

# **Multi-core RISC Processor Design and Implementation**

## **(Rev. 2.02)**

ELEC5881M - Final Report

**Ben David Lancaster**  
Student ID: 201280376

Submitted in accordance with the requirements for the degree of  
Master of Science (MSc)  
in Embedded Systems Engineering

Supervisor: Dr. David Cowell  
Assessor: Mr David Moore

**University of Leeds**  
School of Electrical and Electronic Engineering

August 20, 2019

Word count: 4689

## **Abstract**

This interim report details the 4-month progress on a project to design, implement, and verify, a multi-core FPGA RISC processor. The project has been split into two stages: firstly to build a functional single-core RISC processor, and then secondly to add multiprocessor principles and functionality to it.

Current multiprocessor and network-on-chip communication methods have been discussed and how they could be included in this multi-core RISC design. To-date, a 16-bit instruction set architecture has been designed featuring common load/store instructions, comparison, and bitwise operations. A single-core processor has been implemented in Verilog and verified using simulations/test benches running various simple software programs.

Future tasks have been planned and will focus on the second stage of the project. Work will start on designing a loosely coupled multiprocessor communication interface and bringing them to the single-core processor.

## Revision History

Date	Version	Changes
10/04/2019	2.02	Update future stages.
05/04/2019	2.01	Fix processor RTL diagram.
04/04/2019	2.00	Initial processor RTL diagram.
01/04/2019	1.00	Initial section outline.

Document revisions.

# Declaration of Academic Integrity

The candidate confirms that the work submitted is his/her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated in the report. The candidate confirms that appropriate credit has been given within the report where reference has been made to the work of others.

This copy has been supplied on the understanding that no quotation from the report may be published without proper acknowledgement. The candidate, however, confirms his/her consent to the University of Leeds copying and distributing all or part of this work in any forms and using third parties, who might be outside the University, to monitor breaches of regulations, to verify whether this work contains plagiarised material, and for quality assurance purposes.

The candidate confirms that the details of any mitigating circumstances have been submitted to the Student Support Office at the School of Electronic and Electrical Engineering, at the University of Leeds.

Name: Ben David Lancaster

Date: August 20, 2019

# Table of Contents

<b>1</b>	<b>Introduction</b>	<b>10</b>
1.1	Why Multi-core? . . . . .	10
1.2	Why RISC? . . . . .	11
1.3	Why FPGA? . . . . .	11
<b>2</b>	<b>Background</b>	<b>12</b>
2.1	Amdahl's Law and Parallelism . . . . .	12
2.2	Loosely and Tightly Coupled Processors . . . . .	12
2.3	Network-on-chip Architectures . . . . .	13
<b>3</b>	<b>Project Overview</b>	<b>15</b>
3.1	Project Deliverables . . . . .	15
3.1.1	Core Deliverables (CD) . . . . .	15
3.1.2	Extended Deliverables (ED) . . . . .	16
3.2	Project Timeline . . . . .	17
3.2.1	Project Stages . . . . .	17
3.2.2	Project Stage Detail . . . . .	17
3.2.3	Timeline . . . . .	19
3.3	Resources . . . . .	19
3.3.1	Hardware Resources . . . . .	20
3.3.2	Software Resources . . . . .	21
3.4	Legal and Ethical Considerations . . . . .	21
<b>4</b>	<b>Single-core Design</b>	<b>23</b>
4.1	Introduction . . . . .	23
4.2	Design and Implementation . . . . .	23
4.2.1	Instruction Set Architecture . . . . .	24
4.2.2	Instruction and Data Memory . . . . .	25
4.2.3	Memory Management Unit . . . . .	25
4.2.4	ALU Design . . . . .	25
4.2.5	Decoder Design . . . . .	26
4.2.6	Pipelining . . . . .	27
4.2.7	Design Optimisations . . . . .	27
4.3	Interrupts . . . . .	28

4.3.1	Overview	28
4.3.2	Hardware Implementation	29
4.3.3	Software Interface	29
4.3.4	Design Improvements	31
4.4	Verification	31
<b>5</b>	<b>Interconnect</b>	<b>32</b>
5.1	Introduction	32
5.1.1	Comparison of On-chip Buses	32
5.2	Overview	33
5.2.1	Design Considerations	34
5.3	Interfaces	35
5.3.1	Master to Slave Interface	35
5.3.2	Multi-master Support	36
5.4	Further Work	36
<b>6</b>	<b>Memory Mapping</b>	<b>38</b>
6.1	Introduction	38
6.2	Address Decoding	38
6.2.1	Decoder Optimisations	39
6.3	Memory Map	41
<b>7</b>	<b>Peripherals</b>	<b>43</b>
7.1	Special Registers	43
7.2	Watchdog Timer	43
7.3	GPIO Interface	44
7.4	Timer with Interrupt	44
7.5	UART Interface	44
<b>8</b>	<b>Multi-core Communication</b>	<b>45</b>
8.1	Introduction	45
8.1.1	Design Goals	45
8.1.2	Context Identification	45
8.1.3	Thread Synchronisation	46
8.2	Design Challenges	48
8.2.1	Memory Constraints	48
<b>9</b>	<b>Analysis &amp; Results</b>	<b>50</b>
	<b>References</b>	<b>52</b>
	<b>Appendices</b>	<b>53</b>

<b>A</b>	<b>Additional Figures</b>	<b>53</b>
A.1	Register Set Multiplex . . . . .	53
A.2	Instruction Set Architecture . . . . .	54
<b>B</b>	<b>Configuration Options</b>	<b>55</b>
B.1	System-on-chip Configuration Options . . . . .	55
B.2	Core Options . . . . .	56
B.3	Peripheral Options . . . . .	57
<b>C</b>	<b>Code Listing</b>	<b>58</b>
C.1	vmicro16_soc.config.v . . . . .	58
C.2	top_ms.v . . . . .	60
C.3	vmicro16_soc.v . . . . .	61
C.4	vmicro16_periph.v . . . . .	67
C.5	vmicro16.v . . . . .	73

# List of Figures

2.1	A loosely coupled multiprocessor system. Each node features it's own memory and IO modules and uses a Message Transfer System to perform inter-node communication. Image source: [3]. . . . .	13
2.2	A tightly coupled multiprocessor system. Nodes are directly connected to memory and IO modules. Image source: [3]. . . . .	13
2.3	A multiprocessor network-on-chip architecture with 16 processing nodes. Nodes are connected in a grid formation with routers and links. Image source: [6]. . .	14
3.1	Project stages in a Gantt chart. . . . .	19
3.2	Terasic DE1-SoC development board featuring the Altera Cyclone V FPGA and many peripherals. Image source: [10]. . . . .	20
3.3	Minispartan-6+ development board featuring the Xilinx Spartan 6 XC6SLX9. Note that the XC6SLX9 and XC6SLX25 FPGAs share the same board. Image source: [11]. . . . .	21
4.1	Vmicro16 RISC 5-stage RTL diagram showing: instruction pipelining (data passed forward through clocked register banks at each stage); branch address calculation; ALU operand calculation (rd2 or imm); and program counter incrementing. . . . .	24
4.2	Vmicro16 ALU diagram showing clocked inputs from the previous IDEX stage being . . . . .	25
4.3	Time diagram showing the TIMR0 peripheral emitting a 1us periodic interrupt signal (out) to the processor. The processor acknowledges the interrupt (int_pending_ack) and enters the interrupt mode (regs_use_int) for a period of time. When the interrupt handler reaches the Interrupt Return instruction (indicated by w_intr) the processor returns to normal mode and restores the normal state. . . . .	29
4.5	Interrupt Mask register (0x0108). Each bit corresponds to an interrupt source. 1 signifies the interrupt is enabled for/visible to the core. Bits [7:2] are left to the designer to assign. . . . .	30
4.4	The interrupt vector consists of eight 16-bit values that point to memory addresses of the instruction memory to jump to. . . . .	30
5.1	Waveform showing an APB read transaction. . . . .	33
5.2	Block diagram of the Vmicro16 system-on-chip. . . . .	34



5.3	Foo . . . . .	36
6.1	Schematic showing the address decoder (addr_dec) accepting the active PADDR signal and outputting PSEL chip enable signals to each peripheral. . . . .	39
6.2	Example 4-bit binary comparator which compares the bits (a, b, c, d) to the constant value 1010. The 0s of the constant are inverted and then all are passed to a wide-AND. . . . .	39
6.3	Bits [7:3] of an 8-bit PADDR signal are used as inputs to 5-bit LUTs to generate a PSEL signal. In addition, a default error case is shown allowing the address decoder to detect incorrect PADDR values (e.g. if no PSEL signals are generated). . . . .	40
6.4	Partial address decoding used by the Vmicro16 SoC design. Each peripheral shown only needs to decode a signal bit to determine if it is enabled. . . . .	40
6.5	Memory map showing addresses of various memory sections. . . . .	42
8.1	Block digram showing the main multi-processing components: the CPU array and a peripheral interconnect used for core synchronisation. . . . .	46
8.2	Vmicro16 Special Registers layout (0x0080 - 0x008F). . . . .	46
8.3	Assembly code for locking a mutex. r1 is the address to lock. r3 is zero. r4 is the branch address. . . . .	47
8.5	• . . . . .	48
8.4	Assembly code for a memory barrier. Threads will wait in the barrier_wait function until all other threads have reached that code point. . . . .	49
A.1	Normal mode and interrupt mode register sets are multiplexed to instantly save the context. . . . .	53
A.2	Vmicro16 instruction set architecture. . . . .	54

# List of Tables

3.1	Project stages throughout the life cycle of the project. . . . .	18
B.1	SoC Configuration Options . . . . .	55
B.2	Core Options . . . . .	56
B.3	Peripheral Options . . . . .	57

# List of Listings

1	ALU branch detection using flags: zero (Z), overflow (V), and negative (N). . . .	26
2	Vmicro16's ALU implementation named vmicro16_alu. vmicro16.v . . . . .	26
3	Vmicro16's ALU implementation named vmicro16_alu. vmicro16.v . . . . .	27
4	Vmicro16's decoder module code showing nested bit switches to determine the intended opcode. vmicro16.v . . . . .	27
5	Variable size inputs and outputs to the interconnect. . . . .	36
6	RAM and lock memories instantiated by the shared memory peripheral. . . . .	47

# Chapter 1

## Introduction

1.1 Why Multi-core? . . . . .	10
1.2 Why RISC? . . . . .	11
1.3 Why FPGA? . . . . .	11

This project will detail the design, implementation, and verification, of a new multi-core RISC processor aimed at FPGA devices. This project was chosen due to my interest in processor design, in which I have only previously designed single-core RISC processors and wish to extend this knowledge to gain a basic understanding of multi-core communication, design considerations, and the limitations of parallelism first hand.

I will use this opportunity to further develop my knowledge of FPGA and processor design by implementing, designing, and verifying, a multi-core RISC processor from scratch, including the design of a communication interface between multiple cores.

### 1.1 Why Multi-core?

Moore's Law states that the number of transistors in a chip will double every 2 years []. CPU designers would utilize the additional transistors to add more pipeline stages in the processor to reduce the propagation delay [] which would allow for higher clock frequencies.

The size of transistors have been decreasing [] and today can be manufactured in sub-10 nanometer range. However, the extremely small transistor size increases electrical leakage and other negative effects resulting in unreliability and potential damage to the transistor []. The high transistor count produces large amounts of heat and requires increasing power to supply the chip. These trade-offs are currently managed by reducing the input voltage, utilising complex cooling techniques, and reducing clock frequency. These factors limit the performance of the chip significantly. These are contributing factors to Moore's Law *slowing* down. The capacity limit of the current-generation planar transistors is approaching and so in order for performance increases to continue, other approaches such as alternate transistor technologies like Multigate transistors [1], software and hardware optimisations, and multi-processor architectures are employed.

This report will focus on the latter: to produce a small multi-core processor that can utilise software-based parallelism to gain performance benefits, compared to a larger single-core

design.

## 1.2 Why RISC?

RISC architectures feature simpler and fewer instructions compared to CISC, which emphasises instructions that perform larger tasks. A single CISC instruction might be performed with multiple RISC instructions. Because of the fewer and simpler instructions, RISC machines rely heavily on software optimisations for performance. RISC instruction sets are based on load/store architectures, where most instructions are either register-to-register or memory reading and writing [2]. This constraint greatly reduces complexity.

RISC architectures are easier to design implement, especially for beginners, due to their simpler instructions that share the same pipeline, compared to CISC where there may be different pipeline for each instruction, which would greatly consume FPGA resources.

## 1.3 Why FPGA?

Field programmable gate arrays (FPGA) are a great choice for prototyping digital logic designs due to their programmable nature and quick development times.

My previous experience with FPGAs in previous projects will reduce risk and learning times and allow for more time to be spent on adding and extending features (discusses further in section 3.1).

FPGAs, however, may not be suitable for prototyping all register-transistor logic (RTL) projects. Larger RTL projects, such as large commercial processors, may greatly exceed the logic cell resources available in today's high-end FPGA devices and may only be prototyped through silicon fabrication, which can be expensive. This resource limitation will not be problem as the project aims to produce a small and minimal design specifically for learning about multi-core architectures.

# Chapter 2

## Background

2.1 Amdahl's Law and Parallelism . . . . .	12
2.2 Loosely and Tightly Coupled Processors . . . . .	12
2.3 Network-on-chip Architectures . . . . .	13

### 2.1 Amdahl's Law and Parallelism

In many applications, not restricted to software, there may exist many opportunities for processes or algorithms to be performed in parallel. These algorithms can be split into two parts: a serial part that cannot be parallelised, and a part that can be parallelised. Amdahl's Law defines a formula for calculating the maximum *speedup* of a process with potential parallelism opportunities when ran in parallel with  $n$  many processors. Speedup is a term used to describe the potential performance improvements of an algorithm using an enhanced resource (in this case, adding parallel processors) compared to the original algorithm. Amdahl's Law is defined below, where the potential speedup  $S_p$  is dependant on the portion of program that can be parallelised  $p$  and the number of processing cores  $n$ :

$$S_p = \frac{1}{(1 - p) + \frac{p}{n}} \quad (2.1)$$

This formula will be used throughout the project to gauge the performance of the multi-core design running various software algorithms.

### 2.2 Loosely and Tightly Coupled Processors

Multiprocessor systems can be generalised into two architectures: loosely and tightly coupled, and each architecture has advantages and disadvantages. In loosely coupled systems, each processing node is self-contained – each node has its own dedicated memory and IO modules. Communication between nodes is performed over a *Message Transfer System (MTS)* [3] in a master-slave control architecture.

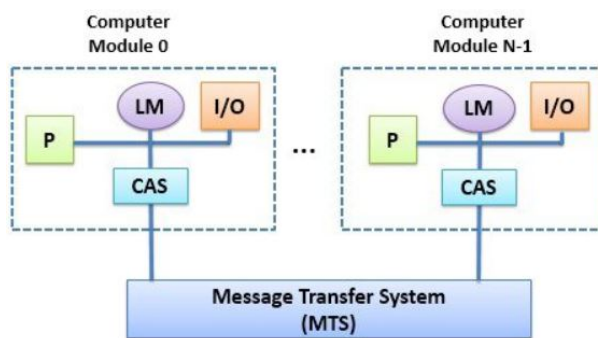
Scalability in loosely coupled systems is generally easier to implement as each node can simply be appended to the shared MTS interface without large modifications to the rest of

the system. Scalability is an important concern in this project as I wish to test the developed solution with a range of processing nodes.

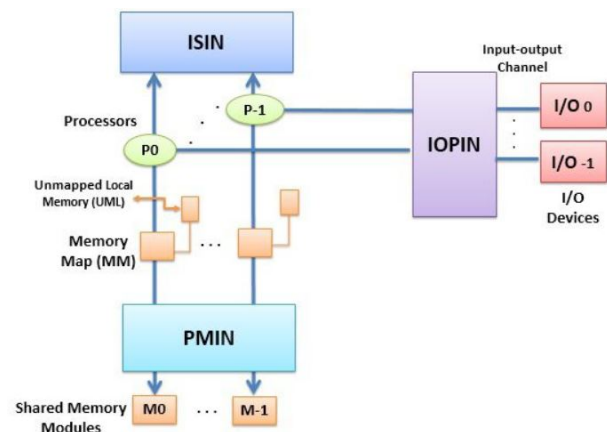
As loosely coupled system's nodes feature their own memory and IO modules, they generally perform better in cases where interaction between nodes is not prominent – each node can store a separate part of the software program in its memory module allowing simultaneous executing of the program.

In scenarios where inter-node communication is prominent however, access to the MTS interface must be scheduled to avoid access conflicts which introduces delays and idle times in the software programs execution, resulting in lower throughput. Figure 2.1 shows a general layout of a loosely coupled multiprocessor system.

Tightly coupled systems feature processing nodes that do not have their own dedicated memory or IO modules – each node is directly connected to a shared memory module using a dedicated port. In scenarios where inter-node communication is prominent, tightly coupled systems are generally better suited as nodes are directly connected to a shared memory and do not need to wait to use a shared bus.



**Figure 2.1:** A loosely coupled multiprocessor system. Each node features its own memory and IO modules and uses a Message Transfer System to perform inter-node communication. Image source: [3].



**Figure 2.2:** A tightly coupled multiprocessor system. Nodes are directly connected to memory and IO modules. Image source: [3].

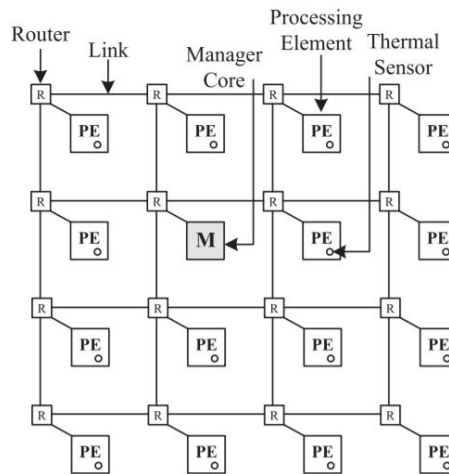
This project will utilise a loosely coupled architecture due to its easier scalability implementation and my previous experience with the design of single-core processors. Although it will require a scheduler to access the MTS, the experience and knowledge gained from this task will be greatly beneficial for future projects.

## 2.3 Network-on-chip Architectures

Network-on-chip (NoC) architectures implement on-chip communication mechanisms that are based on network communication principles, such as routing, switching, and massive scalability [4]. NoC's can generally support hundreds to millions of processing cores. Figure 2.3 shows an example 16-core network-on-chip architecture. NoC's can scale to very large sizes while not sacrificing performance because each processor core is able to drive the network rather than needing to wait for a shared bus to become free before doing so.

The greater the number of cores in a network-on-chip design, the greater quality of service

(QoS) problems arise. As such, network-on-chip architectures suffer the same problems as networks, such as fairness and throughput [5].



**Figure 2.3:** A multiprocessor network-on-chip architecture with 16 processing nodes. Nodes are connected in a grid formation with routers and links. Image source: [6].



# Chapter 3

## Project Overview

3.1	Project Deliverables . . . . .	15
3.1.1	Core Deliverables (CD) . . . . .	15
3.1.2	Extended Deliverables (ED) . . . . .	16
3.2	Project Timeline . . . . .	17
3.2.1	Project Stages . . . . .	17
3.2.2	Project Stage Detail . . . . .	17
3.2.3	Timeline . . . . .	19
3.3	Resources . . . . .	19
3.3.1	Hardware Resources . . . . .	20
3.3.2	Software Resources . . . . .	21
3.4	Legal and Ethical Considerations . . . . .	21

This chapter discusses the the project’s requirements, goals, and structure.

### 3.1 Project Deliverables

The project’s deliverables are split into two sections: core deliverables (CD) – each deliverable must be satisfied for the project to be a minimum viable product (MVP), and extended deliverables (ED) – deliverables that are not required for a MVP – features that only improve upon an existing feature.

#### 3.1.1 Core Deliverables (CD)

The project’s core deliverables are described below.

##### **CD1 Design a compact 16-bit RISC instruction set architecture.**

The instruction set will be the primary interface to control the processor from software. An instruction set will be required to implement the custom multi-core communication interface.

It was decided to design a new instruction set rather than to extend an existing architecture as this will increase my knowledge of the constraints to consider when designing instruction sets and processors.

**CD2 Design and implement a Verilog RISC core that implements the ISA in CD1.**

The Verilog RISC core will be able to run software program written for the instruction set architecture.

**CD3 Design and implement an on-chip interconnect for multi-core processing (2 to 32 cores) using the RISC core from CD2.**

The interconnect will be a chief requirement to enable multi-core communication. The interconnect should support up to 32 cores, however FPGA implementation constraints may limit this due to limited resources.

The interconnect will control communication between the cores to enable software parallelism.

