The internal workings of video game consoles: The GameBoy

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Abstract

English: This report describes the process of writing an emulator for the Nintendo GameBoy hand-held console from 1989 using the documents that are publicly available. The goal of the project was to get some official cartridge program ROMs to run on the emulator. A few components like sound had to be skipped due to time restraints. The solution was done by dividing the task into several stages, bringing in a new functionality with each stage. I began with the CPU and memory, before moving on to the PPU/LCD, and finally the joypad. This report also describes how those components work. The results from running a set of test ROMs indicate that the CPU instructions are 100% correctly emulated. However, there are some timing issues that sadly prevents any official cartridge program ROMs from running correctly.

Svenska: Denna rapport beskriver processen för att utveckla en emulator för Nintendos GameBoy, en handhållen spelkonsol från 1989, med hjälp av de dokument som finns publikt tillgängliga. Målet med projektet var att få några av de officiella kassetternas program att köra på emulatorn. En del komponenter så som ljud fick hoppas över på grund av tidsbrist. Lösningen utfördes genom att dela upp uppgiften i flera steg, där varje steg införde nya funktionaliteter: Jag började med CPUn och minnet innan det var dags för PPU/LCD och till sist joypad. Denna rapport beskriver även hur dessa komponenter fungerar. Resultaten från exekvering av en uppsättning test-ROMs tyder i alla fall på att CPU:ns instruktioner är 100% korrekt emulerade. Dock kvarstår några problem med timingen som tyvärr hindrar de officiella kassetternas program från att köra korrekt.

Table of contents

Background

Ever since I started to learn programming in Visual Basic I have been interested in learning how the code I wrote became runnable in a deeper fashion than knowing that pressing "run" from the Visual Studio development environment executes my code. As I started learning the "better" languages C and C++ I came closer to compilers, how they work and what they do. The more I discovered, the easier it became to write good code. Since I am studying to be a game developer and I tend to be more amused by console games than computer games, I figured I might as well learn how game consoles work. And here we are.

Purpose

The purpose of this project was to gain an insight into how game consoles work. To limit this project to a sensible size I had to choose one console, and the modern ones do not have enough documentation publicly available. So I looked at the older consoles and I found the hand-held GameBoy console from 1989 by Nintendo to be the best choice judging from complexity, size and my time frame, that I already stretched to the double, in order to have a chance to complete this project. The GameBoy has a whole bunch of games. Unfortunately I do not have a number but I would not be surprised if a couple of thousand titles existed. To prove that I have understood the console correctly I was to write an emulator based on what I could learn. If the emulator worked well and could execute some of the official cartridge program ROMs my goal would be accomplished.

Conventions

Explanations for abbreviations and "odd" words that will occur throughout this report:
DMG: The name of the CPU in the GameBoy.
Emulator: A program that mimics a system as close to the real thing as possible.
GLFW: OpenGL FrameWork, a utility library for OpenGL.
HLE: High-Level Emulation. Instead of emulating instructions, the system is emulated based on hardware tests. HLE can be seen as a type of black-box emulation where you input data and get other data back. This is rarely an accurate method to do something as many edge-cases are overlooked.
LLE: Low-Level Emulation, the most accurate method to emulate a system. When done correctly, this method needs a dump of the processing units' program ROM and instruction table in order to work. When LLE is implemented correctly it will behave exactly as the hardware would for every case.
OAM: Object Attribute Memory. Used for sprites.
Opcode: A CPU instruction.
PPU: Pixel Processing Unit, a predecessor to today's Graphical Processing Unit (GPU).
Program ROM: The program ROM is the container of the executable code that exists on a chip.
RNG: Random number generator.
SPU: Sound Processing Unit.

Related work

Emulators have been developed for a very long time but only recently focus begun to shift from compatibility (supporting as many games as possible) to accuracy (mimicking the hardware as closely as possible). The two emulator projects in this area that are worth mentioning here are Gambatte and bsnes. These two projects have been working on very similar things. Gambatte is an emulator of the GameBoy Color, which has backwards compatibility with the original GameBoy that I am looking at. Gambatte's main objective is to emulate the hardware as accurately as possible and it does a very good job at that even though there are still portions left to emulate properly. It is fully functional and most games emulate perfectly. bsnes on the other hand is a Super Nintendo Entertainment System (SNES) emulator. What makes this one worth mentioning here is that bsnes has emulation of the Super GameBoy accessory under development during the time of writing this report. bsnes, just as Gambatte, is an emulator that aims to be as accurate as possible.

There has also been a lot of work done in order to document the GameBoy's system and how it works. Most of this documentation exists only as source code in the mentioned emulator projects but there is also a technical document which was maintained up until 2001. This document is well known among the emulator developers and is referred to as the “Pandocs” due to the original author who goes by the nickname “Pan of -ATX-”, real name unknown. The final maintainer was the author of the GameBoy emulator NO$GMB (read: no-cash GMB). The reason for his emulator not being mentioned above is that his emulator aimed more at compatibility than accuracy and therefore the code in that emulator is not guaranteed to do as the original GameBoy would in every situation.

Problem formulation

The development of the emulator for the Nintendo GameBoy had to be constrained if it was to be completed within the time frame. For this to be possible I had to drop a few things: I chose to drop sound emulation along with cartridge extensions and serial port emulation, since these are the most time-consuming parts to implement compared to what they add functionally. While the cartridge extensions make more games playable they are not really a part of the GameBoy itself, so I chose to emulate only the GameBoy hardware which does not include these extensions. Also, games can be played without sound and without support for multiplayer through the serial connection, but it is a lot harder to play them without the LCD, RAM or CPU. This limited my project to develop a GameBoy emulator with functioning CPU, RAM, PPU/LCD, and joypad. Since the GameBoy's screen clocks in at 60 FPS (frames per second), the emulator must be fast enough to provide the same results. This makes fast code the key to success if you want to run at full speed. A secondary goal was therefore to write code that is as optimized as possible without losing readability.

Problem analysis and method selection

The GameBoy is a portable battery-driven video game console released in 1989, so the system requirements are not that high. The games are stored on exchangeable cartridges that sometimes also carry expansion chips to provide enhancements that the GameBoy itself cannot. Here follows a breakdown of all the components of the GameBoy that needed to be emulated.

