



FACULTY OF APPLIED SCIENCES UNIVERSITY OF WEST BOHEMIA

DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

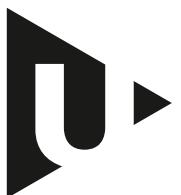
Master's Thesis

ARMv6 Processor Emulator for Raspberry Pi Environment Emulation

Jakub Šilhavý

PILSEN, CZECH REPUBLIC

2023



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Thesis advisor

Ing. Martin Úbl

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Zásady pro vypracování

1. Learn about the ARMv6 architecture, the BCM2835 microcontroller and the Raspberry Pi Zero platform.
2. Analyze the software resources available to emulate this environment.
3. Design an emulator that allows emulation of a subset of the instruction set of the ARM1176JZF-S processor and basic peripheral support for the BCM2835 microcontroller.
4. Implement this emulator in C++ using modern standards.
5. Test the implemented solution on a set of basic tasks and a selected minimalist operating system that supports this platform, evaluate the solution.

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Abstract

This paper examines the potential of emulating a Raspberry Pi Zero, a selected example of one of the most widely adopted architectures for embedded systems — the ARM architecture. The initial chapters delve into a general introduction to the ARM architecture, highlighting its profound significance evidenced by billions of electronic that leverage it. Transitioning to the second part, the thesis addresses the benefits of utilizing an ARM emulator, delineating overall requirements, and reviewing existing methodologies.

The second part centers on the development of a custom Raspberry Pi Zero emulator whose functionality is systematically tested using a set of examples pertinent to operating system development. The thesis concludes with an objective evaluation of the emulator's performance, identifying its key benefits, and suggesting areas for further enhancements.

Abstrakt

Diplomová práce zkoumá potenciál emulace Raspberry Pi Zero, který reprezentuje jednu z nejvíce rozšířených architektur pro vestavěné systémy — architekturu ARM. Úvodní kapitoly se věnují obecnému seznámení se s ARM architekturou, s důrazem na její význam, který je demonstrován více než miliardou elektronických zařízení, které ji využívají. Dále se práce zaměřuje na výhody využívání ARM emulátoru, stanovení celkových požadavků a analýzu existujících možnosti řešení.

Druhá část textu se soustředí na vývoj samotného Raspberry Pi Zero emulátoru, jehož funkčnost je systematicky testována pomocí sady příkladů vztahujících se k vývoji operačních systémů. Práce je zakončena objektivním hodnocením výkonu emulátoru, identifikací jeho klíčových výhod a navrhováním oblastí pro další vylepšení.

Keywords

ARM • Processor • Emulator • Raspberry Pi

Contents

1	Introduction	5
2	Computer Architectures	7
2.1	Classification of Computer Architectures	7
2.1.1	Von Neumann Architecture vs Harvard Architecture	8
2.1.1.1	Von Neumann Architecture	8
2.1.1.2	Harvard Architecture	8
2.1.2	Instruction Set Architectures	9
2.1.2.1	Stack Architecture	9
2.1.2.2	Accumulator Architecture	9
2.1.2.3	Load-Store Architecture	10
2.1.3	Reduced vs Complex Instruction Set Computer	11
2.1.3.1	Complex Instruction Set Computer	11
2.1.3.2	Reduced Instruction Set Computer	12
3	ARM Architecture	13
3.1	History	13
3.2	Processor Cores	14
3.2.1	Classic ARM Processors	14
3.2.2	Embedded Cortex Processors	14
3.2.3	Application Cortex Processors	15
3.3	Instruction Set Architecture	16
3.3.1	Central Processing Unit Modes	16
3.3.2	Exception Model	17
3.3.3	Registers	18
3.3.3.1	Banked Registers	18
3.3.3.2	Control Registers	19
3.3.4	ARM Instructions	20
3.4	Co-processors	22
3.4.1	System Control Co-processor	23
3.4.2	Floating-point Unit	23

4 Raspberry Pi Zero	25
4.1 ARM1176JZF_S	25
4.2 Microcontroller BCM2835	26
4.2.1 Memory-mapped peripherals	27
5 Raspberry Pi Zero Emulation	29
5.1 Terminology	29
5.1.1 Simulation	29
5.1.2 Emulation	30
5.1.3 Virtualization	30
5.2 Existing Solutions	31
5.2.1 CPULator	31
5.2.2 ARMSim#	32
5.2.3 QEMU	33
5.3 General Requirements	34
6 Design of a Raspberry Pi Zero Emulator	37
6.1 Input	37
6.1.1 Executable and Linkage Format	37
6.2 User's Interaction	39
6.3 Core Components	40
6.3.1 System Bus	41
6.3.1.1 Managing Peripherals	42
6.3.1.2 Unaligned Memory Access	43
6.3.2 Executable and Linkage Format File Loader	44
6.3.3 BCM2835 Peripherals	45
6.3.3.1 Memory-mapped Registers	48
6.3.3.2 System Clock Listener	49
6.3.3.3 Random Access Memory	50
6.3.3.4 Debug Monitor	51
6.3.3.5 True Random Number Generator	52
6.3.3.6 ARM Timer	53
6.3.3.7 General Purpose Input/Output	55
6.3.3.8 Interrupt Controller	57
6.3.3.9 Auxiliaries	58
6.3.3.10 Broadcom Serial Controller	61
6.3.4 ARM1176JZF_S	62
6.3.4.1 Central Processing Unit Context	63
6.3.4.2 Instruction Set Architecture Decoder	64
6.3.4.3 Exceptions	66

6.3.4.4	Arithmetic-Logic Unit	67
6.3.4.5	Memory Management Unit	67
6.3.4.6	Central Processing Unit Core	70
6.3.5	Co-processors	71
6.3.5.1	Co-processor 15	72
6.3.5.2	Co-processor 10	74
6.4	External Peripherals	75
6.4.1	External Peripheral Interface	75
6.4.2	Configuration	76
6.4.3	Examples of External Peripherals	77
6.4.3.1	Serial Terminal	78
6.4.3.2	Logic Analyzer	78
6.5	Logging System	78
6.6	User Interface	79
Bibliography		83
List of Abbreviations		87
List of Figures		89
List of Tables		91
List of Listings		93
7 Attachments		95

Introduction

1

Over the past several years, ARM, as a computer architecture, has garnered popularity across a wide array of applications. Its usage spans from low-power solutions and affordable microcontrollers to real-time applications and safety-critical systems, such as medical devices, automotive technology, and aviation. Furthermore, ARM is extensively utilized in personal computers and the cell phone industry. Nowadays, it is estimated that ARM powers over 99% of the world's smartphones [1]. Covering such a diverse range of applications, ARM has tailored its processor cores into various groups known as families. Notable among these is ARMv6, employed in devices like Raspberry Pi Zero. This version introduced innovative technologies such as *TrustZone*, *Jazzle*, and *Single Instruction/Multiple Data* instructions to the Classic line of ARM processor cores.

Emulating such a widely adopted architecture can assist in illustrating concepts of computer organization and operating system principles. In addition to educational purposes, the use of an ARM emulator can prove beneficial in the software development process, particularly when immediate access to a development board may not be feasible. Furthermore, it provides a safety net by enabling developers to experiment with potentially risky code without concerns about damaging real hardware. As a software tool, it can also be integrated into continuous-integration automated testing to identify potential bugs before moving on to testing on actual hardware, which may not be readily available.

This thesis delves into the fundamental principals of the ARM architecture, exploring and evaluating existing emulation solutions tailored for an embedded environment. The primary goal is to design, implement, and rigorously test a comprehensive and extensible Raspberry Pi Zero emulator capable of emulating KIV-RTOS [2] — a real-time operating system developed for educational purposes at the University of West Bohemia.

Computer Architectures

— 2

A computer architecture can be generally considered a low-level principal design of a computer system that defines the interaction of its components that work alongside to accomplish a given task. While there are a number of different computer architectures, some of the most well-known architectures may include Intel, MIPS, ARM, or the increasingly popular RISC-V architecture.

The internal workings of a computer architecture can be explained through the concept known as Instruction Set Architecture, often abbreviated as ISA, which provides a comprehensive understanding of computer's operation capabilities. It also provides insights into how the user can interact with the central processing unit (CPU) based on the specific types of instructions it supports.

2.1 Classification of Computer Architectures

Computer architectures can be categorized by various aspects, such as how they handle data, the addressing modes they provide, how they organize memory, what register set they feature ¹, or the number of operands in an instruction. All these criteria must be taken into consideration when selecting the appropriate architecture for a given application, as each one comes with its own set of advantages and disadvantages. The following sections delve into different types of computer architectures, explaining their fundamental ideologies along with their pros and cons.

¹Although registers are the fastest type of memory, from an operating system perspective, featuring an extensive number of registers can also pose a disadvantage, as it increases the time required to perform a context switch, which might be critical for real-time applications.

2.1.1 Von Neumann Architecture vs Harvard Architecture

As far as memory access is concerned, there are two major architectural ideas that serve as the foundation for nearly all computer architectures: the Von Neumann architecture and the Harvard architecture. While they are distinguished by various factors, including their cost, intended usage environment, and more, their primary differentiation lies in how they organize and access memory.

2.1.1.1 Von Neumann Architecture

The Von Neumann architecture, designed by the mathematician and physicist John von Neumann in 1945, is what can be found in modern personal computers. As illustrated in Figure 2.1, it features a **single memory space for both code and data**, necessitating only a single address and data bus, which could pose the risk of unintentionally overwriting the program's instructions, potentially leading to a system crash. On the other hand, its design is considerably cheaper compared to the Harvard architecture, as it requires less physical space.

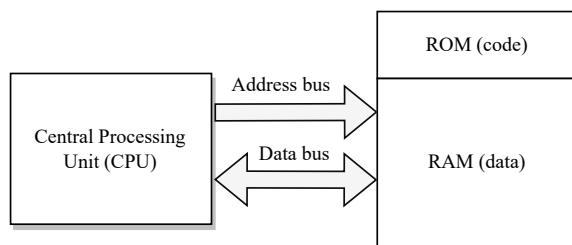


Figure 2.1: Von Neumann architecture

Another potential drawback arises from the fact that data and instructions share the same bus, even though fetching instructions occurs more frequently than data transfers. Consequently, the shared data bus may represent a performance bottleneck within the entire system.

2.1.1.2 Harvard Architecture

Contrastingly, the Harvard architecture employs **distinct memory modules for code and data**, requiring twice the number of bus lines compared to the Von Neumann architecture. This design is typically preferred in scenarios where the performance benefits outweigh the additional costs, such as in microcontrollers, and Field Programmable Gate Arrays, also known as FPGA boards.

Taking advantage of two separate memory modules, it can effectively mitigate resource conflicts and enhance its performance through parallelism and separate memory caching.

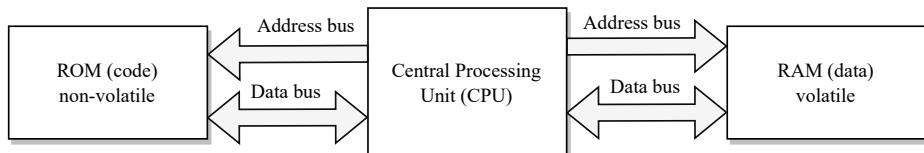


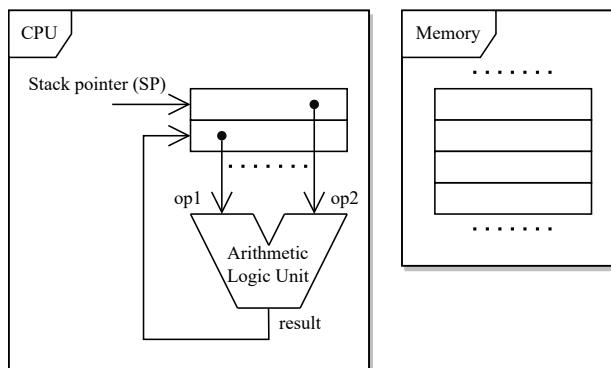
Figure 2.2: Harvard architecture

2.1.2 Instruction Set Architectures

Instruction set architectures can also be categorized by how they handle operands in terms of interacting with memory. As noted previously, each approach may be beneficial for different types of applications.

2.1.2.1 Stack Architecture

The stack architecture, shown in figure 2.3, does not rely on memory to retrieve operands. Instead, the CPU maintains an internal stack, which serves as storage for operands. An operation is executed in a *last-in-first-out* (LIFO) fashion, where two operands are popped off the stack, and the operation's result is consequently pushed back onto the stack.

Figure 2.3: Stack architecture²

A distinct advantage of this architecture is that it makes compiler implementation considerably easier compared to other types of architectures. However, the main drawback is the stack, which introduces a bottleneck that hinders any potential parallelization.

2.1.2.2 Accumulator Architecture

Similar to the stack architecture, the accumulator architecture imposes minimal hardware requirements. It substitutes the stack with a single register called the ac-

²This architectural design is employed, for example, by the Java Virtual Machine.

cumulator, which serves both as an input operand and as storage for the operation's result. Same as the previous architecture, the accumulator represents a bottleneck. Furthermore, it leads to high memory traffic, as every two-operand instruction requires retrieving the second operand from memory.

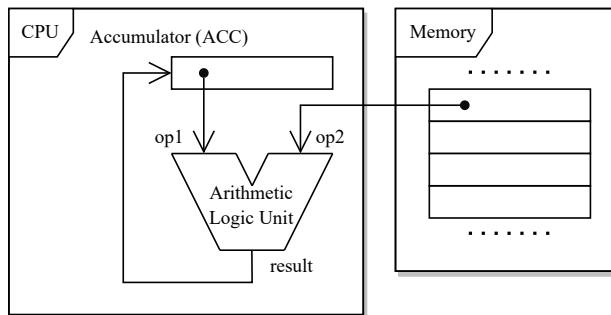


Figure 2.4: Accumulator architecture

2.1.2.3 Load-Store Architecture

The load-store architecture does not utilize memory during arithmetic-logic operations. Instead, **it restricts memory access to a specific pair of instructions, the load and store instructions**. These instructions serve as an interface for reading and writing data to memory. Consequently, when an operation needs to be executed, the CPU must ensure that all operands are stored in individually addressable memory banks, known as CPU registers, before employing the arithmetic-logic unit to proceed with the operation.

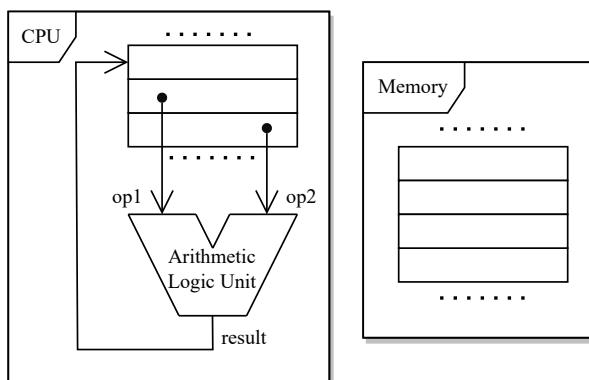


Figure 2.5: Load-store architecture

Figure 2.6 illustrates the process of retrieving operands from memory, carrying out the necessary operation, and then storing the resulting data back in the main memory.

Load-store architectures frequently use fixed-length instructions, providing the potential for more efficient pipelining³, which can result in improved performance. However, a notable drawback of this architecture is its strong reliance on a sophisticated compiler, which may not be as straightforward to implement as in the architectures mentioned previously.

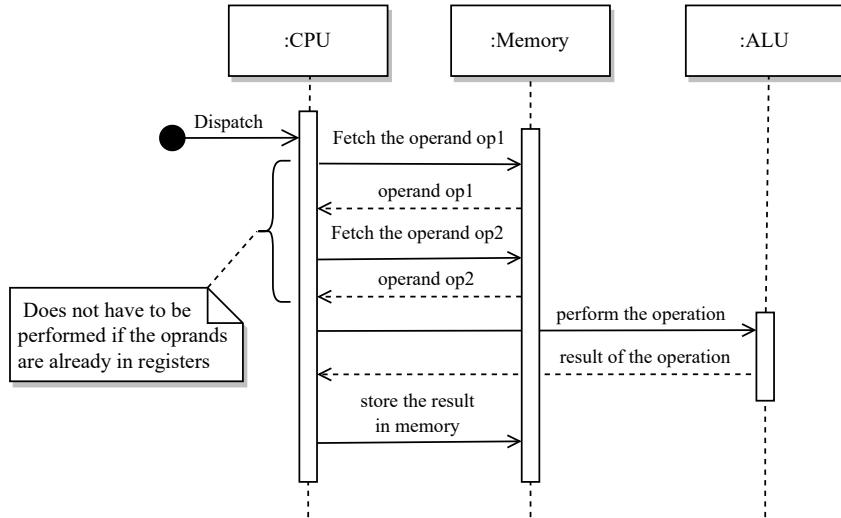


Figure 2.6: Load-store sequence diagram

2.1.3 Reduced vs Complex Instruction Set Computer

RISC (Reduced Instruction Set Computer) and CISC (Complex Instruction Set Computer) are two prominent CPU architectures that have gained widespread adoption over time. They employ distinct approaches in utilizing their respective instruction sets to align with the hardware implementation [3].

2.1.3.1 Complex Instruction Set Computer

The CISC architecture places an **emphasis on the underlying hardware**, leading to the development of complex multi-clock instructions that can vary in length. This length variation may introduce complications in pipelining, which can have an adverse effect on performance. However, implementing custom instructions tailored to specific hardware specification results in smaller code sizes, as they take a more concrete and less abstract approach to achieve the desired functionality. An example of this type of architecture is the x86-64 Intel processor.

³Pipelining is a low-level parallelization technique that involves breaking down the processing of an instruction into multiple stages that can be executed simultaneously.

2.1.3.2 Reduced Instruction Set Computer

RISC, on the other hand, **focuses on the software aspect**, resulting in fewer single-clock instructions of a fixed-size, which facilitate easier pipeline processing. Another significant aspect is that RISC does not perform operations directly on memory. Instead, it adheres to the principle illustrated previously in figure 2.6. Another important consideration in this architecture is that having more general and, perhaps, simpler instructions can potentially increase the size of the final binary. This is because achieving a certain functionality may require the use of multiple instructions, unlike the CISC architecture, which typically accomplishes the same goal with a single instruction. A typical example of this architecture is the ARM architecture, which is described more in detail in the following chapter.

There are other types of computer architectures that can be categorized by various aspects. The objective of this chapter was to provide the reader with introductory insights into some of the key factors that define a computer architecture. For more comprehensive information, readers can refer to the book series *Computer Organization and Design: The Hardware/Software Interface* [4].

ARM Architecture

3

3.1 History

ARM was officially founded as a company in November 1990 under the name Advanced RISC Machines Ltd. It originated as a joint venture involving companies such as Arcon Computers, Apple Computer, and VLSI Technology. Its early indications of future potential became evident with the Nokia 6110 GSM mobile, which experienced a remarkable surge in popularity after its release in 1998. Currently, it is estimated that over 99% of the world's smartphones are built on ARM technology.

Throughout the 2000s, ARM's sustained success enabled it to evolve beyond smartphones and become **arguably the most widely used processor architecture**. Nowadays, ARM technology can be found across a broad spectrum of embedded devices, ranging from sensors and low-power microcontrollers to supercomputers and real-time mission-critical systems [1].



Figure 3.1: Devices leveraging ARM technology

An interesting aspect of ARM is that **it does not engage in silicon manufacturing**. Instead, it preserves the architecture as intellectual property, outsourcing the implementation to its closely aligned silicon partners, who are part of the so-called *Connected Community*. This ARM surrounding community forms a global

network of companies that collaborate by sharing expertise, providing support services, offering design consulting, and supplying tools for creating ARM-powered solutions.

3.2 Processor Cores

ARM classifies its processors into three major groups, which makes it a viable choice for a wide range of applications. Figure 3.2 displays these categories in ascending order based on their capabilities.

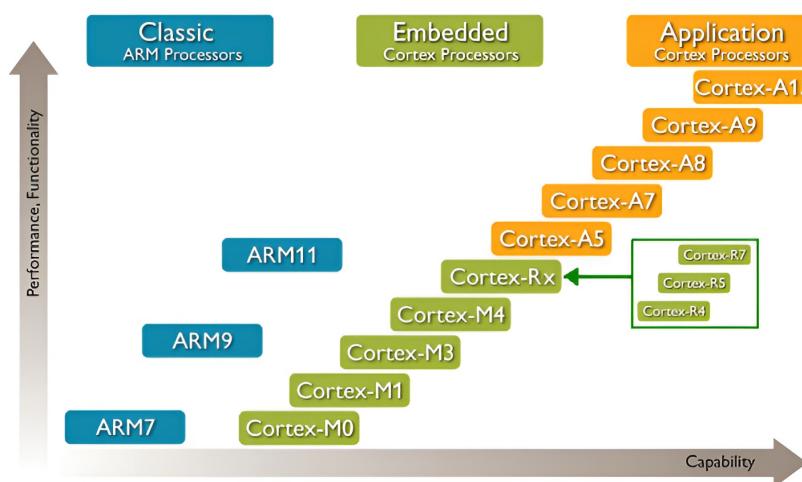


Figure 3.2: ARM processor roadmap

3.2.1 Classic ARM Processors

The Classic ARM Processors represent the company's **initial line of processors**. A typical example within this category is the ARM7TDMI-S CPU core, which was widely embraced by the cellphone industry. Over time, ARM has introduced additional Cortex families, each tailored for their intended domain of applications.

3.2.2 Embedded Cortex Processors

Generally speaking, the Cortex-M family is utilized in **low-cost microcontrollers**, which can be commonly found embedded in Internet of Things (IoT) devices such as home automation systems, wearables¹, or smart locks.

¹Wearable technology refers to any type of smart devices designed to be worn, such as smart-watches, smart glasses, etc.

Usually, the ARM Cortex-M family simplifies or modifies certain features, resulting in slight deviations from the traditional ARM architecture. These modifications may involve different CPU modes, the exception model, or bank registers, all of which are further discussed in the following sections.

Another line of processors targeted for the embedded world is the Cortex-R family, known for delivering high performance and throughput while upholding precise timing properties and minimizing interrupt latency. This characteristic makes it a **suitable core for domains with time-constrained requirements**, including automotive systems, medical devices, and aerospace and defense systems.

3.2.3 Application Cortex Processors

The Cortex-A line of processors is designed for applications that require a general-purpose platform operating system, which is **commonly used in laptops and personal computers**. As a result, they integrate an extended instruction set to improve multimedia processing, along with an advanced memory management system to ensure a seamless human-machine interaction experience.