**CD4 Analyse performance of serial and parallel software algorithms, such as parallel DFT, on the processor.**

To evaluate the effectiveness of the developed solution, a serial and parallel implementation of a simple computing algorithm (parallel reduction, sorting) will be ran on the processor and it's performance analysed. Effectiveness will be rated on total algorithm run-time and the speed-up gained by adding more cores.

**CD5 Allow the RISC core to be easily compiled to multiple FPGA vendors (Xilinx, Altera).**

The developed solution should be generic and portable to allow it to be used across a wide-range of FPGA vendors and devices.

Verilog is a generic implementation-independent hardware-description language and so designing implementation specific modules is recommended.

A key consideration for this requirement is to consider the varying hard IP provided by the FPGA vendors (such as BRAM, ethernet, and PCIe [7, 8]). To overcome this problem, the developed Verilog code will conditionally compile where vendor specific requirements are present.

### 3.1.2 Extended Deliverables (ED)

The project's extended deliverables are described below.

**ED1** Design a RISC core with an instructions-per-clock (IPC) rating of at least 1.0 (a single-cycle CPU).

**ED2** Design a RISC core with a pipe-lined data path to increase the design's clock speed.

**ED3** Design a scalable multi-core interconnect supporting arbitrary (more than 32) RISC core instances (manycore) using Network-on-Chip (NoC) architecture.

**ED4** Design a compiler-backend for the PRCO304 [9] compiler to support the ISA from CD1. This will make it easier to build complex multi-core software for the processor.

**ED5** The RISC core can communicate to peripherals via a memory-mapped addresses using the Wishbone bus.

**ED6** Implement various memory-mapped peripherals such as UART, GPIO, LCD, to aid visual representation of the processor during the demonstration viva.

**ED7** Store instruction memory in SPI flash.

**ED8** Reprogram instruction memory at runtime from host computer.

**ED9** Processor external debugger using host-processor link.

## 3.2 Project Timeline

### 3.2.1 Project Stages

The project is split up into many stages to aid planning and management of the project. There are 8 unique stage areas: 1. Initial project conception; 2 Basic RISC core development; 3. Extended RISC core development; 4. Multi-core development; 5. Processor quality-of-life (QoL) improvements; 6. Compiler development; 7. Demo preparation, and 8. Final report.

The project stages are shown in Table [3.1](#).

### 3.2.2 Project Stage Detail

#### Stages 1.0 through 1.2 – Research and Project Conception

These stages cover initial research of existing problems and solutions in the multiprocessor area. The instruction set architecture is also proposed that later stages will implement.

#### Stages 2.1 through 2.3 – Processor module Design, Implementation, and Integration

These stages cover the design, implementation, and integration of key processor core modules such as the instruction decoder, register sets and local memory. Integration of all the modules is a challenging task because some modules have both asynchronous and synchronous signals that need to be timed correctly in order for other modules to receive valid data. An example of this is the register set which has asynchronous read ports that are later clocked in the instruction decode stage.

#### Stages 3.1 through 3.4 – Advanced Processor Implementation

These stages add advanced features to the processor to provide a more functional product. Although these stages are classified as extended, their technical requirement to design and implement is not great and so are have time allocations in the project schedule. The extended features that these stages introduce are: pipelined processor stages – to drastically increase processor performance; provide a memory-mapped peripheral interface through the MMU; provide a Wishbone master interface to the MMU – allowing external peripherals such as GPIO and LCD displays to be utilised in a modular fashion; and to implement a cache memory for each processor core.

Stage	Title	Start Date	Days	Core	Applicable Deliverables
1.0	Research	Feb 04	7	x	
1.1	Requirement gathering/review	Feb 11	14	x	
1.1	Processor specification, architecture, ISA	Feb 18	100	x	CD1
1.2	Stage/Time Allocation Planning	Feb 25	7	x	
2.1	Decoder, Register Set, impl & integration	Feb 25	14	x	CD2
2.2	Register set impl & integration	Mar 04	14	x	CD2
2.3	Local memory impl & integration	Mar 11	14	x	CD2
3.1	Memory mapped register layout & impl	Apr 01	21		ED5
3.2	Wishbone peripheral bus connected to MMU	Apr 08	21		ED5
3.3	Pipelined implementation and verification	Apr 15	21		ED2
3.4	Cache memory design & impl	Apr 22	28		ED2
4.1	Multi-core communication interface	TBD	TBD	x	CD3
4.2	Shared-memory controller	TBD	TBD	x	CD3
4.3	Scalable multi-core interface (10s of cores)	TBD	TBD	x	CD3
4.4	Multi-core example program (reduction)	TBD	TBD	x	CD4
5.1	SPI-FPGA interface for OTG programming	TBD	TBD		ED7
5.2	FPGA-PC interfacing	TBD	TBD		ED9
5.3	FPGA-PC debugging (instruction breakpoints)	TBD	TBD		ED9
6.1	Compiler backend for vmicro16	TBD	TBD		ED4
6.2	Compiler support for multi-core codegen	TBD	TBD		ED4
7.1	Wishbone peripherals for demo	TBD	TBD	x	CD4
8.1	Final Report	TBD	TBD	x	

Table 3.1: Project stages throughout the life cycle of the project.

### Stages 4.1 through 4.4 – Multiprocessor Functionality

These stages are dedicated to adding multiprocessor functionality using a loosely coupled architecture to the processor.

### Stages 5.1 through 5.3 – Debugging Features

These stages cover debugging features and are classified as extended due to the large development time required to implement them as well as not being related to multiprocessor systems.

### Stages 6.1 through 6.2 – Compiler Backends

These stages cover the implementation of a compiler backend to ease software writing and programming of the processor.

### Stage 7.1 – Wishbone Peripherals

Additional Wishbone peripherals, such as SPI and timers will be added to produce a more useful multiprocessor system.

### Stage 8.1 – Final Report

This stage is dedicated to the final report write-up. It is expected to be an iterative task that is active throughout the lifespan of the project.

### 3.2.3 Timeline

The project stages from Table 3.1 are displayed below in a Gantt chart.

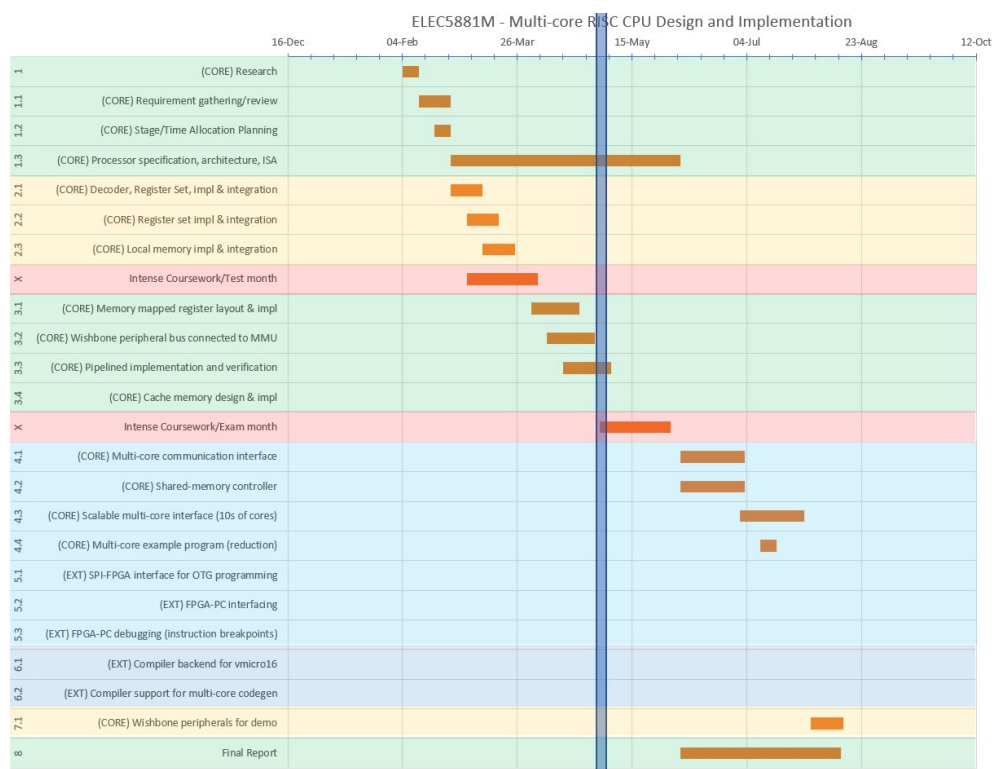


Figure 3.1: Project stages in a Gantt chart.

## 3.3 Resources

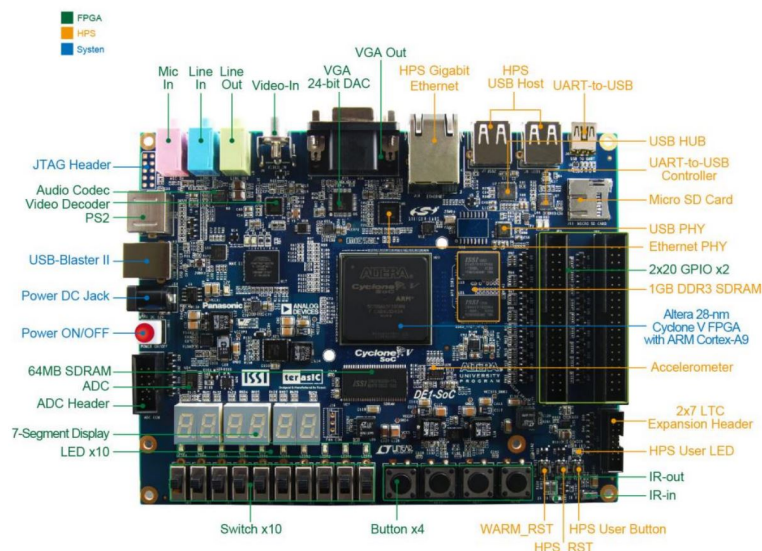
This section describes the hardware and software resources required to fulfil the project.

### 3.3.1 Hardware Resources

Core deliverable [CD5](#) requires the designed RISC core to be implemented and demonstrated on multiple FPGA devices. Although my design should synthesise for physical IC implementation, due to high costs and lengthy production times, it is not a primary development target. Due to having past experience with Xilinx FPGAs from my placement work and experience with Altera from university modules it was decided to target the Xilinx Spartan 6 XC6SLX9 and the Altera Cyclone V.

#### Terasic DE1-SoC Development Board

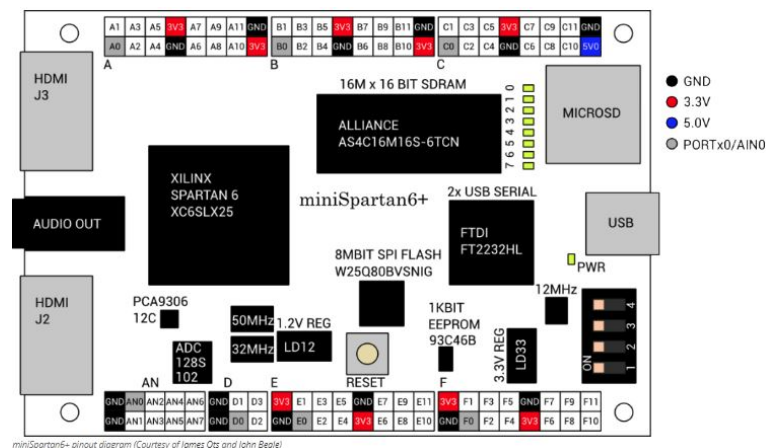
The Terasic DE1-SoC development board features a large Cyclone V FPGA and many peripherals, such as seven-segment displays, 64 MB SDRAM, ADCs, and buttons and switches, which will aid demonstration of the project. The development board is available through the university so the cost is negligible. [Figure 3.2](#) shows the peripherals (green) available to the FPGA.



**Figure 3.2:** Terasic DE1-SoC development board featuring the Altera Cyclone V FPGA and many peripherals. Image source: [\[10\]](#).

#### Minispartan 6+ FPGA Development Board

The Minispartan 6+ is a hobbyist FPGA development board with fewer peripherals than the DE1-SoC. The board features a Xilinx Spartan 6 XC6SLX9 which has far fewer resources than the DE1-SoC's Cyclone V however it's simplicity and my familiarity with Xilinx's software suite will speed up development. The development board is shown in [Figure 3.3](#).



**Figure 3.3:** Minispartan-6+ development board featuring the Xilinx Spartan 6 XC6SLX9. Note that the XC6SLX9 and XC6SLX25 FPGAs share the same board. Image source: [11].

### 3.3.2 Software Resources

#### Intel Quartus

Intel Quartus Prime is a paid-for SoC, CPLD, and FPGA software suite targeting Intel's Stratix, Arria, and Cyclone based FPGAs. The university provides student licences which will be used via VPN.

#### Xilinx ISE Webpack

Xilinx ISE Webpack is Xilinx's free software suite for FPGA development for Spartan 6 based FPGAs. Due to ISE's intuitive and fast work flow, most of the initial simulation and verification processes will be performed using ISE. This will greatly improve development times.

#### Verilator

Verilator is an open-source Verilog to C++ transpiler which provides a C++ interface to simulate Verilog modules and read/write values similar to a test bench. Verilator will be used for specific modules within the RISC core such as the ALU and decoder as Verilator is useful when performing exhaustive verification.

## 3.4 Legal and Ethical Considerations

The RISC core is designed to be used as an academic research and educational tool to aid learning and understanding of RISC and multi-core machines. It should not be use for roles where mission critical or safety is a factor.

The processor does not provide any memory protection features and any software running on the processor has full access to all memory.

The processor does not store/track/predict software instructions. The processor uses pipelining techniques to improve performance which results in future instructions entering

the pipeline even if the software's logical sequence does not include these instructions. This could result in security vulnerabilities similar to Intel's Spectre vulnerability [12].



# Chapter 4

## Single-core Design

4.1	Introduction . . . . .	23
4.2	Design and Implementation . . . . .	23
4.2.1	Instruction Set Architecture . . . . .	24
4.2.2	Instruction and Data Memory . . . . .	25
4.2.3	Memory Management Unit . . . . .	25
4.2.4	ALU Design . . . . .	25
4.2.5	Decoder Design . . . . .	26
4.2.6	Pipelining . . . . .	27
4.2.7	Design Optimisations . . . . .	27
4.3	Interrupts . . . . .	28
4.3.1	Overview . . . . .	28
4.3.2	Hardware Implementation . . . . .	29
4.3.3	Software Interface . . . . .	29
4.3.4	Design Improvements . . . . .	31
4.4	Verification . . . . .	31

### 4.1 Introduction

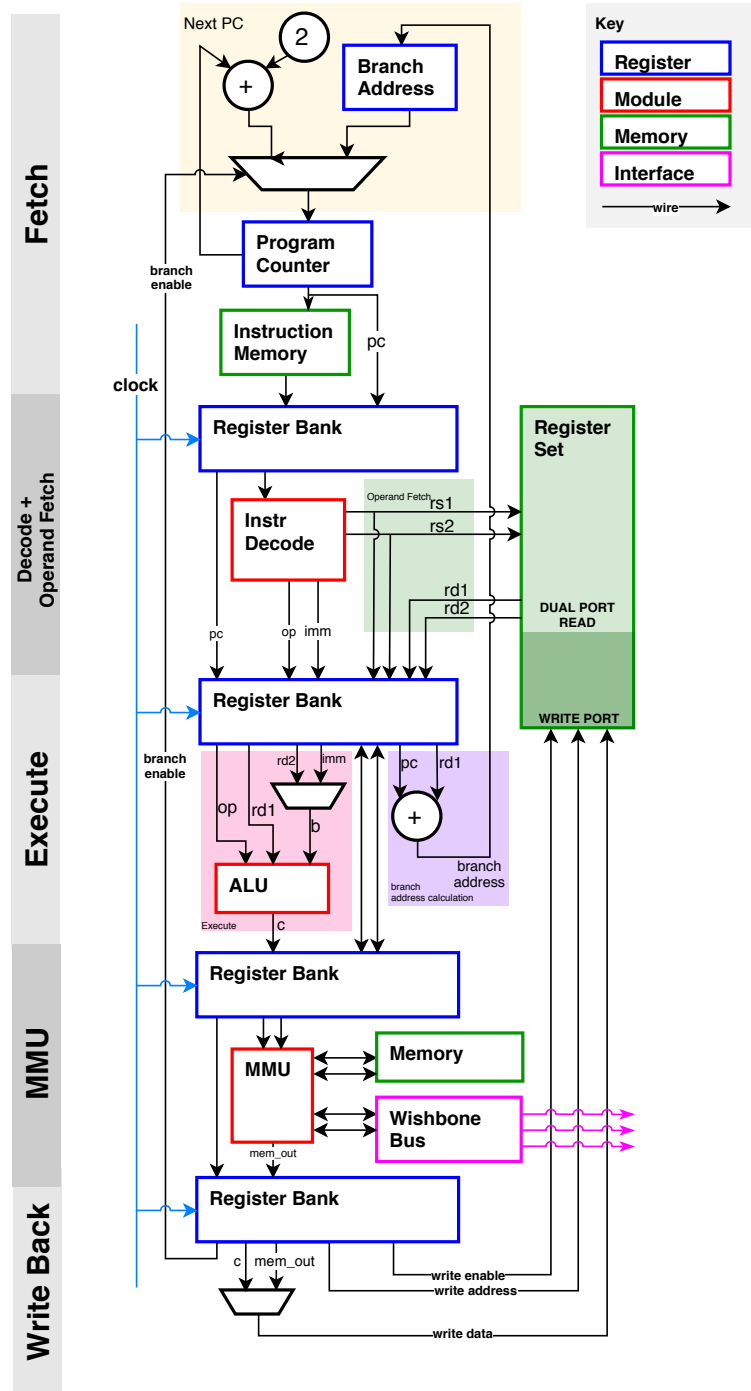
While the majority of this report will focus on the multi-processing functionality of this project, it is important understand the design decisions of the single core to understand the features and limitations of the multi-core system-on-chip as a whole.

### 4.2 Design and Implementation

The single-core design is a traditional 5-stage RISC processor (fetch, decode, execute, memory, write-back). The core uses separate instruction and data memories in the style of a Harvard architecture [? ].

To satisfy **CD5**, the Verilog code will be self-contained in a single file. This reduces the hierarchical complexity and eases cross-vendor project set-up as only a single file is required to be included. A disadvantage with this single file approach is that some external Verilog

verification tools that I plan to use, such as Verilator, do not currently support multiple Verilog modules (due to an unfixed bug) within a single file.



**Figure 4.1:** Vmicro16 RISC 5-stage RTL diagram showing: instruction pipelining (data passed forward through clocked register banks at each stage); branch address calculation; ALU operand calculation (rd2 or imm); and program counter incrementing.

A small reduction in size within the single-core will result in substantial size reductions in

### 4.2.1 Instruction Set Architecture

Core deliverable **CD1** details the background for the requirement of a custom instruction set architecture.

The 16-bit instruction set listing is shown in [Figure A.2](#).

Most instructions are *destructive*, meaning that source operands also act as the destination, hence effectively *destroying* the original source operand. This design decision reduces the complexity of the ISA as traditional three operand instructions, for example `add r0, r0, r1`, can be encoded using only two operands `add r0, r1`. However, this does increase the complexity of compilers as they may need to make temporary copies of registers as the instructions will *destroy* the original data.

The instruction set is split into 7 categories (highlighted by colours in [Figure A.2](#)): special instructions, such as halting and interrupt returns; memory operations, such as loading and storing; bitwise operations, such as XOR and AND; unsigned arithmetic; signed arithmetic; conditional branches; and atomic load/store instructions.

## 4.2.2 Instruction and Data Memory

The design uses separate instruction and data memories similar to a Harvard architecture computer. This architecture was chosen due because it is generally easier to implement, however later resulted in design challenges in large multi-core designs. This is discussed later in the report.

## 4.2.3 Memory Management Unit

It was decided to use a memory management unit (MMU) to make it easier and extensible to communicate with external peripherals or additional registers. This method would transparently use the existing LW/SW instructions which removes the requirement for a unique instruction for each peripheral.

## 4.2.4 ALU Design

The Vmicro16's ALU is an asynchronous module that has 3 inputs: data a; data b; and opcode op; and outputs data c. The ALU is able to operate on both register data (rd1 and rd2) and immediate values. A switch is used to set the b input to either the rd2 or imm value from the previous stage.