CPU

The GameBoy's CPU clocks in at 4 MHz (or 4194304 Hz). This means the CPU will execute 4194304 cycles per second. It has a 1-byte opcode size and has interrupt functionality. There are two sets of opcodes: first the normal opcode table, and then an extended one. All opcodes except those accessing the extended opcode table and the ones taking immediate operand values are only one byte long. Since most PCs today run at several GHz I found it possible to meet this requirement with a simple byte interpreter. This is the oldest method in the book for a reason: it always works. In general it is not as fast as some of the modern approaches like re-compilers but with such a slow CPU as the GameBoy's a re-compiler would most likely even be slower than the interpreter. The interpreter is basically a huge switch statement with a case for every opcode. Since this CPU also has an extended opcode table, the emulator needed an additional switch statement for this. When doing an interpreter solution one also has to take into account the CPU registers and flags. These need to exist as variables compared to re-compiling where the registers and flags in the target CPU are used instead.

RAM

For the RAM/Memory there were two obvious choices. The first one was to put it all in the same array and the second was to divide it into its constituent parts: working RAM, high RAM, video RAM, OAM, sound wave RAM, and external registers. The first option is really easy to implement and lets me use the memory map addresses as index values. The second option on the other hand is trickier to implement but has a few advantages. Firstly, it will save memory if the entire address range is not used. Secondly, it is handy if some of the external registers can overflow since the overflow is easier to check for if the variables representing these registers are made larger. I had to use the second option because the GameBoy has both of the "requirements" needed to make the first option impractical to use.

PPU/LCD

In the GameBoy the PPU and the LCD are connected so tightly together that they are practically the same unit. Based on this fact these two components had to be coupled tightly together in the solution. Since they are so close in hardware it would not make sense to split them apart in an emulator, because this would just add unnecessary overhead. The LCD runs at 60Hz and has a size of 160x144 pixels. The PPU's internal map is 256x256 pixels, so the entire map cannot fit on screen at once. This is solved by two external registers controlling where on the map the LCDs top-left corner is located. The PPU can only be done with HLE because no work has been done on dumping its program ROM. To represent the LCD I used a combination of OpenGL and GLFW which is a library much like the more common GLUT, to create windowed applications, but it gives me control of the main loop. Having control of the main loop is important when developing emulators because anything that can slow the emulator down should be eliminated, and not knowing what happens in the main loop can have dire effects on performance.

Joypad

To emulate the joypad the keyboard was used. A button on the Joypad can be pressed at any time, so for every machine cycle all events should be polled and processed accordingly. Even though most games poll input only once per frame, sometimes not even that frequently, it is not really necessary to poll for input every cycle, but it would be the most correct thing to do from the accuracy aspect. There is even a chance that some games use the joypad input in their RNG calculations, and not being able to influence the RNG in the same way on the emulator as you would be able to on the real console would not be really accurate at all.

Other models and methods

Re-compiling CPU

The re-compiling CPU method does exactly what it sounds like it would be doing: it takes the instructions of the emulated CPU and translates them into its own instructions. One nice side effect of this approach is that the emulated CPU's registers will also be translated, which means the computer's CPU registers will be used directly instead of variables when writing the code. While this method adds overhead in the shape of the re-compiling process it is very efficient for emulating faster CPUs. This emulation model is used by the GameCube and Wii emulator Dolphin where the difference between running the interpreter CPU compared to the re-compiling CPU is a ~500% speed increase on my computer (My CPU is an AMD Athlon64 X2 4600+ and I have 4 GB of RAM).

Threading

Threading can be used to parallelize operations between components where possible, like when it is feasible letting the CPU begin the processing of the next frame in advance instead of waiting for the GPU/PPU or SPU to complete its operations.
This is also only used when emulating faster systems as the threading overhead will otherwise have a bigger impact on performance than the help the threaded implementation gives. However, to make threading more useful, the developer of bsnes (see “Related work”), byuu, developed a low-overhead threading library called libco. Still the GameBoy is not a fast enough system to be helped by threading.

Hacked boot process

This is not as nasty as it sounds. What the hacked boot process does is skipping the steps of BIOS by just initializing the emulated hardware to the values normally generated upon a successful boot. This is a very popular approach because the BIOS does not need to be extracted from the console. Extracting the BIOS often requires the CPU to be removed from the console circuit board and “decapped”. The decapsulation process is beyond the scope of this report, but if you as the reader want to know more there are two web links in the footer with some information.[1][2]