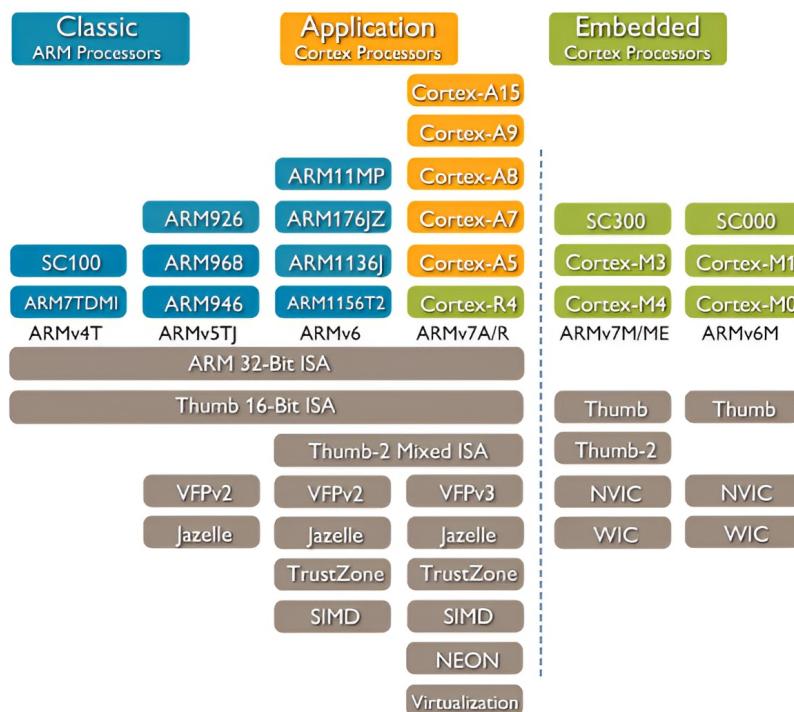


Figure 3.3: Features of different ARM processor cores

Figure 3.3 illustrates the ongoing evolution of capability features across various CPU cores.

For instance, it can be observed that ARMv6 incorporates the *Thumb* instruction set version 2, which is runtime interchangeable with the *ARM* instruction set. Additionally, it includes support for floating-point operations version 2, *Jazelle* for execution of Java bytecode, *TrustZone* for secure data storage, and *Single Instruction/Multiple Data* instructions, often referred to as SIMD instructions.

3.3 Instruction Set Architecture

ARM is a load-store RISC architecture that supports two major sets of fixed-size instructions: the standard 32-bit ARM instruction set and the reduced 16-bit *Thumb* instruction set. The following sections delve into some of the key characteristics of the Classic line of ARM processors. For a more comprehensive understanding, the reader is encouraged to refer to the official ARM Architecture Reference Manual [5].

3.3.1 Central Processing Unit Modes

There are a total of **seven modes in which an ARM CPU can operate**, each represented by a unique 5-bit number stored in the *Current Program Status Register*. The CPU can switch to one of these modes either implicitly, such as when an interrupt occurs, or explicitly as written by the programmer, for example, when switching the current CPU context. All modes except for the *User* mode are privileged, meaning that when the CPU is in the *User* mode, the execution of certain instructions might be restricted².

Table 3.1: List of ARM CPU modes

CPU mode	Description
<i>User</i>	Normal program execution
<i>FIQ</i>	Supports a high-speed data transfer or channel process
<i>IRQ</i>	Used for general-purpose interrupt handling
<i>Supervisor</i>	A protected mode for the operating system
<i>Abort</i>	Implements virtual memory and/or memory protection
<i>Undefined</i>	Supports software emulation of hardware co-processors
<i>System</i>	Runs privileged operating system tasks

²In the context of operating systems, a non-privileged mode is usually used for the execution of user programs, while the kernel operates in a privileged mode.

It is worth noting that Cortex-M utilizes only two CPU modes: *Thread mode*, an unprivileged mode designed for executing application code, and *Handler mode*, a privileged mode intended for handling exceptions.

3.3.2 Exception Model

When an exception or interrupt occurs, the CPU sets the program counter register to the address associated with that exception, known as the interrupt vector, and switches to the corresponding CPU mode, which can be found in table 3.2. The interrupt vector represents a fixed address in RAM where the CPU redirects its execution. Therefore, during the system initialization, these memory locations are typically filled with branch instructions to direct the execution to the corresponding exception handlers.

As illustrated in figure 3.4, this address region, also known as the interrupt vector table, can be found located either in the lower part or the upper part of the virtual address space, depending on the current setting stored in the *System Control Co-processor*.

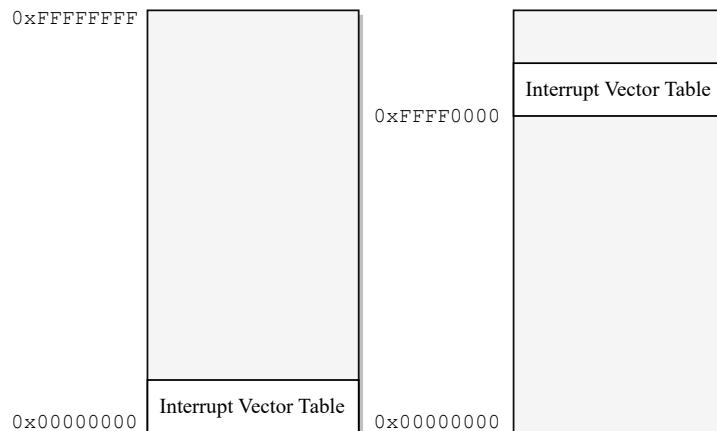


Figure 3.4: Possible locations of the interrupt vector table in RAM

Table 3.2: List of ARM CPU exceptions

Exception	CPU mode	Normal address	High address
<i>Reset</i>	<i>Supervisor</i>	0x00000000	0xFFFF0000
<i>Undefined instruction</i>	<i>Undefined</i>	0x00000004	0xFFFF0004
<i>Software interrupt</i>	<i>Supervisor</i>	0x00000008	0xFFFF0008
<i>Prefetch abort</i>	<i>Abort</i>	0x0000000C	0xFFFF000C

(table continues on the next page)

Table 3.2 (*continued from the previous page*)

Exception	CPU mode	Normal address	High address
<i>Data abort</i>	<i>Abort</i>	0x00000010	0xFFFF0010
<i>Interrupt</i>	<i>IRQ</i>	0x00000018	0xFFFF0018
<i>Fast interrupt</i>	<i>FIQ</i>	0x0000001C	0xFFFF001C

Similar to the previously mentioned CPU modes, the Cortex-M family employs a slightly different exception model.

3.3.3 Registers

ARM offers **16 general-purpose 32-bit registers** labeled **r0** through **r15**, three of which serve special functions, which are listed in table 3.3. The programmer is free to use the remaining registers as needed.

However, specific calling conventions were established to ensure a systematic use of these registers. For instance, registers **r0–r3** are used as argument values passed into a subroutine, while return values are typically stored in registers **r0–r1**. Further details on calling conventions can be found in Chapter 6 of the ARM's Procedure Call Standard Manual [6].

Table 3.3: List of special function ARM registers

Index	Name	Description
13	SP	<i>Stack pointer</i> - holds the address of the top of the stack
14	LR	<i>Link register</i> - holds the return address (when calling a function, it is not pushed onto the stack)
15	PC	<i>Program counter</i> - holds the address of the instruction to be executed

3.3.3.1 Banked Registers

A distinctive feature of ARM is its utilization of so-called *bank* registers. In this concept, **each CPU mode has its own unique set of registers** that are automatically loaded whenever the current CPU mode changes.

The more bank registers are utilized, the faster the switch into the corresponding CPU mode is, as there is no need to preserve the current state by storing all registers

onto the stack. As a result, this concept is extensively employed by the *FIQ* mode for ensuring fast interrupt handling, as the mode's name suggests.

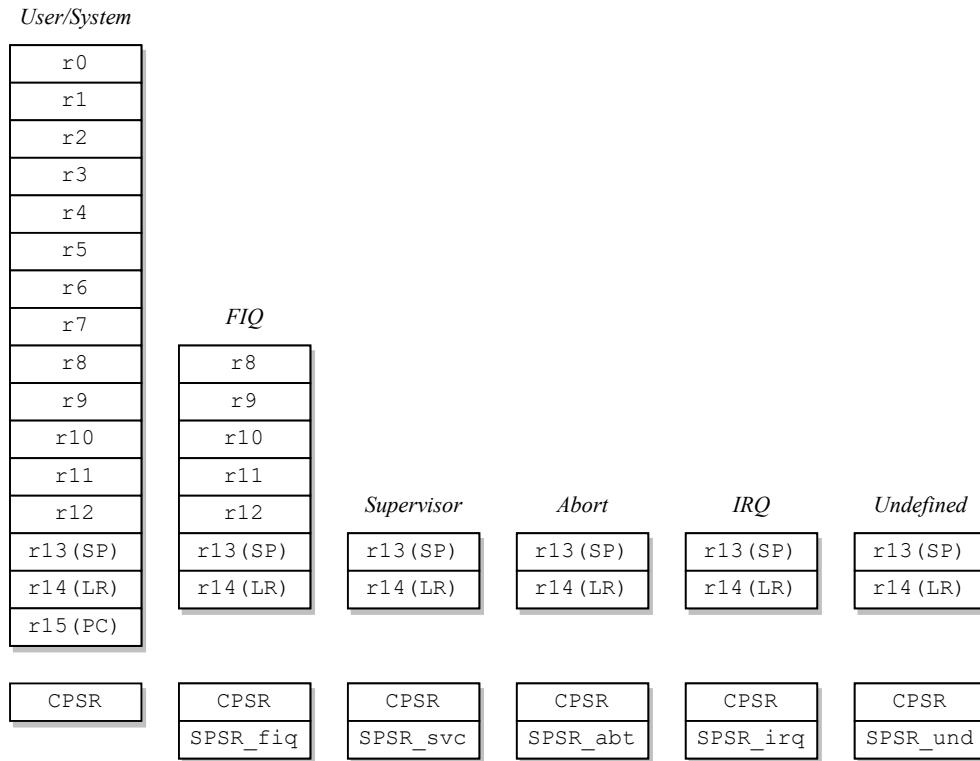


Figure 3.5: Bank registers of different CPU modes

When the CPU is executing 16-bit *Thumb* instructions, only the first 8 registers (*r0-r7*) can be addressed directly. These registers are sometimes referred to as the *Thumb State Low Registers*.

As far as Cortex-M is concerned, since there are only two CPU modes, the banking scheme applies only to the SP register.

3.3.3.2 Control Registers

Current Program Status Register.

The *Current Program Status Register* (CPSR) **preserves the current state of the CPU** along with some additional information. To modify the control register, its content must first be transferred into one of the general-purpose registers using the MRS instruction, as direct modification is not allowed. Subsequently, after the necessary modifications have been made, it can be transferred back from the general-purpose register using the MSR instruction.

This 32-bit register is segmented into four sections, as illustrated in figure 3.6. The initial letters of the section names can function as a bit mask when using the

MRS or MSR instruction to prevent unintentional modifications of bits that are not intended to be changed.

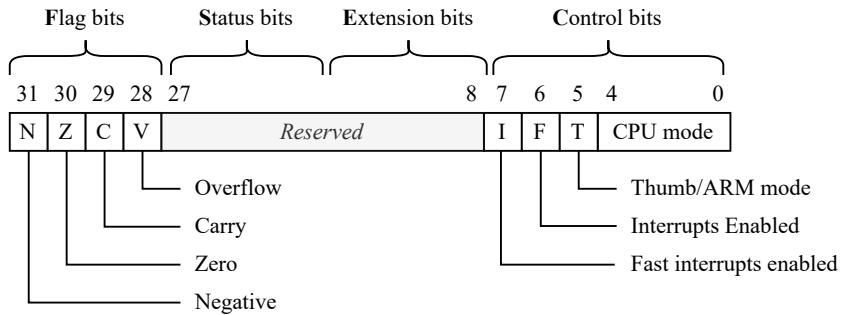


Figure 3.6: Current Program Status Register³

Saved Program Status Register.

The *Saved Program Status Register*, or SPSR, serves as a **copy of the CPSR register** utilized during CPU mode switching. When transitioning to a mode that contains an SPSR register, as shown in figure 3.5, the contents of the CPSR register of the current mode are copied into the SPSR register of the new mode. This process allows the restoration of the original state when reverting to the original CPU mode.

3.3.4 ARM Instructions

As mentioned previously, **all ARM instructions are 32-bits in length**. The most significant four bits of each instruction form a condition field that constrains its execution. The CPU assesses the current state of the flag bits in the CPSR register, and depending on the condition field, the instruction is either skipped or executed. From the programmer's standpoint, this can be accomplished by suffixing the instruction name by the desired condition code, as listed in table 3.4.

In contrast to other architectures, the flag bits are not automatically set upon the execution of an instruction. Instead, it is up to the programmer to choose whether to update them by adding an 'S' to the end of the instruction name. For instance, ADD does not update the flags, whereas ADDS does ⁴.

³The reserved area contains additional information and control bits including the result of SIMD instructions, the status of the Jazelle bit, and endianness, which can also be changed at runtime.

⁴This concept does not apply to instructions like CMP, which, as its sole purpose suggests, implicitly sets the status flags.

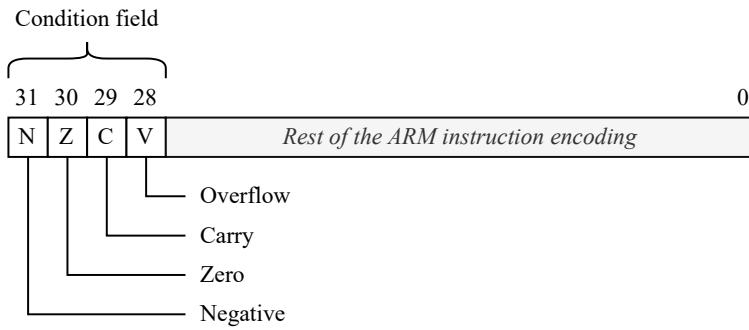


Figure 3.7: Condition field of an ARM instruction

Table 3.4: List of ARM instruction condition codes

Code	Flags tested	Meaning
EQ	Z==1	Equal
NE	Z==0	Not equal
CS or HS	C==1	Unsigned higher or same (or carry set)
CC or LO	C==0	Unsigned lower (or carry clear)
MI	N==1	Negative (mnemonic - „minus“)
PL	N==0	Positive or zero (mnemonic - „plus“)
VS	V==1	Signed overflow (mnemonic - „V set“)
VC	V==0	No signed overflow (mnemonic - „V clear“)
HI	(C==1) && (Z==0)	Unsigned higher
LS	(C==0) (Z==1)	Unsigned lower or same
GE	N==V	Signed greater than or equal
LT	N!=V	Signed less than
GT	(Z==0) && (N==V)	Signed greater than
LE	(Z==1) (N!=V)	Signed less than or equal
AL	Not tested	Always executed (suffix is omitted)

In general, **ARM instructions can be classified into several different categories based on their purposes**, such as *data processing instructions*, *data transfer instructions*, *branch instructions*, or *co-processor instructions*, which are designed for interacting with external CPU co-processors. Detailed ARMv6 instruction encodings can be found, for instance, in the B2 ARM Appendix document [7].

3.4 Co-processors

A co-processor, as its name implies, **operates alongside the main CPU to further extend its functionality**. Examples of co-processors may include a floating-point unit or the system control co-processor. Each co-processor is addressed by a unique 4-bit number⁵, resulting in up to 16 different co-processors that can be attached to an ARM CPU.

As listed in table 3.5, the **CPU interacts with co-processors via three designated instructions**, enabling it to offload specific functions to more specialized hardware suitable for the given task, such as when multiplying two floating-point numbers.

Table 3.5: List of ARM co-processor instructions

Instruction	Description
<i>Coprocessor Data Operation</i> (CDP)	Signals a co-processor to perform an internal operation
<i>Coprocessor Data Transfer</i> (LDC, STC)	Loads or stores a subset of co-processor's registers directly to memory
<i>Coprocessor Register Transfer</i> (MRC, MCR)	Communicates information directly between the CPU and a co-processor

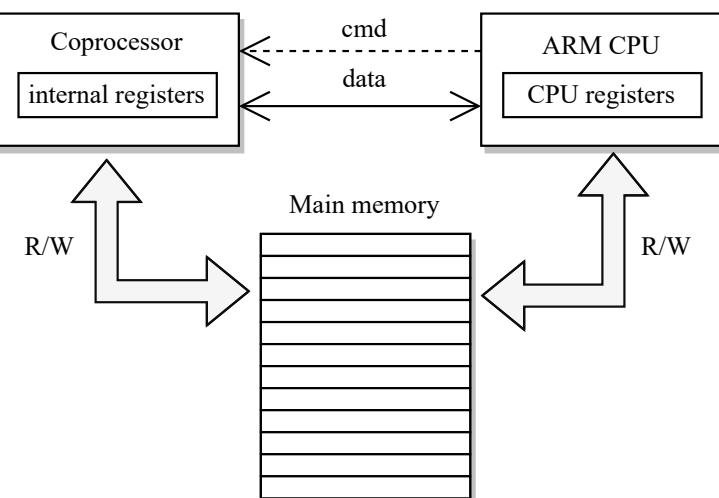


Figure 3.8: Context of an ARM co-processor

⁵The co-processor ID is encoded in every co-processor instruction.

3.4.1 System Control Co-processor

The system control co-processor, or CP15, incorporates a tree-like structure of additional registers that are utilized for **configuring various settings within the overall system**. For instance, the users can configure branch prediction, caching, unaligned-memory access, paging, and so on. Moreover, via CP15, users can enable or disable other co-processors and define their CPU mode access rights.

3.4.2 Floating-point Unit

The floating-point unit, also referred to as the FPU, is represented by two distinct co-processors, CP10 (single-precision) and CP11 (double-precision). This distinction occurs solely at an interface level, meaning that they share the same underlining set of registers, which are treated differently based on the leveraged co-processor. The primary purpose of the FPU is to extend the capability of an ARM CPU by **incorporating floating-point arithmetic instructions**, such as *addition, subtraction, multiplication, division, and square root* operations.

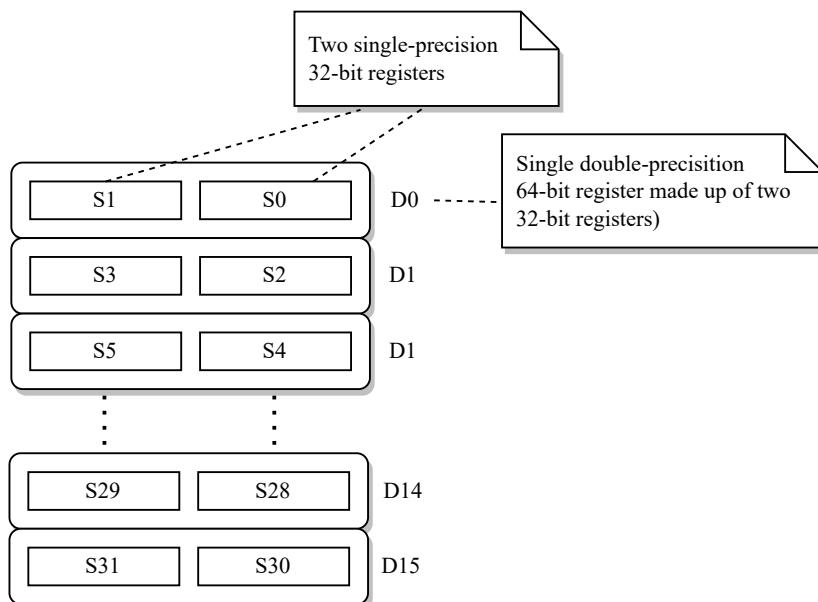


Figure 3.9: Floating-point registers

Additionally, the FPU also provides its own status control register, called FPSCR, which contains the current state of flags. Whenever a comparison instruction is executed, it becomes essential to transfer the FPU flags to the CPU, so they can be used to determine the execution of the next instruction ⁶.

⁶From the programmer's perspective, this process is typically automated by the compiler, which implicitly inserts a subsequent MRC instruction.

Finally, the user can optionally set different rounding modes and exceptions via the exception control register named FPEXC. This register is also employed to activate the FPU. As a result, it must be initially enabled on a co-processor level and subsequently in the FPEXC register as well.

Raspberry Pi Zero

4

Raspberry Pi Zero is a **system on chip**, or SoC, which is a design that integrates various components into a single chip, such as a central and graphics processing unit, memory interfaces, and input-output devices. In the case of Raspberry Pi Zero, it is equipped with 512 MB of RAM, an SD card holder, which is utilized during the booting process, a Mini HDMI adapter, a micro USB port, and the BCM2835 microcontroller, which is powered by the ARM1176JZF_S processor.

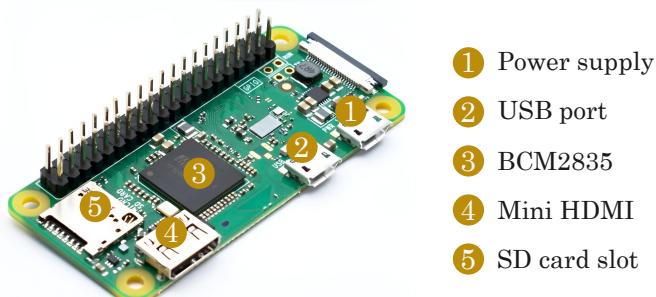


Figure 4.1: Raspberry Pi Zero board

In contrast to other Raspberry Pi boards, such as Raspberry Pi 4, the Zero model **aims to be a compact, cost-effective, and minimalist system**. Nonetheless, it effectively fulfills its role in illustrating fundamental principles shared by more sophisticated boards. This makes it particularly valuable for smaller non-computationally intensive projects or educational purposes. Consequently, it had been chosen as an example for implementing an ARM emulator.

4.1 ARM1176JZF_S

ARM1176JZF_S is a **single-core 800 MHz processor that implements the ARM11 ARM architecture version 6**. It supports both *ARM* and *Thumb* instruction sets, incorporates Jazelle technology for the direct execution of Java bytecodes, and

includes a set of SIMD instructions designed to operate on 16-bit or 8-bit data values within 32-bit registers.

Table 4.1: Breakdown of the processor's name

Section	Meaning
ARM11	Indicates that the processor belongs to the ARM11 family
76	Model identifier within the ARM11 family
J	Presence of Jazelle technology (execution of Java bytecodes)
Z	Support for <i>Thumb-2</i> technology (mix of 16/32-bit instructions)
F	Support for floating-point operations
S	„Secure“ - presence of security features (e.g. TrustZone)

While the majority of its functionality aligns with the principles described in previous chapters, for a more in-depth understanding, the reader can refer to the reference manual [8].

4.2 Microcontroller BCM2835

BCM2835, a microcontroller made by the BROADCOM company, **incorporates a range of memory-mapped peripherals that are made accessible to the ARM processor**. These peripherals include timers, an interrupt controller, General-Purpose Input-Output pins (GPIO), a Universal Serial Bus interface (USB), a Direct Memory Access controller (DMA), an I²C interface, a Serial Peripheral Interface (SPI), and the Universal Asynchronous Receiver-Transmitter, also known as the UART interface¹.

All peripherals, along with their memory-mapped registers, can be found detailed in the BCM2835 ARM Peripherals datasheet [9].

However, it has been observed to contain a number of misleading pieces of information, primarily related to typing errors. Consequently, a separate document has been generated, explicitly enumerating known errors found across various chapters [10].

¹The BCM2835 microcontroller also includes a couple of peripherals intended for use by the GPU. However, due to complexity reasons, they were not taken into consideration in this paper.

4.2.1 Memory-mapped peripherals

From the programmer's perspective, memory-mapped peripherals are **devices that can be found located on a predefined known addresses in memory**². For instance, according to the datasheet, the GPIO controller can be found located at **0x20200000**.

In addition to the ARM's Memory Management Unit (MMU), the BCM2835 microcontroller is equipped with a second coarse-grained MMU responsible for mapping ARM physical addresses to system bus addresses.