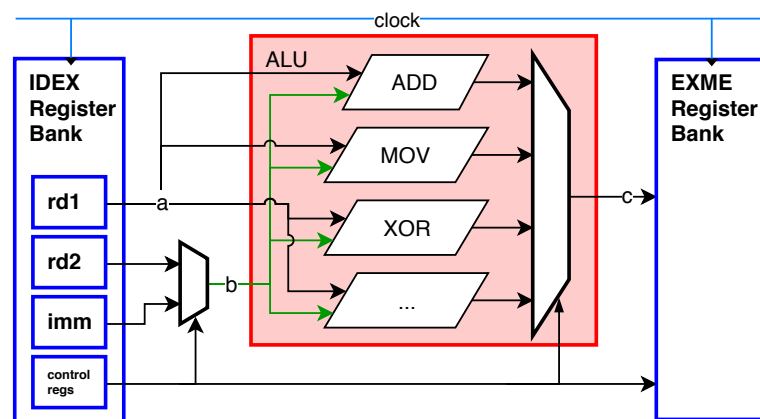


Figure 4.2: Vmicro16 ALU diagram showing clocked inputs from the previous IDEX stage being

The ALU also performs comparison (CMP) operations in which it returns flags similar to X86's overflow, signed, and zero, flags. The combination of these flags can be used to easily compute relationships between the two input operands. For example, if the zero flag is not equal to the signed flag, then the relationship between inputs  $a$  and  $b$  is that  $a < b$ .

```

1  module branch (
2      input [3:0] flags,
3      input [7:0] cond,
4      output reg en
5  );
6      always @(*)
7          case (cond)
8              `VMICRO16_OP_BR_U:   en = 1;
9              `VMICRO16_OP_BR_E:   en = (flags[`VMICRO16_SFLAG_Z] == 1);
10             `VMICRO16_OP_BR_NE:  en = (flags[`VMICRO16_SFLAG_Z] == 0);
11             `VMICRO16_OP_BR_G:   en = (flags[`VMICRO16_SFLAG_Z] == 0) &&
12                                   (flags[`VMICRO16_SFLAG_N] == flags[`VMICRO16_SFLAG_V]);
13             `VMICRO16_OP_BR_L:   en = (flags[`VMICRO16_SFLAG_Z] != flags[`VMICRO16_SFLAG_N]);
14             `VMICRO16_OP_BR_GE:  en = (flags[`VMICRO16_SFLAG_Z] == flags[`VMICRO16_SFLAG_N]);
15             `VMICRO16_OP_BR_LE:  en = (flags[`VMICRO16_SFLAG_Z] == 1) ||
16                                   (flags[`VMICRO16_SFLAG_N] != flags[`VMICRO16_SFLAG_V]);
17             default:              en = 0;
18         endcase
19     endmodule

```

Listing 1: ALU branch detection using flags: zero (Z), overflow (V), and negative (N).

The Verilog implementation of the ALU is shown in Listing 2. The ALU's asynchronous output is clocked with other registers, such as destination register `rs1` and other control signals, in the EXME register bank.

```

1  always @(*) case (op)
2      // branch/nop, output nothing
3      `VMICRO16_ALU_BR,
4      `VMICRO16_ALU_NOP:   c = {DATA_WIDTH{1'b0}};
5      // load/store addresses (use value in rd2)
6      `VMICRO16_ALU_LW,
7      `VMICRO16_ALU_SW:   c = b;
8      // bitwise operations
9      `VMICRO16_ALU_BIT_OR:   c = a | b;
10     `VMICRO16_ALU_BIT_XOR:   c = a ^ b;
11     `VMICRO16_ALU_BIT_AND:   c = a & b;
12     `VMICRO16_ALU_BIT_NOT:   c = ~(b);
13     `VMICRO16_ALU_BIT_LSHFT: c = a << b;
14     `VMICRO16_ALU_BIT_RSHFT: c = a >> b;

```

Listing 2: Vmicro16's ALU implementation named `vmicro16_alu`. `vmicro16.v`

### 4.2.5 Decoder Design

Instruction decoding occurs in the between the IFID and IDEX stages. The decoder extracts register selects and operands from the input instruction. The decoder outputs are asynchronous which allows the register selects to be passed to the register set and register data to be read asynchronously. The register selects and register read data is then clocked into the IDEX register bank.

```

1  always @(*) case (instr[15:11])
2      `VMICRO16_OP_BR:      alu_op = `VMICRO16_ALU_BR;
3      `VMICRO16_OP_MULT:    alu_op = `VMICRO16_ALU_MULT;
4
5      `VMICRO16_OP_CMP:     alu_op = `VMICRO16_ALU_CMP;
6      `VMICRO16_OP_SETC:    alu_op = `VMICRO16_ALU_SETC;
7
8      `VMICRO16_OP_BIT:     casez (instr[4:0])
9          `VMICRO16_OP_BIT_OR:    alu_op = `VMICRO16_ALU_BIT_OR;
10         `VMICRO16_OP_BIT_XOR:   alu_op = `VMICRO16_ALU_BIT_XOR;
11         `VMICRO16_OP_BIT_AND:   alu_op = `VMICRO16_ALU_BIT_AND;
12         `VMICRO16_OP_BIT_NOT:   alu_op = `VMICRO16_ALU_BIT_NOT;
13         `VMICRO16_OP_BIT_LSHFT: alu_op = `VMICRO16_ALU_BIT_LSHFT;
14         `VMICRO16_OP_BIT_RSHFT: alu_op = `VMICRO16_ALU_BIT_RSHFT;
15     default:                alu_op = `VMICRO16_ALU_BAD; endcase

```

**Listing 4:** Vmicro16's decoder module code showing nested bit switches to determine the intended opcode. vmicro16.v

In [Listing 4](#), it can be seen that the first 4 opcode cases (BR, MULT, CMP, SETC) are represented using the same 15-11 (opcode) bits, however the BIT instructions share the same opcode and so require another bit range to be compared to determine the output function.

## 4.2.6 Pipelining

In the interim progress update, the processor design featured *instruction pipelining* to meet requirement [ED1](#). Instruction pipelining allows instructions executions to be overlapped in the pipeline, resulting in higher throughput (up to one instruction per clock) at the expense of 5-6 clocks of latency and code complexity. As the development of the project shifted from single-core to multi-core, it became obvious that the complexity of the pipelined processor would inhibit the integration of multi-core functionality. It was decided to remove the instruction pipelining functionality and use a simpler state-machine based pipeline that is much simpler to extend and would cause fewer challenges later in the project.

## 4.2.7 Design Optimisations

In a design that has many instantiations of the same component, a small resource saving improvement within the component can have a significant overall savings improvement if it is instantiated many times. Project requirement [CD5](#) requires the design to be compiled for a range of FPGA sizes, and so space saving optimisations are considered.

### Register Set Size Improvements

A register set in a CPU is a fast, temporary, and small memory that software instructions directly manipulate to perform computation. In the Vmicro16 instruction set, eight registers named r0 to r7 are available to software. The instruction set allows up to two registers to be references in most instructions, for example the instruction add r0, r1 tells the processor to perform the following actions:

- Clock 1.** Fetch r0 and r1 from the register set
- Clock 2.** Add the two values together in the ALU
- Clock 3.** Store the result back the register set in r0

For task 1, it was originally decided to use a dual port register set (meaning that two data reads can be performed in a single clock, in this case r0 and r1), however due to the asynchronous design of the register set (for speed) the RTL produced consumed a significant amount of FPGA resources, approximately 256 flip-flops ( $16 \text{ (data width)} * 8 \text{ (registers)} * 2 \text{ (ports)}$ ). To reduce this, it was decided to split task 1 into two steps over two clock cycles using a single-port register set. This required the processor pipe-line to use another clock cycle resulting in slightly lower performance, however the size improvements will allow for more cores to be instantiated in the design. This optimisation is also applied to the interrupt register set, resulting in a saving of approximately 256 flip-flops per core (128 in the normal mode register set, and 128 in the interrupt register set). As shown, adding a single clock delay saves a significant amount of LUTs. This saving is amplified when instantiating many cores.

### 4.3 Interrupts

Interrupts are a technique used by processors to run software functions when an event occurs within the processor, such as exceptions, or signalled from an external source, such as a UART receiver signalling it has received new data. Today, it is common for micro-controllers, soft-processors, and desktop processors, to all feature interrupts. Modern implementations support an *interrupt vector* which is a memory array that contains addresses to different *interrupt handlers* (a software function called when a particular interrupt is received).

Although interrupts are not a requirement for a multi-core system, it was decided to implement this functionality to boost my understanding of such systems. In addition, example demos provided with this project are better visualised with a interrupt functionality.

#### 4.3.1 Overview

The interrupt functionality in this project supports the following:

- Per-core 8 cell interrupt vector accessible to software.  
Software programs running on the Vmicro16 processor can edit the interrupt vector to add their own interrupt handlers at runtime.
- Fast context switching.  
A dedicated interrupt register set is multiplexed with the normal mode register set to provide instant context switching. It should be noted that only the registers are saved during a context switch. The means that the stack is not saved. A schematic of the register multiplex is shown in [Figure A.1](#).
- Parametrised interrupt sources and widths. Users can configure the width of the interrupt in signals and the data width per interrupt source via the `vmicro16_soc_config.v`. By default, 8 interrupt sources are available and each can provide 8-bits of data.

### 4.3.2 Hardware Implementation

#### Context Switching

When acting upon an incoming interrupt the current state the processor must be saved so that changes from the interrupt handler, such as register writes and branches, do not affect the current state. After the interrupt handler function signals it has finished (by using the *Interrupt Return* INTR instruction) the saved state is restored. In the case of the Vmicro16 processor, the program counter `r_pc[15:0]` and register set `regs` instance are the only states that are saved. Going forth, the terms *normal mode* and *interrupt mode* are used to describe what registers the processor should use when executing instructions.

When saving the state, to avoid clocking 128 bits (8 registers of 16 bits) into another register (which would increase timing delays and logic elements), a dedicated register set for the interrupt mode (`regs_isr`) is multiplexed with the normal mode register set (`regs`). Then depending on the mode (identified by the register `regs_use_int`) the processor can easily switch between the two large states without significantly affecting timing.

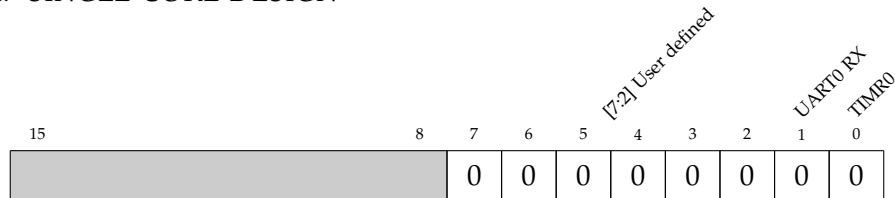
The timing diagram in [Figure 4.3](#) visually describes this process.



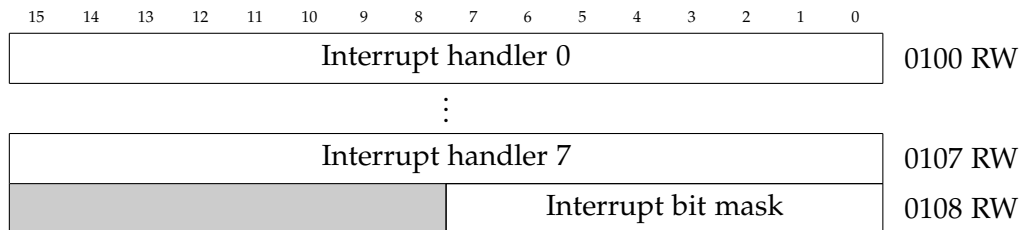
**Figure 4.3:** Time diagram showing the TIMR0 peripheral emitting a 1us periodic interrupt signal (out) to the processor. The processor acknowledges the interrupt (int\_pending\_ack) and enters the interrupt mode (regs\_use\_int) for a period of time. When the interrupt handler reaches the Interrupt Return instruction (indicated by w\_intr) the processor returns to normal mode and restores the normal state.

### 4.3.3 Software Interface

To enable software to



**Figure 4.5:** Interrupt Mask register (0x0108). Each bit corresponds to an interrupt source. 1 signifies the interrupt is enabled for/visible to the core. Bits [7:2] are left to the designer to assign.



**Figure 4.4:** The interrupt vector consists of eight 16-bit values that point to memory addresses of the instruction memory to jump to.

### Interrupt Vector (0x0100-0x0107)

The interrupt vector is a per-core register that is used to store the addresses of interrupt handlers. An interrupt handler is simply a software function residing in instruction memory that is branched to when a particular interrupt is received.

### Interrupt Mask (0x0108)

The interrupt mask is a per-core register that is used to mask/listen specific interrupt sources. This enables processing cores to individually select which interrupts they respond to. This allows for multi-processor designs where each core can be used for a particular interrupt source, improving the time response to the interrupt for time critical programs. The Interrupt Mask register is an 8-bit read/write register where each bit corresponds to a particular interrupt source and each bit corresponds with the interrupt handler in the interrupt vector.

### Software Example

To better understand the usage of the described interrupt registers, a simple software program is described below. The following software program produces a simple and power efficient routine to initialise the interrupt vector and interrupt mask.

```

1  entry:
2      // Set interrupt vector at 0x100
3      // Move address of isr0 function to vector[0]
4      movi    r0, isr0
5      // create 0x100 value by left shifting 1 8 bits
6      movi    r1, #0x1
7      movi    r2, #0x8
8      lshft   r1, r2
9      // write isr0 address to vector[0]
10     sw      r0, r1
11
12     // enable all interrupts by writing 0x0f to 0x108
13     movi    r0, #0x0f
14     sw      r0, r1 + #0x8
15     halt    // enter low power idle state
16

```



```

17  isr0:                                // arbitrary name
18      movi    r0, #0xff                // do something
19      intr                                // return from interrupt

```

A more complex example software program utilising interrupts and the TIMR0 interrupt is described in section ??.

#### 4.3.4 Design Improvements

The hardware and software interrupt design have changed throughout the projects cycle. In initial versions of the interrupt implementation, the software program, while waiting for an interrupt, would be in a tight infinite loop (branching to the same instruction). This resulted in the processor using all pipeline stages during this time. The pipeline stages produce many logic transitions and memory fetches which raise power consumption and temperatures. This is quite noticeable especially when running on the Spartan-6 LX9 FPGA.

To improve this, it was decided to implement a new state within the processor's state machine that, when entered, did not produce high frequency logic transitions or memory fetches. The HALT instruction was modified to enter this state and the only way to leave is from an interrupt or top-level reset. This removes the need for a software infinite loop that produces high frequency logic transitions (decoding, ALU, register reads, etc.) and memory fetches.

## 4.4 Verification

Various verification techniques are employed to ensure correct operation of the processor.

The first technique involves using static assertions to identify incorrect configuration parameters at compile time, such as having zero instruction memory and scratch memory depth. These assertions use the `static_assert` for top level checks and `static_assert_ng` for checks inside generate blocks.

The second verification technique is to use assertions in always blocks to identify incorrect behavioural states. This is done using the `rassert` (run-time assert) macro.

The third verification technique is to use automatic verifying test benches. These test benches drive components of the processor, such as the ALU and decoder, and check the output against the correct value. This uses the `rassert` macro.

The final method of verification is to verify the complete design via a behavioural test bench. The design is passed a compiled software program with a known expected output, and is ran until the `r_halt` signal is raised. The test bench then checks the value on the `debug0`, `debug1`, and `debug2` signals against the expected value. If this matches, then it is assumed that sub-components of the design also operate correctly. This technique does not monitor the states of sub-components and statistics (such as time taken to execute an instruction), there leaves the possibility that some components could have entered an illegal state.

# Chapter 5

## Interconnect

5.1	Introduction	32
5.1.1	Comparison of On-chip Buses	32
5.2	Overview	33
5.2.1	Design Considerations	34
5.3	Interfaces	35
5.3.1	Master to Slave Interface	35
5.3.2	Multi-master Support	36
5.4	Further Work	36

### 5.1 Introduction

The Vmicro16 processor needs to communicate with multiple peripheral modules (such as UART, timers, GPIO, and more) to provide useful functionality for the end user.

Previous peripheral interface designs of mine have been directly connected to a main driver with unique inputs and outputs that the peripheral required. For example, a timer peripheral would have dedicated wires for it's load and prescaler values, wires for enabling and resetting, and wires for reading. A memory peripheral would have wires for it's address, read and write data, and a write enable signal. This resulted in each peripheral having a unique interface and unique logic for driving the peripheral, which consumed significant amounts of limited FPGA resources.

It can be seen that many of the peripherals need similar inputs and outputs (for example read and write data signals, write enables, and addresses), and because of this, a standard interface can be used to interface with each peripheral. Using a standard interface can reduce logic requirements as each peripheral can be driven by a single driver.

#### 5.1.1 Comparison of On-chip Buses

The choice of on-chip interconnect has changed multiple times over the life-cycle of this project, primary due to ease of implementation and resource requirements.

Originally, it was planned to use the Wishbone bus [?] due to it's popularity within open-source FPGA modules and good quality documentation.

Late in the project, it was decided to use the AMBA APB protocol [?] as it is more commonly used in large commercial designs and understanding how the interface worked would better benefit myself. APB describes an intuitive and easy to implement 2-state interface aimed at communicating with low-throughput devices, such as UARTs, timers, and watchdogs.

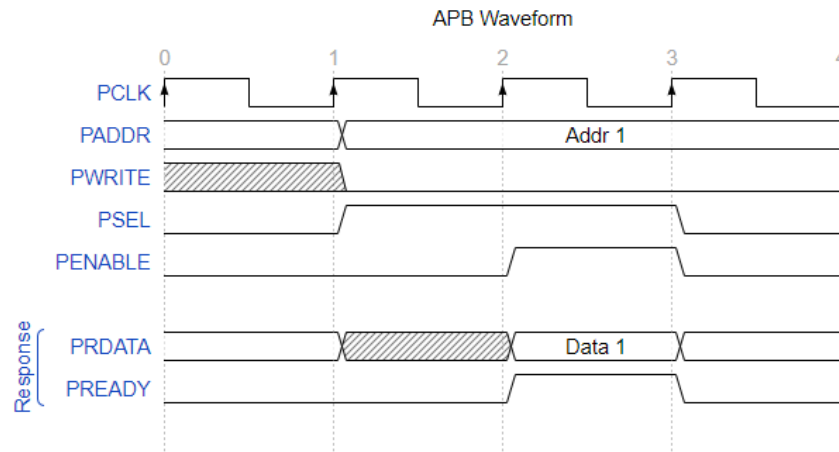


Figure 5.1: Waveform showing an APB read transaction.

## 5.2 Overview

The system-on-chip design is split into 3 main parts: peripheral interconnect (red), CPU array (gray), and the instruction memory interconnect (green).

A block diagram of this project is shown in [Figure 5.2](#)

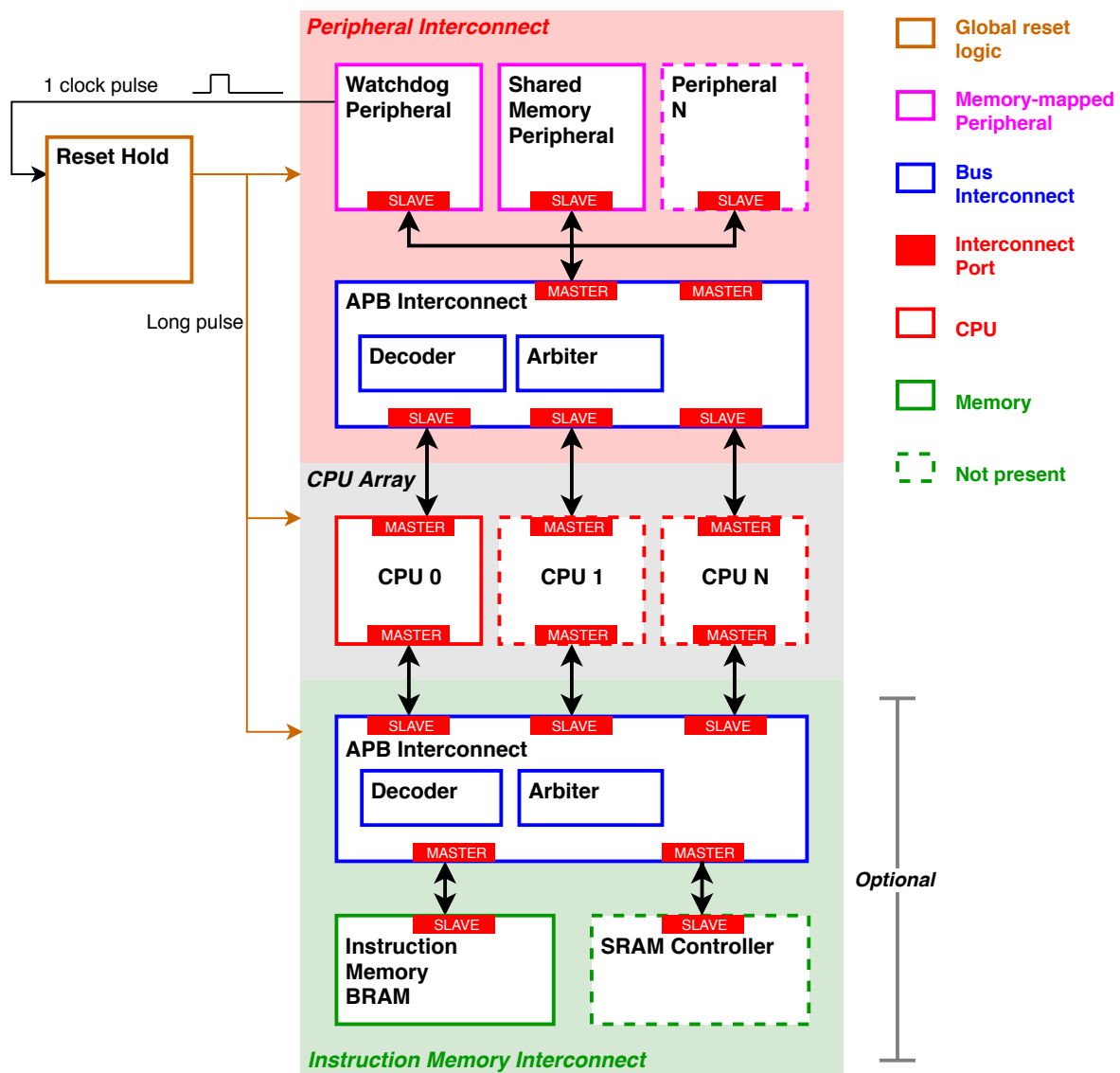


Figure 5.2: Block diagram of the Vmicro16 system-on-chip.