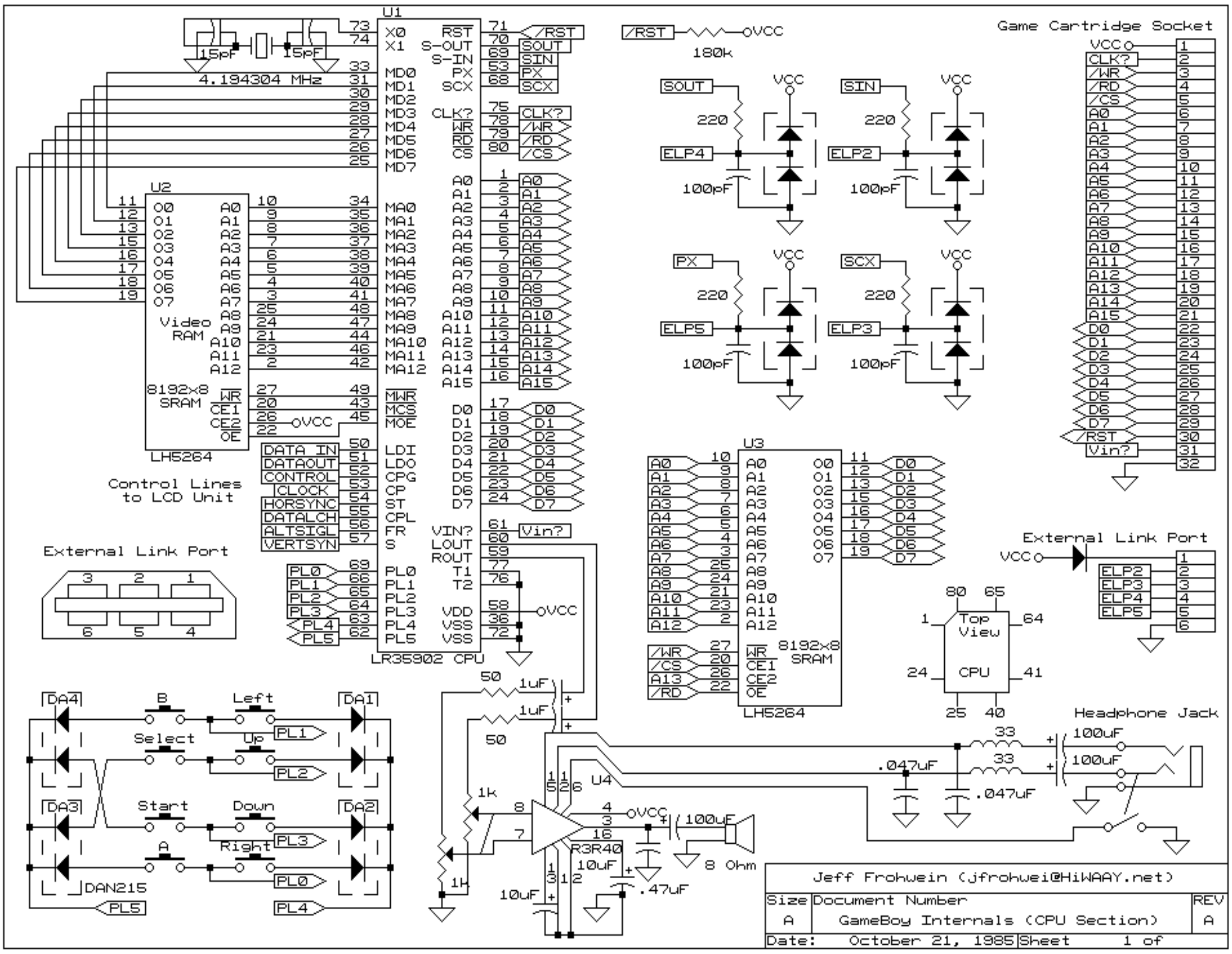
Plugin-based

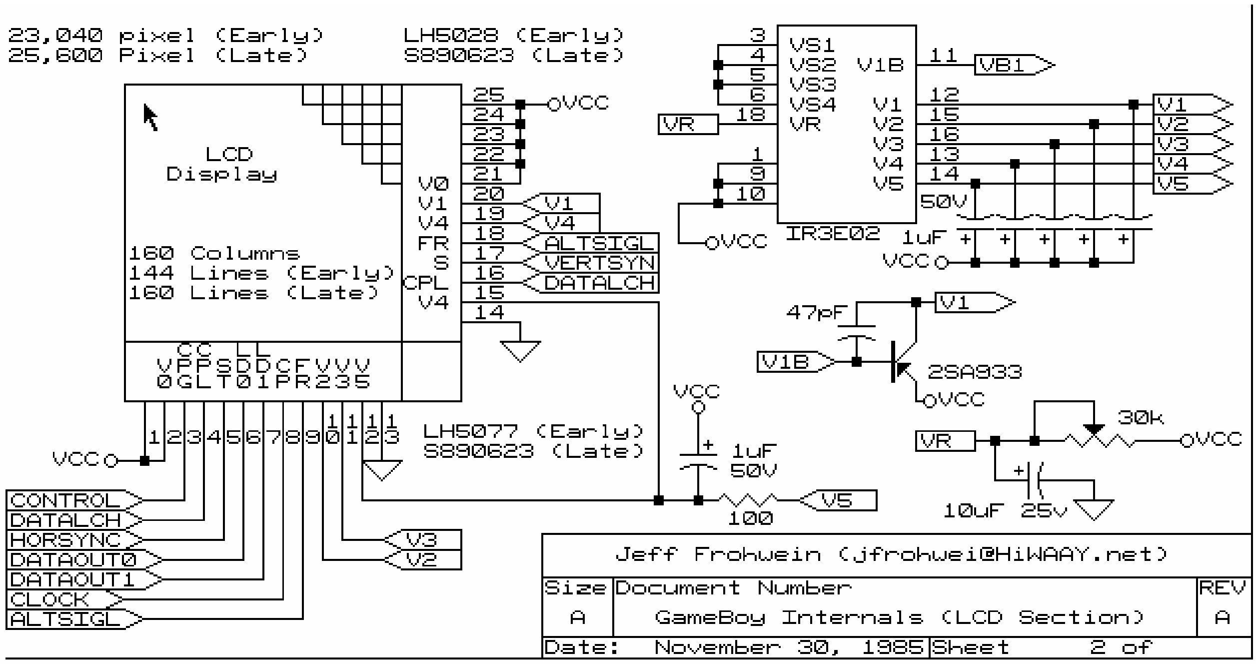
What this does is modularize the emulator even further and in the process make it more customizable. This design lets the developer implement only the parts that he or she wants to and leaves the playing field open for others. Another advantage from this is that if you have an idea on how to make a better GPU/PPU implementation for a given system, you will not have to write an emulator for the other components first in order to test your idea. This method is mostly used when there are still a lot of uncertainties regarding how the hardware in the console actually works. Once that has been properly figured out this concept is usually dropped because there is less overhead to not manage DLL plug-ins, and you have better control over all the components of the emulator.

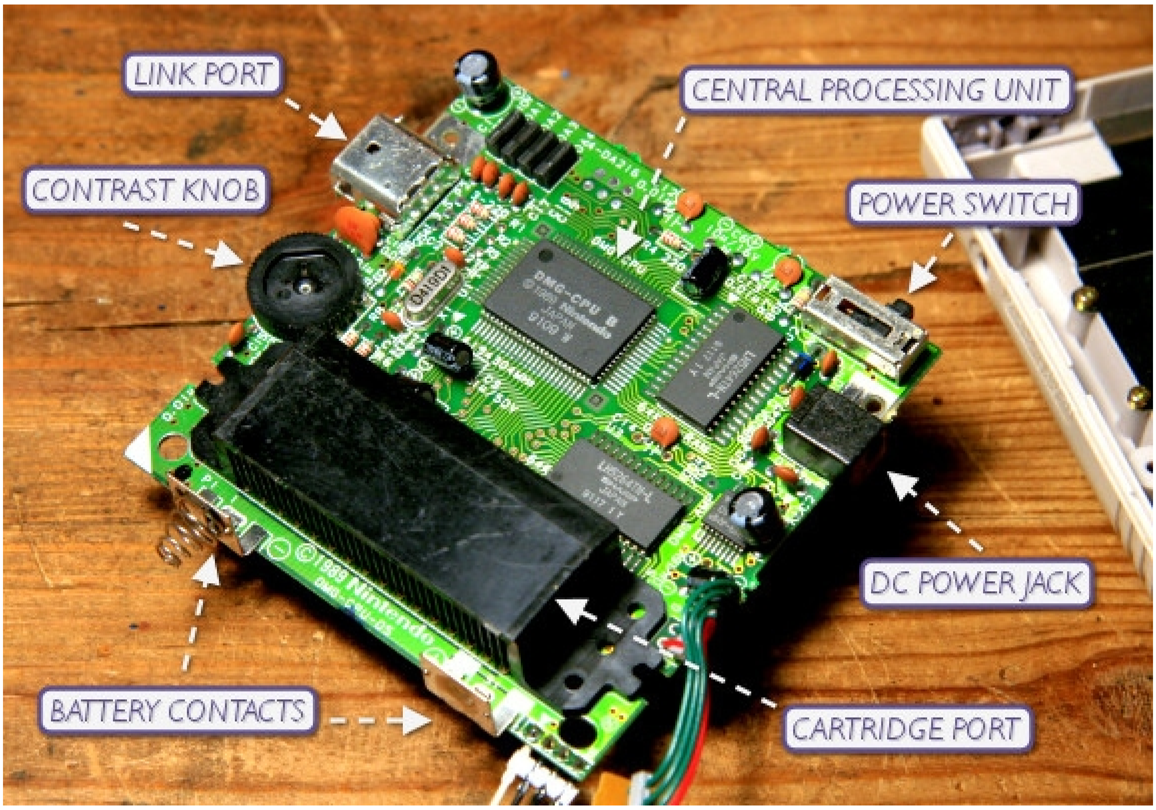
1 http://uvicrec.blogspot.com/
2 http://siliconcert.com/decap.htm