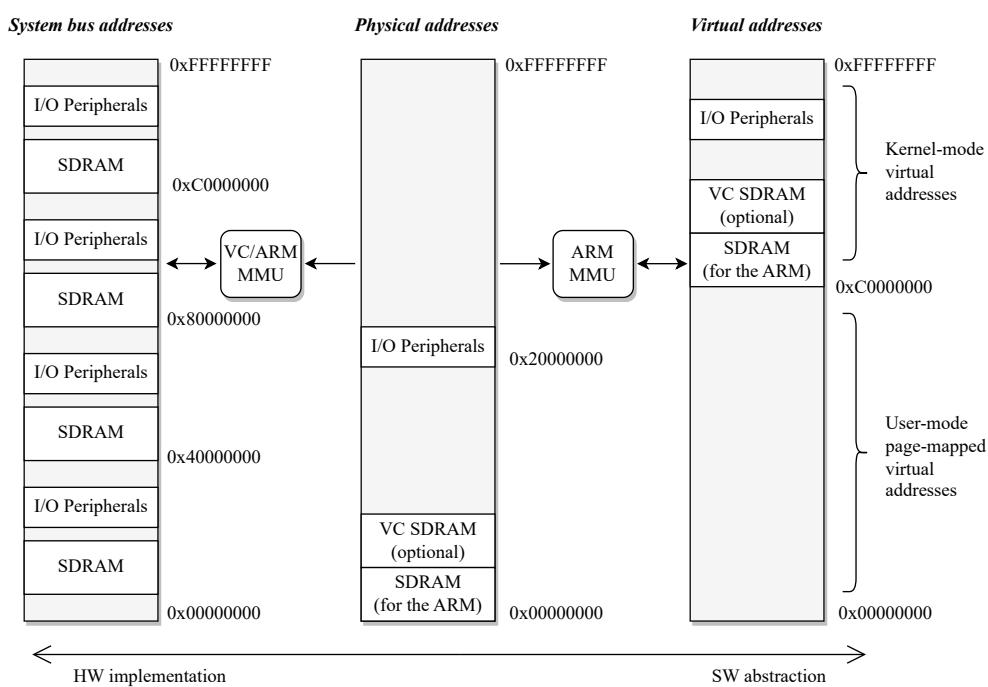


Figure 4.2: BCM2835 address translation processes

If the ARM MMU is employed, the first stage in a memory read-write operation involves translating the virtual address to a physical address based on the page table hierarchy set up by the kernel. Subsequently, once a physical address is obtained, it is mapped to a bus address that corresponds to the particular chip involved in the operation. This mapping occurs due to the fact that memory, such as flash or Synchronous Dynamic Random Access Memory (SDRAM), may often be composed of multiple chips, each potentially implementing different caching policies.

Unless specifically intended, from an emulation standpoint, the second translation can often be omitted, as it delves too deeply into hardware-specific details.

²In this context, the term „memory“ refers to the entire address space rather than the physical memory.

Raspberry Pi Zero Emulation

5

Emulating Raspberry Pi Zero on a different platform, such as x86, can offer several benefits and serve various purposes.

For instance, it can be a powerful **tool for educational purposes**, allowing students and beginners to learn about the ARM architecture in a visual and user-friendly way. Furthermore, it can be valuable for illustrating concepts like operating system principles and embedded system development¹. The author suggests that **it could find applications in a continues-integration development process**, where it might be utilized for executing an initial set of unit and regression tests to identify early bugs before carrying out testing on real hardware, which may not always be readily available. Examples of applicable domains may include medical devices, automotive, and other safety-related systems. Another potential benefit is that it implicitly provides a level of isolation, which **allows developers to experiment with potentially risky code** without worrying about damaging their board.

All these reasons are further accentuated by ARM's omnipresence, as it is arguably one of the most widely adopted architectures worldwide.

5.1 Terminology

5.1.1 Simulation

In general, a simulation is a computer program designed to replicate a specific process or sequence of events, with the goal of gaining a thorough understanding of its behavior, especially in cases where a comprehensive analytical mathematical solution may be unknown. Simulations are typically parameterized, allowing them to be rerun with different input parameters to investigate how different changes impact the observed values. They are commonly employed in various scenarios, such as modeling traffic in a city, simulating disease outbreaks, or predicting weather conditions.

¹If modularized, it can also be extended by other external modules, allowing the user to create a fully-customized system.

5.1.2 Emulation

In emulation, each instruction of architecture *A*, an emulated architecture, is replaced with one or more instructions of architecture *B*, the underlying architecture. This typically results in an implicit slowdown in performance as it requires more time to achieve the same functionality. The primary advantage of an emulator is that it enables the execution of a program that is not originally written for the underlying architecture. Some popular examples of emulators include DOSBox, which can be used for playing retro video games on a modern computer, and QEMU [11], a full-emulation system capable of running various architectures.

5.1.3 Virtualization

Unlike emulation, virtualization allows the execution of a guest application, possibly written for a different operating system, directly on the underlying hardware. This is achieved through a hypervisor, installed on top of the host operating system, which manages the execution of multiple distinct host machines that remain „invisible“ to each other. Examples of such hypervisors include Xen, KVM, and Microsoft’s Hyper-V. These days, virtualization plays a vital role in cloud-based solutions, as it enables dynamic allocation of virtual machines that can be utilized for various purposes, such as web servers, load balancers, computing units, and more.

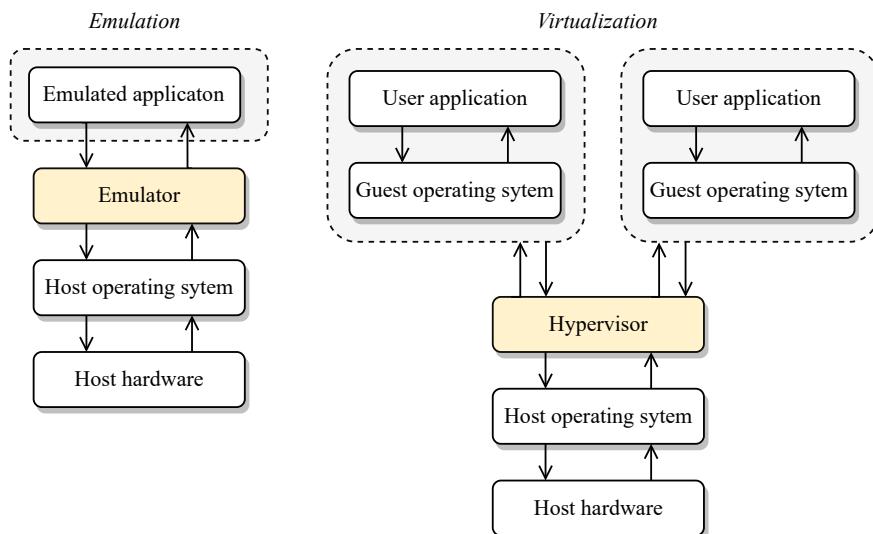


Figure 5.1: Emulation vs. virtualization

Another popular technology that belongs to the emulation/virtualization category is Docker. However, it adopts a slightly different approach by primarily emulating software rather than the underlying hardware.

5.2 Existing Solutions

There are several available solutions that can serve as ARM emulators. However, it becomes evident that not all of them may be entirely suitable for the comprehensive and configurable emulation of an embedded environment. The following sections provide a review of some existing ARM emulators.

5.2.1 CPULator

CPULator is a sophisticated online emulator and debugger that offers **support not only for ARMv7 but also for MISP and Nios II architectures** [12]. It is specifically designed as a tool for learning assembly-language programming and gaining insight into computer organization. As a **web browser-based application**, it is accessible from any device, making it an **excellent starting point for beginners**. This accessibility is particularly advantageous for those who might be deterred by the complexities of installing a custom build of QEMU, for example.

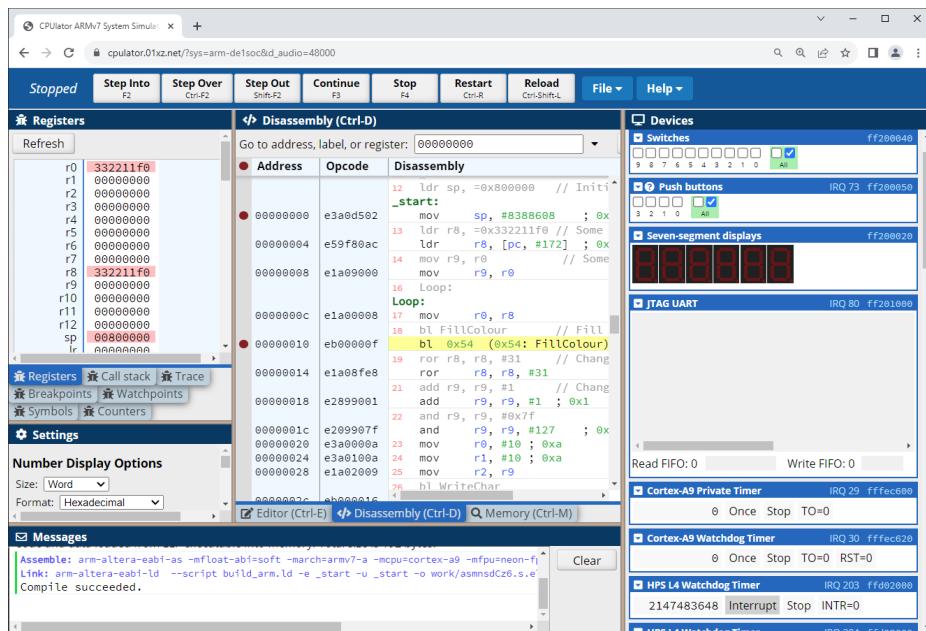


Figure 5.2: CPULator

Its core is written in C++ and compiled into WebAssembly, resulting in a user-friendly modern-looking interface that offers various debugging features such as breakpoints, single step, reverse step, step over function, step out of a function, modifying registers, showing stack call, and more. An input file² can either be loaded from the user's computer or entirely written and compiled using its built-in editor.

²It supports both the C programming language and ARMv7 assembly.

In addition to the build-in compiler, it allows the user to directly upload an already built binary file. According to its documentation, CPULATOR boasts an outstanding emulation speed of 13 mega-instructions per second. As far as ARM is concerned, it features a 4 GB flat model with a maximum usable memory of 2042 MB. It also incorporates several input/output devices including a video graphics array (VGA), buttons, watchdog timers, seven-segment displays, and more. However, the integration of custom external peripherals would be a welcomed feature.

Despite its support for floating-point numbers, CPULATOR **lacks support for a memory-management unit**, making it impossible to leverage the full 4 GB address space. Similarly, it **restricts the user from switching the default CPU mode**, rendering it unsuitable for demonstrating most of the operating system principles. Nevertheless, successfully fulfills its intended purpose as an excellent tool for learning the ARM assembly language.

5.2.2 ARMSim#

Another tool designed primarily for educational purposes is the ARMSim# emulator, developed at the University of Victoria in Canada [13]. This **desktop application, created using the .NET technology**, allows users to observe and debug the execution of ARM assembly programs on a system utilizing the ARM7TDMI processor³, which implements the **ARMv4 architecture**. Similar to CPULATOR, it supports debugging features such as stepping through the source code and viewing the current contents of both the CPU registers and memory. According to the CPULATOR's comparison chart, ARMSim# is claimed to be capable of executing up to 3 mega-instructions per second.

The emulator **features so-called plugins that further extend its functionality in a modular fashion**. Examples of these plugins may include *SWIInstructions*, which encapsulate a variety of system calls, such as reading and writing to a file, or *EmbestBoard*, allowing the core to interact with external peripherals such as a keyboard, segment display, or a 40x15 display — all of which are also interacted with via system calls.

ARMSim# also supports vector floating-point instructions; however, similar to CPULATOR, it **lacks support for a memory-management unit**. It can be concluded that while it finds application in learning the ARM assembly language, it does not provide features for advanced system-level programming, like developing an operating system, **nor does it support the concept of memory-mapped peripherals**, which can be found in the majority of embedded devices.

³As mentioned previously, this processor was widely adopted by the cell phone industry. However, it is no longer licensed by ARM and may be considered outdated.

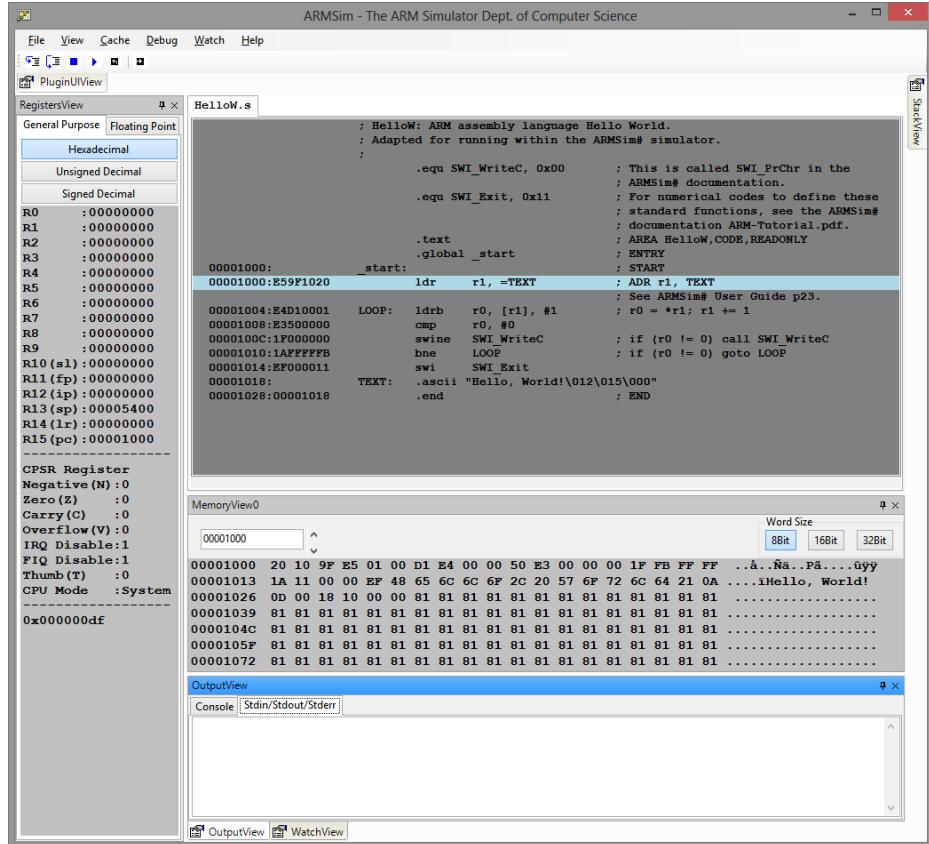


Figure 5.3: ARMSim#

5.2.3 QEMU

QEMU stands out as a powerful **cross-platform full-emulation system**, written in C, with the capability to emulate operating systems across various architectures, including x86, MIPS, ARM, and PowerPC [11]. While it may not offer the same visual appeal as some of its counterparts, its versatility surpasses them. QEMU can operate in both graphics mode, if supported by the guest operating system, and terminal-only mode. In terms of debugging, **it allows the attachment of the GNU debugger**, a tool heavily utilized in Linux-based operating systems.

However, when attempting to emulate the Raspberry Pi Zero environment, **QEMU does not provide a plug-and-play solution upon installation**. By default, it expects an ARM-based system to boot up from address 0x00010000. In contrast, the Raspberry Pi Zero's *first stage bootloader* necessitates the kernel's reset vector to be situated at address 0x00008000. Consequently, users face two options. They can either relocate their kernel to the required address or modify QEMU's source code to change the kernel load address and create a custom build. It is important to mention that the second approach may pose certain challenges for beginners.

The entire process of running a custom image built for Raspberry Pi Zero is detailed in the KIV/OS - dodatek A document [14].

While QEMU does support most of the features that the previous emulators lack, its versatility may also come with certain disadvantages when emulating the Raspberry Pi Zero environment. Specifically, there are reported **issues related to the system timer**, hindering the implementation of a preemptive scheduler in the custom operating system. Furthermore, it lacks a straightforward solution for attaching external hardware peripherals. In the case of the Raspberry Pi, it can be inferred that QEMU might not be the optimal choice for emulating such an embedded environment, given its primary focus on emulating more general-purpose operating systems.

5.3 General Requirements

Reviewing existing solutions renders a set of general requirements for an ideal emulator designed to emulate the Raspberry Pi Zero environment.

Preciseness.

It is evident that the emulator should identically mimic a real Raspberry Pi Zero board. This is arguably the most crucial requirement to fulfill, as failing to do so could result in unexpected behavior. Ideally, if the user compiles and runs their application inside the emulator, they should be presented the same output as if it was executing on real hardware. However, this may sometimes be challenging to achieve, especially considering time constraints mentioned previously.

Effectiveness.

In terms of performance, a slowdown in emulation speed is nearly inevitable. Nevertheless, the emulator should leverage modern technologies to mitigate these effects. Consequently, the use of certain programming languages like Python might be ruled out, as they could adversely impact overall performance. Moreover, the emulator should strive to consume only a reasonable amount of the system's resources.

User-friendliness.

The final emulator should introduce users to embedded development principles through a visual and user-friendly interface ⁴. They should have the capability to perform all the previously mentioned actions, such as setting breakpoints and viewing the contents memory and registers, without the necessity of connecting an external debugger. This is particularly crucial for beginners, as they should have

⁴In practice, this can be measured, for instance, through surveys.

access to these features effortlessly upon installation. Another essential requirement is that users should not be restricted to the use of the emulator on a single platform, such as Windows.

Extensibility.

In the embedded world, microcontrollers are frequently programmed to communicate with external devices, including motors, displays, sensors, or even other microcontrollers. Therefore, the emulator should facilitate the integration of external devices that can be developed independently of the emulator itself, thereby enabling other developers to contribute to the project. This functionality would empower users to configure a real-world scenario tailored to their specific application.

Design of a Raspberry Pi Zero Emulator

6

When designing a complex software system, it is important to take into consideration deciding factors such as the intended usage environment, interaction methods, system dependencies, preferred technologies, or different components constructing the final application. Addressing these questions early on enhances the likelihood of its successful completion as well as its long-term maintainability.

This chapter outlines the key design decisions made within the implementation process of the **ZeroMate emulator**, which is the chosen name for the project¹.

6.1 Input

The emulator necessitates a single input file in the ELF format, simplifying the booting process. In this process, the *stage 1 bootloader*, residing in ROM, reads the contents of the SD card and then initiates and delegates control to the GPU, which subsequently resets the CPU and loads the kernel into RAM.

This file is further referred to as the **kernel** since the emulator was designed within the context of operating systems development. Nevertheless, the input file can fundamentally represent any application intended for execution on Raspberry Pi Zero. Figure 6.2 illustrates the general process of building an ELF file, which contains all essential data and information required for code emulation.

6.1.1 Executable and Linkage Format

ELF stands for *Executable and Linkage Format* [15], and it is one of the most commonly used formats for executable files, especially on Unix-like systems. There are a number of other representations used in embedded development. For instance, the *Motorola S-Record format*, or SREC for short, is often used for programming non-volatile types of memory, such as flash or EEPROM.

¹It combines the word *Zero*, as in Raspberry Pi Zero, and *Mate*, which in this case is used as a synonym for a friend or „buddy“.

In terms of this project, the key advantage of ELF over SREC is that ELF is **used for both linkage and execution**. Therefore, if the kernel is compiled with debug symbols turned on², the symbol table stored in the final ELF file can be used during the parsing process, which is discussed in section 6.3.2, to provide the user with function names as they were used in the source code, which should improve the readability of the final disassembly. SREC, on the other hand, is **only used for execution**. Therefore, it can be viewed as highly compressed as it comprises only the necessary information for uploading firmware onto a microcontroller^{6.1}, which is commonly referred to as flashing.

It can be concluded that ELF provides more information that can be useful when reconstructing the original source code. Hence, it is used as the supported format for the input files. It is worth mentioning that this choice does not have as much impact on the core functionality as it does on visual aspects, which is discussed more in detail in section 6.6.

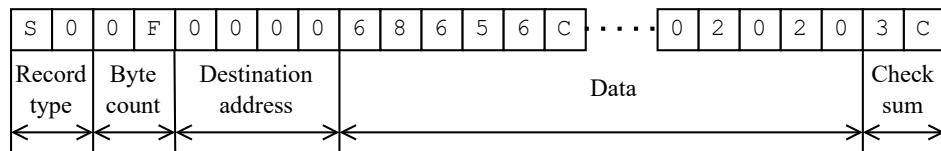


Figure 6.1: Single SREC record (16-bit addressing)

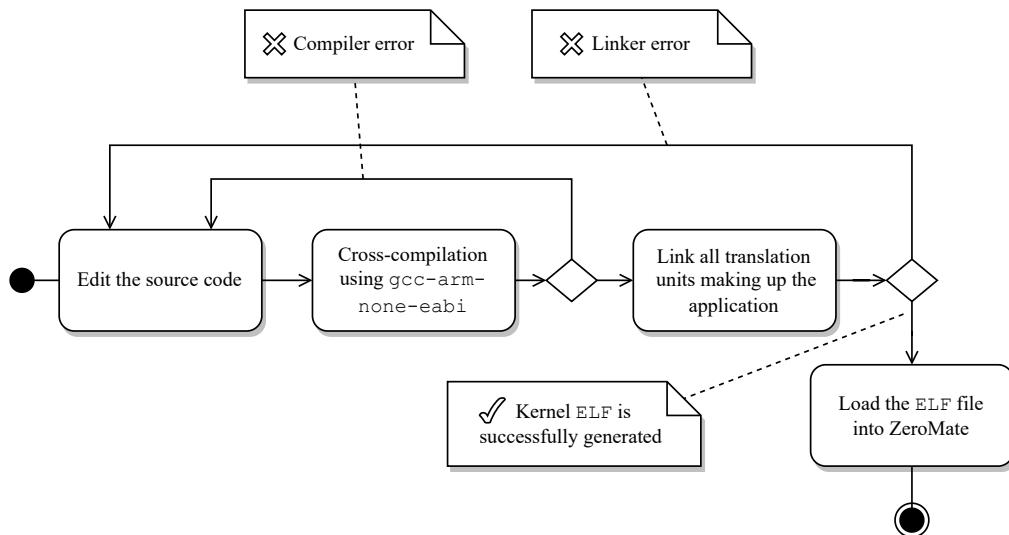


Figure 6.2: Process of building an ELF file (input for the emulator)³

²In the case of the `gcc-arm-none-eabi` compiler, the `-g -O0` flags should be used.

³Cross-compiling is a process where the source code targets a different platform than the one it is compiled on.

6.2 User's Interaction

As shown in the deployment diagram in figure 6.4, the emulator was **designed to run as a native desktop application on Windows, Linux, and MacOS operating systems**. It places a strong emphasis on visualization, serving as a debugging tool to assist with troubleshooting embedded applications targeting Raspberry Pi Zero.

The primary interaction with the system, from the user's perspective, is visualized in figure 6.3, where the user is provided with an interface that allows them to load an input file as well as to control the state of the emulation.