### 5.2.1 Design Considerations

There are several design issues to consider for this project. These are listed below:

- **Design size limitations**

The target devices for this project are small to medium sized FPGAs (featuring approximately 10,000 to 30,000 logic cells). Because of this, it is important to use a bus interconnect that has a small logic footprint yet is able to scale reasonably well.

- **Ease of implementation**

The interconnect and any peripherals should be easy to implement within a reasonable time.

- **Scalable**

The interconnect should allow for easy scalability of master and slave interfaces with minimal code changes.



5.3.2 Multi-master Support

Design Goals

DG1. Foo  
Bing

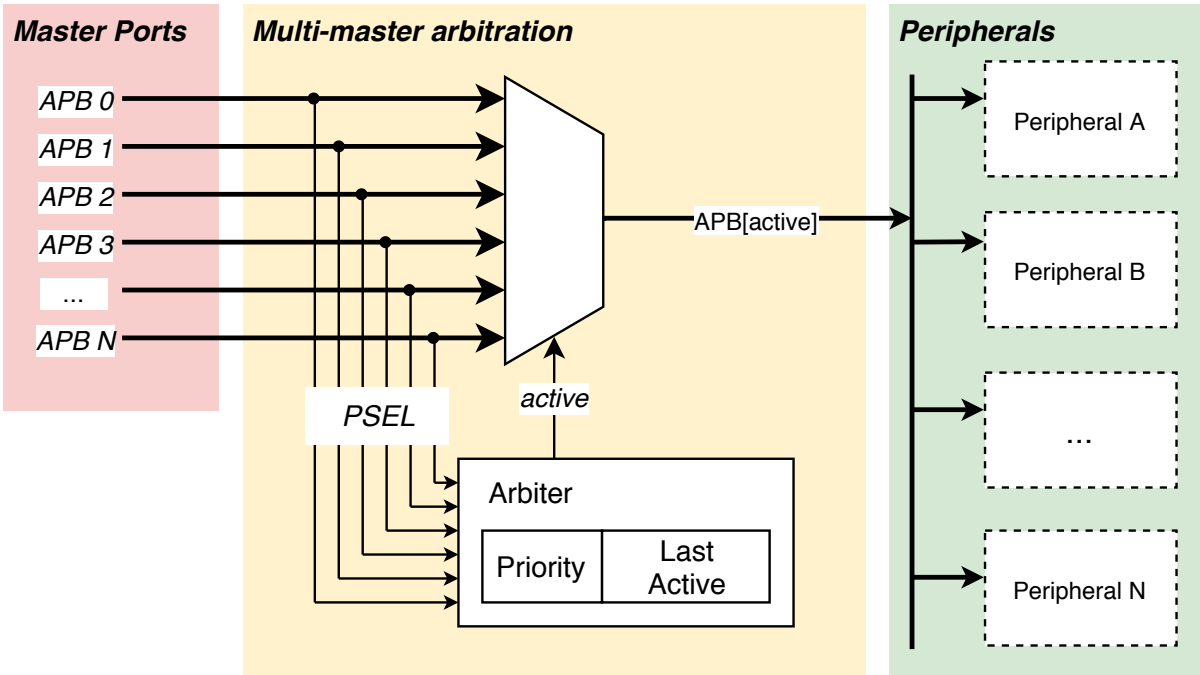
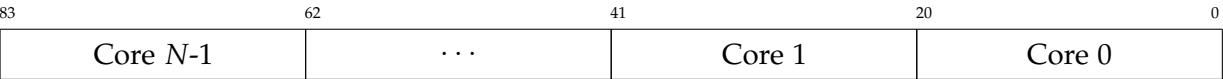


Figure 5.3: Foo

```
1  input      [MASTER_PORTS*BUS_WIDTH-1:0]  S_PADDR,
2  input      [MASTER_PORTS-1:0]            S_PWRITE,
3  input      [MASTER_PORTS-1:0]            S_PSELx,
4  input      [MASTER_PORTS-1:0]            S_PENABLE,
5  input      [MASTER_PORTS*DATA_WIDTH-1:0] S_PWDATA,
6  output reg [MASTER_PORTS*DATA_WIDTH-1:0] S_PRDATA,
7  output reg [MASTER_PORTS-1:0]            S_PREADY,
```

Listing 5: Variable size inputs and outputs to the interconnect.



5.4 Further Work

The submitted design is acceptable for a multi-core system as it fulfils the following requirements:

- Support an arbitrary number of peripherals.
- Supports memory-mapped address decoding.

- Supports multiple master interfaces.

# Chapter 6

## Memory Mapping

6.1	Introduction	38
6.2	Address Decoding	38
6.2.1	Decoder Optimisations	39
6.3	Memory Map	41

The Vmicro16 processor uses a memory-mapping scheme to communicate with peripherals and other cores. This chapter describes the design decisions and implementation of the memory-map used in this project.

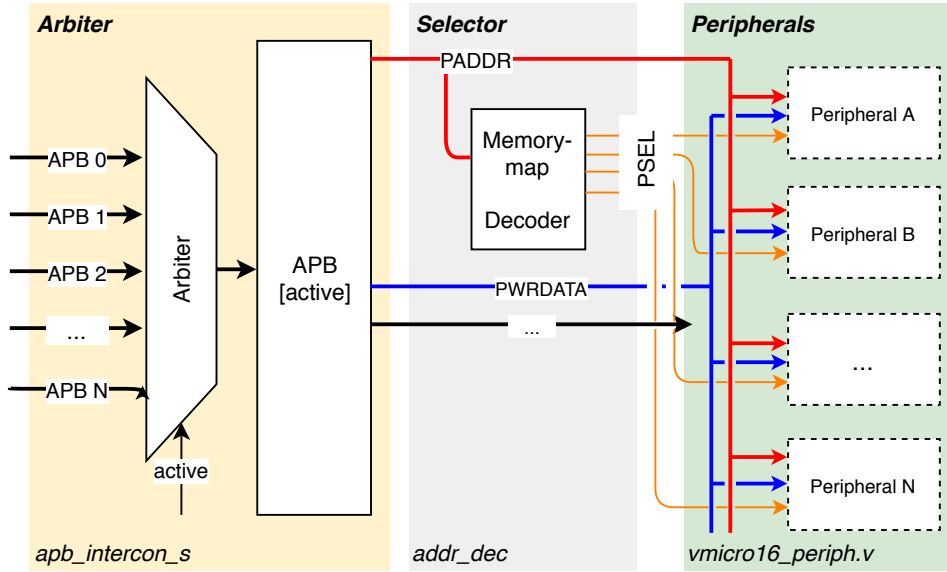
### 6.1 Introduction

Memory mapping is a common technique used by CPUs, micro-controllers, and other system-on-chip devices, that enables peripherals and other devices to be accessed via a memory address on a common bus. In a processor use-case, this allows for the reuse of existing instructions (commonly memory load/store instructions) to communicate with external peripherals with little additional logic.

### 6.2 Address Decoding

An address decoder is used to determine the peripheral that the address is requesting. The address decoder module, `addr_dec` in `apb_intercon.v`, takes the 16-bit `PADDR` from the active APB interface and checks for set bits to determine which peripheral to select. The decoder outputs a chip enable signal `PSEL` for the selected peripheral. For example, if bit 12 is set in `PADDR` then the shared memory peripheral's `PSEL` is set high and others to low. A schematic for the decoder is shown in [Figure 6.1](#).

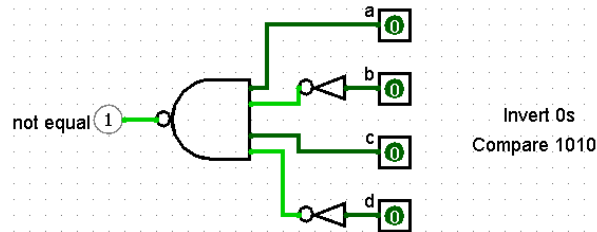




**Figure 6.1:** Schematic showing the address decoder (*addr\_dec*) accepting the active PADDR signal and outputting PSEL chip enable signals to each peripheral.

### 6.2.1 Decoder Optimisations

Performing a 16-bit equality comparison of the PADDR signal against each peripheral memory address consumes a significant amount of logic. Depending on the synthesis tools and FPGA features, a 16-bit comparator might require a fixed 16-bit value input to compare against (where the 0s are inverted) and a wide-AND to reduce and compare [13, 14]. An example 4-bit comparator is shown below in Figure 6.2.

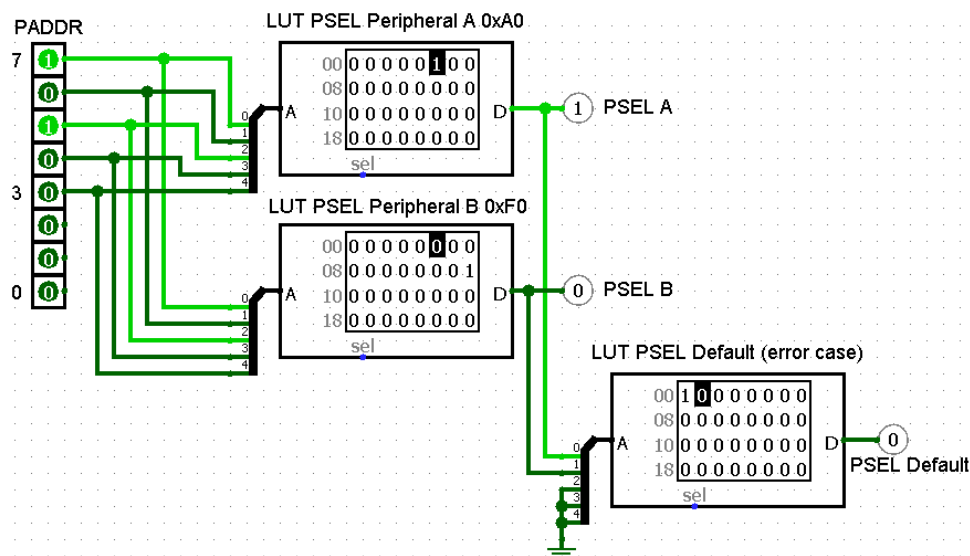


**Figure 6.2:** Example 4-bit binary comparator which compares the bits (a, b, c, d) to the constant value 1010. The 0s of the constant are inverted and then all are passed to a wide-AND.

As we are targeting FPGAs, which use LUTs to implement combinatorial logic, we can conveniently utilise Verilog's `==` operator on fairly large operands without worrying about consuming too many resources. The targeted FPGA devices in this project, the Cyclone V and Spartan 6, feature 6-input LUTs which allow 64 different configurations [15, 16]. Knowing this, we can design the address decoder to utilise the FPGA's LUTs more effectively and reduce its footprint significantly.

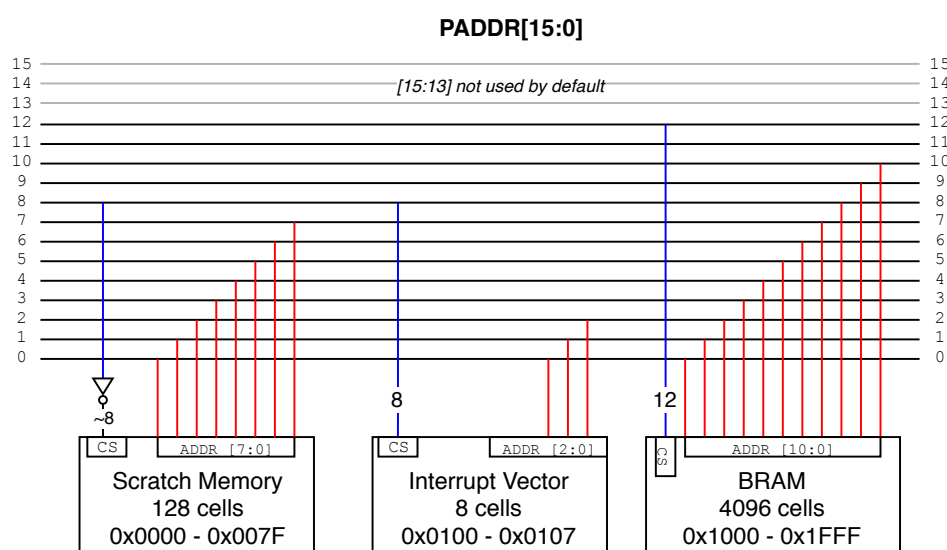
We can use part of the PADDR signal as a chip select and the other bits as sub-addresses to interface with the peripheral. The addressing bits are passed into the FPGA's 6-input LUTs which are programmed (via the bitstream) to output 1 or 0 depending on the address. Figure 6.3 below shows a LUT based approach to address decoding which will utilise approximately one ALM/CLB module per peripheral chip select (PSEL) and one for error detection. This method

of comparison (LUT based) is utilised in the `addr_dec` module in `apb_intercon.v`.



**Figure 6.3:** Bits [7:3] of an 8-bit PADDR signal are used as inputs to 5-bit LUTs to generate a PSEL signal. In addition, a default error case is shown allowing the address decoder to detect incorrect PADDR values (e.g. if no PSEL signals are generated).

The address decoding methods discussed above are examples of *full-address* decoding, where each bit (whether required or not) is compared. It is possible to further reduce the required logic by utilising *partial-address* decoding [17]. Partial-address decoding can reduce logic requirements by not using all bits. For example, if bits in address 0x0100 do not conflict with bits in other addresses (i.e. bit 8 is high in more than 1 address), then the address decoder needs only concern bit 8, not the other bits. This is visualised in Figure 6.4 below. This method is utilised in the MMU's address decoder (module `vmicro16_mmu` in `vmicro16.v`:181). As this is an optimisation per core, significant resources can be saved when a large number of cores are used.



**Figure 6.4:** Partial address decoding used by the Vmicro16 SoC design. Each peripheral shown only needs to decode a signal bit to determine if it is enabled.

### 6.3 Memory Map

The system-on-chip's memory map is shown below in [Figure 6.5](#). The addresses for each peripheral have been carefully chosen for both:

- Easy software access – creating addresses via software requires few instructions (normally one to four MOVI and LSHIFT instructions to address 0x0000 to 0xffff), which increases software performance.
- and Reducing address decoding logic – most addresses can be decoded using partial decoding techniques.

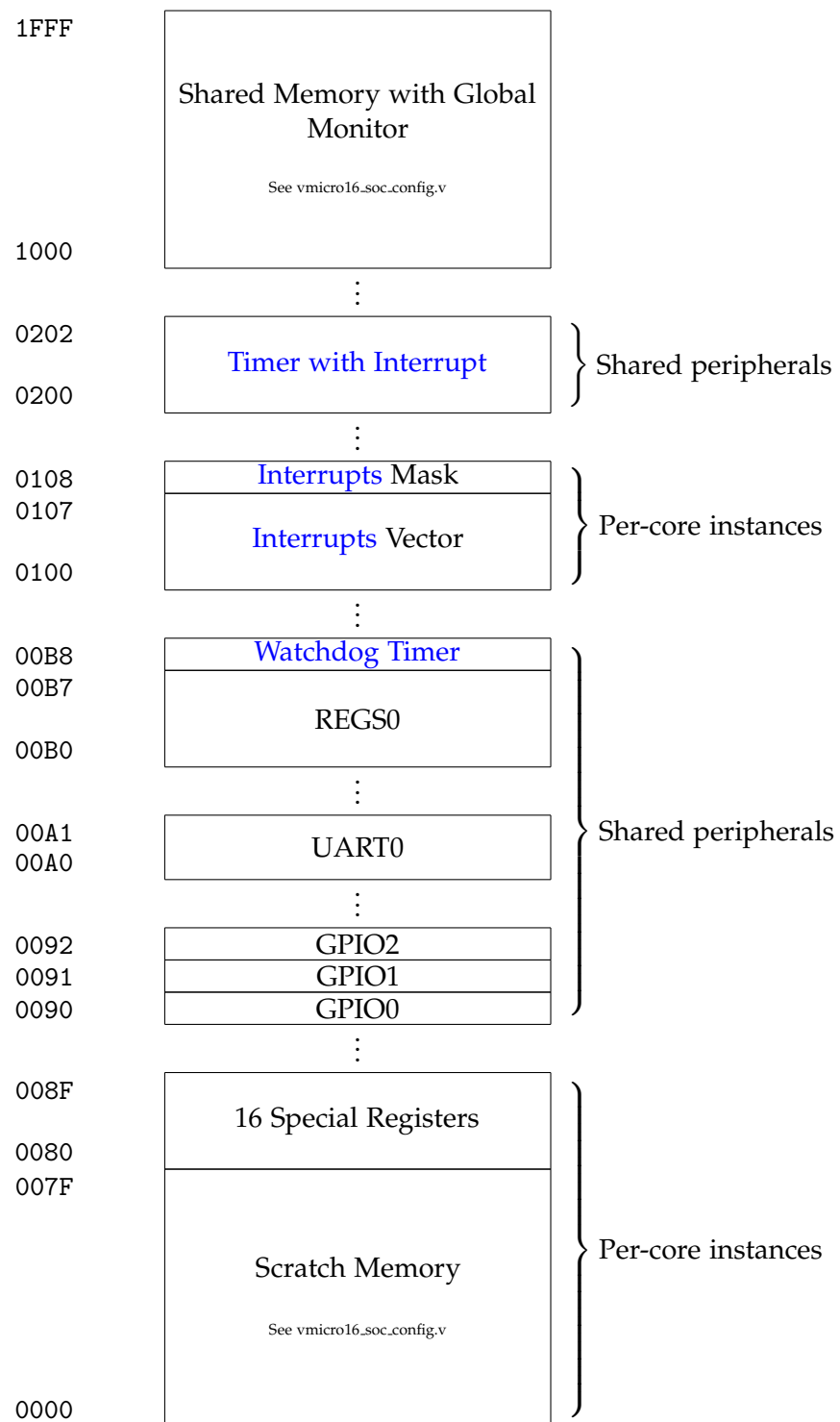


Figure 6.5: Memory map showing addresses of various memory sections.

# Chapter 7

## Peripherals

7.1 Special Registers . . . . .	43
7.2 Watchdog Timer . . . . .	43
7.3 GPIO Interface . . . . .	44
7.4 Timer with Interrupt . . . . .	44
7.5 UART Interface . . . . .	44

To provide user's with useful functionality, common system-on-chip peripherals were created. This section describes each peripheral and it's design decisions.

### 7.1 Special Registers

From the software perspective, it is important for both the developer and software algorithms to know the target system's architecture to better utilise the resources available to them. Software written for one architecture with  $N$  cores must also run on an architecture with  $M$  cores. To enable such portability, the software must query the system for information such as: number of processor cores and the current core identifier. Without this information, the developer would be required to produce software for each individual architecture (e.g. an Intel i5 with 4 cores or an Intel i7 with 8 cores, or an NVIDIA GTX 970 with.

### 7.2 Watchdog Timer

In any multi-threaded system there exists the possibility for a deadlock – a state where all threads are in a waiting state – and algorithm execution is forever blocked. This can occur either by poor software programming or incorrect thread arbitration by the processor. A common method of detecting a deadlock is to make each thread signal that it is not blocked by resetting a countdown timer. If the countdown timer is not reset, it will eventually reach zero and it is assumed that all threads are blocked as none have reset the countdown.

In this system-on-chip design, software can reset the watchdog timer by writing any 16-bit value to the address 0x00B8.

This peripheral is optional and can be enabled using the configuration parameters described in [Configuration Options](#).