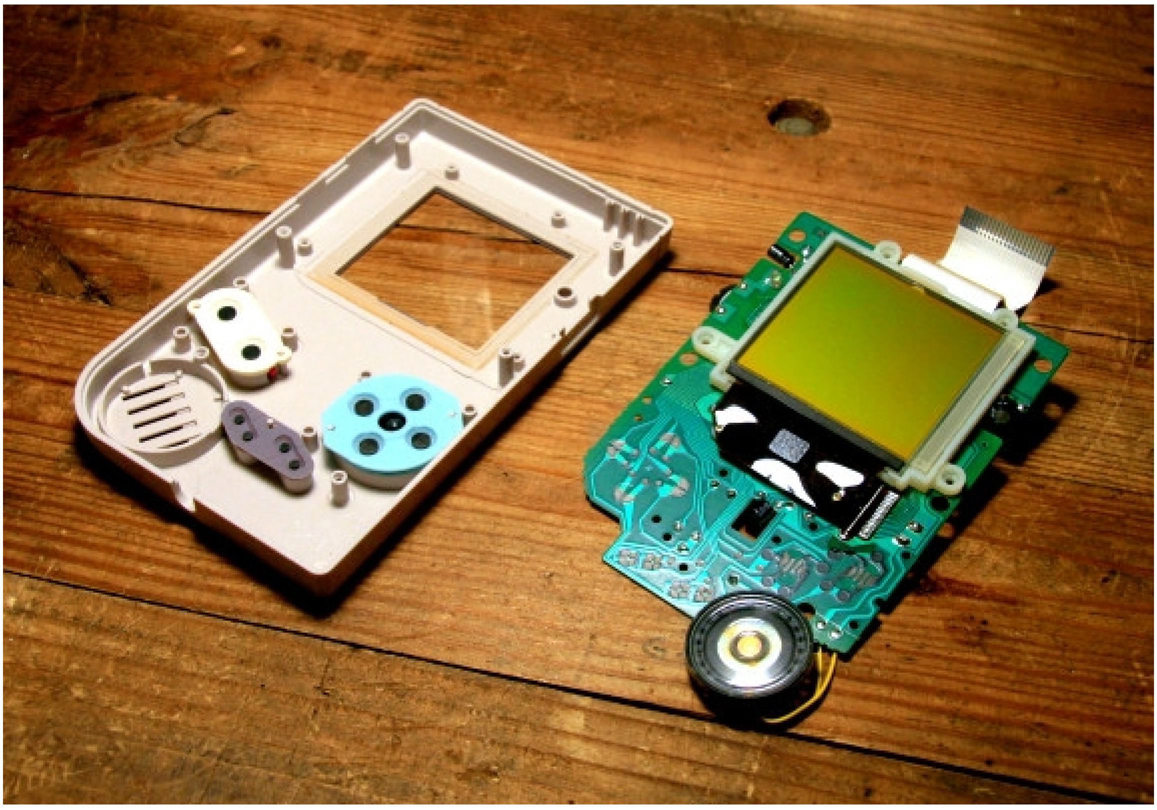
Solution

The language selected to solve this task was C++. The task was then solved in stages to keep the development process under control. How the code where divided into files and classes was decided using the following schematics and pictures of the GameBoy's guts [GBHard][GBAut]. That was done to make the code be more like a real GameBoy.








On the LCD circuit board all the components are hidden behind the LCD.

Stage 1: The main system

The main system had to be implemented first because it wraps all the components together and initializes everything. During this initialization process the window is created and set up to draw using orthographic projection; since the GameBoy does not have any 3D capabilities it is unnecessary to have the third dimension enabled. Here also a small hack is applied which ensures a greater accuracy of the pixel drawing, i.e. a greater number of pixels will be correctly aligned to the pixel grid. If the screen creation is successful the initialization will move on and load the cartridge ROM file that was specified as a parameter during the emulator's launch. If this file is not found the emulator will shut down with an error. Once the ROM is loaded the components will be created in the following order: Memory, Joypad, LCD and CPU.

The CPU has to be created last as it needs pointers to each and every one of the previously mentioned components. This is because everything is enslaved to the CPU's clock. While the real GameBoy has a global clock called the machine clock the CPU ticks at a multiple of the rate of the machine clock so nothing is really sacrificed by using the CPU's clock instead of the machine clock. Also, it makes the implementation of the CPU a lot easier. The reason for this is that the GameBoy CPU has instructions that take several machine clock cycles to complete and if the timing was done using the machine clock the emulated CPU would be running one machine clock cycle at a time. That would force the implementation to know where in the opcode it was between machine clock ticks as it would only run one tick at a time.

When the CPU is created by the main system wrapper it also loads the BIOS of the GameBoy. This BIOS sets up important parts of the memory and verifies the cartridge ROM by running some sort of validity check. If this check fails the BIOS will lock up and the GameBoy has to be restarted. The emulator will be shut down if the BIOS ROM file is not found. Once the initialization is complete the main loop of the emulator is entered. All this loop does is execute the CPU one instruction at a time until the emulator is terminated by the user.