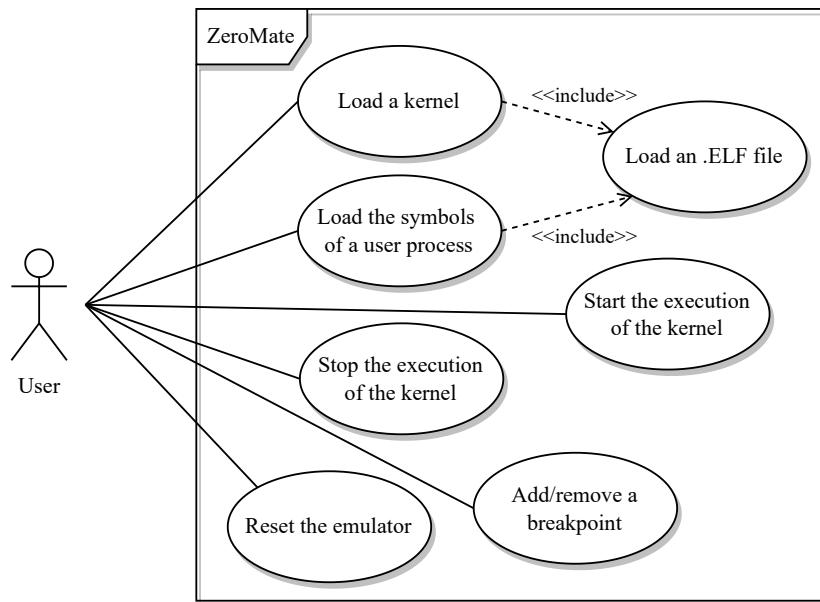


Figure 6.3: Primary use-cases of the ZeroMate emulator

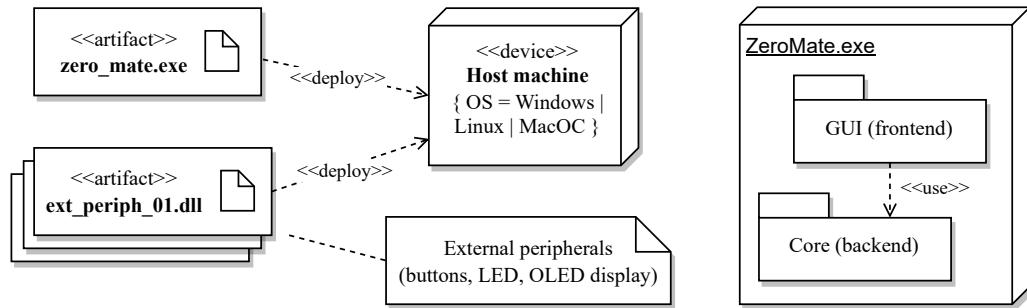


Figure 6.4: Deployment diagram of the ZeroMate emulator

The main application is designed as a **two-tier architecture**. In this arrangement, the top layer, which is the GUI, serves the dual purpose of visualizing data and acting as the primary user interface. The following chapters delve into the architectural structure of the core of the emulator.

6.3 Core Components

There are a number of different components working alongside to achieve a thorough emulation of a given kernel. Among these components, the **ARM1176JZF_S** component, which represents the CPU itself, may arguably stand out as the most complex one due to its encapsulation of various sub-components, including the CPU context, ALU, MMU, ISA decoder, and more. The role of every component will be examined further in the following sections.

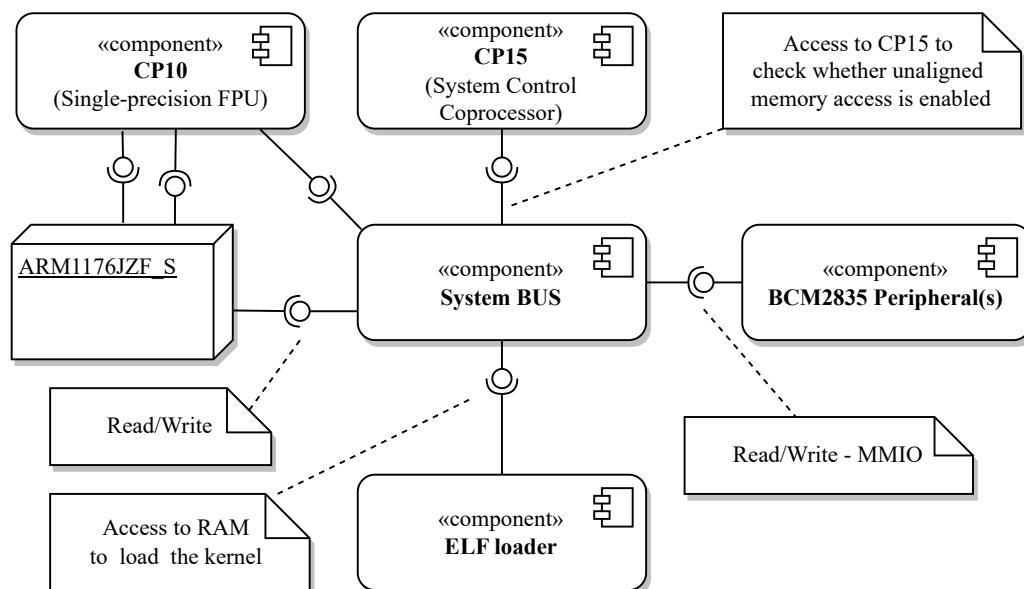


Figure 6.5: Core components of the ZeroMate emulator

Figure 6.5 illustrates the fundamental interactions among the core components. It can be observed that the majority of the components communicate with one another via the system bus⁴. For example, when the CPU executes a load/store instruction, it propagates the target address to the system bus, and the system bus then forwards the request to the corresponding peripheral associated with that address.

⁴What ZeroMate denotes as the system bus is typically regarded as the primary CPU bus.

6.3.1 System Bus

As mentioned previously, the system bus serves as an **intermediate unified interface** for accessing the RAM or any of the BCM2835 memory-mapped peripherals [9]. Each peripheral that is meant to be mapped into the address space must implement the same interface, so the bus can forward the read/write request independently of the peripheral's implementation (see section 6.3.3). All actions associated with the request itself are then handled internally within the target peripheral.

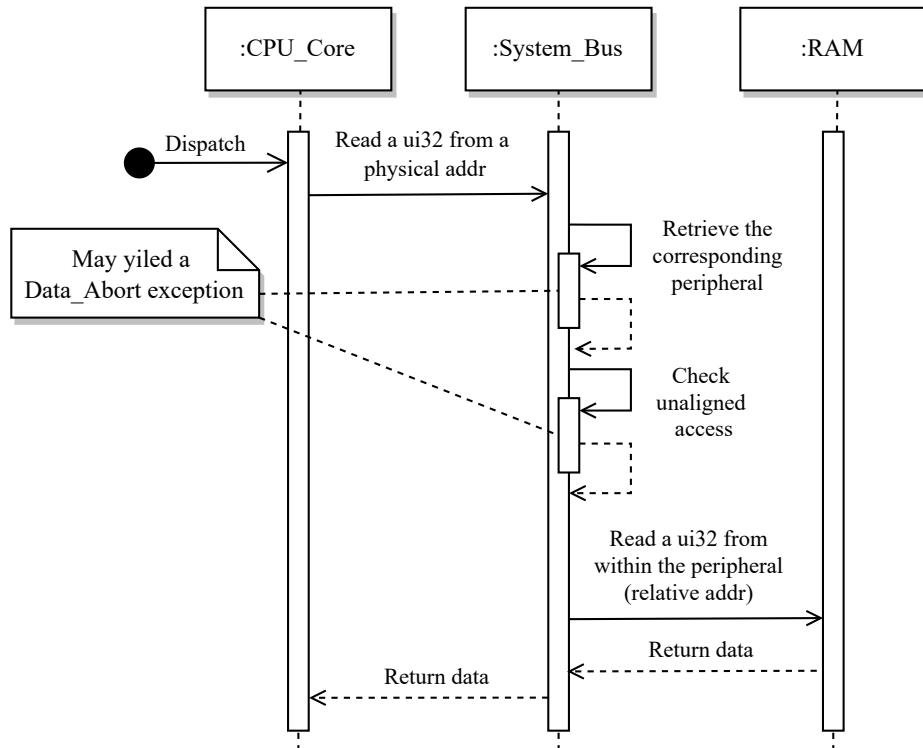


Figure 6.6: Example of a read/write data request issued by the CPU

As shown in figure 6.6, there are two internal steps the system bus carries out before proceeding with the request. First, the bus needs to determine what peripheral should the request be forwarded to. Secondly, it checks whether unaligned memory access is taking place or not.

In reality, the main system bus does not manage peripherals the same way it does in ZeroMate. It only serves as a medium for connecting different types of memory-mapped devices. Nevertheless, from an architectural point of view, it is a reasonable place for implementing common validity checks as it plays the role of a single point of access to all memory-mapped peripherals.

Additionally, the system bus ensures that the peripheral receives an **address relative to its location in the address space**⁵. In other words, it does not have any knowledge about its location on the bus, which is desired, as it decreases coupling and increases cohesion between the two components [16].

Source code 6.1: System bus interface for I/O operations

```

1 class CBus final {
2 public:
3     template<typename Type>
4     void Write(std::uint32_t addr, Type value);
5
6     template<typename Type>
7     [[nodiscard]] Type Read(std::uint32_t addr);
8 };

```

It can be argued that permitting the reading or writing of a general data type may diverge from real hardware specifications, as the system bus is typically of a fixed size, e.g. 32 bits. This simplification was made for convenience reasons when accessing predefined data structures in the RAM, such as the page table(s).

6.3.1.1 Managing Peripherals

The system bus component maintains a collection of references to all memory-mapped input-output devices, further referred to as **MMIOs**. Whenever a peripheral needs to be attached to the bus, it is inserted into the appropriate position within the collection. This ensures that the entire collection remains sorted in ascending order based on the starting addresses of the peripherals. This property enables the use of a binary search algorithm, resulting in faster lookup times, particularly in $O(\log_2 n)$ time complexity [17], which is crucial for improving the overall speed of the emulation.

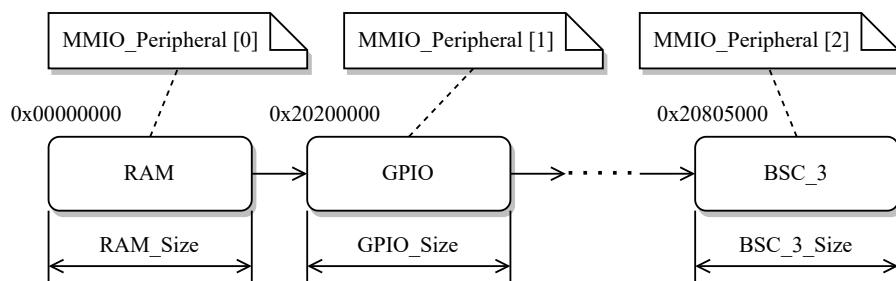


Figure 6.7: Collection of memory-mapped peripherals

⁵The relative address is calculated as the address contained in the R/W request issued by the CPU minus the address of the peripheral on the system bus.

According to statistics, on average, **load-store instructions account for more than 50% of all instructions in an x86 application** [18]. Although this research applies to a different architecture, it is reasonable to conclude that optimizing peripheral access efficiency might be crucial for emulation speed.

When connecting a peripheral, the bus must also ensure that there is no overlap between two peripherals and that they all fit within the address space, which, on a 32-bit architecture, spans out to 4GB.

6.3.1.2 Unaligned Memory Access

Unaligned memory access occurs when the **CPU attempts to read or write data from an address that is not divisible by the word size**. For example, reading 4 bytes from address 0x00000011 triggers unaligned access as the address is not word-aligned⁶. Nevertheless, this behavior can optionally be disabled, for example, for compatibility reasons, in the system control co-processor CP15 using the following sequence of instructions.

Source code 6.2: Enabling unaligned access in CP15

```
1 mrc p15, #0, r0, c1, c0, #0      ;@ Copy ctrl reg of CP15 to R0
2 orr r0, #0x400000                 ;@ Set bit 22 in R0
3 mcr p15, #0, r0, c1, c0, #0      ;@ Update CP15
```

⁶A word is a fixed-size number of bits that the CPU can process as a single unit. In the case of ARM1176JZF-S, one word equivocates to 4 bytes.

6.3.2 Executable and Linkage Format File Loader

The main objective of this module is to **parse an input ELF file** and copy the `.text` section, **word by word**, into RAM, as specified by the linker script. Additionally, it performs code disassembly, which is a process of reconstructing the source code from machine code. This allows the user to observe individual instructions in a more user-friendly way as they are executed.

For visualization purposes, the component also features the capability to parse an ELF file without copying its data into memory, which can be useful for viewing user processes that are compiled separately from the kernel itself. During this process, the **ELF loader** also **demangles all symbols** found in the input file⁷, thereby presenting the user with function names that have not undergone modification by the compiler for its internal purposes.

Source code 6.3: Example of symbol demangling

```
1 Demangle("_ZNSt6vectorIiSaIiEE9push_backERKi") =
2 "std::vector<int, std::allocator<int>>::push_back(int const&)"
```

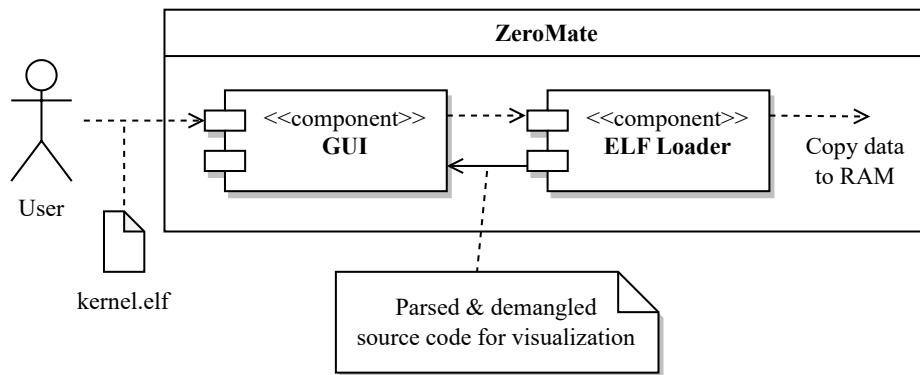


Figure 6.8: Loading an input ELF file (kernel)

⁷Demangling is a process of transforming C/C++ ABI identifiers (like RTTI symbols) into the original C/C++ source [19].

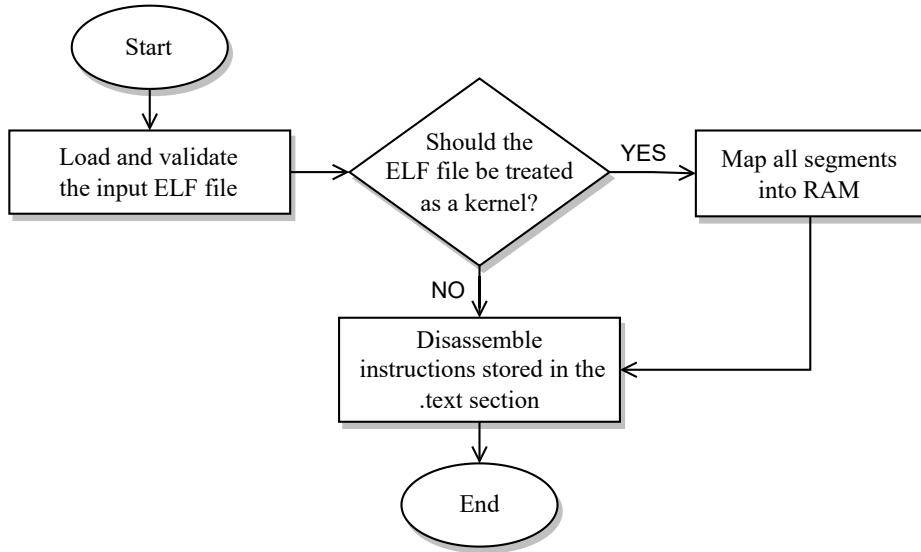


Figure 6.9: Internal logic of the ELF Loader component

It is important to emphasize that ZeroMate does not perform the tasks of parsing an ELF file and demangling symbols all by itself. Instead, it utilizes two external open-source libraries, *ELFIO* [20] and *Demumble* [21], to accomplish these functions.

6.3.3 BCM2835 Peripherals

ZeroMate distinguishes between two types of peripherals; those directly integrated with the microcontroller, such as RAM, ARM timer, or the interrupt controller, and those referred to as external peripherals, which are externally connected to another internal peripheral, the GPIO pins, forming a cascading set of connected peripherals. Examples of external peripherals may include buttons, switches, LEDs, displays, or keyboards. The following sections focus on the internal peripherals of Raspberry Pi Zero.

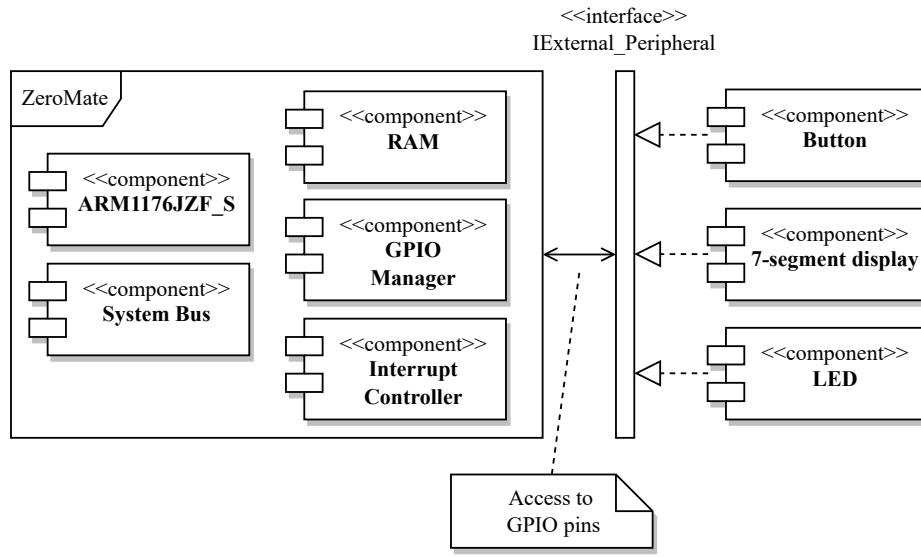


Figure 6.10: Internal vs External peripherals

In section 6.3.1, it is explained that the system bus manages a collection of references to all peripherals that are mapped into the address space. Using a general interface, the bus does not need to be concerned about how each peripheral functions internally. It simply forwards a R/W request initiated by the CPU to the corresponding peripheral.

Every BCM2835 peripheral encapsulates a set of registers, whose functions are detailed in the manual [9]⁸. By reading from or writing to these registers, the internal state of the peripheral can be modified, which is specific for each peripheral.

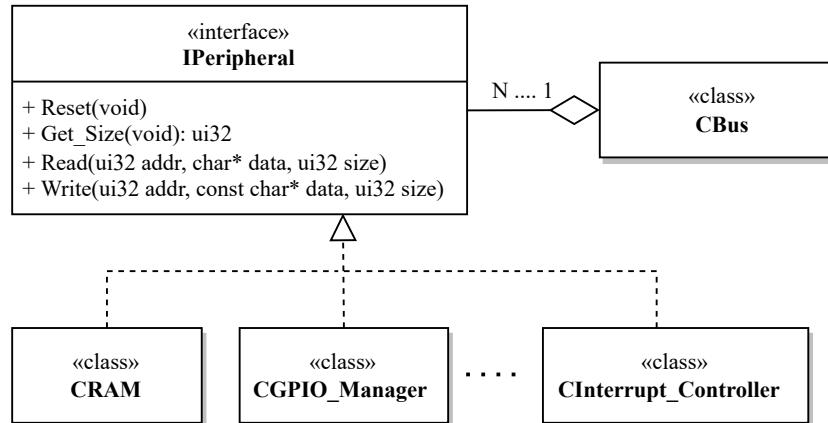


Figure 6.11: Hierarchy of internal peripherals

The `Get_Size()` method is used primarily for detecting bus collisions when

⁸The BCM2835 manual is known to contain several typographical errors. As a result, the community surrounding it published a list of these errors along with their respective corrections [10].

mapping peripherals into the address space, which was mentioned previously in section 6.3.1.1.

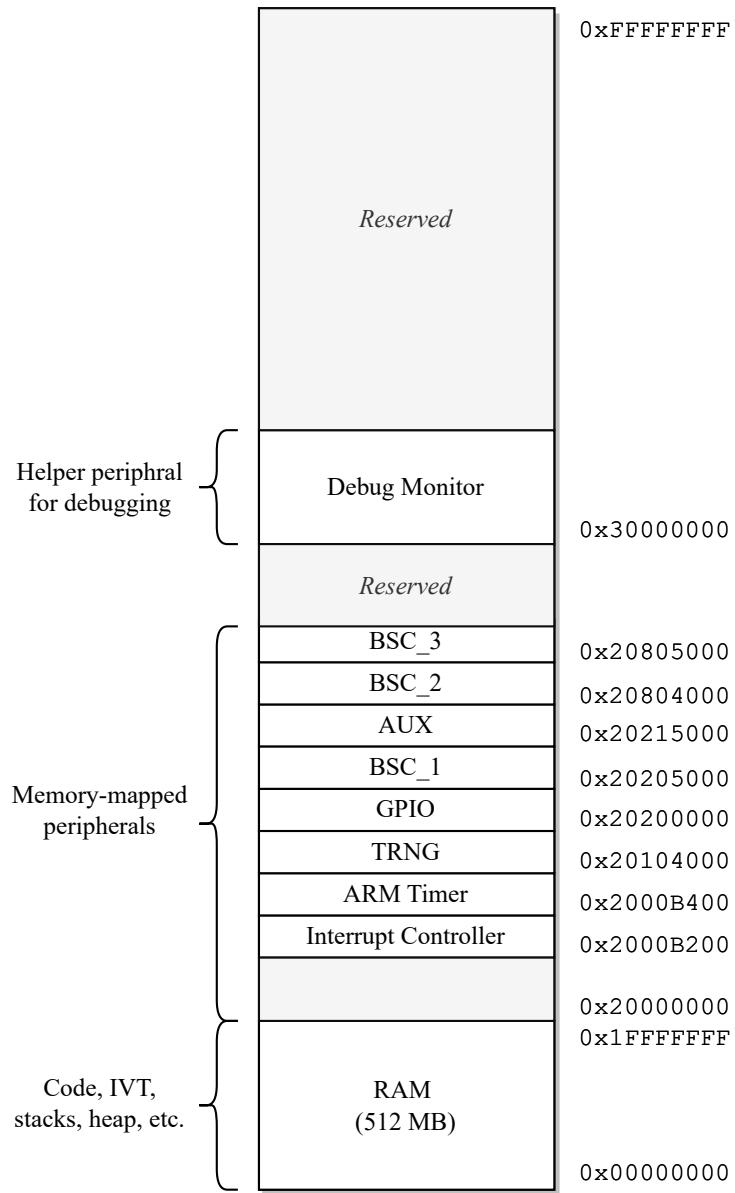


Figure 6.12: BCM2835 physical memory layout emulated by ZeroMate

It can be noticed that **ZeroMate does not account for all BCM2835 peripherals** since emulating every single one in its entirety would pose a significant complexity. Consequently, ZeroMate focuses emulation efforts on the most frequently utilized peripherals, such as the ARM timer, GPIO, IC, and others.

Nonetheless, the system's overall design is structured to allow for a smooth integration of additional peripherals in the future if needed. The following sections

explain the fundamental emulation principles of each of the peripherals listed in figure 6.12.

6.3.3.1 Memory-mapped Registers

As mentioned previously, each BCM2835 peripheral encapsulates a set of registers, through which the user can interact with the peripheral. From an implementation perspective, these registers can be represented as a fixed-size array of 32-bit integers, which are addressed relative to the peripheral's base address.