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Reset Watchdog																00B8 W

### 7.3 GPIO Interface

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
GPIO0 Output																0090 RW
GPIO1 Output																0091 RW
GPIO1 Input																0092 R

### 7.4 Timer with Interrupt

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
Load Value																0200 RW
													I	R	S	0201 W
Prescaler																0202 W

### 7.5 UART Interface

15	8	7	1	0		
			Transmit Data		00A0 W	
			Receive Data		00A1 R	
				E	I	00A2 R/W

# Chapter 8

## Multi-core Communication

8.1	Introduction	45
8.1.1	Design Goals	45
8.1.2	Context Identification	45
8.1.3	Thread Synchronisation	46
8.2	Design Challenges	48
8.2.1	Memory Constraints	48

So far we have discussed the features and design of the Vmicro16 system-on-chip. This section will discuss the multi-processing functionality and how to use it.

### 8.1 Introduction

Multi-processing functionality is the primary deliverable of this project.

#### 8.1.1 Design Goals

- **Support common synchronisation primitives.**

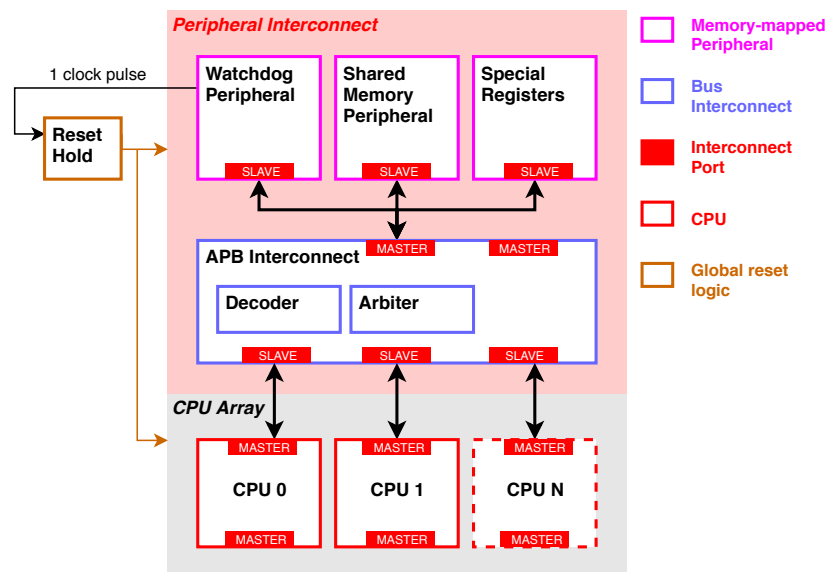
Software should be able to implement common synchronisation primitives, such as mutexes, semaphores, and memory barriers, to perform atomic operations and avoid race conditions, which are critical in parallel and concurrent software applications.

- **Context identification.**

The SoC should expose configuration information such as: the number of processing cores, amount of shared and scratch memory, and the `CORE_ID`, to each thread.

#### 8.1.2 Context Identification

A goal of the multi-processing functionality of this project is allow software written for it to be run on any number of cores. This means that a software program will scale to use all cores in the SoC without needing to rewrite the software. To enable this functionality, the software must be able to read contextual information about the SoC, such as the number of cores, how much global and scratch memory is available, and what the `CORE_ID` of the current core is.



**Figure 8.1:** Block diagram showing the main multi-processing components: the CPU array and a peripheral interconnect used for core synchronisation.

This information is provided through the Special Registers peripheral (0x0080 - 0x008F), shown in Figure 8.1. This register set provides relevant information for writing software that can dynamically scale for various SoC configurations.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0		
								CORE_ID								0080	R
								NUM_CORES								0081	R
SHARED_MEMORY cells (default 4096)																0082	R
								NUM_PERIPHERALS								0083	R
SCRATCH_MEMORY cells (default 64)																0084	RW
User defined																0085	RW
⋮																	
User defined																008F	RW

**Figure 8.2:** Vmicro16 Special Registers layout (0x0080 - 0x008F).

### 8.1.3 Thread Synchronisation

In multi-threaded software it is important

The mutex functionality is implemented using a similar scheme to that of ARM's *Global Monitor* [? ].

#### Mutexes

In software, a mutex is an object used to control access to a shared resource. The term *object* is used as it's implementation is normally platform dependant, meaning that the processor may provide a hardware mechanism or is left for the operating system to provide.



In this project, mutexes are provided by the processor through the Shared Memory Peripheral (0x1000 to 0x1FFF) which provides a large RAM-style memory accessible by all cores through the peripheral interconnect bus. This large memory is explicitly defined to use the FPGA's BRAM blocks using Xilinx's Verilog `ram_style="block"` attribute to avoid wasting LUTs when using high core counts. The peripheral allows each memory cell to be *locked*, meaning that only the cell owner can modify it's contents. This is implemented by using another large memory, `locks`, to store the `CORE_ID + 1` of the owner, as shown in Listing 6. In this system, a lock containing the value zero indicates an unlocked cell. As `CORE_ID`s are indexed from zero, one is added to each cell. For example, if core two wants to lock a memory cell, the value three is written to the lock.

```

1  reg [15:0]          ram    [0:8191]; // 16KB large RAM memory
2  reg [clog2(CORES):0] locks [0:8181]; // memory cell owner

```

Listing 6: RAM and lock memories instantiated by the shared memory peripheral.

To lock and unlock cells, the instructions `LWEX` and `SWEX` instructions are used. These instructions are similar to the `LW`/`SW` instructions but provide locking functionality. The `EX` in the instruction names indicate *exclusive access*. `LWEX` is used to read memory contents (like `LW`) and also lock the cell if not already locked. If a core attempts to lock an already locked cell, the lock does not change. Unlocking is done by the `SWEX` instruction, which conditionally writes to the memory cell if it is locked by the same core. Unlike `SW`, `SWEX` returns a zero for success and one for failure if it is locked by another core.

Figure 8.3 shows a simple assembly function to lock a memory cell.

```

1  lock_mutex:
2      // attempt lock
3      lwex r0, r1
4      // check success
5      swex r0, r1
6      cmp  r0, r3
7      // if not equal (NE), retry
8      movi r4, lock_mutex
9      br   r4, BR_NE
10 critical:
11     // core has the mutex

```

Figure 8.3: Assembly code for locking a mutex. `r1` is the address to lock. `r3` is zero. `r4` is the branch address.

## Barriers

Barriers are a useful software sequence used to block execution until all other threads (or a subset) have reached the same point. Barriers are often used for broadcast and gather actions (sending values to each core or receiving them). They are also used to synchronise program execution if some threads have more work to do than others.

The Vmicro16 processor provides barrier synchronisation through the Shared Memory Peripheral. Like the mutex code, the barrier code uses the `LWEX` and `SWEX` instructions to lock a memory cell. Instead of immediately checking the lock as an abstract object, the barrier code treats the cell as a normal memory cell containing a numeric value. Figure 8.4 shows a software example of this. When the `barrier_reached` code is reached, the code will increment the shared memory value by 1, indicating that the number of threads that have reached this point has increased by one (`r5`). The `barrier_wait` function

is then entered which waits until this numeric value (r5) is equal to the number of threads (r7) in the system. If this is true, then all threads have reached the barrier\_wait function and can continue with normal program execution.

## 8.2 Design Challenges

### 8.2.1 Memory Constraints



Figure 8.5: •

```
1  barrier_reached:
2      // load latest count
3      lwex    r0, r5
4      // try increment count
5      // increment by 1
6      addi    r0, r3 + #0x01
7      // attempt store
8      swex    r0, r5
9
10     // check success (== 0)
11     cmp      r0, r3
12     // branch if failed
13     movi     r4, barrier_reached
14     br       r4, BR_NE
15
16  barrier_wait:
17     // load the count
18     lw       r0, r5
19     // compare with number of threads
20     cmp      r0, r7
21     // jump back to barrier if not equal
22     movi     r4, barrier_wait
23     br       r4, BR_NE
```

**Figure 8.4:** Assembly code for a memory barrier. Threads will wait in the barrier\_wait function until all other threads have reached that code point.

## **Chapter 9**

# **Analysis & Results**

## References

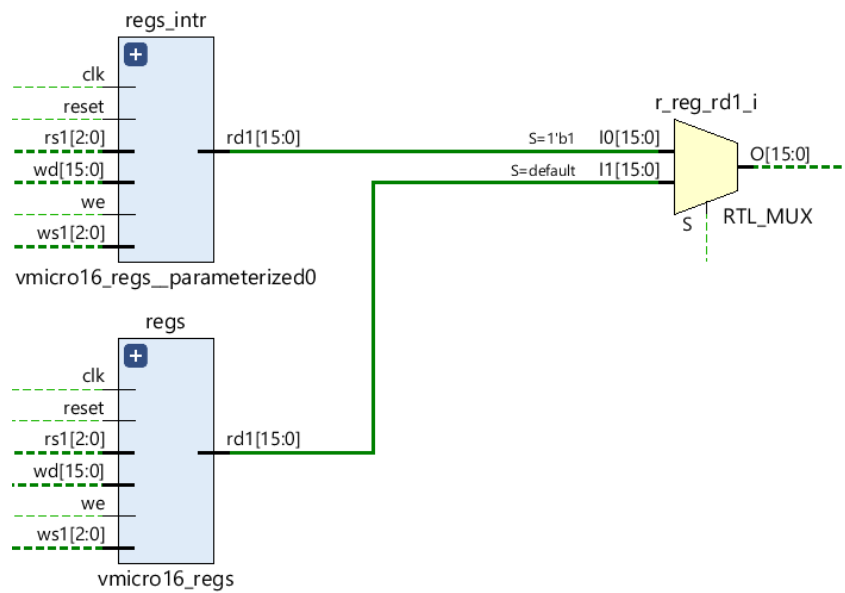
- [1] V. Subramanian, "Multiple gate field-effect transistors for future CMOS technologies," *IETE Technical review*, vol. 27, no. 6, pp. 446–454, 2010.
- [2] M. J. Flynn, *Computer architecture: Pipelined and parallel processor design*. Jones & Bartlett Learning, 1995.
- [3] Tech Differences, "Difference between loosely coupled and tightly coupled multiprocessor system (with comaprison chart)," Jul 2017. [Online]. Available: <https://techdifferences.com/difference-between-loosely-coupled-and-tightly-coupled-multiprocessor-system.html> (Accessed 2019-04-20).
- [4] L. Benini and G. De Micheli, "Networks on Chips: A new SoC paradigm," *Computer*, vol. 35, pp. 70–78, 02 2002.
- [5] D. Zhu, L. Chen, S. Yue, T. M. Pinkston, and M. Pedram, "Balancing On-Chip Network Latency in Multi-application Mapping for Chip-Multiprocessors," in *2014 IEEE 28th International Parallel and Distributed Processing Symposium*, May 2014, pp. 872–881.
- [6] N. Chatterjee, S. Paul, and S. Chattopadhyay, "Fault-tolerant dynamic task mapping and scheduling for network-on-chip-based multicore platform," *ACM Transactions on Embedded Computing Systems*, vol. 16, pp. 1–24, 05 2017.
- [7] Xilinx, *Spartan-6 FPGA Block RAM Resources*, Xilinx.
- [8] Altera, *Recommended HDL Coding Styles - QII51007-9.0.0*, Altera.
- [9] B. Lancaster, "FPGA-based RISC Microprocessor and Compiler," vol. 3.14, pp. 37–50. [Online]. Available: <https://github.com/bendl/prco304> (Accessed March 2018).
- [10] Terasic Technologies, "SoC Platform - Cyclone - DE1-SoC Board." [Online]. Available: <https://www.terasic.com.tw/cgi-bin/page/archive.pl?Language=English&No=836> (Accessed 2019-04-20).
- [11] *MiniSpartan6+*, Scarab Hardware, 2014. [Online]. Available: <https://www.scarabhardware.com/minispartan6/> (Accessed 2019-04-20).
- [12] P. Kocher, D. Genkin, D. Gruss, W. Haas, M. Hamburg, M. Lipp, S. Mangard, T. Prescher, M. Schwarz, and Y. Yarom, "Spectre attacks: Exploiting speculative execution," *arXiv preprint arXiv:1801.01203*, 2018.
- [13] A. Palchadhuri and R. S. Chakraborty, *High Performance Integer Arithmetic Circuit Design on FPGA: Architecture, Implementation and Design Automation*. Springer, 2015, vol. 51.
- [14] V. Salauyou and M. Gruszewski, "Designing of hierarchical structures for binary comparators on fpga/soc," in *IFIP International Conference on Computer Information Systems and Industrial Management*. Springer, 2015, pp. 386–396.
- [15] Xilinx, *Spartan-6 FPGA Configurable Logic Block - User Guide - UG384*, Xilinx.

- [16] Altera, *Cyclone V Device Handbook - Device Interfaces and Integration - CV-5V2*, Altera.
- [17] A. S. Tanenbaum, *Structured Computer Organization*. Pearson Education India, 2016.

# Appendix A

## Additional Figures

### A.1 Register Set Multiplex



**Figure A.1:** Normal mode and interrupt mode register sets are multiplexed to instantly save the context.

## A.2 Instruction Set Architecture

	15-11	10-8	7-5	4-0	rd ra simm5
	15-11	10-8	7-0		rd imm8
	15-11	10-0			nop
	15	14:12	11:0		extended immediate
SPCL	00000	11 bits			NOP
SPCL	00000	11h'000			NOP
SPCL	00000	11h'001			HALT
SPCL	00000	11h'002			Return from interrupt
LW	00001	Rd	Ra	s5	Rd <= RAM[Ra+s5]
SW	00010	Rd	Ra	s5	RAM[Ra+s5] <= Rd
BIT	00011	Rd	Ra	s5	bitwise operations
BIT_OR	00011	Rd	Ra	00000	Rd <= Rd   Ra
BIT_XOR	00011	Rd	Ra	00001	Rd <= Rd ^ Ra
BIT_AND	00011	Rd	Ra	00010	Rd <= Rd & Ra
BIT_NOT	00011	Rd	Ra	00011	Rd <= ~Ra
BIT_LSHFT	00011	Rd	Ra	00100	Rd <= Rd << Ra
BIT_RSHFT	00011	Rd	Ra	00101	Rd <= Rd >> Ra
MOV	00100	Rd	Ra	X	Rd <= Ra
MOVI	00101	Rd		i8	Rd <= i8
ARITH_U	00110	Rd	Ra	s5	unsigned arithmetic
ARITH_UADD	00110	Rd	Ra	11111	Rd <= uRd + uRa
ARITH_USUB	00110	Rd	Ra	10000	Rd <= uRd - uRa
ARITH_UADDI	00110	Rd	Ra	0AAAA	Rd <= uRd + Ra + AAAA
ARITH_S	00111	Rd	Ra	s5	signed arithmetic
ARITH_SADD	00111	Rd	Ra	11111	Rd <= sRd + sRa
ARITH_SSUB	00111	Rd	Ra	10000	Rd <= sRd - sRa
ARITH_SSUBI	00111	Rd	Ra	0AAAA	Rd <= sRd - sRa + AAAA
BR	01000	Rd		i8	conditional branch
BR_U	01000	Rd		0000 0000	Any
BR_E	01000	Rd		0000 0001	Z=1
BR_NE	01000	Rd		0000 0010	Z=0
BR_G	01000	Rd		0000 0011	Z=0 and S=0
BR_GE	01000	Rd		0000 0100	S=0
BR_L	01000	Rd		0000 0101	S != 0
BR_LE	01000	Rd		0000 0110	Z=1 or (S != 0)
BR_S	01000	Rd		0000 0111	S=1
BR_NS	01000	Rd		0000 1000	S=0
CMP	01001	Rd	Ra	X	SZO <= CMP(Rd, Ra)
SETC	01010	Rd		Imm8	Rd <= (Imm8_f_SZO) ? 1 : 0
MULT	01011	Rd	Ra	X	Rd <= uRd * uRa
HALT	01100		X		
LWEX	01101	Rd	Ra	s5	Rd <= RAM[Ra+s5]
SWEX	01110	Rd	Ra	s5	RAM[Ra+s5] <= Rd Rd <= 0 1 if success

Figure A.2: Vmicro16 instruction set architecture.



# Appendix B

## Configuration Options

B.1 System-on-chip Configuration Options	55
B.2 Core Options	56
B.3 Peripheral Options	57

The following configuration options are defined in `vmicro16_soc_config.v`.

### B.1 System-on-chip Configuration Options

Macro	Default	Purpose
CORES	4	Number of CPU cores in the SoC
SLAVES	7	Number of peripherals
DEF_USE_WATCHDOG		Enable watchdog module to detect deadlocks and infinite loops

**Table B.1:** SoC Configuration Options

## B.2 Core Options

Macro	Default	Purpose
DATA_WIDTH	16	Width of CPU registers in bits
DEF_CORE_HAS_INSTR_MEM	//	Enable a per core instruction memory cache
DEF_MEM_INSTR_DEPTH	64	Instruction memory cache per core
DEF_MEM_SCRATCH_DEPTH	64	RW RAM per core
DEF_ALU_HW_MULT	1	Enable/disable HW multiply (1 clock)
FIX_T3	//	Enable a T3 state for the APB transaction
DEF_GLOBAL_RESET	//	Enable synchronous reset logic
DEF_USE_REPROG	//	Programme instruction memory via UART0. Requires DEF_GLOBAL_RESET

**Table B.2:** Core Options

### B.3 Peripheral Options

Macro	Default	Purpose
APB.WIDTH		AMBA APB PADDR signal width
APB.PSELX_GPIO0	0	GPIO0 index
APB.PSELX_UART0	1	UART0 index
APB.PSELX_REGS0	2	REGS0 index
APB.PSELX_BRAM0	3	BRAM0 index
APB.PSELX_GPIO1	4	GPIO1 index
APB.PSELX_GPIO2	5	GPIO2 index
APB.PSELX_TIMR0	6	TIMR0 index
APB.BRAM0_CELLS	4096	Shared memory words
DEF_MMU_TIM0_S	16'h0000	Per core scratch memory start/end address
DEF_MMU_TIM0_E	16'h007F	"
DEF_MMU_SREG_S	16'h0080	Per core special registers start/end address
DEF_MMU_SREG_E	16'h008F	"
DEF_MMU_GPIO0_S	16'h0090	Shared GPIO0 start/end address
DEF_MMU_GPIO0_E	16'h0090	"
DEF_MMU_GPIO1_S	16'h0091	"
DEF_MMU_GPIO1_E	16'h0091	"
DEF_MMU_GPIO2_S	16'h0092	"
DEF_MMU_GPIO2_E	16'h0092	"
DEF_MMU_UART0_S	16'h00A0	Shared UART start/end address
DEF_MMU_UART0_E	16'h00A1	"
DEF_MMU_REGS0_S	16'h00B0	Shared registers start/end address
DEF_MMU_REGS0_E	16'h00B7	"
DEF_MMU_BRAM0_S	16'h1000	Shared memory with global monitor start/end address
DEF_MMU_BRAM0_E	16'h1FFF	"
DEF_MMU_TIMR0_S	16'h0200	Shared timer peripheral start/end address
DEF_MMU_TIMR0_E	16'h0202	"

Table B.3: Peripheral Options

# Appendix C

## Code Listing

C.1	vmicro16_soc_config.v	58
C.2	top_ms.v	60
C.3	vmicro16_soc.v	61
C.4	vmicro16_periph.v	67
C.5	vmicro16.v	73