Stage 2: CPU instructions and memory handling

The CPU and Memory components of the emulator were developed in parallel as the CPU relies on the memory to work and mistakes in the memory handling is mostly found during the development of the CPU. The GameBoy CPU has ten registers: ten 8-bit general purpose registers, two special registers used as stack pointer and program counter, and one flag register. The seven 8-bit registers and the flag register can be paired up to form four 16-bit registers. This was emulated by forming unions of the two 8-bit registers that could become a pair for every register, as demonstrated by the following line of code:

```
union { uint16_t paired; struct { uint8_t lsb; uint8_t msb; } single; } register;
```

This forms a union of two registers placing the low byte register first in the struct that creates the pair. Putting the low byte register first is a compensation for the little endian layout of the targeted PC CPUs. In this union the register can be accessed both as its individual registers and as a paired register.

The most common instructions (read: instructions that take arguments embedded in the opcode itself) where emulated using inline functions to reduce code repetition without any added function calls after compilation. The more unique instructions where emulated in-place in the switch statements that make up the opcode tables (explained next).

In addition to the regular opcode table, from here on referred to as the main table, the GameBoy CPU has an extended opcode table accessed by the opcode 0xCB from the main table. The main table contains the common opcodes like add, sub, ld, pop, push, inc, dec, call, jp, and cp. The extended table contains opcodes more focused on bit manipulation. Each table was implemented with its own switch statement interpreter. The correct interpreter is chosen by reading the next opcode to execute, and if this opcode is 0xCB the next opcode is read and the extended table is chosen to parse it, otherwise the main table is used.

On the memory side arrays were chosen to emulate each RAM chip in the GameBoy. These arrays are stored in dynamic memory to save space on the stack. While an emulator must be fast, there is really no performance penalty using this solution as the dynamic allocation occurs during the creation of the memory handler class and not while the cartridge ROM is executed. Each external register is emulated with its own variable. As mentioned earlier this makes it easier to check for arithmetic overflows. In the GameBoy there is one external register that can overflow and that is the Timer. When the Timer overflows it raises an interrupt which is used to execute timed events in any cartridge ROM. It is easier to check for an overflow in the Timer when it is defined as a variable that can hold values larger than the defined overflow value (0xFF). If this value is surpassed the interrupt is raised and the Timer is reset. Compare this to if a variable that could only hold one byte was used. Then the flags of the computer would have to be consulted to know if the overflow happened. Some of these external registers are also limited to only read or write. For this, bitmasks were applied to control what gets read from or written to those registers. The memory handler has two timers actually. The first one has already been discussed but it should be added that this timer can be turned on and off, and also have its pace controlled from another external register. The other timer is always active and ticks at 16384 Hz. When the address of this timer is written to, the timer is reset.

Implementing the DMA transfers, which are a part of memory handling, was postponed for the sprites stage as working sprite drawing is needed to verify that the DMA transfers are working correctly.

Stage 3: Interrupts and the HALT state

Interrupts and proper emulation of the HALT state, activated by execution of the HALT opcode, to the CPU was now added. The GameBoy has five different interrupts that can occur and these are: V-sync (LCD), LCD status, Timer, Serial transfer, and Joypad input, where the LCD status interrupt can be made to happen for four different reasons by changing settings for it in the external registers. The four reasons for this interrupt will be further discussed in the next section. The GameBoy CPU can only handle interrupts before each opcode fetch which means the CPU cannot deal with an interrupt mid-instruction. For interrupts to occur they have to be enabled and for an interrupt to be handled the interrupt master flag (called IME) has to be set. This flag is controlled by the opcodes DI, EI, and RETI, and also by the interrupt handler. There is however a bug in the hardware which made the HALT state quite complex to implement. The HALT state is left when an enabled interrupt occurs, no matter if the IME is enabled or not. However, if the IME is disabled the program counter register is frozen for one incrementation process upon leaving the HALT state. This is devastating if the instruction following the HALT instruction is another HALT instruction, as this will cause the GameBoy's CPU to lock up because the program counter will forever warp back to the second HALT instruction. The following example shows the behavior of the HALT instruction:

```
        ; IME = Disabled

        ; Example code 1:
0x76 (HALT)
0x00 (NOP)

        ; Execution of code:
ReadOpcode(1) = 0x76  ; PC register is increased after every read
HALT                  ; Halt state entered
--Interrupt--         ; Halt state exited
ReadOpcode(2) = 0x00  ; Read new opcode, since IME is disabled PC register is frozen
                      ; for one incrementation process making 0x00 being read twice
NOP                   ; Idle
ReadOpcode(2) = 0x00  ; Since the PC register is frozen, opcode 2 is read again
NOP

        ; Example code 2:
0x76 (HALT)
0xEE 0x0A (XOR A,10)

        ; Execution of code:
ReadOpcode(1) = 0x76
HALT
--Interrupt--
ReadOpcode(2) = 0xEE
XOR A,238             ; Since the PC register is frozen opcode 2 will also be read as the
                      ; immediate value
ReadOpcode(3) = 0x0A  ; The immediate value of opcode 2 (0x0A) is now treated as an opcode
                      ; instead
LD A,(BC)

        ; Example code 3:
0x76 (HALT)
0x76 (HALT)

        ; Execution of code:
ReadOpcode(1) = 0x76
HALT
--Interrupt--
ReadOpcode(2) = 0x76
HALT
--Interrupt--         ; Same interrupt as last time since no interrupts can be are processed
                      ; in between HALTs when IME is disabled
ReadOpcode(2) = 0x76  ; Same opcode is read again as PC is frozen
HALT
--Interrupt--
ReadOpcode(2) = 0x76  ; And again because PC is re-frozen from exiting the last HALT state
...
...                   ; Continues until the GameBoy is turned off or the battery runs out
...
```