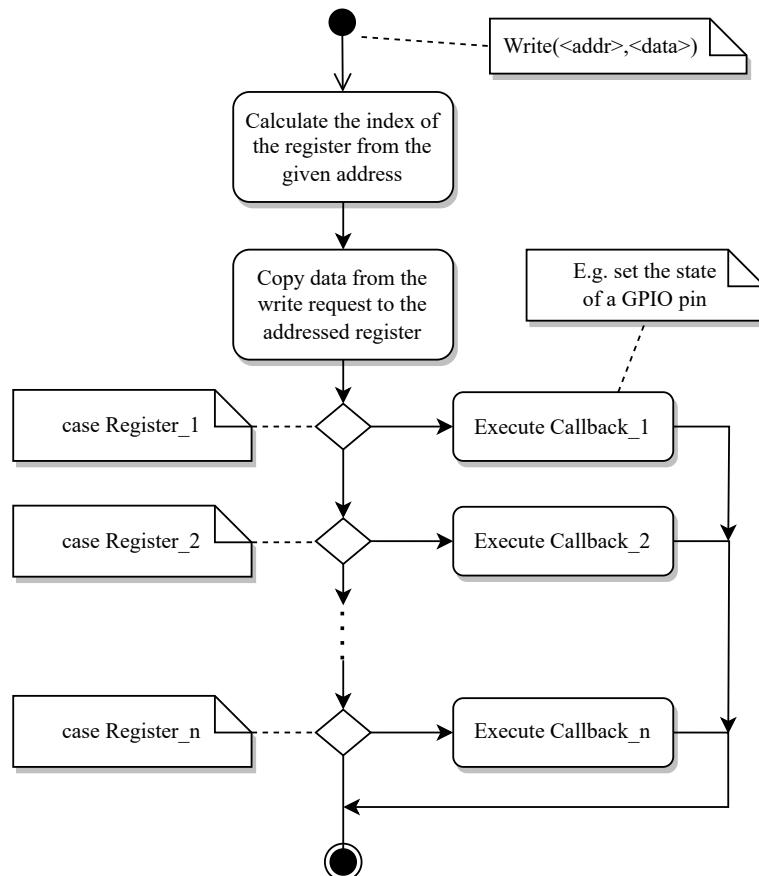


Figure 6.13: Writing to a peripheral's register⁹

Whenever a read/write request is sent through the bus, the peripheral identifies the addressed register, and the execution is then dispatched to the corresponding callback function, which carries out the necessary actions associated with that

⁹Reading works in a similar way. Optionally, there might be some prior actions taken before the value of the register is copied from the peripheral, such as inserting a random number into the data register when utilizing TRGN 6.3.3.5.

specific register. Generally, this approach can be applied to the vast majority of memory-mapped peripherals.

6.3.3.2 System Clock Listener

Optionally, each peripheral can implement the `ISystem_Clock_Listener` interface, which allows it to register with the CPU as a system clock listener. Whenever an instruction is executed, the CPU notifies all of its system clock listeners of how many CPU cycles it took to execute the instruction, allowing them to update themselves accordingly. Examples of such listeners may include the ARM Timer 6.3.3.6 or the AUX 6.3.3.9 and BSC 6.3.3.10 peripherals, which encapsulate time-based hardware communication functions.

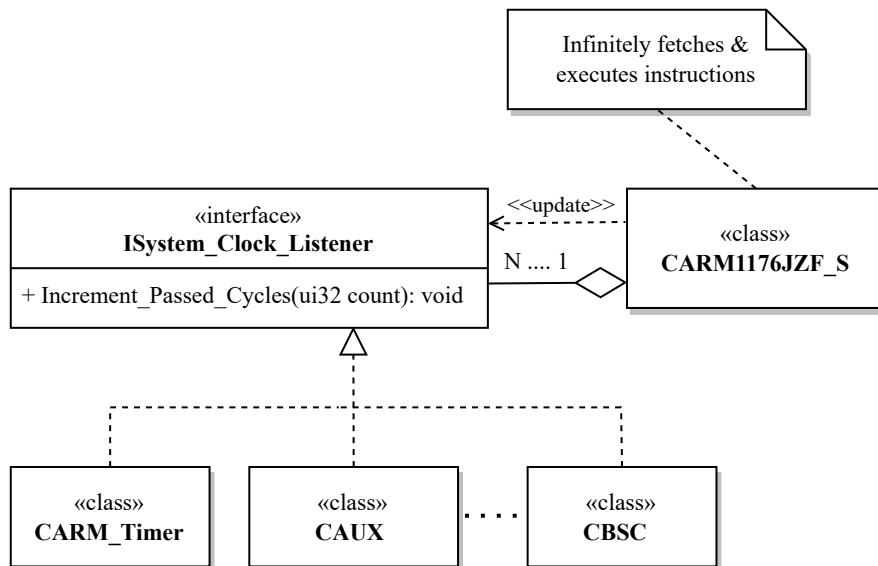


Figure 6.14: `ISystem_Clock_Listener` interface

It is important to mention that **updating a system clock listener is, from the emulated CPU's perspective, a blocking operation**. Therefore, the peripheral's callback function should avoid any unnecessary actions that might further prevent the CPU from executing the next instruction. Alternatively, updating system clock listeners could be performed asynchronously within a separate thread. However, this approach would introduce additional concurrency-related challenges that would require thorough consideration.

6.3.3.3 Random Access Memory

From an oversimplified perspective, a computer consists of two essential components; the CPU and memory. One key parameter used to classify various types of memory is their ability to retain data even after the power supply is shut down. Raspberry Pi Zero is equipped with an SD card slot, which houses non-volatile¹⁰ memory for storing the kernel image. However, from ZeroMate's point of view, this type of memory is implicitly provided by the host machine.

The board is also featured with 512MB of RAM, which functions as volatile memory for executing the kernel code. It accommodates runtime-critical sections such as the stacks¹¹, heap, page tables, or the interrupt vector table, often referred to as the IVT.

The implementation of RAM is straightforward since it can be represented as an array of bytes as shown in the figure 6.15 below. However, the downside of this approach is that it immediately takes up 512 MB of the host's RAM, which may become an issue on older computers with limited resources.

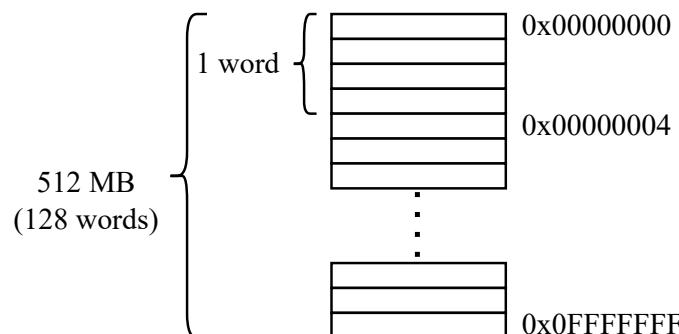


Figure 6.15: RAM implementation as a continuous piece of memory

A more effective approach would involve dynamically allocating fragmented pieces of memory as they are being addressed by the CPU. However, the author would argue that such an implementation would be algorithmically more complex, which could lead to distracting errors when implementing memory-related instruction, especially in the early stages of development. As a result, it was classified as a *nice-to-have* feature that would be worth addressing in the future once the emulator has been thoroughly QA-tested.

¹⁰Non-volatile memory is capable of persisting data even after the supply voltage is turned off.

¹¹ARM1176JZF_S uses a different set of registers for each CPU mode.

6.3.3.4 Debug Monitor

The debug monitor plays the role of a memory-mapped output device for displaying 8-bit character-based information.

The component is not included in Raspberry Pi Zero itself; its presence serves solely for debugging purposes during the development of ZeroMate.

The ZeroMate project also includes a basic driver of the peripheral that the user can seamlessly integrate into their build system. This allows them to use „**print-like**“ **functions** they might be familiar with from high-level programming languages, which may result in easier troubleshooting and resolving errors.

Source code 6.4: Demonstration of the use of the debug monitor

```

1 #include "monitor.h"
2
3 int main() {
4     bool flag = false;
5     unsigned int my_var = 155;
6
7     sMonitor << "Hello_World\n";
8     sMonitor << "myVar=" << my_var << '\n';
9     sMonitor << "flag=" << flag << '\n';
10
11    return 0;
12 }
```

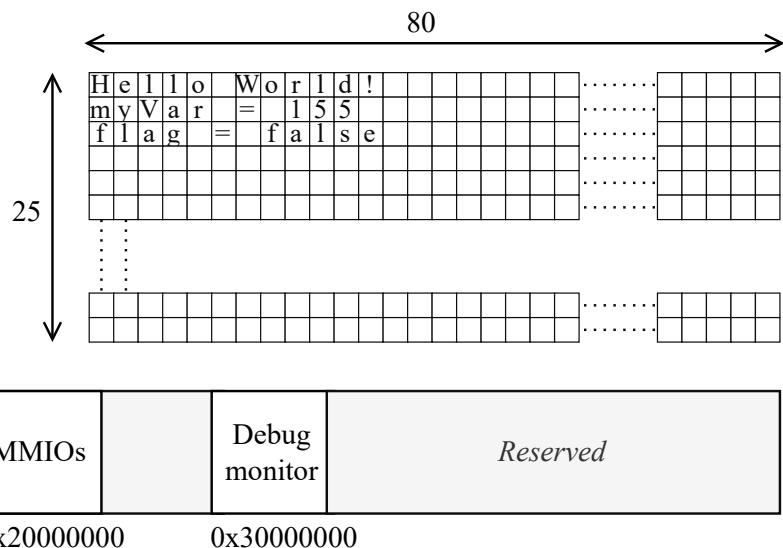


Figure 6.16: Memory-mapped debug monitor

To attain the same capabilities in practice, the user would need to utilize a form of serial communication, such as UART, through which they could transmit characters to an external device¹². This is commonly achieved by running software like *PuTTY* [22] on the user's computer.

As shown in figure 6.16, the debug monitor is mapped to an unoccupied address 0x30000000. It is structured as a flat memory region, which is managed by the driver the user code interacts with. The size of the monitor was chosen to be 80x25 8-bit characters¹³.

6.3.3.5 True Random Number Generator

The TRNG peripheral is an integrated 32-bit hardware random number generator. Although it is not documented in the official BCM2835 manual [9], its existence can be confirmed, for instance, by examining the implementation in the GNU/Linux kernel [23].

For simplification purposes, ZeroMate primarily focuses on providing random numbers while omitting more advanced features such as configuring the generator's speed, generating interrupts, or the warm-up count. The warm-up count refers to the process of generating and immediately discarding a set of random numbers before the initialization is completed¹⁴.

From the user's code perspective, the process of **retrieving a random number consists of two steps**, which are displayed in figure 6.17.

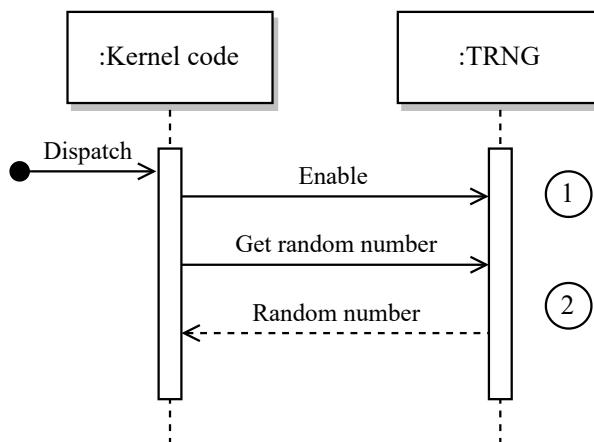


Figure 6.17: Reading random numbers from the TRNG peripheral

¹²While there are alternative methods to achieve the same functionality, this approach is among the most common ones.

¹³From an implementation point of view, it could vary in size as long as it does not overlap with other memory regions.

¹⁴The initial values are „less random“.

Enabling TRNG.

The TRNG peripheral is enabled by setting bit 0 of the **control register** to 1. If implemented, this action would also trigger the processing of „warming up“, which was mentioned previously.

Reading random numbers.

First, the user should check the availability of random numbers in the TRNG's queue by examining the most significant 8 bits of the **status register**. If this number is 0, they should wait until the generator accumulates a sufficient amount of entropy to generate a random number. When data is ready, reading from the **data register** will retrieve a random number from the queue.

ZeroMate can almost instantly generate a random number using a pseudo-random number generator. As a result, when reading the most significant 8 bits of the status register, the user will consistently receive the value 1, meaning they can read random numbers without delay.

Utilizing a pseudo-random number generator, such as an *LCG* [24] or *Mersenne-Twister*, **can greatly improve the performance of the emulation**. Depending on the implementation, accessing a true random number generator via the host operating system may have a detrimental impact on overall speed, as it may continually gather entropy from user inputs, like key presses or cursor movements. This can potentially lead to a blocking operation if there is currently insufficient entropy available.

6.3.3.6 ARM Timer

One of the most frequently used functions of the ARM timer is to periodically trigger interrupts, whether it is for toggling an LED, generating a PWM signal, or switching the current CPU context, which is an integral part of any preemptive OS scheduler.

As shown in figure 6.18, there are two data/control paths through which the timer can be interacted with. The first path, when the timer is treated as a memory-mapped peripheral, serves the purpose of reading from and writing to its internal registers in order to configure its desired functionality. This may involve steps such as setting up the prescaler, enabling interrupts, or defining the initial threshold value. The other path is used implicitly by the CPU to notify the peripheral about how many CPU cycles it took to execute the last instruction. The ARM timer then leverages the prescaler to divide the input frequency, as the main CPU frequency may not always be suitable for the given task.

As far as ZeroMate is concerned, all time-related functionalities, such as the ARM timer, UART, or I²C, are for synchronization purposes, inherently derived from the CPU's clock.

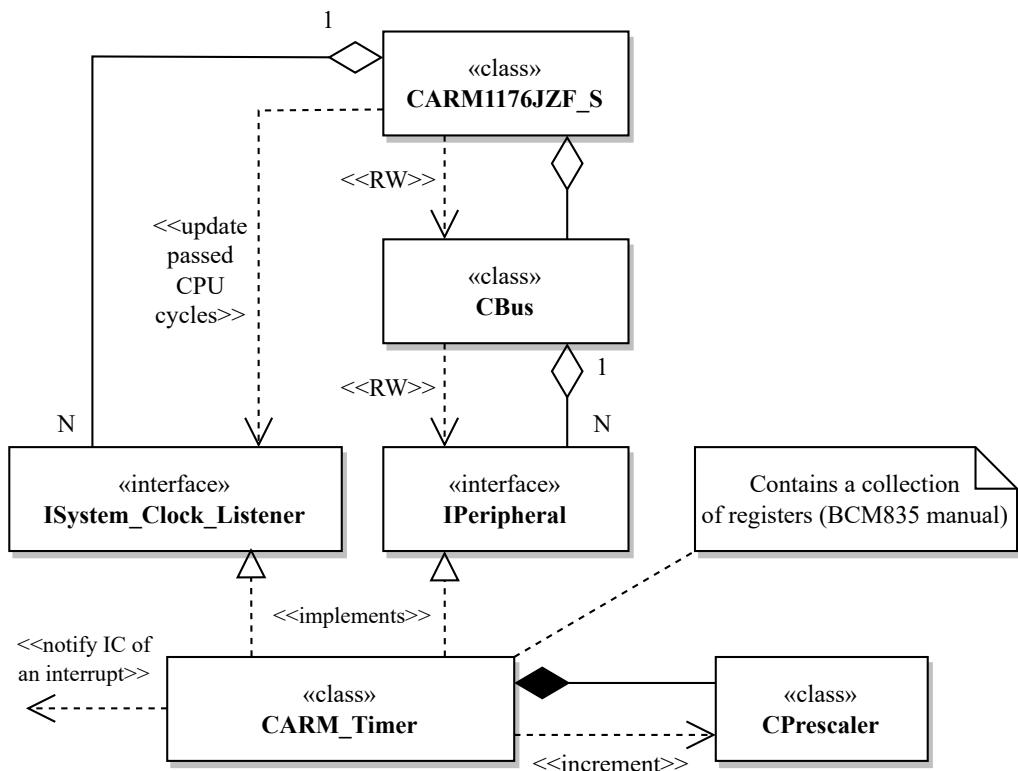


Figure 6.18: Context of the ARM timer component

As stated previously, the purpose of the prescaler is to divide the CPU's frequency by a factor of 1, 16, or 256, which ultimately affects the timer's period - how rapidly the **value register** counts down to zero. Additionally, the timer's period can be adjusted by modifying the value in the **load register**, which serves to re-initialize the value register whenever it reaches zero. If enabled, with each such event, the timer will trigger an interrupt. This concept is visualized in figure 6.19.

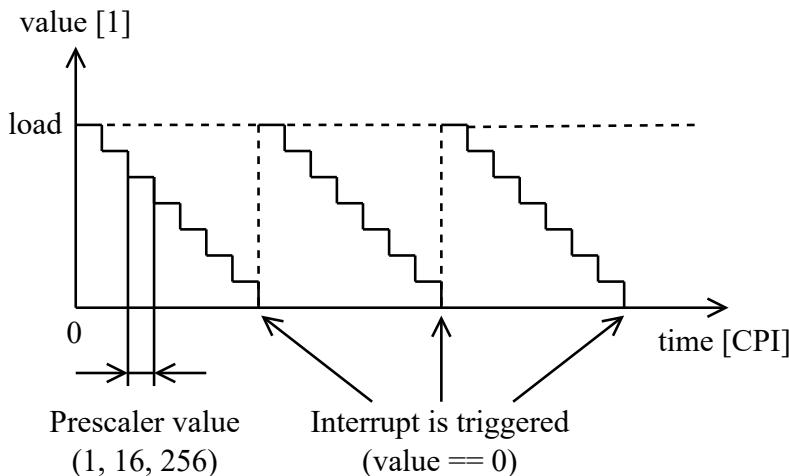


Figure 6.19: Content of the value register of the ARM timer over time

6.3.3.7 General Purpose Input/Output

The GPIO manager is a peripheral that manages the **54 general-purpose input-output pins** (GPIO) that are available to the programmer. These GPIO pins also function as a connecting interface for all external devices, which is shown in figure 6.10. Each pin is represented as a separate class encapsulating its current state, which consists of the pin's function, a list of enabled interrupts, an indication of any pending interrupts, and its current state.

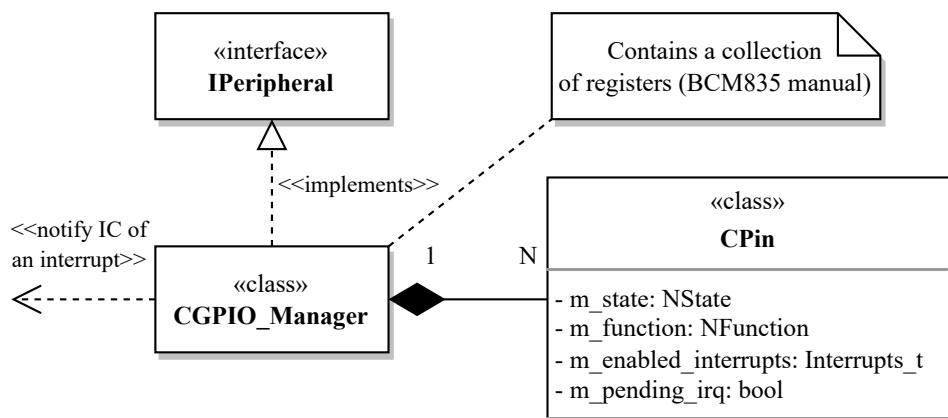


Figure 6.20: Structure of the GPIO manager¹⁵

All GPIO pin functions, as well as interrupt types, can be found explained in the **BCM2835 manual** [9].

The pin's function restricts the way the pin can be interacted with. For instance, when the user tries to read from an output pin, they will be prompted with a warning

¹⁵The CPin class also exposes a set of functions that allow the caller to access its private members.

message indicating that their action is inconsistent with the current pin configuration.

ZeroMate does not provide support for analog pins. Therefore, all GPIO pins mentioned in this document are regarded as digital pins, with only two possible states, HIGH and LOW.

Emulation of latches.

Some of the GPIO registers work, on a hardware level, as latches, which may not be as intuitive from a software emulation point of view. An example of this principle would be the GPSETx and GPCLRx registers, which respectively set an output pin to a logical one and zero. These registers are stateless, meaning they do not retain their previous state internally. One approach to emulate such behavior is to reset the register to its default value after a write operation has been performed.

Source code 6.5: SW emulation of a HW latch register

```
1 void Set_Pin_High(std::uint32_t& gpset0)
2 {
3     // Iterate over all bits of gpset0.
4     // If gpset0[i]==1, then set the
5     // corresponding pin to HIGH.
6
7     gpset0 = 0; // SW latch emulation
8 }
```

Detecting Interrupts.

Whenever the state of a pin changes, a series of checks is performed to determine whether an interrupt has occurred. One of the most commonly used types of interrupts is triggered by a change in the logical value of a specific pin, either transitioning from HIGH to LOW or vice versa. The types of interrupt to be detected for each pin can be specified in the corresponding registers. When an interrupt is detected, it is reported to the interrupt controller, which can then initiate further actions, which is captured in figure 6.20.

6.3.3.8 Interrupt Controller

The interrupt controller serves as the primary interface for managing all peripherals that can generate interrupts. Through the interrupt controller, users can enable or disable various interrupt sources, including GPIO pins, the ARM timer, and the UART peripheral. **When an interrupt is signaled to the interrupt controller, it checks whether the source is enabled; otherwise, the event is disregarded.**

From the CPU's point of view, after an instruction is executed, it checks with the interrupt controller to ascertain the existence of any pending interrupts. If the interrupt controller has a record of a pending interrupt, and global interrupts are enabled, the CPU proceeds to throw an IRQ exception.

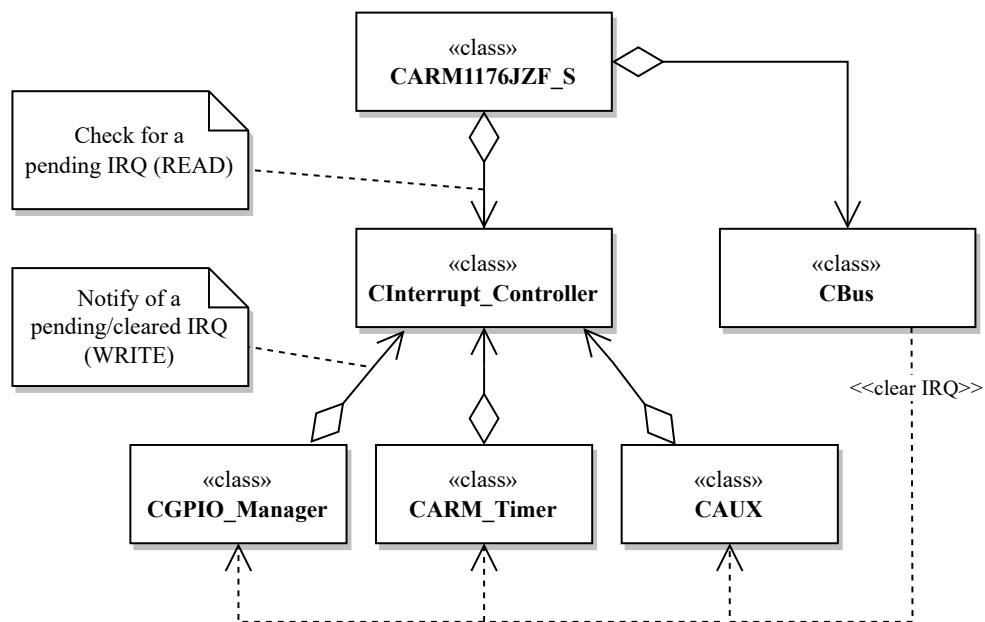


Figure 6.21: Context of the interrupt controller

In terms of design, the interrupt controller encapsulates an associative storage that pairs each IRQ source¹⁶ with its associated metadata, indicating whether it is enabled and if there is a pending interrupt. From the CPU's perspective, this storage is read-only, as its only purpose is to check for any pending interrupts. The contents of this storage are modified by the peripherals themselves, either when they generate an interrupt or clear a pending interrupt.