### C.1 vmicro16\_soc\_config.v

Configuration file for configuring the vmicro16\_soc.v and vmicro16.v features.

```
1 // Configuration defines for the vmicro16_soc and vmicro16 cpu.
2
3 `ifndef VMICRO16_SOC_CONFIG_H
4 `define VMICRO16_SOC_CONFIG_H
5
6 `include "clog2.v"
7
8 `define FORMAL
9
10 `define CORES 8
11 `define SLAVES 8
12
13 //////////////////////////////////////////////////
14 // Core parameters
15 //////////////////////////////////////////////////
16 // Per core instruction memory
17 // Set this to give each core its own instruction memory cache
18 `define DEF_CORE_HAS_INSTR_MEM
19
20 // Top level data width for registers, memory cells, bus widths
21 `define DATA_WIDTH 16
22
23 // Set this to use a workaround for the MMU's APB T2 clock
24 //`define FIX_T3
25
26 // Instruction memory (read only)
27 // Must be large enough to support software program.
28 `ifdef DEF_CORE_HAS_INSTR_MEM
29 // 64 16-bit words per core
30 `define DEF_MEM_INSTR_DEPTH 64
31 `else
32 // 4096 16-bit words global
33 `define DEF_MEM_INSTR_DEPTH 4096
34 `endif
35
36 // Scratch memory (read/write) on each core.
37 // See `DEF_MMU_TIMO_* defines for info.
38 `define DEF_MEM_SCRATCH_DEPTH 64
39
40 // Enables hardware multiplier and mult rr instruction
41 `define DEF_ALU_HW_MULT 1
42
43 // Enables global reset (requires more luts)
44 //`define DEF_GLOBAL_RESET
```

```

45
46 // Enable a watch dog timer to reset the soc if threadlocked
47 //`define DEF_USE_WATCHDOG
48
49 // Enables instruction memory programming via UART0
50 //`define DEF_USE_REPROG
51
52 `ifdef DEF_USE_REPROG
53     `ifndef DEF_GLOBAL_RESET
54         `error_DEF_USE_REPROG_requires_DEF_GLOBAL_RESET
55     `endif
56 `endif
57
58 //////////////////////////////////////////////////
59 // Memory mapping
60 //////////////////////////////////////////////////
61 `define APB_WIDTH      (2 + `clog2(`CORES) + `DATA_WIDTH)
62
63 `define APB_PSELX_GPIO0 0
64 `define APB_PSELX_UART0 1
65 `define APB_PSELX_REGSO 2
66 `define APB_PSELX_BRAMO 3
67 `define APB_PSELX_GPIO1 4
68 `define APB_PSELX_GPIO2 5
69 `define APB_PSELX_TIMRO 6
70 `define APB_PSELX_WDOGO 7
71
72 `define APB_GPIO0_PINS 8
73 `define APB_GPIO1_PINS 16
74 `define APB_GPIO2_PINS 8
75
76 // Shared memory words
77 `define APB_BRAMO_CELLS 4096
78
79 //////////////////////////////////////////////////
80 // Memory mapping
81 //////////////////////////////////////////////////
82 // TIMO
83 // Number of scratch memory cells per core
84 `define DEF_MMU_TIMO_CELLS 64
85 `define DEF_MMU_TIMO_S 16'h0000
86 `define DEF_MMU_TIMO_E 16'h007F
87 // SREG
88 `define DEF_MMU_SREG_S 16'h0080
89 `define DEF_MMU_SREG_E 16'h008F
90 // GPIO0
91 `define DEF_MMU_GPIO0_S 16'h0090
92 `define DEF_MMU_GPIO0_E 16'h0090
93 // GPIO1
94 `define DEF_MMU_GPIO1_S 16'h0091
95 `define DEF_MMU_GPIO1_E 16'h0091
96 // GPIO2
97 `define DEF_MMU_GPIO2_S 16'h0092
98 `define DEF_MMU_GPIO2_E 16'h0092
99 // UART0
100 `define DEF_MMU_UART0_S 16'h00A0
101 `define DEF_MMU_UART0_E 16'h00A1
102 // REGSO
103 `define DEF_MMU_REGSO_S 16'h00B0
104 `define DEF_MMU_REGSO_E 16'h00B7
105 // WDOGO
106 `define DEF_MMU_WDOGO_S 16'h00B8
107 `define DEF_MMU_WDOGO_E 16'h00B8
108 // BRAMO
109 `define DEF_MMU_BRAMO_S 16'h1000
110 `define DEF_MMU_BRAMO_E 16'h1fff
111 // TIMRO
112 `define DEF_MMU_TIMRO_S 16'h0200
113 `define DEF_MMU_TIMRO_E 16'h0202
114
115 //////////////////////////////////////////////////
116 // Interrupts
117 //////////////////////////////////////////////////
118 // Enable/disable interrupts
119 // Disabling will free up resources for other features
120 `define DEF_ENABLE_INT
121 // Number of interrupt in signals
122 `define DEF_NUM_INT 8
123 // Default interrupt bitmask (0 = hidden, 1 = enabled)
124 `define DEF_INT_MASK 0
125 // Bit position of the TIMRO interrupt signal
126 `define DEF_INT_TIMRO 0
127 // Interrupt vector memory location
128 `define DEF_MMU_INTSV_S 16'h0100
129 `define DEF_MMU_INTSV_E 16'h0107
130 // Interrupt vector memory location
131 `define DEF_MMU_INTSM_S 16'h0108
132 `define DEF_MMU_INTSM_E 16'h0108
133
134

```

135     `endif

## C.2 top\_ms.v

Top level module that connects the SoC design to hardware pins on the FPGA.

```

1  module seven_display # (
2      parameter INVERT = 1
3  ) (
4      input  [3:0] n,
5      output [6:0] segments
6  );
7      reg [6:0] bits;
8      assign segments = (INVERT ? ~bits : bits);
9
10     always @(n)
11     case (n)
12         4'h0: bits = 7'b0111111; // 0
13         4'h1: bits = 7'b0000110; // 1
14         4'h2: bits = 7'b1011011; // 2
15         4'h3: bits = 7'b1001111; // 3
16         4'h4: bits = 7'b1100110; // 4
17         4'h5: bits = 7'b1101101; // 5
18         4'h6: bits = 7'b1111101; // 6
19         4'h7: bits = 7'b0000111; // 7
20         4'h8: bits = 7'b1111111; // 8
21         4'h9: bits = 7'b1100111; // 9
22         4'hA: bits = 7'b1110111; // A
23         4'hB: bits = 7'b1111100; // B
24         4'hC: bits = 7'b0111001; // C
25         4'hD: bits = 7'b1011110; // D
26         4'hE: bits = 7'b1111001; // E
27         4'hF: bits = 7'b1110001; // F
28     endcase
29 endmodule
30
31
32 // minispartan6+ XC6SLX9
33 module top_ms # (
34     parameter GPIO_PINS = 8
35 ) (
36     input          CLK50,
37     input  [3:0]   SW,
38     // UART
39     input          RXD,
40     output         TXD,
41     // Peripherals
42     output [7:0]   LEDS,
43
44     // 3v3 input from the s6 on the deisoc
45     input          S6_3v3,
46
47     // SSDs
48     output [6:0]   ssd0,
49     output [6:0]   ssd1,
50     output [6:0]   ssd2,
51     output [6:0]   ssd3,
52     output [6:0]   ssd4,
53     output [6:0]   ssd5
54 );
55     //wire [15:0]      M_PADDR;
56     //wire            M_PWRITE;
57     //wire [5-1:0]    M_PSELx; // not shared
58     //wire            M_PENABLE;
59     //wire [15:0]     M_PWDATA;
60     //wire [15:0]     M_PRDATA; // input to intercon
61     //wire            M_PREADY; // input to intercon
62
63     wire [7:0]  gpio0;
64     wire [15:0] gpio1;
65     wire [7:0]  gpio2;
66
67     vmicro16_soc soc (
68         .clk      (CLK50),
69         .reset    (~SW[0]),
70
71         //M_PADDR    (M_PADDR),
72         //M_PWRITE   (M_PWRITE),
73         //M_PSELx    (M_PSELx),
74         //M_PENABLE  (M_PENABLE),
75         //M_PWDATA   (M_PWDATA),

```

```

76      //M_PRDATA    (M_PRDATA),
77      //M_PREADY    (M_PREADY),
78
79      // UART
80      .uart_tx (TXD),
81      .uart_rx (RXD),
82
83      // GPIO
84      .gpio0    (LEDS[3:0]),
85      .gpio1    (gpio1),
86      .gpio2    (gpio2),
87
88      // DEBUG
89      .debug0    (LEDS[4])
90      // .debug1    (LEDS[7:4])
91  );
92
93  assign LEDS[7:5] = {TXD, RXD, S6_3v3};
94
95  // SSD displays (split across 2 gpio ports 1 and 2)
96  wire [3:0] ssd_chars [0:5];
97  assign ssd_chars[0] = gpio1[3:0];
98  assign ssd_chars[1] = gpio1[7:4];
99  assign ssd_chars[2] = gpio1[11:8];
100 assign ssd_chars[3] = gpio1[15:12];
101 assign ssd_chars[4] = gpio2[3:0];
102 assign ssd_chars[5] = gpio2[7:4];
103 seven_display ssd_0 (.n(ssd_chars[0]), .segments (ssd0));
104 seven_display ssd_1 (.n(ssd_chars[1]), .segments (ssd1));
105 seven_display ssd_2 (.n(ssd_chars[2]), .segments (ssd2));
106 seven_display ssd_3 (.n(ssd_chars[3]), .segments (ssd3));
107 seven_display ssd_4 (.n(ssd_chars[4]), .segments (ssd4));
108 seven_display ssd_5 (.n(ssd_chars[5]), .segments (ssd5));
109
110 endmodule

```

### C.3 vmicro16\_soc.v

```

1  //
2  //
3
4  `include "vmicro16_soc_config.v"
5  `include "clog2.v"
6  `include "formal.v"
7
8  module pow_reset # (
9      parameter INIT = 1,
10     parameter N = 8
11 ) (
12     input      clk,
13     input      reset,
14     output reg resethold
15 );
16     initial resethold = INIT ? (N-1) : 0;
17
18     always @(*)
19         resethold = |hold;
20
21     reg [`clog2(N)-1:0] hold = (N-1);
22     always @(posedge clk)
23         if (reset)
24             hold <= N-1;
25         else
26             if (hold)
27                 hold <= hold - 1;
28 endmodule
29
30 // Vmicro16 multi-core SoC with various peripherals
31 // and interrupts
32 module vmicro16_soc (
33     input clk,
34     input reset,
35
36     // UART0
37     input      uart_rx,
38     output     uart_tx,
39     //
40     output     [`APB_GPIO0_PINS-1:0] gpio0,
41     output     [`APB_GPIO1_PINS-1:0] gpio1,
42     output     [`APB_GPIO2_PINS-1:0] gpio2,
43     //
44     output     halt,
45     //

```

```

46     output    [`CORES-1:0]          debug0,
47     output    [`CORES*8-1:0]        debug1
48 );
49 wire [`CORES-1:0] w_halt;
50 assign halt = &w_halt;
51
52 assign debug0 = w_halt;
53
54 // Watchdog reset pulse signal.
55 // Passed to pow_reset to generate a longer reset pulse
56 wire wdreset;
57 wire prog_prog;
58
59 // soft register reset hold for brams and registers
60 wire soft_reset;
61 `ifdef DEF_GLOBAL_RESET
62     pow_reset # (
63         .INIT      (1),
64         .N          (8)
65     ) por_inst (
66         .clk        (clk),
67         `ifdef DEF_USE_WATCHDOG
68         .reset      (reset | wdreset | prog_prog),
69         `else
70         .reset      (reset),
71         `endif
72         .resethold  (soft_reset)
73     );
74 `else
75     assign soft_reset = 0;
76 `endif
77
78 // Peripherals (master to slave)
79 wire [`APB_WIDTH-1:0] M_PADDR;
80 wire M_PWRITE;
81 wire [`SLAVES-1:0] M_PSELx; // not shared
82 wire M_PENABLE;
83 wire [`DATA_WIDTH-1:0] M_PWDATA;
84 wire [`SLAVES*`DATA_WIDTH-1:0] M_PRDATA; // input to intercon
85 wire [`SLAVES-1:0] M_PREADY; // input
86
87 // Master apb interfaces
88 wire [`CORES*`APB_WIDTH-1:0] w_PADDR;
89 wire [`CORES-1:0] w_PWRITE;
90 wire [`CORES-1:0] w_PSELx;
91 wire [`CORES-1:0] w_PENABLE;
92 wire [`CORES*`DATA_WIDTH-1:0] w_PWDATA;
93 wire [`CORES*`DATA_WIDTH-1:0] w_PRDATA;
94 wire [`CORES-1:0] w_PREADY;
95
96 // Interrupts
97 `ifdef DEF_ENABLE_INT
98     wire [`DEF_NUM_INT-1:0] ints;
99     wire [`DEF_NUM_INT*`DATA_WIDTH-1:0] ints_data;
100     assign ints[7:1] = 0;
101     assign ints_data[`DEF_NUM_INT*`DATA_WIDTH-1:`DATA_WIDTH] =
102         {`DEF_NUM_INT*(`DATA_WIDTH-1){1'b0}};
103 `endif
104
105 apb_intercon_s # (
106     .MASTER_PORTS  (`CORES),
107     .SLAVE_PORTS    (`SLAVES),
108     .BUS_WIDTH      (`APB_WIDTH),
109     .DATA_WIDTH     (`DATA_WIDTH),
110     .HAS_PSELX_ADDR (1)
111 ) apb (
112     .clk            (clk),
113     .reset          (soft_reset),
114     // APB master to slave
115     .S_PADDR        (w_PADDR),
116     .S_PWRITE        (w_PWRITE),
117     .S_PSELx         (w_PSELx),
118     .S_PENABLE       (w_PENABLE),
119     .S_PWDATA        (w_PWDATA),
120     .S_PRDATA        (w_PRDATA),
121     .S_PREADY        (w_PREADY),
122     // shared bus
123     .M_PADDR         (M_PADDR),
124     .M_PWRITE         (M_PWRITE),
125     .M_PSELx         (M_PSELx),
126     .M_PENABLE       (M_PENABLE),
127     .M_PWDATA        (M_PWDATA),
128     .M_PRDATA        (M_PRDATA),
129     .M_PREADY        (M_PREADY)
130 );
131
132 `ifdef DEF_USE_WATCHDOG
133     vmicro16_watchdog_apb # (
134         .BUS_WIDTH  (`APB_WIDTH),

```



```

135     .NAME          ("WDOG0")
136 ) wdog0_apb (
137     .clk           (clk),
138     .reset         (),
139     // apb slave to master interface
140     .S_PADDR       (),
141     .S_PWRITE      (M_PWRITE),
142     .S_PSELx       (M_PSELx[`APB_PSELX_WDOG0]),
143     .S_PENABLE     (M_PENABLE),
144     .S_PWDATA      (),
145     .S_PRDATA      (),
146     .S_PREADY      (M_PREADY[`APB_PSELX_WDOG0]),
147
148     .wdreset       (wdreset)
149 );
150 `endif
151
152 vmicro16_gpio_apb # (
153     .BUS_WIDTH     (`APB_WIDTH),
154     .DATA_WIDTH    (`DATA_WIDTH),
155     .PORTS         (`APB_GPIO0_PINS),
156     .NAME          ("GPIO0")
157 ) gpio0_apb (
158     .clk           (clk),
159     .reset         (soft_reset),
160     // apb slave to master interface
161     .S_PADDR       (M_PADDR),
162     .S_PWRITE      (M_PWRITE),
163     .S_PSELx       (M_PSELx[`APB_PSELX_GPIO0]),
164     .S_PENABLE     (M_PENABLE),
165     .S_PWDATA      (M_PWDATA),
166     .S_PRDATA      (M_PRDATA[`APB_PSELX_GPIO0*`DATA_WIDTH +: `DATA_WIDTH]),
167     .S_PREADY      (M_PREADY[`APB_PSELX_GPIO0]),
168     .gpio          (gpio0)
169 );
170
171 // GPIO1 for Seven segment displays (16 pin)
172 vmicro16_gpio_apb # (
173     .BUS_WIDTH     (`APB_WIDTH),
174     .DATA_WIDTH    (`DATA_WIDTH),
175     .PORTS         (`APB_GPIO1_PINS),
176     .NAME          ("GPIO1")
177 ) gpio1_apb (
178     .clk           (clk),
179     .reset         (soft_reset),
180     // apb slave to master interface
181     .S_PADDR       (M_PADDR),
182     .S_PWRITE      (M_PWRITE),
183     .S_PSELx       (M_PSELx[`APB_PSELX_GPIO1]),
184     .S_PENABLE     (M_PENABLE),
185     .S_PWDATA      (M_PWDATA),
186     .S_PRDATA      (M_PRDATA[`APB_PSELX_GPIO1*`DATA_WIDTH +: `DATA_WIDTH]),
187     .S_PREADY      (M_PREADY[`APB_PSELX_GPIO1]),
188     .gpio          (gpio1)
189 );
190
191 // GPIO2 for Seven segment displays (8 pin)
192 vmicro16_gpio_apb # (
193     .BUS_WIDTH     (`APB_WIDTH),
194     .DATA_WIDTH    (`DATA_WIDTH),
195     .PORTS         (`APB_GPIO2_PINS),
196     .NAME          ("GPIO2")
197 ) gpio2_apb (
198     .clk           (clk),
199     .reset         (soft_reset),
200     // apb slave to master interface
201     .S_PADDR       (M_PADDR),
202     .S_PWRITE      (M_PWRITE),
203     .S_PSELx       (M_PSELx[`APB_PSELX_GPIO2]),
204     .S_PENABLE     (M_PENABLE),
205     .S_PWDATA      (M_PWDATA),
206     .S_PRDATA      (M_PRDATA[`APB_PSELX_GPIO2*`DATA_WIDTH +: `DATA_WIDTH]),
207     .S_PREADY      (M_PREADY[`APB_PSELX_GPIO2]),
208     .gpio          (gpio2)
209 );
210
211 apb_uart_tx # (
212     .DATA_WIDTH    (8),
213     .ADDR_EXP      (4) //2^4 = 16 FIFO words
214 ) uart0_apb (
215     .clk           (clk),
216     .reset         (soft_reset),
217     // apb slave to master interface
218     .S_PADDR       (M_PADDR),
219     .S_PWRITE      (M_PWRITE),
220     .S_PSELx       (M_PSELx[`APB_PSELX_UART0]),
221     .S_PENABLE     (M_PENABLE),
222     .S_PWDATA      (M_PWDATA),
223     .S_PRDATA      (M_PRDATA[`APB_PSELX_UART0*`DATA_WIDTH +: `DATA_WIDTH]),

```

```

224     .S_PREADY    (M_PREADY[`APB_PSELX_UART0]),
225     // uart wires
226     .tx_wire     (uart_tx),
227     .rx_wire     ()
228 );
229
230 timer_apb timr0 (
231     .clk          (clk),
232     .reset        (soft_reset),
233     // apb slave to master interface
234     .S_PADDR      (M_PADDR),
235     .S_PWRITE     (M_PWRITE),
236     .S_PSELx      (M_PSELx[`APB_PSELX_TIMRO]),
237     .S_PENABLE    (M_PENABLE),
238     .S_PWDATA     (M_PWDATA),
239     .S_PRDATA     (M_PRDATA[`APB_PSELX_TIMRO*`DATA_WIDTH +: `DATA_WIDTH]),
240     .S_PREADY     (M_PREADY[`APB_PSELX_TIMRO])
241     //
242     `ifdef DEF_ENABLE_INT
243     ,.out          (ints    [`DEF_INT_TIMRO]),
244     .int_data     (ints_data[`DEF_INT_TIMRO*`DATA_WIDTH +: `DATA_WIDTH])
245     `endif
246 );
247
248 // Shared register set for system-on-chip info
249 // RO = number of cores
250 vmicro16_regs_apb # (
251     .BUS_WIDTH      (`APB_WIDTH),
252     .DATA_WIDTH     (`DATA_WIDTH),
253     .CELL_DEPTH     (8),
254     .PARAM_DEFAULTS_RO  (`CORES),
255     .PARAM_DEFAULTS_R1  (`SLAVES)
256 ) regs0_apb (
257     .clk          (clk),
258     .reset        (soft_reset),
259     // apb slave to master interface
260     .S_PADDR      (M_PADDR),
261     .S_PWRITE     (M_PWRITE),
262     .S_PSELx      (M_PSELx[`APB_PSELX_REGSO]),
263     .S_PENABLE    (M_PENABLE),
264     .S_PWDATA     (M_PWDATA),
265     .S_PRDATA     (M_PRDATA[`APB_PSELX_REGSO*`DATA_WIDTH +: `DATA_WIDTH]),
266     .S_PREADY     (M_PREADY[`APB_PSELX_REGSO])
267 );
268
269 vmicro16_bram_ex_apb # (
270     .BUS_WIDTH      (`APB_WIDTH),
271     .MEM_WIDTH      (`DATA_WIDTH),
272     .MEM_DEPTH      (`APB_BRAMO_CELLS),
273     .CORE_ID_BITS   (`clog2(`CORES))
274 ) bram_apb (
275     .clk          (clk),
276     .reset        (soft_reset),
277     // apb slave to master interface
278     .S_PADDR      (M_PADDR),
279     .S_PWRITE     (M_PWRITE),
280     .S_PSELx      (M_PSELx[`APB_PSELX_BRAMO]),
281     .S_PENABLE    (M_PENABLE),
282     .S_PWDATA     (M_PWDATA),
283     .S_PRDATA     (M_PRDATA[`APB_PSELX_BRAMO*`DATA_WIDTH +: `DATA_WIDTH]),
284     .S_PREADY     (M_PREADY[`APB_PSELX_BRAMO])
285 );
286
287 // There must be atleast 1 core
288 `static_assert(`CORES > 0)
289 `static_assert(`DEF_MEM_INSTR_DEPTH > 0)
290 `static_assert(`DEF_MMU_TIMO_CELLS > 0)
291
292
293 // Single instruction memory
294 `ifndef DEF_CORE_HAS_INSTR_MEM
295 // slave input/outputs from interconnect
296 wire [ `APB_WIDTH-1:0]      instr_M_PADDR;
297 wire                        instr_M_PWRITE;
298 wire [1-1:0]                instr_M_PSELx; // not shared
299 wire                        instr_M_PENABLE;
300 wire [ `DATA_WIDTH-1:0]     instr_M_PWDATA;
301 wire [1*`DATA_WIDTH-1:0]    instr_M_PRDATA; // slave response
302 wire [1-1:0]                instr_M_PREADY; // slave response
303
304 // Master apb interfaces
305 wire [ `CORES*`APB_WIDTH-1:0] instr_w_PADDR;
306 wire [ `CORES-1:0]           instr_w_PWRITE;
307 wire [ `CORES-1:0]           instr_w_PSELx;
308 wire [ `CORES-1:0]           instr_w_PENABLE;
309 wire [ `CORES*`DATA_WIDTH-1:0] instr_w_PWDATA;
310 wire [ `CORES*`DATA_WIDTH-1:0] instr_w_PRDATA;
311 wire [ `CORES-1:0]           instr_w_PREADY;
312