Stage 4: PPU and basic LCD functionality

During stage 4 the PPU and LCD basics was implemented, which means the background and window drawing was done as well as the various steps the PPU and LCD goes through to draw one frame. The window here works as a second background above the normal background. The following steps had to be implemented, in the following order: OAM search, LCD transfer, and H-sync (these three steps are repeated until the entire frame is drawn), then finally a V-sync happens. H-sync and V-sync are synchronization periods for the LCD's drawing to maintain a steady pace for each draw period. H-sync happens when the scanline is drawn and the LCD waits to begin the next while V-sync happens every time a frame is completed and the LCD waits to begin the next frame. During the OAM search the OAM memory is scanned and any sprites that will occur on the scanline are memorized. Sprites are further discussed in the next section. The LCD transfer step is when the data to be drawn is uploaded by the PPU to the LCD, which the LCD plots in real time. After this comes the H-sync where the LCD prepares for the next scanline to be drawn. During the LCD transfer stage the background, window, and sprites are drawn. When the LCD is drawing it will ask the LCD Controller register (one of the external registers) what it should do. In this register background, window, and sprites can be enabled or disabled by the cartridge program ROM, as well as a few other settings like which area of the video RAM that should be used for tile maps and tile data. These tiles, that have a predefined size of 8x8 pixels, are the only way to draw something on the GameBoy, since the hardware is too limited to support anything else. Each pixel in a tile can have one out of four different shades. This shade is extracted and checked against the LCD's palette for what "color" the shade represents. Since the LCD is monochrome it does not have colors but intensity levels of how lit the pixels are. The "colors" for all pixels is stored in a two-dimensional array representing the screen. The same process is repeated for the window. The GameBoy has a total of four intensities of pixel lighting which are: off, slightly lit, almost lit and fully lit.

The LCD status interrupts were also added to the LCD during this stage. As explained earlier this interrupt is customizable so that the cartridge program ROM can select any combination of four triggers. The first trigger is the H-sync period, the second the V-sync period (yes, V-sync can trigger two interrupts), the third is OAM search, and finally there is the LCD Y coordinate interrupt. The last mentioned interrupt is triggered when the LCD Y coordinate equals a certain value called the LCD Y Compare. This value is changed from the cartridge program ROM through an external register.

During the V-sync interrupt the two-dimensional screen array is also drawn to the emulator program window using the GL_POINTS method, which draws one pixel-sized dot on the coordinate specified by the function glVertex2i(x,y). To enhance the GameBoy feel the "color" 0 has been converted to the color of the GameBoy LCD when it is turned off. All "colors" are then defined as more intense shades of that color until black is reached.

Stage 5: Sprites and DMA transfers

Implementing sprites took some thought due to the limitations of the GameBoy LCD, where only 10 sprites can be handled per scanline. These 10 sprites are extracted in the most primitive way: it is the first 10 sprites that appear in memory for that scanline to be drawn. To simplify the drawing in the emulator these sprites are sorted by a variant of the Shell Sort algorithm. This variant of Shell Sort will perform at the same worst case as Bubble Sort ($O(n^2)$) but has a better best case of about $O(n^{4/3})$. The sprites are sorted according to the drawing rules, which are: sprites with an X coordinate closer to 0 has priority over the ones with an X coordinate further away from 0, so in the event of sprites overlapping each other the sprite closer to 0 will appear above the other one. If the sprites would have the same X coordinates the sprite that appears first in OAM gets priority over the other sprite. Sorting the sprites according to those rules makes the drawing several times easier as the sprites can be drawn in the order they appear.

The real hardware does not draw like this though. Since the LCD in hardware has a fixed beam-direction it will draw the sprites in the order they would appear on screen, starting from the left. This actually means that in hardware everything is calculated for each pixel (background, window, and sprites). If the drawing is not pixel-based there may be some graphical anomalies from wrongly timed interrupts in the case where the LCD Y coordinate interrupt is used for animation.

The OAM provides instructions for how the sprites are to be drawn. These include flipping the sprite along the vertical axis or the horizontal axis, or both, and which of the two sprite palettes that should be used to choose the pixels' colors. There is also a setting in the LCD controller that when set enables sprites to have double height. When this setting is set the sprite pairs are stored next to each other in the OAM memory. The upper sprite is always located on an even address and the lower sprite is always located on an odd address. The upper sprite also always appear before the lower sprite in memory. Selecting the upper or lower sprite - which sprite to draw depends on which scanline that is being drawn - is then performed like this:

```
Upper sprite: [memory address defined by OAM] & 0xFE
Lower sprite: [memory address defined by OAM] | 0x01
```

What the above pseudo code does is to reset the last bit in the address given by the OAM making the address even if the upper sprite is wanted, and sets the last bit of the address if the lower sprite is wanted. The OAM can also decide if a sprite should be drawn above or behind the background. This also includes the window. When this option is set, sprites will only be drawn where the current color is 0, as that color is transparent both for the background and window. The same thing applies to sprites, the color 0 is transparent, so the background and window will shine through.

DMA transfers were more straightforward. The DMA transfer will copy 160 bytes from video RAM to the OAM. Where to start copying is specified by writing to the DMA transfer register. Doing so also initializes the transfer. Since this register is only one byte the entire address cannot be contained so only the upper half of the address is used, and the lower half is always 0. So if 0xA5 is written to the DMA transfer register it means address 0xA500 will be the start address of the transfer.

Stage 6: The joypad

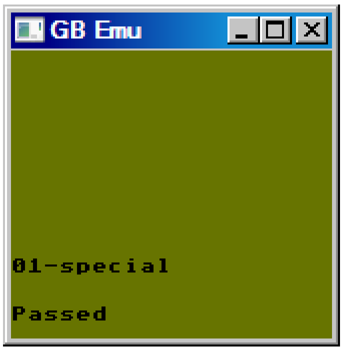
This is probably the simplest part to implement of the entire emulator. Since the joypad can receive input at any time, a function that polls the windowing system for events and then processes all the keyboard events was made. Since the D-pad is placed on a pivot inside the GameBoy certain rules had to be applied in the polling function: up & down and left & right are D-pad combinations that cannot be pressed at the same time on a healthy GameBoy, and therefore these combinations should not be allowed on a properly coded emulator.

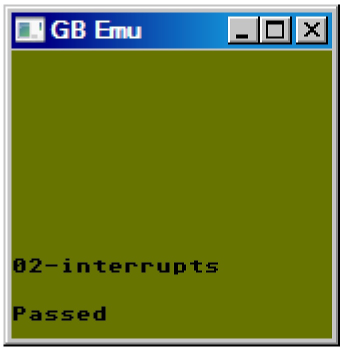
After each poll the external registers are updated with what buttons where pressed, and if the joypad interrupt is set the interrupt flag will also be triggered by the Joypad activity.