The ARM1176JZF_S processor also features so-called fast interrupts, or FIQ for short. However, ZeroMate does not offer support for it as it primarily focuses on fundamental principles rather than more advanced features.

¹⁶You can find a comprehensive list of all available IRQ sources in the BCM2835 datasheet [9].

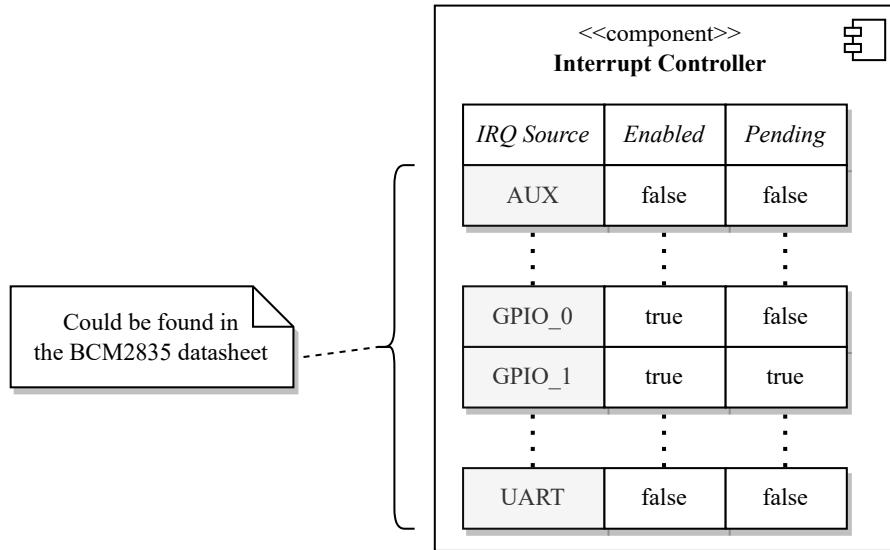


Figure 6.22: Encapsulated information about IRQ sources

It is worth mentioning that the interrupt controller of the BCM2835 microcontroller distinguishes between two types of interrupt sources: Basic IRQ and IRQ, both of which are listed in the BCM2835 datasheet [9]. Nevertheless, from a design perspective, the underlying principles remain the same.

6.3.3.9 Auxiliaries

The auxiliary peripheral comprises three distinct peripherals: Mini_UART, SPI_0, and SPI_1. Among these, only Mini_UART is currently supported by Zero-Mate.

There are two primary registers shared among all auxiliary peripherals: the enable register, responsible for activating the respective peripheral, and the IRQ register, which signals pending interrupts. The remaining registers are specific to each peripheral, as depicted in the figure below.



Figure 6.23: Registers of the AUX peripheral

Whenever a read/write request is received, using the technique described in section 6.3.3.1, the AUX class can efficiently redirect the execution to the relevant auxiliary peripheral, which will subsequently handle the request internally.

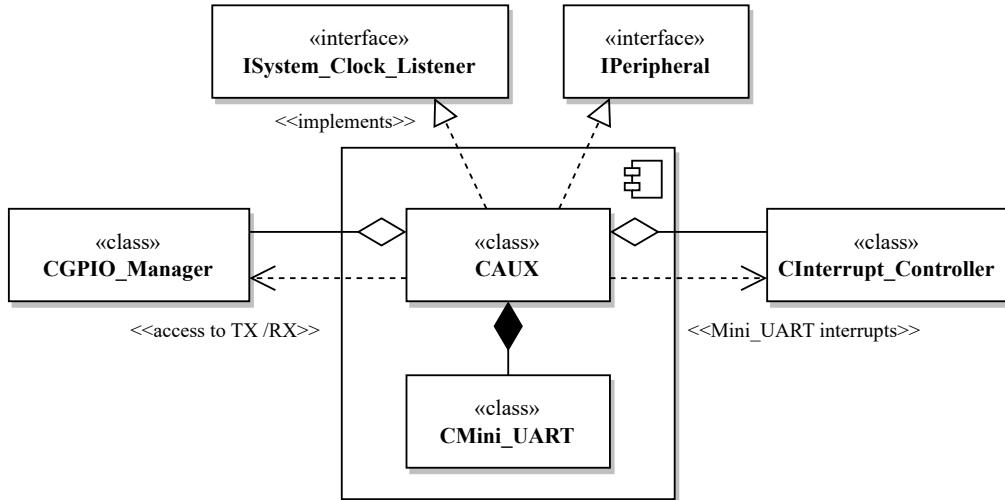


Figure 6.24: Structure of the AUX peripheral

Figure 6.24 shows the internal structure and dependencies of the AUX peripheral. It can be noticed that it implements the `ISystem_Clock_Listener` interface 6.3.3.2, which allows it to synchronize with the rest of the system.

Mini_UART.

UART, short Universal Asynchronous Receiver-Transmitter, inherently operates as asynchronous communication, which means there is no explicit synchronization between the two devices. Since these devices may have different clock speeds, they must adjust their frequencies to establish a common speed known as the baudrate, which expresses how many bits can be received/transmitted per second.

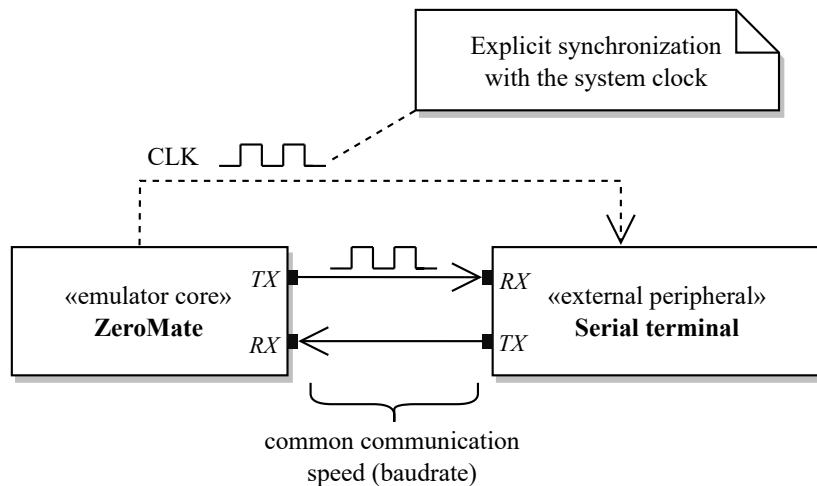


Figure 6.25: UART communication with an external peripheral

The BCM2835 microcontroller does not incorporate a full version of UART. Instead, it supports a simplified version known as Mini_UART, which omits some of

the extended features. As a result, the user is only able to modify the baudrate and the number of data bits transferred within a single frame, which can be either seven or eight. The remaining parameters, such as parity and the number of stop bits, are fixed according to the datasheet [9].

In ZeroMate, all external peripherals are provided read-only access to the system clock, enabling them to synchronize themselves if required. This approach contradicts the fundamental principles of asynchronous communication since it introduces a form of synchronization. However, this design decision was made to enhance the emulation's reliability while still enabling users to utilize **Mini_UART** as if they were interacting with real hardware.

The implementation of **Mini_UART** communication can be accomplished through a state machine driven by a pre-divided system clock as shown in figure 6.27. When a predefined number of CPU cycles have passed, the state machine updates itself to transmit and receive the next bit of the current data frame, which can be seen in figure 6.26¹⁷.

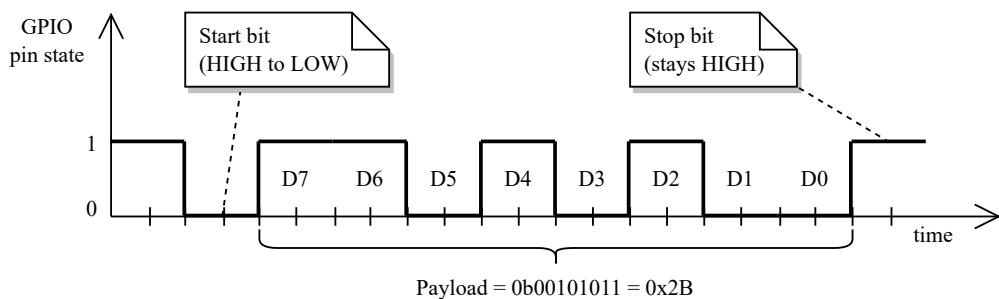


Figure 6.26: Example of a **Mini_UART** data frame with 8 bits of data

Receiving data can be implemented in a similar manner. Instead of setting the value of the TX pin, the state machine reads the value of the RX, which has been set previously by the external peripheral.

¹⁷Transmitting a single bit can be done by setting the corresponding TX pin to the desired value. Further details on what GPIO pins are designated for **Mini_UART** can be found in the datasheet [9].

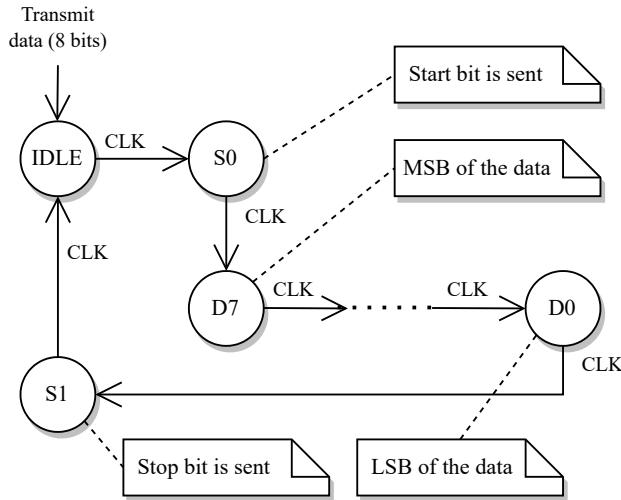


Figure 6.27: Mini_UART state machine (transmitting 8 bits)

6.3.3.10 Broadcom Serial Controller

The Broadcom serial controller, often abbreviated as BSC, is a peripheral device that allows the user to communicate with external devices, typically sensors, using the I²C protocol, which is a synchronous serial communication standard. I²C utilizes two GPIO pins: SDA for data transmission and SCL for synchronization. Raspberry Pi Zero is equipped with three of these devices that can be found mapped to their respective addresses in figure 6.12.

From a design point of view, the emulation of an I²C bus is nearly identical to UART, with the primary distinctions being the frame structure and the synchronous transmission of individual bits using an additional GPIO pin instead of the emulated CPU's clock.

While there are various configurations of the I²C communication protocol ^a, ZeroMate exclusively supports only one, which is presented in figure 6.28. As stated previously, ZeroMate emphasizes the emulation of fundamental principles, rather than attempting to implement every conceivable configuration, which would only add unnecessary complexity without delivering any added value.

^aThey vary in voltage levels for representing logical 1 and 0, as well as in how they define the start and stop bits using the SDA and SCL signals.

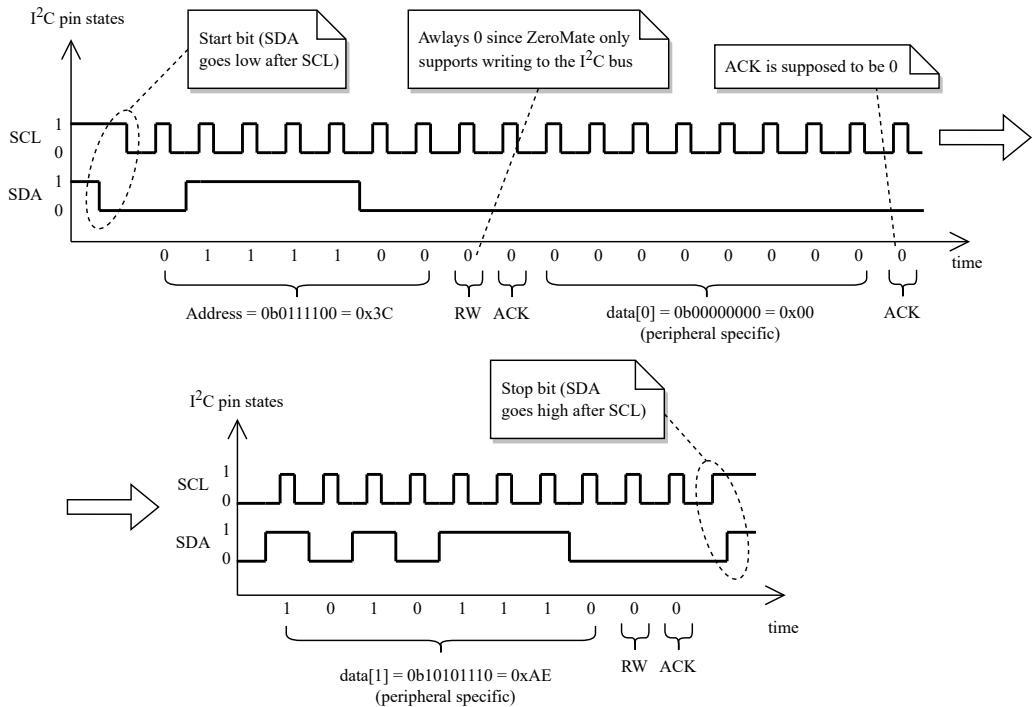


Figure 6.28: Structure of an I^2C frame

The ZeroMate emulator comes with several standalone external peripherals that employ the same communication interface. Users can connect these peripherals to the system based on their preferences using a configuration file, which is further discussed in section 6.4.

6.3.4 ARM1176JZF_S

All the previously mentioned peripherals are not self-sufficient in operation; they require external control. This is where **ARM1176JZF_S**, which serves as the central processing unit in the **BCM2835** microcontroller, comes into play, as it executes individual 32-bit ARM instructions that may utilize these peripherals in various ways.

In terms of architecture, the **ARM1176JZF_S** component is divided into several tightly integrated building blocks, as shown in figure 6.29, to maintain a structured and organized design. The subsequent sections detail how each of these sub-peripherals contributes to the overall emulation of the **ARM1176JZF_S** processor.

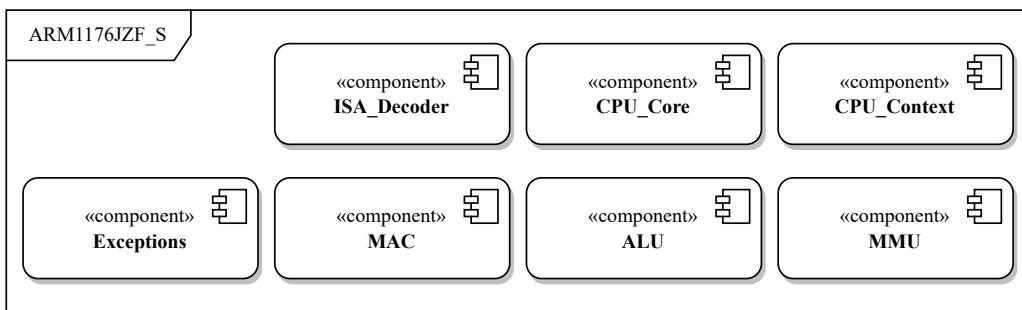


Figure 6.29: Internal components of the ARM1176JZF_S processor

6.3.4.1 Central Processing Unit Context

The **CPU context** functions as an **encapsulation of the current state of the CPU**, including details such as the current contents of the registers and the active CPU mode. It is designed to provide an interface for accessing registers, enabling transitions between different modes, and offering other utility functions that abstract the underlying low-level logic, such as reading the state of individual bits of the control register.

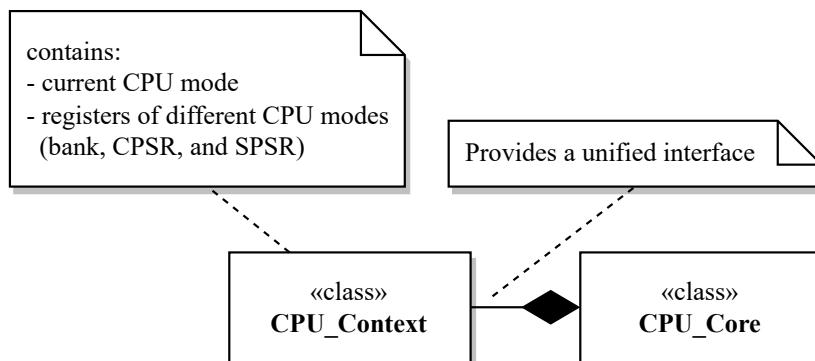


Figure 6.30: Relationship between the CPU context and the CPU core

Bank Registers.

One of the presented challenges involves implementing so-called *bank* registers, where each CPU mode possesses its distinct subset of registers that are automatically loaded when the mode changes. Additional information regarding this topic is available in section A2.3 of the official ARM Architecture Reference Manual [5].

As illustrated in listing 6.6, one approach to address this challenge involves creating a lookup table for all bank registers within each CPU mode, effectively replacing the ones used in the User/System mode, which are otherwise used by default.

Source code 6.6: Retrieving a CPU register

```

1 uint32_t& Get_Register(uint32_t idx, NCPU_Mode mode)
2 {
3     // Check if a banked register should be returned
4     if (m_banked_regs.at(mode).contains(idx))
5         return m_banked_regs[mode][idx];
6
7     // A non-banked register is being addressed
8     return m_banked_regs[NCPU_Mode::System][idx];
9 }
```

Control Registers.

The current program state register and the saved program state registers, commonly known as the CPSR and SPSR registers, are implemented in a similar way, with each CPU mode having its designated pair of these registers.

6.3.4.2 Instruction Set Architecture Decoder

The primary role of the instruction set architecture decoder, abbreviated as the ISA decoder, is to analyze a 32-bit value and ascertain the type of the ARM instruction it represents, so it could be treated and decoded accordingly. This task must be executed with the utmost efficiency, as it is repetitively performed for each instruction the CPU executes.

In the case of the emulated CPU, the ISA decoder functions as a „black box“ offering a single-function interface, as demonstrated in listing 6.7 below.

Source code 6.7: Interface of the ISA decoder

```

1 // Returns the type of a given 32-bit ARM instruction
2 [[nodiscard]] static CInstruction::NType
3 Get_Instruction_Type(uint32_t instruction) noexcept;
```

The typical and sole use-case of this interface is further illustrated in the sequence diagram shown in Figure 6.31. In this diagram, the CPU fetches the next instruction from RAM and employs the ISA decoder to determine its type, enabling it to proceed with the execution.

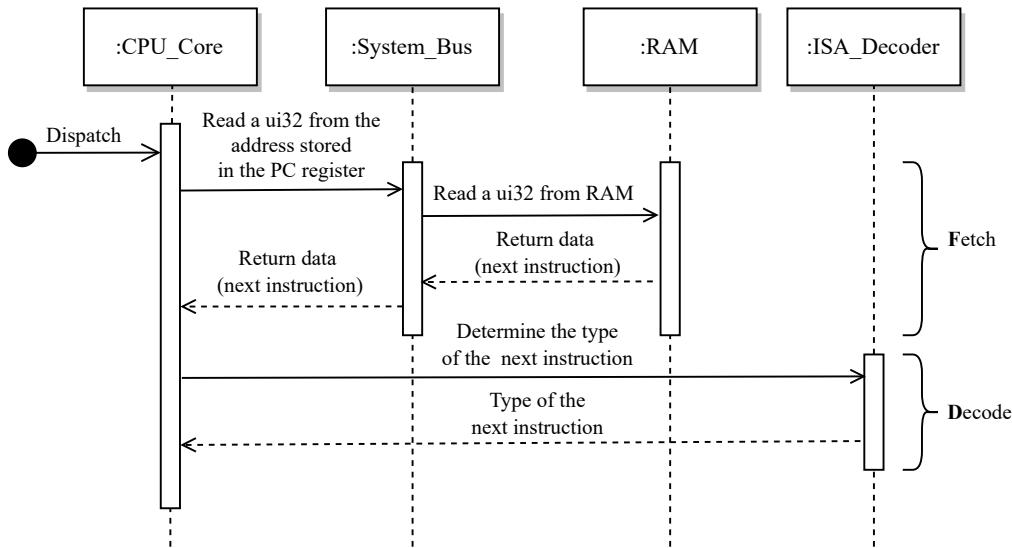


Figure 6.31: Use of the ISA decoder by the CPU

Internally, the ISA decoder maintains a look-up table of instructions masks that are sequentially applied to the given 32-bit value until the operation's result matches the expected value associated with the current mask. Each mask serves the purpose of zeroing out the variable bits specific to the instruction, leaving only the known bits in place, the expected value, which is then used to unambiguously determine the type of instruction.

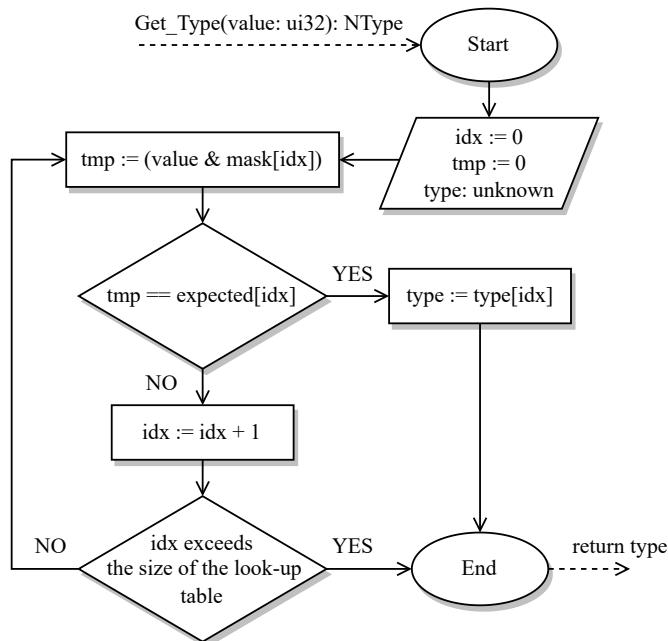


Figure 6.32: Algorithm for decoding ARM instructions

Figure 6.32 shows the algorithm for decoding ARM instructions, which, in the

worst-case scenario, operates with time complexity of $O(n)$, where n represents the size of the look-up table. **To ensure unambiguous decoding, it is essential to test the bit masks in a specific order, starting with the most restrictive one and proceeding to the least restrictive one, based on the number of bits set within each mask.** Otherwise, there might be a risk of incorrectly identifying the instruction type, inevitably leading to unexpected behavior.

Once an instruction is classified, the 32-bit value can be encapsulated within its corresponding class representation, providing an interface to access the specific fields relevant to that instruction. The contents of the look-up table can be constructed using resources such as the B2 Appendix authored by Andrew Sloss and Chris Wright, which provides ARM instruction encodings [7].