```

```

313 `ifdef DEF_USE_REPROG
314     wire [`clog2(`DEF_MEM_INSTR_DEPTH)-1:0] prog_addr;
315     wire [`DATA_WIDTH-1:0] prog_data;
316     wire prog_we;
317     uart_prog_rom_prog (
318         .clk          (clk),
319         .reset        (reset | wdreset),
320         // input stream
321         .uart_rx      (uart_rx),
322         // programmer
323         .addr         (prog_addr),
324         .data         (prog_data),
325         .we           (prog_we),
326         .prog         (prog_prog)
327     );
328 `endif
329
330 `ifdef DEF_USE_REPROG
331     vmicro16_bram_prog_apb
332 `else
333     vmicro16_bram_apb
334 `endif
335 # (
336     .BUS_WIDTH        (`APB_WIDTH),
337     .MEM_WIDTH        (`DATA_WIDTH),
338     .MEM_DEPTH        (`DEF_MEM_INSTR_DEPTH),
339     .USE_INITS        (1),
340     .NAME              ("INSTR_ROM_G")
341 ) instr_rom_apb (
342     .clk              (clk),
343     .reset            (reset),
344     .S_PADDR          (instr_M_PADDR),
345     .S_PWRITE         (0),
346     .S_PSELx          (instr_M_PSELx),
347     .S_PENABLE        (instr_M_PENABLE),
348     .S_PWDATA         (0),
349     .S_PRDATA         (instr_M_PRDATA),
350     .S_PREADY         (instr_M_PREADY)
351
352     `ifdef DEF_USE_REPROG
353     ,
354     .addr             (prog_addr),
355     .data             (prog_data),
356     .we               (prog_we),
357     .prog             (prog_prog)
358     `endif
359 );
360
361 apb_intercon_s # (
362     .MASTER_PORTS    (`CORES),
363     .SLAVE_PORTS      (1),
364     .BUS_WIDTH        (`APB_WIDTH),
365     .DATA_WIDTH       (`DATA_WIDTH),
366     .HAS_PSELX_ADDR   (0)
367 ) apb_instr_intercon (
368     .clk              (clk),
369     .reset            (soft_reset),
370     // APB master from cores
371     // master
372     .S_PADDR          (instr_w_PADDR),
373     .S_PWRITE         (instr_w_PWRITE),
374     .S_PSELx          (instr_w_PSELx),
375     .S_PENABLE        (instr_w_PENABLE),
376     .S_PWDATA         (instr_w_PWDATA),
377     .S_PRDATA         (instr_w_PRDATA),
378     .S_PREADY         (instr_w_PREADY),
379     // shared bus slaves
380     // slave outputs
381     .M_PADDR          (instr_M_PADDR),
382     .M_PWRITE         (instr_M_PWRITE),
383     .M_PSELx          (instr_M_PSELx),
384     .M_PENABLE        (instr_M_PENABLE),
385     .M_PWDATA         (instr_M_PWDATA),
386     .M_PRDATA         (instr_M_PRDATA),
387     .M_PREADY         (instr_M_PREADY)
388 );
389 `endif
390
391 genvar i;
392 generate for(i = 0; i < `CORES; i = i + 1) begin : cores
393
394     vmicro16_core # (
395         .CORE_ID        (i),
396         .DATA_WIDTH     (`DATA_WIDTH),
397
398         .MEM_INSTR_DEPTH (`DEF_MEM_INSTR_DEPTH),
399         .MEM_SCRATCH_DEPTH (`DEF_MMU_TIMO_CELLS)
400     ) c1 (
401         .clk            (clk),

```

```

402         .reset      (soft_reset),
403
404         // debug
405         .halt        (w_halt[i]),
406
407         // interrupts
408         .ints         (ints),
409         .ints_data    (ints_data),
410
411         // Output master port 1
412         .w_PADDR      (w_PADDR  [`APB_WIDTH*i +: `APB_WIDTH] ),
413         .w_PWRITE     (w_PWRITE  [i] ),
414         .w_PSELx      (w_PSELx   [i] ),
415         .w_PENABLE    (w_PENABLE [i] ),
416         .w_PWDATA     (w_PWDATA  [`DATA_WIDTH*i +: `DATA_WIDTH]),
417         .w_PRDATA     (w_PRDATA  [`DATA_WIDTH*i +: `DATA_WIDTH]),
418         .w_PREADY     (w_PREADY  [i] )
419
420 `ifndef DEF_CORE_HAS_INSTR_MEM
421     // APB instruction rom
422     , // Output master port 2
423     .w2_PADDR      (instr_w_PADDR  [`APB_WIDTH*i +: `APB_WIDTH] ),
424     // .w2_PWRITE    (instr_w_PWRITE [i] ),
425     .w2_PSELx      (instr_w_PSELx   [i] ),
426     .w2_PENABLE    (instr_w_PENABLE [i] ),
427     // .w2_PWDATA    (instr_w_PWDATA  [`DATA_WIDTH*i +: `DATA_WIDTH]),
428     .w2_PRDATA     (instr_w_PRDATA  [`DATA_WIDTH*i +: `DATA_WIDTH]),
429     .w2_PREADY     (instr_w_PREADY  [i] )
430 `endif
431 );
432 end
433 endgenerate
434
435
436 //////////////////////////////////////
437 // Formal Verification
438 //////////////////////////////////////
439 `ifndef FORMAL
440 wire all_halted = &w_halt;
441 //////////////////////////////////////
442 // Count number of clocks each core is spending on
443 // bus transactions
444 //////////////////////////////////////
445 reg [15:0] bus_core_times    [0:`CORES-1];
446 reg [15:0] core_work_times   [0:`CORES-1];
447 reg [15:0] instr_fetch_times [0:`CORES-1];
448 integer i2;
449 initial
450     for(i2 = 0; i2 < `CORES; i2 = i2 + 1) begin
451         bus_core_times[i2] = 0;
452         core_work_times[i2] = 0;
453     end
454
455 // total bus time
456 generate
457     genvar g2;
458     for (g2 = 0; g2 < `CORES; g2 = g2 + 1) begin : formal_for_times
459         always @(posedge clk) begin
460             if (w_PSELx[g2])
461                 bus_core_times[g2] <= bus_core_times[g2] + 1;
462
463             // Core working time
464             `ifndef DEF_CORE_HAS_INSTR_MEM
465                 if (!w_PSELx[g2] && !instr_w_PSELx[g2])
466                     `else
467                         if (!w_PSELx[g2])
468                             `endif
469                             if (!w_halt[g2])
470                                 core_work_times[g2] <= core_work_times[g2] + 1;
471
472             end
473         end
474     endgenerate
475
476 reg [15:0] bus_time_average = 0;
477 reg [15:0] bus_reqs_average = 0;
478 reg [15:0] fetch_time_average = 0;
479 reg [15:0] work_time_average = 0;
480 //
481 always @(all_halted) begin
482     for (i2 = 0; i2 < `CORES; i2 = i2 + 1) begin
483         bus_time_average = bus_time_average + bus_core_times[i2];
484         bus_reqs_average = bus_reqs_average + bus_core_reqs_count[i2];
485         work_time_average = work_time_average + core_work_times[i2];
486         fetch_time_average = fetch_time_average + instr_fetch_times[i2];
487     end
488
489     bus_time_average = bus_time_average / `CORES;
490     bus_reqs_average = bus_reqs_average / `CORES;

```

```

491     work_time_average = work_time_average / `CORES;
492     fetch_time_average = fetch_time_average / `CORES;
493 end
494
495 //////////////////////////////////////
496 // Count number of bus requests per core
497 //////////////////////////////////////
498 // 1 clock delay of w_PSELx
499 reg [`CORES-1:0] bus_core_reqs_last;
500 // rising edges of each
501 wire [`CORES-1:0] bus_core_reqs_real;
502 // storage for counters for each core
503 reg [15:0] bus_core_reqs_count [0:`CORES-1];
504 initial
505     for(i2 = 0; i2 < `CORES; i2 = i2 + 1)
506         bus_core_reqs_count[i2] = 0;
507
508 // 1 clk delay to detect rising edge
509 always @(posedge clk)
510     bus_core_reqs_last <= w_PSELx;
511
512 generate
513     genvar g3;
514     for (g3 = 0; g3 < `CORES; g3 = g3 + 1) begin : formal_for_reqs
515         // Detect new reqs for each core
516         assign bus_core_reqs_real[g3] = w_PSELx[g3] >
517             bus_core_reqs_last[g3];
518
519         always @(posedge clk)
520             if (bus_core_reqs_real[g3])
521                 bus_core_reqs_count[g3] <= bus_core_reqs_count[g3] + 1;
522     end
523 endgenerate
524
525 `ifndef DEF_CORE_HAS_INSTR_MEM
526     //////////////////////////////////////
527     // Time waiting for instruction fetches
528     // from global memory
529     //////////////////////////////////////
530     integer i3;
531     initial
532         for(i3 = 0; i3 < `CORES; i3 = i3 + 1)
533             instr_fetch_times[i3] = 0;
534
535     // total bus time
536     // Instruction fetches occur on the w2 master port
537     generate
538         genvar g4;
539         for (g4 = 0; g4 < `CORES; g4 = g4 + 1) begin : formal_for_fetch_times
540             always @(posedge clk)
541                 if (instr_w_PSELx[g4])
542                     instr_fetch_times[g4] <= instr_fetch_times[g4] + 1;
543         end
544     endgenerate
545 `endif
546
547 `endif // end FORMAL
548
549
550 `endif // end FORMAL
551
552 endmodule

```

## C.4 vmicro16\_periph.v

Various memory-mapped APB peripherals, such as GPIO, UART, timers, and memory.

```

1 // Vmicro16 peripheral modules
2
3 `include "vmicro16_soc_config.v"
4 `include "formal.v"
5
6 // Simple watchdog peripheral
7 module vmicro16_watchdog_apb # (
8     parameter BUS_WIDTH = 16,
9     parameter NAME = "WD",
10    parameter CLK_HZ = 50_000_000
11 ) (
12     input clk,
13     input reset,
14
15     // APB Slave to master interface

```

```

16     input  [0:0]                S_PADDR, // not used (optimised out)
17     input                S_PWRITE,
18     input                S_PSELx,
19     input                S_PENABLE,
20     input  [0:0]                S_PWDATA,
21
22     // prdata not used
23     output [0:0]                S_PRDATA,
24     output                S_PREADY,
25
26     // watchdog reset, active high
27     output reg                wdreset
28 );
29 //assign S_PRDATA = (S_PSELx & S_PENABLE) ? gpio : 16'h0000;
30 assign S_PREADY = (S_PSELx & S_PENABLE) ? 1'b1 : 1'b0;
31 wire  we        = (S_PSELx & S_PENABLE & S_PWRITE);
32
33 // countdown timer
34 reg [`clog2(CLK_HZ)-1:0] timer = CLK_HZ;
35
36 wire w_wdreset = (timer == 0);
37
38 // infer a register to aid timing
39 initial wdreset = 0;
40 always @(posedge clk)
41     wdreset <= w_wdreset;
42
43 always @(posedge clk)
44     if (we) begin
45         $display($time, "\t%s <= RESET", NAME);
46         timer <= CLK_HZ;
47     end else begin
48         timer <= timer - 1;
49     end
50 endmodule
51
52 module timer_apb # (
53     parameter CLK_HZ = 50_000_000
54 ) (
55     input clk,
56     input reset,
57
58     input clk_en,
59
60     // 0 16-bit value R/W
61     // 1 16-bit control R    b0 = start, b1 = reset
62     // 2 16-bit prescaler
63     input  [1:0]                S_PADDR,
64
65     input                S_PWRITE,
66     input                S_PSELx,
67     input                S_PENABLE,
68     input  [`DATA_WIDTH-1:0]    S_PWDATA,
69
70     output reg  [`DATA_WIDTH-1:0] S_PRDATA,
71     output                S_PREADY,
72
73     output out,
74     output [`DATA_WIDTH-1:0] int_data
75 );
76 //assign S_PRDATA = (S_PSELx & S_PENABLE) ? swex_success ? 16'hFOFO : 16'h0000;
77 assign S_PREADY = (S_PSELx & S_PENABLE) ? 1'b1 : 1'b0;
78 wire  en        = (S_PSELx & S_PENABLE);
79 wire  we        = (en & S_PWRITE);
80
81 reg [`DATA_WIDTH-1:0] r_counter = 0;
82 reg [`DATA_WIDTH-1:0] r_load = 0;
83 reg [`DATA_WIDTH-1:0] r_pres = 0;
84 reg [`DATA_WIDTH-1:0] r_ctrl = 0;
85
86 localparam CTRL_START = 0;
87 localparam CTRL_RESET = 1;
88 localparam CTRL_INT   = 2;
89
90 localparam ADDR_LOAD = 2'b00;
91 localparam ADDR_CTRL = 2'b01;
92 localparam ADDR_PRE = 2'b10;
93
94 always @(*) begin
95     S_PRDATA = 0;
96     if (en)
97         case(S_PADDR)
98             ADDR_LOAD: S_PRDATA = r_counter;
99             ADDR_CTRL: S_PRDATA = r_ctrl;
100             //ADDR_CTRL: S_PRDATA = r_pres;
101             default:  S_PRDATA = 0;
102         endcase
103     end
104
105 // prescaler counts from r_pres to 0, emitting a stb signal

```

```

106 // to enable the r_counter step
107 reg [`DATA_WIDTH-1:0] r_pres_counter = 0;
108 wire counter_en = (r_pres_counter == 0);
109 always @(posedge clk)
110     if (r_pres_counter == 0)
111         r_pres_counter <= r_pres;
112     else
113         r_pres_counter <= r_pres_counter - 1;
114
115 always @(posedge clk)
116     if (we)
117         case(S_PADDR)
118             // Write to the load register:
119             // Set load register
120             // Set counter register
121             ADDR_LOAD: begin
122                 r_load <= S_PWDATA;
123                 r_counter <= S_PWDATA;
124                 $display($time, "\t\ttimr0: WRITE LOAD: %h", S_PWDATA);
125             end
126             ADDR_CTRL: begin
127                 r_ctrl <= S_PWDATA;
128                 $display($time, "\t\ttimr0: WRITE CTRL: %h", S_PWDATA);
129             end
130             ADDR PRES: begin
131                 r_pres <= S_PWDATA;
132                 $display($time, "\t\ttimr0: WRITE PRES: %h", S_PWDATA);
133             end
134             endcase
135         else
136             if (r_ctrl[CTRL_START]) begin
137                 if (r_counter == 0)
138                     r_counter <= r_load;
139                 else if(counter_en)
140                     r_counter <= r_counter -1;
141             end else if (r_ctrl[CTRL_RESET])
142                 r_counter <= r_load;
143
144 // generate the output pulse when r_counter == 0
145 // out = (counter reached zero && counter started)
146 assign out = (r_counter == 0) && r_ctrl[CTRL_START]; // && r_ctrl[CTRL_INT];
147 assign int_data = {`DATA_WIDTH{1'b1}};
148 endmodule
149
150
151 // APB wrapped programmable vmicro16_bram
152 module vmicro16_bram_prog_apb # (
153     parameter BUS_WIDTH = 16,
154     parameter MEM_WIDTH = 16,
155     parameter MEM_DEPTH = 64,
156     parameter APB_PADDR = 0,
157     parameter USE_INITS = 0,
158     parameter NAME = "BRAMPROG",
159     parameter CORE_ID = 0
160 ) (
161     input clk,
162     input reset,
163     // APB Slave to master interface
164     input [`clog2(MEM_DEPTH)-1:0] S_PADDR,
165     input S_PWRITE,
166     input S_PSELx,
167     input S_PENABLE,
168     input [BUS_WIDTH-1:0] S_PWDATA,
169
170     output [BUS_WIDTH-1:0] S_PRDATA,
171     output S_PREADY,
172
173     // interface to program the instruction memory
174     input [`clog2(`DEF_MEM_INSTR_DEPTH)-1:0] addr,
175     input [`DATA_WIDTH-1:0] data,
176     input we,
177     input prog
178 );
179 wire [MEM_WIDTH-1:0] mem_out;
180
181 assign S_PRDATA = (S_PSELx & S_PENABLE) ? mem_out : 16'h0000;
182 assign S_PREADY = (S_PSELx & S_PENABLE) ? 1'b1 : 1'b0;
183 wire s_we = (S_PSELx & S_PENABLE & S_PWRITE);
184
185 wire [`clog2(`DEF_MEM_INSTR_DEPTH)-1:0] mem_addr = we ? addr : S_PADDR;
186 wire [`DATA_WIDTH-1:0] mem_data = we ? data : S_PWDATA;
187 wire mem_we = we | s_we;
188
189 vmicro16_bram # (
190     .MEM_WIDTH (MEM_WIDTH),
191     .MEM_DEPTH (MEM_DEPTH),
192     .NAME ("BRAMPROG"),
193     .USE_INITS (0),
194     .CORE_ID (-1)
195 ) bram_apb (

```

```

196         .clk          (clk),
197         .reset        (reset),
198
199         .mem_addr     (mem_addr),
200         .mem_in       (mem_data),
201         .mem_we       (mem_we),
202         .mem_out      (mem_out)
203     );
204 endmodule
205
206 // APB wrapped vmicro16_bram
207 module vmicro16_bram_apb # (
208     parameter BUS_WIDTH    = 16,
209     parameter MEM_WIDTH    = 16,
210     parameter MEM_DEPTH    = 64,
211     parameter APB_PADDR    = 0,
212     parameter USE_INITS    = 0,
213     parameter NAME         = "BRAM",
214     parameter CORE_ID      = 0
215 ) (
216     input clk,
217     input reset,
218     // APB Slave to master interface
219     input  [`clog2(MEM_DEPTH)-1:0] S_PADDR,
220     input                          S_PWRITE,
221     input                          S_PSELx,
222     input                          S_PENABLE,
223     input  [BUS_WIDTH-1:0]         S_PWDATA,
224
225     output [BUS_WIDTH-1:0]         S_PRDATA,
226     output                          S_PREADY
227 );
228 wire [MEM_WIDTH-1:0] mem_out;
229
230 assign S_PRDATA = (S_PSELx & S_PENABLE) ? mem_out : 16'h0000;
231 assign S_PREADY = (S_PSELx & S_PENABLE) ? 1'b1 : 1'b0;
232 assign we       = (S_PSELx & S_PENABLE & S_PWRITE);
233
234 always @(*)
235     if (S_PSELx && S_PENABLE)
236         $display($time, "\t\t%s => %h", NAME, mem_out);
237
238 always @(posedge clk)
239     if (we)
240         $display($time, "\t\t%s[%h] <= %h", NAME,
241             S_PADDR, S_PWDATA);
242
243 vmicro16_bram # (
244     .MEM_WIDTH (MEM_WIDTH),
245     .MEM_DEPTH (MEM_DEPTH),
246     .NAME      (NAME),
247     .USE_INITS (1),
248     .CORE_ID   (-1)
249 ) bram_apb (
250     .clk      (clk),
251     .reset    (reset),
252
253     .mem_addr (S_PADDR),
254     .mem_in   (S_PWDATA),
255     .mem_we   (we),
256     .mem_out  (mem_out)
257 );
258 endmodule
259
260 // Shared memory with hardware monitor (LWEX/SWEX)
261 module vmicro16_bram_ex_apb # (
262     parameter BUS_WIDTH    = 16,
263     parameter MEM_WIDTH    = 16,
264     parameter MEM_DEPTH    = 64,
265     parameter CORE_ID_BITS = 3,
266     parameter SWEX_SUCCESS = 16'h0000,
267     parameter SWEX_FAIL    = 16'h0001
268 ) (
269     input clk,
270     input reset,
271
272     // |19 |18 |16 |15 |0|
273     // | LWEX | SWEX | 3 bit CORE_ID | S_PADDR |
274     input  [`APB_WIDTH-1:0] S_PADDR,
275
276     input                          S_PWRITE,
277     input                          S_PSELx,
278     input                          S_PENABLE,
279     input  [MEM_WIDTH-1:0]         S_PWDATA,
280
281     output reg [MEM_WIDTH-1:0]     S_PRDATA,
282     output                          S_PREADY
283 );
284 // exclusive flag checks
285 wire [MEM_WIDTH-1:0] mem_out;