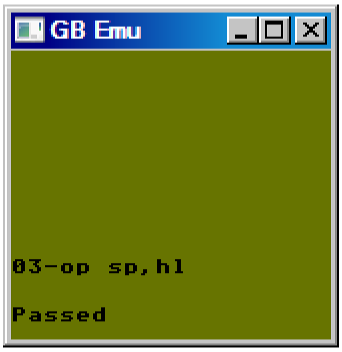
The joypad can also be turned on and off which means that when the joypad is turned off, all button activity must be ignored and the external register reset on every poll. An interesting note about the external joypad register is that instead of the corresponding bits being set to 1 when something happens, this is their normal state. Bits are reset when something happens. This also applies when turning the joypad on or off as a 1 turns it off and a 0 turns it on.

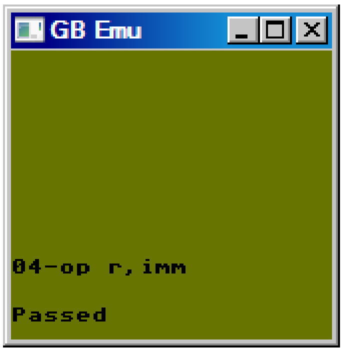
Results

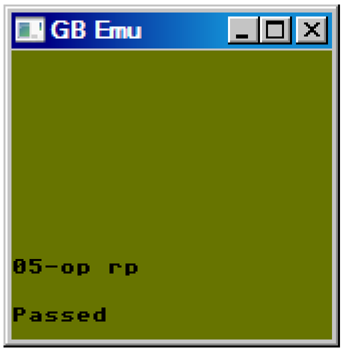
In its current state the emulator can unfortunately not run any official cartridge program ROMs. This is due to what I think is one final bug in the timing. The performance is almost up to full speed when it is being run on my stationary computer. Running it on my laptop gives a quite big hit on performance, since my laptop has only a single core 1.4 GHz Intel CPU. The biggest bottle neck is the keyboard polling which is to be expected as the windowing system is polled once every 4 CPU cycles (or once per machine cycle if you wish). Below are some images showing the current state of the emulator. The first picture shows the emulator as the BIOS is setting up the hardware to run a cartridge program ROM. The next eleven pictures show Blargg's CPU instruction tests and the results they produce after execution in the emulator. They all show "Passed" which means every CPU instruction in my emulator works exactly as on the DMG. The last three pictures show Blargg's instruction timing test and the game Alleyway during its start screen and an AI controlled demo level. I would have liked to show some screen shots from Tetris, but the game is refusing to draw anything in the current state of the emulator.

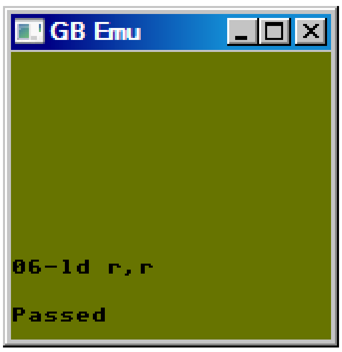


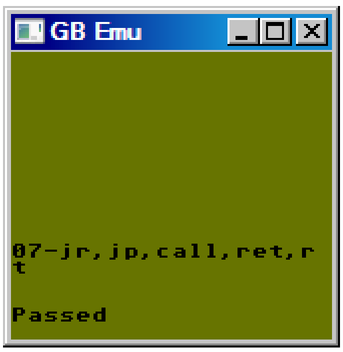


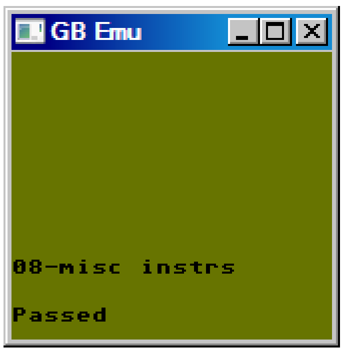


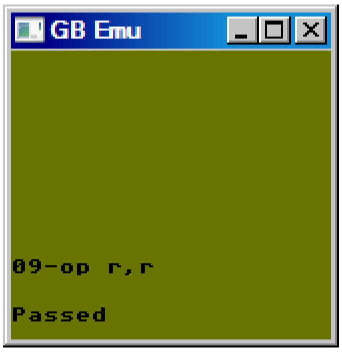


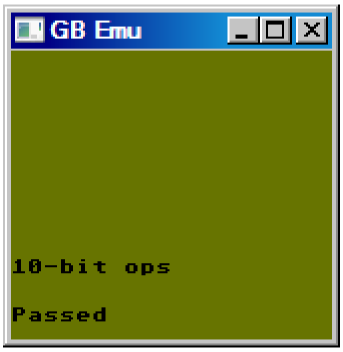


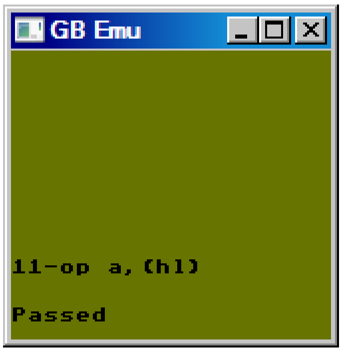


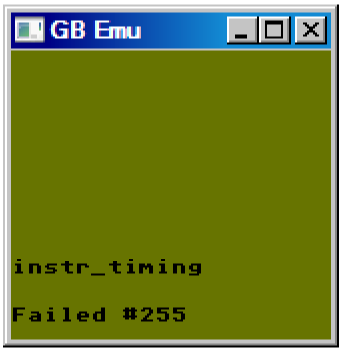


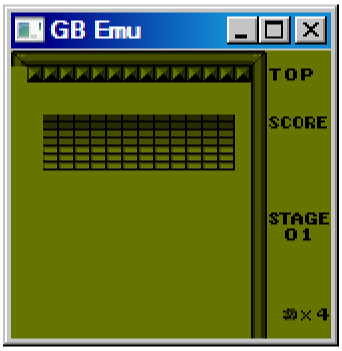












Analysis of results

Developing this emulator was a long and bumpy road. I had to rewrite parts of the code several times before it would reach a functioning state. The biggest hurdles I had were drawing on the LCD, a non-functional reading from memory, and a few opcodes that were not the least friendly. The part of the emulator I found myself rewriting most was the cycle-based timing of the CPU. I really had not thought that through properly, so I had started with decrementing the CPU clock right after the opcode was done. I later turned this into a look-up table. I had not yet realized that I needed to do more things each cycle. When that finally hit me, which was way later than it should have been, I made a function called AddCycle() that runs the other parts of the GameBoy.