6.3.4.3 Exceptions

Exceptions can originate from various components within the ZeroMate emulator. These exceptions may arise from factors such as the absence of an addressed page, unaligned memory access, or the execution of a privileged instruction in a non-privileged CPU mode. ZeroMate handles ARM CPU exceptions as runtime errors on the host machine. As a result, the emulated CPU core must be prepared for the possibility that the currently executing instruction may abruptly trigger an exception that must be properly handled. Figure 6.33 shows the hierarchy of CPU exceptions, where each class may include additional information pertaining to the exception, such as a descriptive message, the address at which it occurred, or the address of the vector associated with that specific exception.

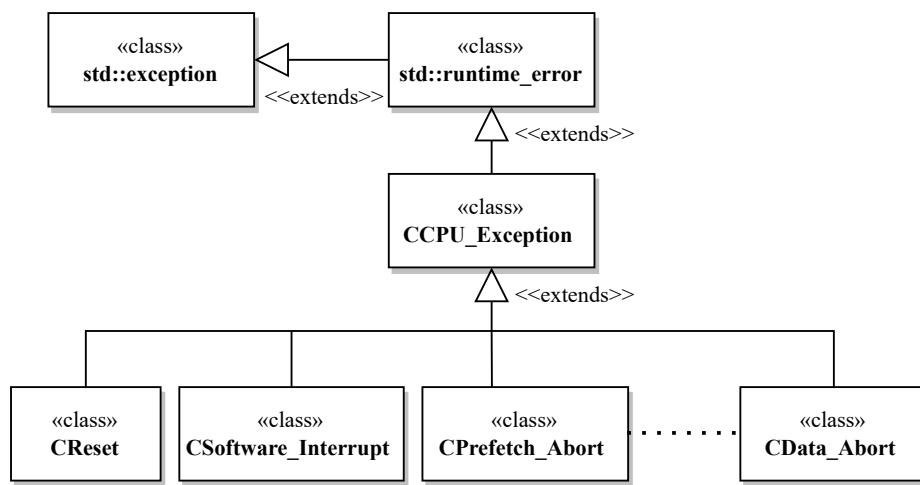


Figure 6.33: Hierarchy of the CPU exceptions

6.3.4.4 Arithmetic-Logic Unit

As the name suggests, the arithmetic-logic unit, also known as the ALU, is responsible for carrying out **arithmetic and logical operations**, such as addition, subtraction, comparison, etc.

From a design standpoint, the ALU can be envisioned as a set of collaborative functions concealed behind a single function interface, which is made accessible to the central processing unit as shown in figure 6.34.

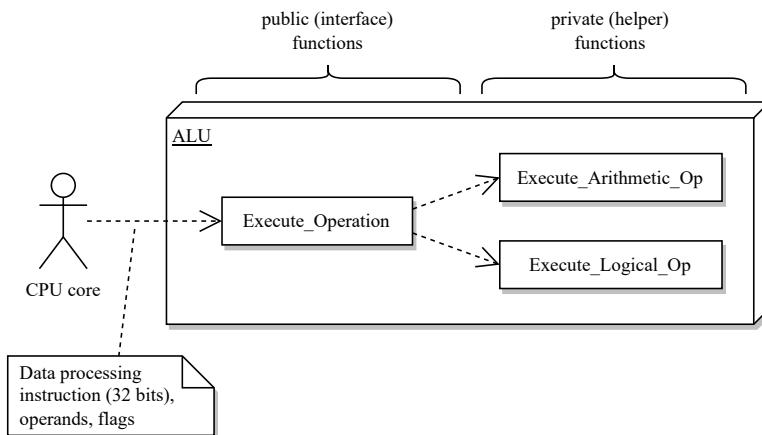


Figure 6.34: Architectural structure of the ALU

As illustrated in the figure above, when the ALU is employed, the CPU must provide both the current state of its flags and the data processing instruction currently in execution, which is internally analyzed by the ALU to determine the specific type of operation to be carried out.

MAC Unit.

The ARM1176JZF_S also incorporates a module referred to as MAC, specifically designed for performing a variety of **multiplication operations**. These operations can involve the multiplication of either signed or unsigned 32-bit integers, signed or unsigned 64-bit integers, or multiplication with addition, where a third value is added to the result of the multiplication. All instruction encodings can be found in the B2 Appendix document [7]. From an implementation perspective, it can be integrated in a manner similar to the ALU.

6.3.4.5 Memory Management Unit

If enabled, the memory management unit, often referred to as the MMU, comes into play just before the CPU sends a read/write request to the system bus. **Its primary function is to convert a 32-bit virtual address into a corresponding 32-bit**

physical address based on the information stored in the corresponding page table, allowing the user to reorganize the address space to their needs. Furthermore, it performs a series of checks, the failure of which could result in a MMU abort¹⁸.

1. In the initial step, the MMU retrieves the page associated with the address from the first-level page table to ascertain its type. This type indicates whether it references a nested second-level page table or a physical frame. In the latter case, the MMU also confirms the page's presence in RAM, as it might have been swapped out, for example, to a file.
2. When addressing a physical frame, the MMU checks access privileges to the targeted frame based on the current mode of the CPU in order to ensure that no security policy is being violated.

If all checks have been successfully passed, the MMU proceeds to convert the virtual address into a corresponding physical one. More detailed information about how the MMU operates can be found in chapter 6 of the ARM1176JZF_S Technical Reference Manual [8].

The ZeroMate emulator lacks support for nested page tables, which inevitably introduces certain limitations in the emulation. As a result, it utilizes a first-level page table that spans over the entire address space.

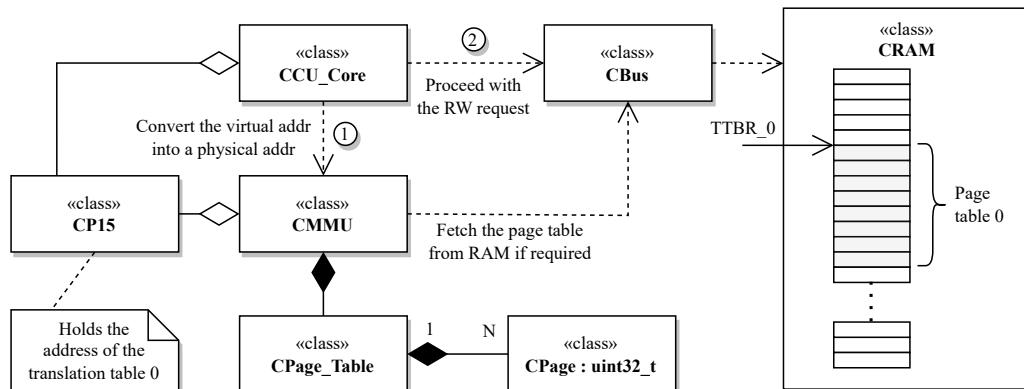


Figure 6.35: Utilization of the MMU when processing a RW request

Placing a strong emphasis on the Memory Management Unit (MMU), Figure 6.35 illustrates the essential steps to be taken when executing a read/write instruction. Whenever the address of page table 0 changes in the TTBR_0 register, the MMU retrieves the entire page table from RAM and stores it within its private data structure.

¹⁸Users of the x86 architecture might already be acquainted with the concept of a *page fault*, which, in this context, can be thought of in a similar way.

This approach eliminates the need to repeatedly read it for each memory access, which would otherwise negatively impact the overall performance of the emulation. Once a physical address is obtained, the CPU can then proceed with the request.

Implementation.

The implementation of a first-level page table can be tacked as an array of 4096 classes called `CPage`¹⁹. These classes serve as an abstraction for accessing individual fields of individual pages, where each page is represented as a 32-bit value.

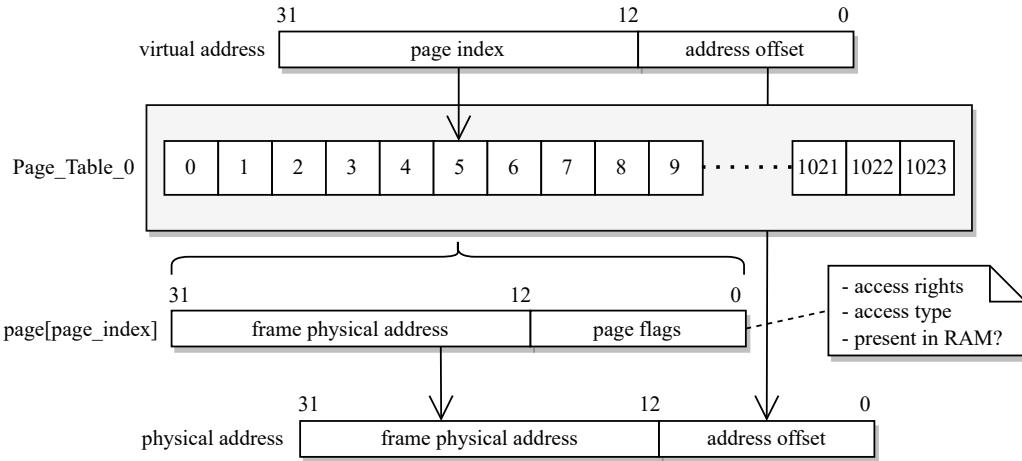


Figure 6.36: Structure of the first-level page table

Translation Lookaside Buffer.

Once a virtual address undergoes the process of translation, it is stored, along with its corresponding physical address, in a look-up table²⁰. In a real system, this table is known as the Translation Lookaside Buffer, or TLB for short. The next time the same address is used, it doesn't have to go through the translation process again, which enhances performance. When a request is made to invalidate the TLB through co-processor 15, ZeroMate clears this associative data structure to prevent invalid addressing across various virtual address spaces.

¹⁹ Assuming the page granularity is 1MB, covering the entire 4GB address space requires 4096 page table entries.

²⁰ It can be implemented, for instance, as an `std::unordered_map<uint32_t, uint32_t>`

6.3.4.6 Central Processing Unit Core

The central processing unit utilizes the functionality of all previously mentioned components. In terms of design, it is composed of multiple private member functions that are invoked based on the type of instruction currently being executed. These functions can be seen as microprograms, as they handle the specific operations associated with the current instruction.

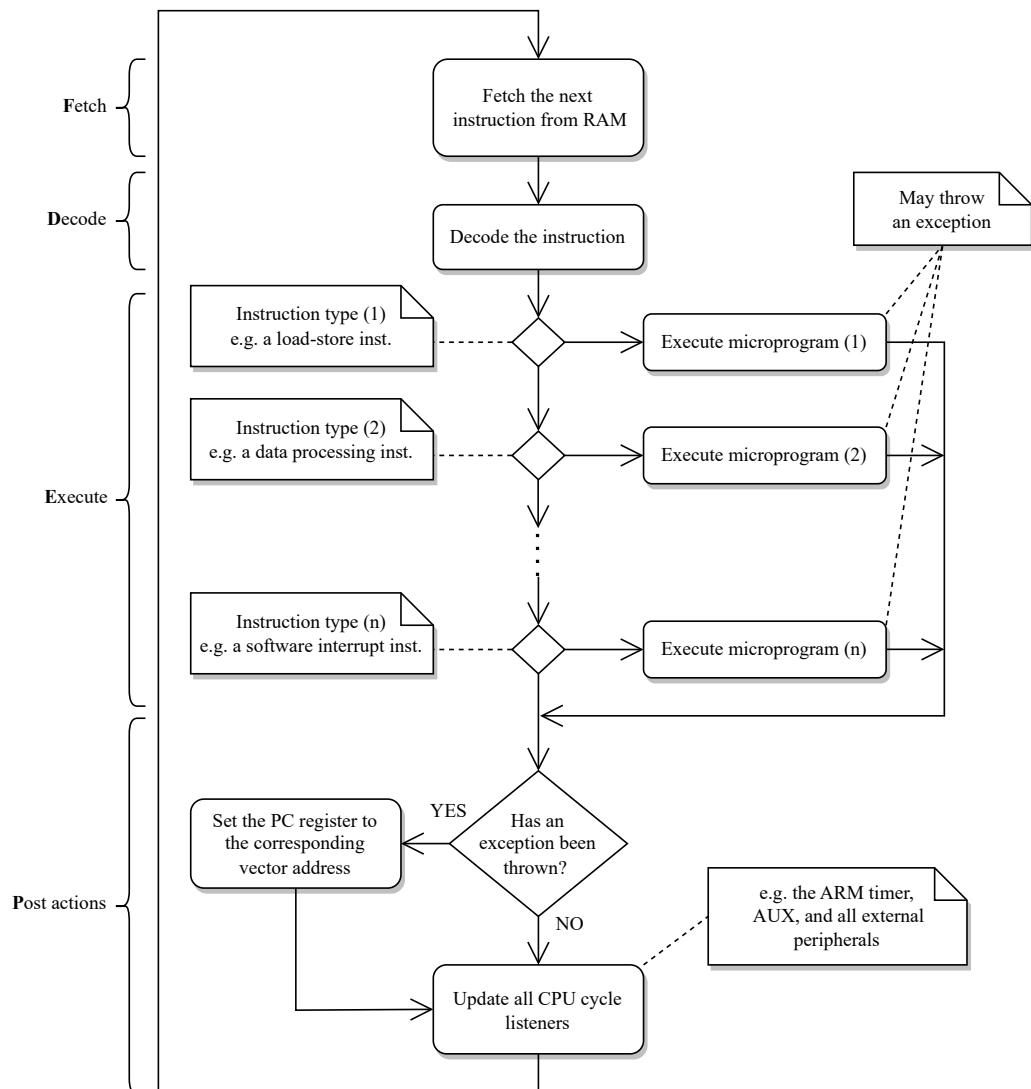


Figure 6.37: Execution loop of the emulated CPU

As shown in figure 6.37, the microprograms are called within an infinite loop known as the execution loop, which fetches the next instruction from RAM, decodes it using the ISA decoder, and directs the execution to the appropriate microprogram responsible for carrying out the necessary steps to execute it. These steps

may include tasks such as reading data from the stack, modifying register contents, utilizing the arithmetic-logic unit, and more.

It is worth noting that a real system is significantly more complex than how ZeroMate implements it. However, the author would contend that any form of emulation involves trade-offs that result in the omission of certain details.

Catching Exceptions.

As described in section 6.3.4.3, the CPU must handle any exceptions that may arise during the execution of the current instruction. When an exception occurs, the CPU switches to the corresponding mode, saves the return address in the link register, as if it were invoking a function call, and sets the address of the next instruction to the value stored at the corresponding offset in the interrupt vector table.

Updating CPU clock listeners.

As discussed in section 6.3.3.2, prior to advancing to the next instruction, the CPU informs all peripherals subscribed as system clock listeners about the number of CPU cycles required to execute the previous instruction.

While it is true that each instruction may require a varying number of CPU cycles for execution, in the current implementation, ZeroMate empirically averages this number to 8, which presents a potential area for future improvement. Users should be aware that the emulation speed does not match the speed of real hardware, and as a result, they may need to adjust timings in their firmware accordingly.

6.3.5 Co-processors

ZeroMate takes into account two co-processors, the design and functionality of which are described in the following two sections. Although their capabilities may be somewhat limited compared to what a real system offers, they serve the purpose of demonstrating the fundamental principles of interactions that can also be applied in practice.

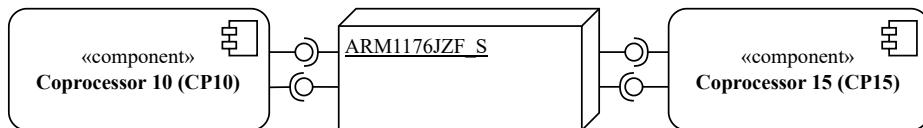


Figure 6.38: Component diagram of the CPU and its co-processors

The CPU communicates with individual co-processors through three types of instructions: *data transfer*, *register transfer*, and *data operation*. When the emulated

CPU detects a co-processor instruction, it does not perform any further analysis but promptly delegates it to the appropriate co-processor, determined by the ID encoded within the instruction itself. The co-processor then internally performs decoding and execution of the instruction using technique similar to that used by the emulated CPU.

Although the ZeroMate emulator currently accommodates only two co-processors, its overall design allows for a seamless integration of additional ones in the future, should the need arise. As shown in figure 6.39, the CPU maintains a collection of available co-processors, all of which implement the same interface, through which they are controlled by the CPU.

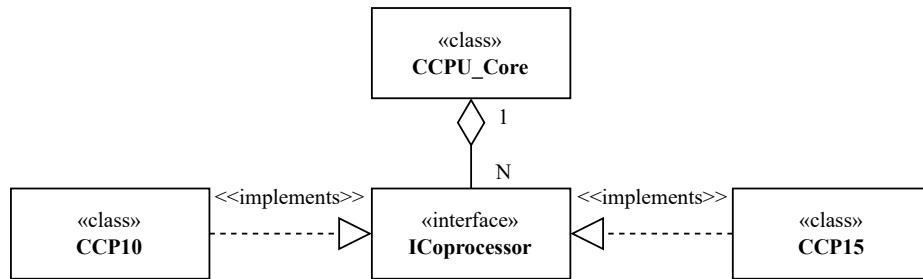


Figure 6.39: Co-processor hierarchy

6.3.5.1 Co-processor 15

The system control co-processor (CP15) comprises a tree-like hierarchy of 32-bit registers that are used to enable a variety of additional features. These features include caching policy, branch prediction, unaligned memory access, setting up access to other co-processors, and many more²¹. As far as ZeroMate is concerned, its emulation efforts are directed primarily towards the following registers.

Table 6.1: List of emulated CP15 registers

Primary register	Secondary Index register	Description
C1	C0	Control Register (see table 6.2)
	2	Co-processor Access Control Register
C2	C0	Translation Table Base Register 0 (TBBR_0)

(table continues on the next page)

²¹The list of all registers along with their functions can be found detailed in chapter 3 of the ARM1176JZF_S Technical Reference Manual [8].

Table 6.1 (*continued from the previous page*)

Primary register	Secondary Index register	Description
	1	Translation Table Base Register 1 (TBBR_1)
	2	Translation Table Base Control
C8	C7	Invalidate unified TLB unlocked entries

Other frequently used CP15 registers are implemented for the purpose of completeness, even though modifying them has no effect. If a user's firmware attempts to write to an unimplemented register, a warning message will be displayed, indicating this specific functionality is beyond the emulator's capabilities.

Table 6.2: List of emulated flags of the CP15 control registers

Bit position	Description
0	Enables the MMU
13	Determines the location of exception vectors (0x00000000 vs 0xFFFF0000)
22	Enables unaligned data access operations

From an emulation perspective, CP15 serves as an organized repository of information that is queried from within other components of the application, so they can, if required, carry out their designated actions accordingly.

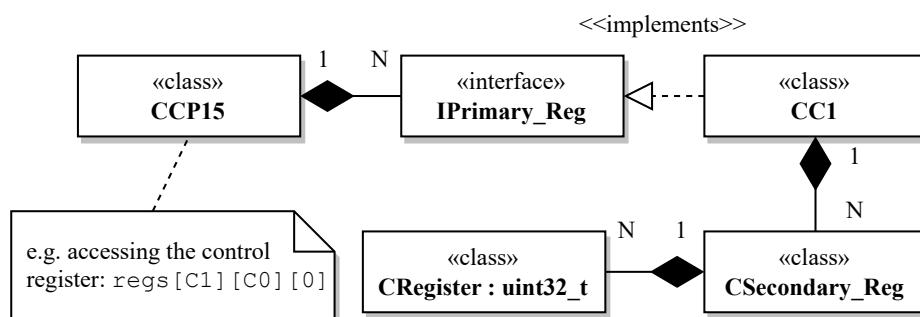


Figure 6.40: Design of the co-processor 15 register hierarchy (uses primary register C1 as an example)

6.3.5.2 Co-processor 10

Co-processor 10 allows users to work with single-precision (32-bit) floating-point numbers. The design of this co-processor closely resembles that of the CPU, as illustrated in figure 6.37. In this design, each instruction is first decoded and consequently executed within a private member function, which can be considered a microprogram.

While ZeroMate supports most common vector floating-point instructions of version 2 (VFPv2 ^a), including addition, subtraction, multiplication, division, and square root, it simplifies its implementation by omitting support for various rounding modes and floating-point exceptions.

^aAll VFP instruction can be found listed in chapter C3 of the ARM1176JZF_S Technical Reference Manual [8].

In terms of design, the floating-point unit, commonly denoted as the FPU, consists of an array of 32 internal registers, each 32 bits in size. Despite representing floating-point numbers, their underlining data type remains `uint32_t`, enabling seamless data exchange between the CPU and the FPU.

However, it is essential to emphasize that all operations must be executed as floating-point operations. As a result, the 32-bit number can be encapsulated within a class that overrides its math operators, effectively hiding implementation details from the caller. Whenever an operation needs to be carried out, the register internally performs the following steps.

1. For all operands, convert the raw 32-bit value into a `float` using the IEEE 754 floating-point representation [25]. This conversion can be accomplished through the helper member function shown in source code 6.8.
2. Carry out the floating-point operation.
3. Store the result back as a `uint32_t` using the same technique demonstrated in source code 6.8.

Source code 6.8: Conversion between `uint32_t` and `float`

```
1 template <typename Type>
2   [[nodiscard]] Type Get_Value_As() const
3 {
4   return std::bit_cast<Type>(m_value); // since C++20
5 }
```

6.4 External Peripherals

All the modules described previously form the core of the emulator, which is compiled as a standalone application. Furthermore, the **ZeroMate emulator offers a public single-header interface that enables the implementation of third-party external peripherals**, which can be compiled independently of the toolchain used for the core itself. In other words, users can choose their preferred programming language for developing an external peripheral, with the condition that they implement the interface and compile it as a shared library²².

Using a configuration file, these external peripherals can be then loaded by the core at runtime, enabling the user to create a custom circuit of external peripherals. Compiling as a shared library offers the advantage of creating multiple instances of the same peripheral. For instance, the user can employ multiple instances of `led.dll` to assemble a traffic light system, which can then be controlled by their custom firmware.

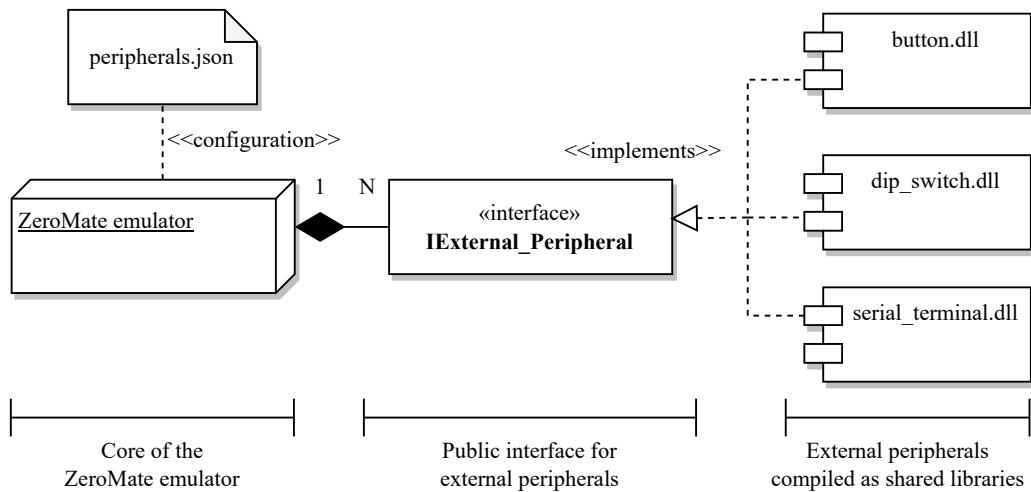


Figure 6.41: External peripheral interface

6.4.1 External Peripheral Interface

Upon construction, **every external peripheral is given access to the GPIO pins**, as it is their primary way of interaction with the core of the emulator. The interface also mandates that they implement a `Get_GPIO_Subscription` function, responsible for returning a set of GPIO pins they wish to subscribe to²³. Whenever the state

²²The format of a shared library is `.dll` on Windows and `.so` on Linux, respectively.

