHz. We can only assume that Xbox's PIII 733MHz will outperform GameCube's Gekko at 485MHz.

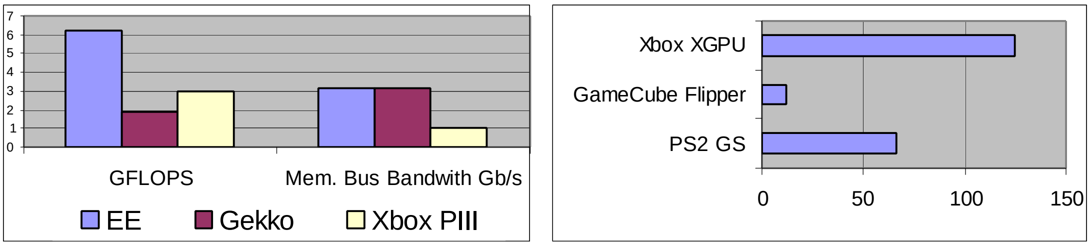

Fig. 7. CPU's Floating point performance and memory bus bandwidth (left) and GPU Polygon performance (right)

PlayStation 2 Emotion Engine processor can handle 6.2 gigaflops. That is 6.2 billions floating-point operations per second. According to MicroDesign Resources [11], editor of the Microprocessor Report, that makes the chip two times faster than a 733-MHz Pentium III at handling tasks like full-motion video. It was not possible to obtain exact SPEC benchmarks for the Emotion Engine but trusting MicroDesign conclusions this would make PlayStation 2 processor the fastest of them three.

PS2 works with 2 channels running at 800MHz implemented on the CPU itself to communicate with memory giving it a 3.2 GB/s bandwidth. Although Xbox memory bandwidth is 6.4GB/s let us not forget that this is a shared bandwidth with the GPU. Xbox PIII Front Side Bus runs at a clock frequency of 133MHz and gives us round about 1GB/s bandwidth. With Nintendo's Game Cube the situation is similar. The memory bus bandwidth is shared between the GPU and the CPU. The Gekko's FSB and memory bus both run at a clock frequency of 162MHz and depending on the data it is transferring the bandwidth can go from 1.3Gb/s to 5.2Gb/s since it can use compressing/decompressing techniques between Gekko and Flipper. It is being considered for graphical representation in figure 7 the mid value of 3.25 Gb/s. The memory bandwidth to the CPU is considered always a potential bottleneck and in this situation Xbox is clearly in the worst position.

If we look at the Graphics Processing Unit, Xbox's XGPU is clearly the winner. It is the fastest Graphics Processor of these three consoles capable of generating a theoretical 125 million of polygons per second. Although a lot of people can say that the published graphical benchmarks are just marketing there are also many that stick for them. Having a very fast GPU the XBOX position in relation to the memory bandwidth potential bottleneck can worsen. Xbox has a unified memory architecture (UMA) whereby the GPU and CPU share a single memory space (data, graphics, instructions and textures are all there) with memory control provided by the GPU. UMA has a significant advantage in that it allows the CPU, DVD and disk controllers, and GPU to access common data without copying. For example: models and textures can be streamed off the DVD into memory and used directly by the GPU. However, the history of UMA is not clean; In the 80's IBM's PCjr already had this type of memory and when working with graphics the CPU virtually stopped. Two out of every three memory cycles were being allotted to deal with this graphics traffic. With such a powerful GPU it is not yet clear if we will not have the same problem, especially if the full XGPU programmable pipeline is used to the limit. It is possible that on the reasons behind nVidia XGPU clock frequency reduction, from 300Mhz to 250MHz and finally 233 MHz, was this potential memory bandwidth bottleneck.

The Xbox differs from all the other consoles in one point. It comes with a 8GB built-in hard disk. That hard disk can open up some good possibilities. Games can load quickly because they can cache levels on the speedy hard drive rather than having to read all of the game's information from the disc. But this also finishes with the consoles stateless feature. Remains to be seen if advantages will outperform this disadvantage.

4 Conclusion

Plenty was said about these three game consoles but plenty more could be said. All three processors are using SIMD processing at least for floating point calculation. Although Emotion Engine is the oldest of the three processors it still outperforms all the others in terms of computational power and has a lot to offer. It is a processor that can be used not only for 3D animation but can also be used in other environments that demand a lot of floating point capacity like physical simulations. Nevertheless, a CPU does not make a good games console on its own. It needs a good GPU. In our case study nVidia's XGPU is a good potential partner. Another word goes for the GameCube that has used the smallest number of chips. In only two chips, plus memory, it integrates all the features a games console needs.

Games are becoming much more sophisticated. Developers are beginning to explore new ways of exploring the potential for plot and story further blurring the distinction between games and movies. The use of artificial intelligence is increasing and games are starting evolve based on the decisions made by the players. The advent of the Internet brought the possibility of multi-player interaction or the next scene download in a game. It is allowing people to play together, to talk together and to plan strategies together. It is creating new forms of interaction, and it is completely redefining the game experience.

Game servers start to exist and they can serve as the information distribution hub in a gaming community. With this online gaming world if you are not connected you are losing the progress of the game. This can lead to another form of gaming: continuous play. The facility to play anywhere, any time will become common.

Future games will truly take advantage of mobile technology, directly integrating with the player's lifestyle and sensing intimate data such as location, proximity to other players, and mood.

So how does the hardware evolve here? Graphics, image processing and display will have to move towards movie like experience. More powerful Graphics processors with huge floating-point calculation capacity will have concentrate on this job. CPU will go off-loaded more and more of the imaging processing and concentrate on the intelligence and processing of the physical world of the game. Their design will have to be rethought to consider remote data loading and processing via broadband Internet connections. IBM, Toshiba and Sony are already working on a processor architecture - codenamed CELL- that will be optimised for multimedia packet processing over the broadband network.

Storage will become commonplace in game consoles. The gamer will be downloading content onto these machines, games, music, movies and other things.

To allow for the mobility and continuous play consoles will have to share games information with PDA like devices with Internet connectivity. Smaller memory cards or direct information replication can do the job.

The gamer is always expecting more and consoles manufactures are trying to offer the best gaming experience. They are fighting for the gamer.

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