The reading-from-memory problem I did not actually solve myself. I gave up on that problem after about three days of trying to find the bug. When a few programming friends of mine could not see it either I asked my supervisor who finally found it. The bug was shamefully simple: I had accidentally used the program counter register as index into the memory map instead of the actual address to read from.

The war with the opcodes was probably the biggest battle during this project. In the beginning I had only one document which was compiled from various text files that used to exist online. This document contained a few errors and it even missed an opcode! It is amazing how emulators could work back then with that undocumented opcode, but I guess most games do not utilize it. When there was no information on how the DAA (Decimal Adjust Accumulator) opcode worked in the document I used, I contacted byuu, the developer of bsnes, for help getting good information about this CPU. He showed me an official programmer's manual for the Zilog Z80 CPU (which the DMG CPU is based on). While a few opcodes were not explained in this programmer's manual due to them being replaced by more GameBoy-specific opcodes it helped me solve many bugs, implement my first version of the DAA opcode, and find the missing opcode and implement that (SBC n). At this point I was almost passing the CPU's program ROM execution, but for some reason the last thing it tried to do was to write to an external register that is not mentioned anywhere in the documents I had access to at this point of the project. And as it turns out, it is not mentioned in any documentation I have today either. This was my first contact with external register 0xFF50, where the least significant bit presumably tells the CPU whether to read from the program ROM or the cartridge ROM for the 0x0-0xFF address range. Since I to this point had used a boolean in the CPU code to check for when to read from the CPU's program ROM I could now remove it and use this external register instead which resulted in nicer code.

Thinking I had fixed the opcodes and the CPU's program ROM execution I used Blargg's GameBoy emulator test suite, a set of ROMs developed by Shay Green using a real GameBoy as testing-platform. Shay Green is known as Blargg to the emulator community. The emulator failed all 11 tests, which meant I had at least one faulty opcode in each opcode group. As all opcodes did exactly what the documents I had specified, I was a bit depressed. I actually tracked down an e-book scanned from the official programming guide of the GameBoy and GameBoy Color in order to get forward. I found this e-book thanks to a tip from a user on byuu's bsnes forum. Looking over all the opcodes again I found some really disturbing differences between this manual and those I already had. Now I could finally implement everything correctly, I thought. I changed the opcodes to match the official programmers guide and ran Blargg's tests again. Now a lot of the tests passed, but some still failed. But at least now I could count the failures on my fingers. There were three tests that refused to pass: "DAA", "LDHL SP,e", and "ADD SP,e". Regarding the stack pointer-related opcodes I do not know the reason behind one of the required steps needed for them to execute correctly. That is, during the addition between the stack pointer and the signed variable e, e is unsigned during the evaluation of the flags. What concerned me most was the "LDHL SP,e" opcode though, for this opcode even the official programmer's guide is wrong in how it works. While the manual tells me the carry and half-carry flags are set if the resulting value overflows in the 3rd or 4th nibble (the nibbles of the most significant byte) the flags are really set by overflows from the nibbles in the least significant byte. The "DAA" opcode I assumed from the beginning would be a nightmare to implement and I was right. Though my second solution worked, it was very slow and I started to run short of time. At this point I noted that Gambatte used an approach similar to what I used, so I copied its optimized version of the algorithm leaving my own slow version as a comment.

Besides all these hiccups the development have been pretty straightforward and only a few timing issues remain in the parts that I was to implement. No information on how to do that timing exists and I have not figured out how to do it. Every fix attempted left the results unchanged or made things worse. Also the opcode cycle test fails with "Failure #255" which according to the source code of that test, does not exist.

Future work

The only major thing left to understand about the GameBoy in order to make emulation more accurate is the LCD read pointer. When the LCD reads from OAM or video RAM and that same memory is read by the CPU, the CPU will receive the data pointed to by the LCD read pointer instead of the data at the requested address. This can probably be achieved in two ways: the first one is to write a test program that is to be uploaded to the real GameBoy. This test program would then run a very extensive test and print the results on the screen. These results would then be gathered in such a way that they can be used to implement this function. The other method is to dump the program ROMs of both the PPU and LCD (if it has its own program ROM that is). This would require them to be removed from the GameBoy and have them “decapped”, and from there extract the program ROMs and dump the opcode table. Using that information it should be possible to decompile the program ROMs into assembler. From the resulting code from that process it might be seen how the LCD read pointer operates. Dumping the program ROM of the PPU and the LCD (again, if it has a program ROM) may also help in optimizing, and maybe even correcting parts we do not know are wrong in the PPU emulation.

Summary and conclusions

To complete this project on time a few things that does not affect playability too much would have to be sacrificed: sound, serial connection and extension chips. The extension chips do have an impact on the number of playable games though. Since the GameBoy has a 4 MHz CPU and a 60 FPS screen the code has to be quite fast for the emulator to run at full speed.

Due to me dropping a few things there were only four components to implement: CPU, PPU/LCD, Memory and Joypad. These components where implemented using the language C++ with help from OpenGL and the OpenGL Frame Work (GLFW). The implementation was a bit bumpy but most things where solved in the end. Currently there is probably only one timing issue left to straighten out. I had to implement this emulator in stages to keep the project under a manageable complexity. The process was split up into these stages: "The main system", "CPU instructions and memory handling", "Interrupts and the HALT state", "PPU and basic LCD functionality", "Sprites and DMA transfers", and "Joypad".

The biggest problem found during the implementation process was that I discovered I had not grasped how complex some of the timing is in the GameBoy. That mistake cost me a couple of rewrites of the CPU code. On a deeper level I had problems with especially one CPU instruction that was seemingly wrongly described in all documentation I had access to. This included the official development manual by Nintendo. Besides that problem I had not had any major issues with the documentation, just some small hiccups with typing mistakes in the code and a few moments where I understood the documentation wrong.

In conclusion, using the documents that exist online it is possible to write a GameBoy emulator with quite good compatibility and accuracy. The documents are however somewhat tricky to understand and contain a fair amount of errors, so some experience in reading technical documents and reading between the lines is required to fully understand them. The documentation needed to write an emulator as accurate as Gambatte is however not publicly available in any other format than the Gambatte source code, and the Gambatte source code is not a light reading. There is currently only one major question mark in GameBoy emulation and that is how memory accessing is done when the video RAM and OAM are busy. This behavior has not been figured out and an extraction of the PPU program ROM is probably necessary to solve that riddle. Extracting the PPU program ROM was not done in this project because it is a very expensive and slow process, and it requires an understanding of how the guts of a microchip works.

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All links where confirmed alive on 2011-05-29.

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