²³ZeroMate allows for connecting multiple external peripherals to the same GPIO pins, effectively creating a parallel connection.

of a GPIO changes, the emulator iterates through all external peripherals, examining their GPIO subscriptions, and duly informing them of the change. Additionally, they receive information about the number of CPU cycles it took to execute the last instruction, the same way internal peripherals do, effectively serving as an emulated replacement for an independent system clock.

Certain external peripherals, such as a serial terminal, come with their own system clock. However, in ZeroMate, all timing functions derived from the emulated CPU frequency.

Optionally, **they are provided access to the logging system**, which proves to be invaluable for debugging or providing insights into their current state. External peripherals are not obliged to implement a graphical user interface; nevertheless, they are implicitly provided with a context that they can utilize to render themselves within each frame.

6.4.2 Configuration

Upon startup, ZeroMate attempts to read a single configuration file in the JSON format that details the connections of external peripherals. Table 6.3 outlines the obligatory fields that must be provided for every peripheral. ZeroMate handles the construction and management of all external peripherals within its dedicated address space on the host machine.

Table 6.3: Information stored in `peripherals.json`

Field	Example	Description
name	"7-segment Display"	Unique name associated with the peripheral
connection	[2, 3, 4]	Set of GPIO pins the peripheral is connected to
lib_dir	"peripherals"	Directory where the shared library is held
lib_name	"seven_seg_display"	Name of the shared library

Figure 6.42 provides a visual representation of a custom connection that connects two 7-segment displays in parallel, having them simultaneously display the same piece of information.

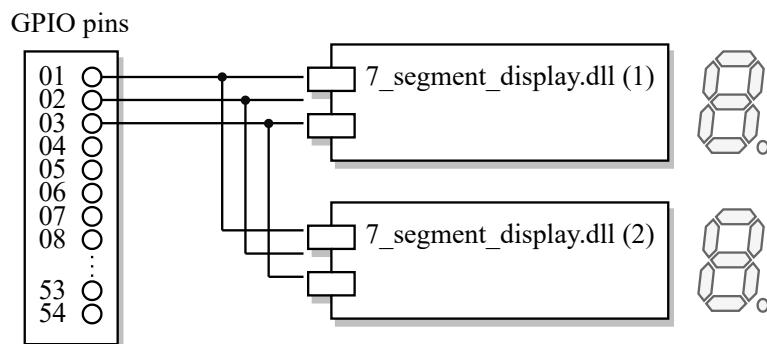


Figure 6.42: Illustration of connection of two parallel 7-segment displays

6.4.3 Examples of External Peripherals

ZeroMate is shipped with several external peripherals out of the box, most of which mirror the ones found on the DPP-01 board [26], which was designed for educational purposes within the KIV/OS class at the University of West Bohemia.

Table 6.4: List of emulated external DPP-01 peripherals

Peripheral	Additional information
button.dll	-
dip_switch.dll	-
led.dll	Features multiple color support
7_seg_display.dll	7-segment display controlled via a shift register
ssd1306_oled.dll	OLED display controlled via the I ² C protocol

Table 6.5: List of additional external peripherals

Peripheral	Additional information
serial_terminal.dll	Used for the UART communication
logic_analyzer.dll	Visualization of GPIO pins' state over time

6.4.3.1 Serial Terminal

The serial terminal serves as the **counterpart in full-duplex UART communication**, enabling the user to communicate externally with the firmware running in the emulator. In practice, this is exemplified by programs such as *PuTTY* [22], which establish communication with the development board through the host's operating system. From a design perspective, it employs the same algorithmic techniques as those described in section 6.3.3.9.

6.4.3.2 Logic Analyzer

The logic analyzer works as a **read-only observer of the current state of the GPIO pins** it is connected to. It graphically represents their state over time, allowing the user to visually debug individual frames of various low-level communication protocols, such as UART or I²C.

Depending on the specific use-case, the logic analyzer can either periodically sample the state of the GPIO pins ²⁴, or it can sample them whenever there is a change in the state of any of the monitored pins. This feature can be especially valuable when observing synchronous types of communications.

6.5 Logging System

The ZeroMate project implements a custom logging system, which can be utilized both within the emulator's core and by the external peripherals. From a design perspective, the logging system component serves as a central access point, acting as a proxy to forward log messages to individual endpoint loggers. This design enables the implementation of multiple loggers for various purposes, such as logging to a file, console, or graphical user interface.

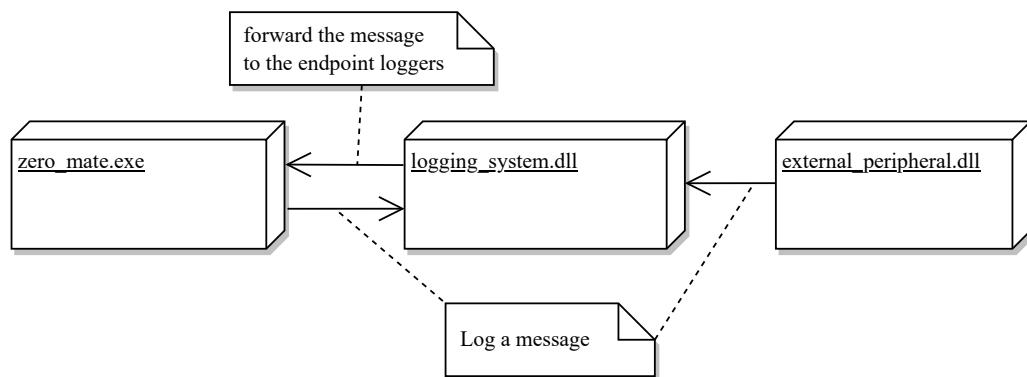


Figure 6.43: Utilization of the logging system throughout the project

²⁴The frequency is derived from the emulated CPU clock.

The logging system is compiled separately as a shared library, making it usable across all project targets. When it receives a message, it applies a uniform formatting and forwards it to all endpoint loggers.

The **ILogger** interface requires that all endpoint loggers implement the *Debug*, *Info*, *Warning*, and *Error* callback functions, which are commonly found in the majority of logging systems. Moreover, each endpoint logger can have a different logging level²⁵, allowing them to filter out messages that do not meet their specific criteria.

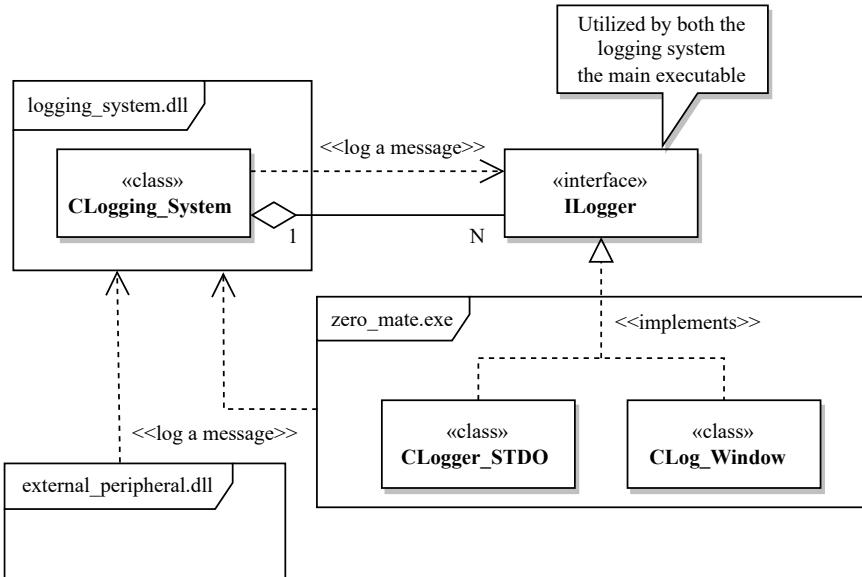


Figure 6.44: Hierarchy of endpoint loggers utilized by the logging system

6.6 User Interface

ZeroMate places a strong emphasis on the visual aspects of emulation, aiming to assist the user in debugging and troubleshooting potential bugs or issues. It serves as a frontier interface, through which the user can interact with the emulator and view the current system's state. ZeroMate consists of a set of hierarchically structured windows, each displaying information about distinct aspects of the emulator's core.

Figure 6.45 shows the architectural structure of all GUI windows, with each window being periodically rendered within each frame.

²⁵For instance, when the logging level is set to *Warning*, the logger will only accept messages classified as *Warning* or *Error*.

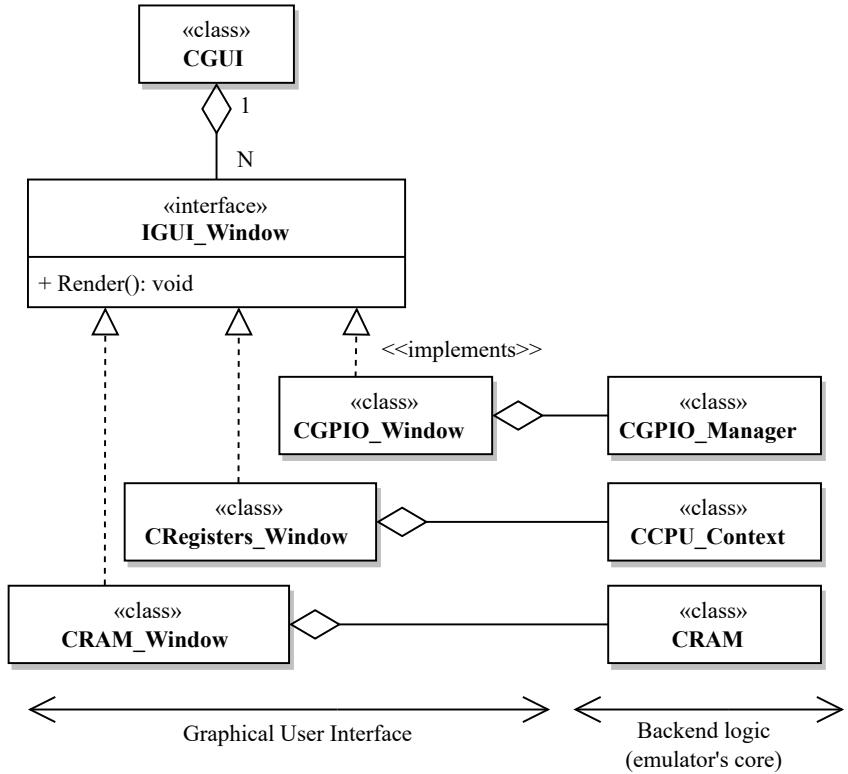


Figure 6.45: Structure of GUI windows

From figure 6.45, it can be observed that every class windows has access to the part of the emulator's core whose state is supposed to visualize. This imposes a one-direction dependency, allowing the core to be potentially used with different GUI libraries in the future, should the need arise.

In general, all windows can be categorized into three main types: *component windows*, *utility windows*, and the *primary source code window*. The component windows are designed to display the current state of specific components, such as the CPU context, RAM, CPU registers, co-processors, and others. Utility windows aim to enhance the user experience. This category includes windows like the logging window, the top bar menu, and the control window, which enable users to control the state of execution. Lastly, the primary source code window is arguably of utmost importance, as it presents the disassembled source code organized into different functions. It provides the user with information about the current line of execution and it allows them to set breakpoints at their desired locations.

Further design as well as implementation details regarding both the core and GUI components can be found in the documentation generated from the source code. This documentation is accessible online through GitHub Pages [27].

Yet to be done....

Did some emulation speed measurements...426,922,064 instructions of KIV-RTOS (TODO: append the raw data into the attachments); top 3 most frequently insts. highlighted

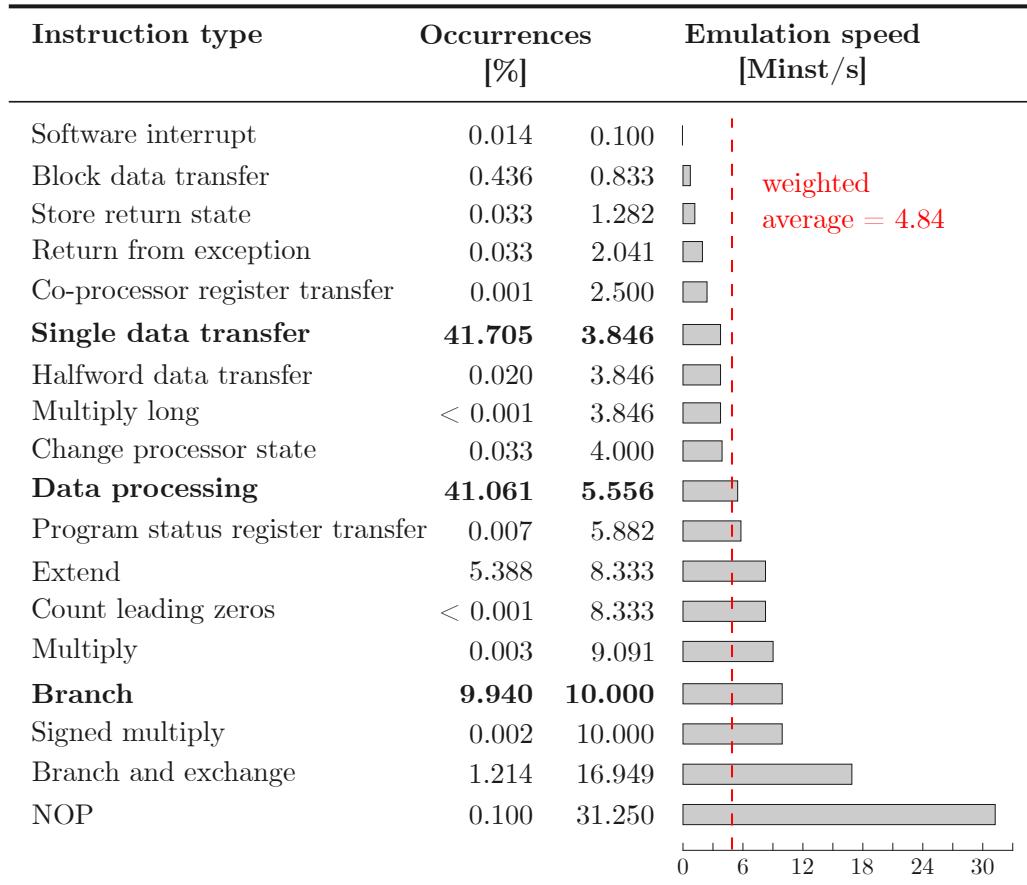


Figure 6.46: ZeroMate's emulation performance of KIV-RTOS

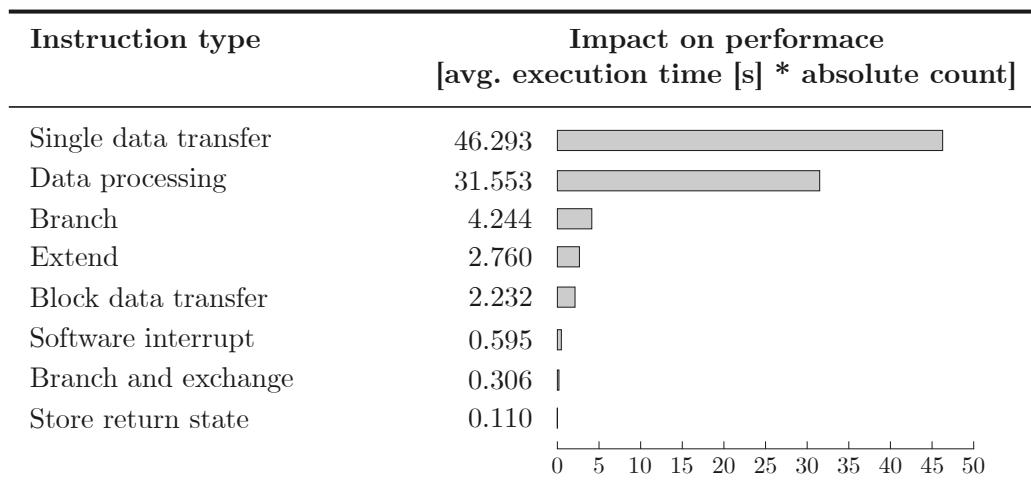


Figure 6.47: Top 8 most performance-affecting instructions

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List of Abbreviations

SIMD - Single Instruction/Multiple Data
IoT - Internet of Things
ARM - Advanced RISC Machines
RAM - Random Access Memory
ROM - Read-Only Memory
ELF - Executable Linkage Format
GPU - Graphics Processing Unit
SREC - Motorola S-record (file format)
GUI - Graphical User Interface
EEPROM - Electrically Erasable Programmable Read-only Memory
CPU - Central Processing Unit
ALU - Arithmetic-Logic Unit
MAC - MAC Unit (performs multiply-accumulate operations)
MMU - Memory Management Unit
ISA - Instruction Set Architecture
MMIO - Memory-mapped Input-Output device
I/O - Input-Output
R/W - Read-Write
ABI - Application Binary Interface
RTTI - Run-Time Type Information
GPIO - General Purpose Input/Output
LED - Light-emitting diode
SD - Secure Digital
IVT - Interrupt Vector table
QA - Quality Assurance
UART - Universal Asynchronous Receiver/Transmitter
TRNG - True Random Number Generator
LCG - Linear Congruential Generator
OS - Operating System
 I^2C - Inter-Integrated Circuit
SPI - Serial Peripheral Interface CPI - Cycles Per Instruction

List of Abbreviations

IC - Interrupt Controller
PWM - Pulse Width Modulation
IRQ - Interrupt Request
FIQ - Fast Interrupt Request
AUX - Auxiliary
MSB - Most Significant Bit
LSB - Least Significant Bit
TX - Transmit
RX - Receive
BSC - Broadcom Serial Controller
CPSR - Current Program Status Register
SPSR - Saved Program Status Register
TLB - Translation Lookaside Buffer
TTBR - Translation Table Base Register
CP10 - Co-processor 10
CP15 - Co-processor 15
VFP - Vector Floating-Point
FPU - Floating-Point Unit
OLED - Organic Light-Emitting Diode
STD0 - Standard Output
SP - Stack Pointer
RISC - Reduced Instruction Set Computer
CISC - Complex Instruction Set Computer
ACC - Accumulator
LIFO - Last-In-First-Out
FPGA - Field Programmable Gate Array
SoC - System on Chip
HDMI - High-Definition Multimedia Interface
USB - Universal Serial Bus
SDRAM - Synchronous Dynamic Random Access Memory
VGA - Video Graphics Array

List of Figures

2.1	Von Neumann architecture	8
2.2	Harvard architecture	9
2.3	Stack architecture ²⁶	9
2.4	Accumulator architecture	10
2.5	Load-store architecture	10
2.6	Load-store sequence diagram	11
3.1	Devices leveraging ARM technology	13
3.2	ARM processor roadmap	14
3.3	Features of different ARM processor cores	15
3.4	Possible locations of the interrupt vector table in RAM	17
3.5	Bank registers of different CPU modes	19
3.6	Current Program Status Register ²⁷	20
3.7	Condition field of an ARM instruction	21
3.8	Context of an ARM co-processor	22
3.9	Floating-point registers	23
4.1	Raspberry Pi Zero board	25
4.2	BCM2835 address translation processes	27
5.1	Emulation vs. virtualization	30
5.2	CPUlator	31
5.3	ARMSim#	33
6.1	Single SREC record (16-bit addressing)	38
6.2	Process of building an ELF file (input for the emulator) ²⁸	38
6.3	Primary use-cases of the ZeroMate emulator	39
6.4	Deployment diagram of the ZeroMate emulator	39
6.5	Core components of the ZeroMate emulator	40
6.6	Example of a read/write data request issued by the CPU	41
6.7	Collection of memory-mapped peripherals	42
6.8	Loading an input ELF file (kernel)	44

6.9	Internal logic of the ELF Loader component	45
6.10	Internal vs External peripherals	46
6.11	Hierarchy of internal peripherals	46
6.12	BCM2835 physical memory layout emulated by ZeroMate	47
6.13	Writing to a peripheral's register ²⁹	48
6.14	ISystem_ClockListener interface	49
6.15	RAM implementation as a continuous piece of memory	50
6.16	Memory-mapped debug monitor	51
6.17	Reading random numbers from the TRNG peripheral	52
6.18	Context of the ARM timer component	54
6.19	Content of the value register of the ARM timer over time	55
6.20	Structure of the GPIO manager ³⁰	55
6.21	Context of the interrupt controller	57
6.22	Encapsulated information about IRQ sources	58
6.23	Registers of the AUX peripheral	58
6.24	Structure of the AUX peripheral	59
6.25	UART communication with an external peripheral	59
6.26	Example of a Mini_UART data frame with 8 bits of data	60
6.27	Mini_UART state machine (transmitting 8 bits)	61
6.28	Structure of an I ² C frame	62
6.29	Internal components of the ARM1176JZF_S processor	63
6.30	Relationship between the CPU context and the CPU core	63
6.31	Use of the ISA decoder by the CPU	65
6.32	Algorithm for decoding ARM instructions	65
6.33	Hierarchy of the CPU exceptions	66
6.34	Architectural structure of the ALU	67
6.35	Utilization of the MMU when processing a RW request	68
6.36	Structure of the first-level page table	69
6.37	Execution loop of the emulated CPU	70
6.38	Component diagram of the CPU and its co-processors	71
6.39	Co-processor hierarchy	72
6.40	Design of the co-processor 15 register hierarchy (uses primary register C1 as an example)	73
6.41	External peripheral interface	75
6.42	Illustration of connection of two parallel 7-segment displays	77
6.43	Utilization of the logging system throughout the project	78
6.44	Hierarchy of endpoint loggers utilized by the logging system	79
6.45	Structure of GUI windows	80
6.46	ZeroMate's emulation performance of KIV-RTOS	81
6.47	Top 8 most performance-affecting instructions	82

List of Tables

3.1	List of ARM CPU modes	16
3.2	List of ARM CPU exceptions	17
3.3	List of special function ARM registers	18
3.4	List of ARM instruction condition codes	21
3.5	List of ARM co-processor instructions	22
4.1	Breakdown of the processor's name	26
6.1	List of emulated CP15 registers	72
6.2	List of emulated flags of the CP15 control registers	73
6.3	Information stored in <code>peripherals.json</code>	76
6.4	List of emulated external DPP-01 peripherals	77
6.5	List of additional external peripherals	77

List of Listings

6.1	System bus interface for I/O operations	42
6.2	Enabling unaligned access in CP15	43
6.3	Example of symbol demangling	44
6.4	Demonstration of the use of the debug monitor	51
6.5	SW emulation of a HW latch register	56
6.6	Retrieving a CPU register	64
6.7	Interface of the ISA decoder	64
6.8	Conversion between <code>uint32_t</code> and <code>float</code>	74

Attachments

7