```



```

286         reg                swex_success = 0;
287
288     localparam ADDR_BITS = `clog2(MEM_DEPTH);
289
290     // hack to create a 1 clock delay to S_PREADY
291     // for bram to be ready
292     reg cdelay = 1;
293     always @(posedge clk)
294         if (S_PSELx)
295             cdelay <= 0;
296         else
297             cdelay <= 1;
298
299     //assign S_PRDATA = (S_PSELx & S_PENABLE) ? swex_success ? 16'hFOFO : 16'h0000;
300     assign S_PREADY = (S_PSELx & S_PENABLE & (!cdelay)) ? 1'b1 : 1'b0;
301     assign we       = (S_PSELx & S_PENABLE & S_PWRITE);
302     wire en         = (S_PSELx & S_PENABLE);
303
304     // Similar to:
305     // http://infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.dui0204f/Cihbghef.html
306
307     // mem_wd is the CORE_ID sent in bits [18:16]
308     localparam TOP_BIT_INDEX = `APB_WIDTH - 1;
309     localparam PADDR_CORE_ID_MSB = TOP_BIT_INDEX - 2;
310     localparam PADDR_CORE_ID_LSB = PADDR_CORE_ID_MSB - (CORE_ID_BITS-1);
311
312     // [LWEX, CORE_ID, mem_addr] from S_PADDR
313     wire lwex = S_PADDR[TOP_BIT_INDEX];
314     wire swex = S_PADDR[TOP_BIT_INDEX-1];
315     wire [CORE_ID_BITS-1:0] core_id = S_PADDR[PADDR_CORE_ID_MSB:PADDR_CORE_ID_LSB];
316     // CORE_ID to write to ex_flags register
317     wire [ADDR_BITS-1:0] mem_addr = S_PADDR[ADDR_BITS-1:0];
318
319     wire [CORE_ID_BITS:0] ex_flags_read;
320     wire is_locked = |ex_flags_read;
321     wire is_locked_self = is_locked && (core_id == (ex_flags_read-1));
322
323     // Check exclusive access flags
324     always @(*) begin
325         swex_success = 0;
326         if (en)
327             // bug!
328             if (!swex && !lwex)
329                 swex_success = 1;
330             else if (swex)
331                 if (is_locked && !is_locked_self)
332                     // someone else has locked it
333                     swex_success = 0;
334                 else if (is_locked && is_locked_self)
335                     swex_success = 1;
336         end
337
338     always @(*)
339         if (swex)
340             if (swex_success)
341                 S_PRDATA = SWEX_SUCCESS;
342             else
343                 S_PRDATA = SWEX_FAIL;
344             else
345                 S_PRDATA = mem_out;
346
347     wire reg_we = en && ((lwex && !is_locked)
348         || (swex && swex_success));
349
350     reg [CORE_ID_BITS:0] reg_wd;
351     always @(*) begin
352         reg_wd = {{CORE_ID_BITS}{1'b0}};
353
354         if (en)
355             // if wanting to lock the addr
356             if (lwex)
357                 // and not already locked
358                 if (!is_locked) begin
359                     reg_wd = (core_id + 1);
360                 end
361             else if (swex)
362                 if (is_locked && is_locked_self)
363                     reg_wd = {{CORE_ID_BITS}{1'b0}};
364         end
365
366     // Exclusive flag for each memory cell
367     vmicro16_bram # (
368         .MEM_WIDTH (CORE_ID_BITS + 1),
369         .MEM_DEPTH (MEM_DEPTH),
370         .USE_INITS (0),
371         .NAME ("rexram")
372     ) ram_exflags (
373         .clk (clk),
374         .reset (reset),

```

```

375         .mem_addr    (mem_addr),
376         .mem_in      (reg_wd),
377         .mem_we      (reg_we),
378         .mem_out     (ex_flags_read)
379     );
380
381     always @(*)
382     if (S_PSELx && S_PENABLE)
383         $display($time, "\t\tBRAMex[%h] READ %h\tCORE: %h",
384             mem_addr, mem_out, S_PADDR[16+: CORE_ID_BITS]);
385
386     always @(posedge clk)
387     if (we)
388         $display($time, "\t\tBRAMex[%h] WRITE %h\tCORE: %h",
389             mem_addr, S_PWDATA, S_PADDR[16+: CORE_ID_BITS]);
390
391     vmicro16_bram # (
392         .MEM_WIDTH    (MEM_WIDTH),
393         .MEM_DEPTH    (MEM_DEPTH),
394         .USE_INITS    (0),
395         .NAME          ("BRAMexinst")
396     ) bram_apb (
397         .clk           (clk),
398         .reset         (reset),
399
400         .mem_addr     (mem_addr),
401         .mem_in       (S_PWDATA),
402         .mem_we       (we && swex_success),
403         .mem_out      (mem_out)
404     );
405 endmodule
406
407 // Simple APB memory-mapped register set
408 module vmicro16_regs_apb # (
409     parameter BUS_WIDTH      = 16,
410     parameter DATA_WIDTH    = 16,
411     parameter CELL_DEPTH     = 8,
412     parameter PARAM_DEFAULTS_RO = 0,
413     parameter PARAM_DEFAULTS_R1 = 0
414 ) (
415     input clk,
416     input reset,
417     // APB Slave to master interface
418     input  [`clog2(CELL_DEPTH)-1:0] S_PADDR,
419     input S_PWRITE,
420     input S_PSELx,
421     input S_PENABLE,
422     input [DATA_WIDTH-1:0] S_PWDATA,
423
424     output [DATA_WIDTH-1:0] S_PRDATA,
425     output S_PREADY
426 );
427 wire [DATA_WIDTH-1:0] rd1;
428
429 assign S_PRDATA = (S_PSELx & S_PENABLE) ? rd1 : 16'h0000;
430 assign S_PREADY = (S_PSELx & S_PENABLE) ? 1'b1 : 1'b0;
431 assign reg_we = (S_PSELx & S_PENABLE & S_PWRITE);
432
433 always @(*)
434     if (reg_we)
435         $display($time, "\t\tREGS-APB[%h] <= %h",
436             S_PADDR, S_PWDATA);
437
438     always @(*)
439         `rassert(reg_we == (S_PSELx & S_PENABLE & S_PWRITE))
440
441     vmicro16_regs # (
442         .CELL_DEPTH    (CELL_DEPTH),
443         .CELL_WIDTH    (DATA_WIDTH),
444         .PARAM_DEFAULTS_RO (PARAM_DEFAULTS_RO),
445         .PARAM_DEFAULTS_R1 (PARAM_DEFAULTS_R1)
446     ) regs_apb (
447         .clk           (clk),
448         .reset         (reset),
449         // port 1
450         .rs1           (S_PADDR),
451         .rd1           (rd1),
452         .we            (reg_we),
453         .ws1           (S_PADDR),
454         .wd            (S_PWDATA)
455         // port 2 unconnected
456         // .rs2         (),
457         // .rd2         ()
458     );
459 endmodule
460
461 // Simple GPIO write only peripheral
462 module vmicro16_gpio_apb # (

```

```

464     parameter BUS_WIDTH  = 16,
465     parameter DATA_WIDTH = 16,
466     parameter PORTS      = 8,
467     parameter NAME       = "GPIO"
468 ) (
469     input clk,
470     input reset,
471     // APB Slave to master interface
472     input [0:0]          S_PADDR, // not used (optimised out)
473     input                S_PWRITE,
474     input                S_PSELx,
475     input                S_PENABLE,
476     input [DATA_WIDTH-1:0] S_PWDATA,
477
478     output [DATA_WIDTH-1:0] S_PRDATA,
479     output                S_PREADY,
480     output reg [PORTS-1:0] gpio
481 );
482 assign S_PRDATA = (S_PSELx & S_PENABLE) ? gpio : 16'h0000;
483 assign S_PREADY = (S_PSELx & S_PENABLE) ? 1'b1 : 1'b0;
484 assign ports_we = (S_PSELx & S_PENABLE & S_PWRITE);
485
486 always @(posedge clk)
487     if (reset)
488         gpio <= 0;
489     else if (ports_we) begin
490         $display($time, "\t\%s <= %h", NAME, S_PWDATA[PORTS-1:0]);
491         gpio <= S_PWDATA[PORTS-1:0];
492     end
493 endmodule

```

## C.5 vmicro16.v

Vmicro16 CPU core module.

```

1  // This file contains multiple modules.
2  // Verilator likes 1 file for each module
3  /* verilator lint_off DECLFILENAME */
4  /* verilator lint_off UNUSED */
5  /* verilator lint_off BLKSEQ */
6  /* verilator lint_off WIDTH */
7
8  // Include Vmicro16 ISA containing definitions for the bits
9  `include "vmicro16_isa.v"
10
11  `include "clog2.v"
12  `include "formal.v"
13
14
15
16  // This module aims to be a SYNCHRONOUS, WRITE_FIRST BLOCK RAM
17  // https://www.xilinx.com/support/documentation/user_guides/ug473_7Series_Memory_Resources.pdf
18  // https://www.xilinx.com/support/documentation/user_guides/ug383.pdf
19  // https://www.xilinx.com/support/documentation/sw_manuals/xilinx2016_4/ug901-vivado-synthesis.pdf
20  module vmicro16_bram # (
21      parameter MEM_WIDTH  = 16,
22      parameter MEM_DEPTH  = 64,
23      parameter CORE_ID    = 0,
24      parameter USE_INITS  = 0,
25      parameter PARAM_DEFAULTS_R0 = 0,
26      parameter PARAM_DEFAULTS_R1 = 0,
27      parameter PARAM_DEFAULTS_R2 = 0,
28      parameter PARAM_DEFAULTS_R3 = 0,
29      parameter NAME       = "BRAM"
30  ) (
31      input clk,
32      input reset,
33
34      input [clog2(MEM_DEPTH)-1:0] mem_addr,
35      input [MEM_WIDTH-1:0] mem_in,
36      input mem_we,
37      output reg [MEM_WIDTH-1:0] mem_out
38  );
39  // memory vector
40  (* ram_style = "block" *)
41  reg [MEM_WIDTH-1:0] mem [0:MEM_DEPTH-1];
42
43  // not synthesizable
44  integer i;
45  initial begin
46      for (i = 0; i < MEM_DEPTH; i = i + 1) mem[i] = 0;
47      mem[0] = PARAM_DEFAULTS_R0;

```

```

48 mem[1] = PARAM_DEFAULTS_R1;
49 mem[2] = PARAM_DEFAULTS_R2;
50 mem[3] = PARAM_DEFAULTS_R3;
51
52 if (USE_INITS) begin
53     //define TEST_SW
54     `ifdef TEST_SW
55     $readmemh("E:\\Projects\\uni\\vmicro16\\sw\\verilog_memh.txt", mem);
56     `endif
57
58     `define TEST_ASM
59     `ifdef TEST_ASM
60     $readmemh("E:\\Projects\\uni\\vmicro16\\sw\\asm.s.hex", mem);
61     `endif
62
63     //define TEST_COND
64     `ifdef TEST_COND
65     mem[0] = {`VMICRO16_OP_MOVI, 3'h7, 8'hC0}; // lock
66     mem[0] = {`VMICRO16_OP_MOVI, 3'h7, 8'hC0}; // lock
67     `endif
68
69     //define TEST_CMP
70     `ifdef TEST_CMP
71     mem[0] = {`VMICRO16_OP_MOVI, 3'h0, 8'h0A};
72     mem[1] = {`VMICRO16_OP_MOVI, 3'h1, 8'h0B};
73     mem[2] = {`VMICRO16_OP_CMP, 3'h1, 3'h0, 5'h1};
74     `endif
75
76     //define TEST_LWEX
77     `ifdef TEST_LWEX
78     mem[0] = {`VMICRO16_OP_MOVI, 3'h0, 8'hC5};
79     mem[1] = {`VMICRO16_OP_SW, 3'h0, 3'h0, 5'h1};
80     mem[2] = {`VMICRO16_OP_LW, 3'h2, 3'h0, 5'h1};
81     mem[3] = {`VMICRO16_OP_LWEX, 3'h2, 3'h0, 5'h1};
82     mem[4] = {`VMICRO16_OP_SWEX, 3'h3, 3'h0, 5'h1};
83     `endif
84
85     //define TEST_MULTICORE
86     `ifdef TEST_MULTICORE
87     mem[0] = {`VMICRO16_OP_MOVI, 3'h0, 8'h90};
88     mem[1] = {`VMICRO16_OP_MOVI, 3'h1, 8'h33};
89     mem[2] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
90     mem[3] = {`VMICRO16_OP_MOVI, 3'h0, 8'h80};
91     mem[4] = {`VMICRO16_OP_LW, 3'h2, 3'h0, 5'h0};
92     mem[5] = {`VMICRO16_OP_MOVI, 3'h1, 8'h33};
93     mem[6] = {`VMICRO16_OP_MOVI, 3'h1, 8'h33};
94     mem[7] = {`VMICRO16_OP_MOVI, 3'h1, 8'h33};
95     mem[8] = {`VMICRO16_OP_MOVI, 3'h0, 8'h91};
96     mem[9] = {`VMICRO16_OP_SW, 3'h2, 3'h0, 5'h0};
97     `endif
98
99     //define TEST_BR
100    `ifdef TEST_BR
101    mem[0] = {`VMICRO16_OP_MOVI, 3'h0, 8'h0};
102    mem[1] = {`VMICRO16_OP_MOVI, 3'h3, 8'h3};
103    mem[2] = {`VMICRO16_OP_MOVI, 3'h1, 8'h2};
104    mem[3] = {`VMICRO16_OP_ARITH_U, 3'h0, 3'h1, 5'b11111};
105    mem[4] = {`VMICRO16_OP_BR, 3'h3, `VMICRO16_OP_BR_U};
106    mem[5] = {`VMICRO16_OP_MOVI, 3'h0, 8'hFF};
107    `endif
108
109    //define ALL_TEST
110    `ifdef ALL_TEST
111    // Standard all test
112    // REGS0
113    mem[0] = {`VMICRO16_OP_MOVI, 3'h0, 8'h81};
114    mem[1] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0}; // MMU[0x81] = 6
115    mem[2] = {`VMICRO16_OP_SW, 3'h2, 3'h0, 5'h1}; // MMU[0x82] = 6
116    // GPIO0
117    mem[3] = {`VMICRO16_OP_MOVI, 3'h0, 8'h90};
118    mem[4] = {`VMICRO16_OP_MOVI, 3'h1, 8'hD};
119    mem[5] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
120    mem[6] = {`VMICRO16_OP_LW, 3'h2, 3'h0, 5'h0};
121    // TIMO
122    mem[7] = {`VMICRO16_OP_MOVI, 3'h0, 8'h07};
123    mem[8] = {`VMICRO16_OP_LW, 3'h3, 3'h0, 5'h03};
124    // UART0
125    mem[9] = {`VMICRO16_OP_MOVI, 3'h0, 8'hA0}; // UART0
126    mem[10] = {`VMICRO16_OP_MOVI, 3'h1, 8'h41}; // ascii A
127    mem[11] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
128    mem[12] = {`VMICRO16_OP_MOVI, 3'h1, 8'h42}; // ascii B
129    mem[13] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
130    mem[14] = {`VMICRO16_OP_MOVI, 3'h1, 8'h43}; // ascii C
131    mem[15] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
132    mem[16] = {`VMICRO16_OP_MOVI, 3'h1, 8'h44}; // ascii D
133    mem[17] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
134    mem[18] = {`VMICRO16_OP_MOVI, 3'h1, 8'h45}; // ascii D
135    mem[19] = {`VMICRO16_OP_SW, 3'h1, 3'h0, 5'h0};
136    mem[20] = {`VMICRO16_OP_MOVI, 3'h1, 8'h46}; // ascii E

```

```

137     mem[21] = {`VMICRO16_OP_SW,      3'h1, 3'h0, 5'h0};
138     // BRAM0
139     mem[22] = {`VMICRO16_OP_MOVI,    3'h0, 8'hC0};
140     mem[23] = {`VMICRO16_OP_MOVI,    3'h1, 8'hA};
141     mem[24] = {`VMICRO16_OP_SW,      3'h1, 3'h0, 5'h5};
142     mem[25] = {`VMICRO16_OP_LW,      3'h2, 3'h0, 5'h5};
143     // GPIO1 (SSD 24-bit port)
144     mem[26] = {`VMICRO16_OP_MOVI,    3'h0, 8'h91};
145     mem[27] = {`VMICRO16_OP_MOVI,    3'h1, 8'h12};
146     mem[28] = {`VMICRO16_OP_SW,      3'h1, 3'h0, 5'h0};
147     mem[29] = {`VMICRO16_OP_LW,      3'h2, 3'h0, 5'h0};
148     // GPIO2
149     mem[30] = {`VMICRO16_OP_MOVI,    3'h0, 8'h92};
150     mem[31] = {`VMICRO16_OP_MOVI,    3'h1, 8'h56};
151     mem[32] = {`VMICRO16_OP_SW,      3'h1, 3'h0, 5'h0};
152     `endif
153
154     //`define TEST_BRAM
155     `ifndef TEST_BRAM
156     // 2 core BRAM0 test
157     mem[0] = {`VMICRO16_OP_MOVI,    3'h0, 8'hC0};
158     mem[1] = {`VMICRO16_OP_MOVI,    3'h1, 8'hA};
159     mem[2] = {`VMICRO16_OP_SW,      3'h1, 3'h0, 5'h5};
160     mem[3] = {`VMICRO16_OP_LW,      3'h2, 3'h0, 5'h5};
161     `endif
162 end
163
164
165 always @(posedge clk) begin
166     // synchronous WRITE_FIRST (page 13)
167     if (mem_we) begin
168         mem[mem_addr] <= mem_in;
169         $display($time, "\t\t%s[%h] <= %h",
170                 NAME, mem_addr, mem_in);
171     end else
172         mem_out <= mem[mem_addr];
173 end
174
175 // TODO: Reset impl = every clock while reset is asserted, clear each cell
176 //       one at a time, mem[i++] <= 0
177 endmodule
178
179
180 module vmicro16_core_mmu # (
181     parameter MEM_WIDTH      = 16,
182     parameter MEM_DEPTH      = 64,
183
184     parameter CORE_ID        = 3'h0,
185     parameter CORE_ID_BITS   = `clog2(`CORES)
186 ) (
187     input clk,
188     input reset,
189
190     input req,
191     output busy,
192
193     // From core
194     input [MEM_WIDTH-1:0] mmu_addr,
195     input [MEM_WIDTH-1:0] mmu_in,
196     input mmu_we,
197     input mmu_lwex,
198     input mmu_swex,
199     output reg [MEM_WIDTH-1:0] mmu_out,
200
201     // interrupts
202     output reg [`DATA_WIDTH*`DEF_NUM_INT-1:0] ints_vector,
203     output reg [`DEF_NUM_INT-1:0] ints_mask,
204
205     // TO APB interconnect
206     output reg [`APB_WIDTH-1:0] M_PADDR,
207     output reg M_PWRITE,
208     output reg M_PSELx,
209     output reg M_PENABLE,
210     output reg [MEM_WIDTH-1:0] M_PWDATA,
211     // from interconnect
212     input [MEM_WIDTH-1:0] M_PRDATA,
213     input M_PREADY
214 );
215 localparam MMU_STATE_T1 = 0;
216 localparam MMU_STATE_T2 = 1;
217 localparam MMU_STATE_T3 = 2;
218 reg [1:0] mmu_state = MMU_STATE_T1;
219
220 reg [MEM_WIDTH-1:0] per_out = 0;
221 wire [MEM_WIDTH-1:0] tim0_out;
222
223 assign busy = req || (mmu_state == MMU_STATE_T2);
224
225 // more luts than below but easier
226 //wire tim0_en = (mmu_addr >= `DEF_MMU_TIMO_S)

```

```

227 //      <<< (mmu_addr <= `DEF_MMU_TIMO_E);
228 //wire sreg_en = (mmu_addr >= `DEF_MMU_SREG_S);
229 //      <<< (mmu_addr <= `DEF_MMU_SREG_E);
230 //wire intv_en = (mmu_addr >= `DEF_MMU_INTSV_S);
231 //      <<< (mmu_addr <= `DEF_MMU_INTSM_E);
232 //wire intm_en = (mmu_addr >= `DEF_MMU_INTSM_S);
233 //      <<< (mmu_addr <= `DEF_MMU_INTSM_E);
234
235 wire tim0_en = ~mmu_addr[12] && ~mmu_addr[9] && ~mmu_addr[7];
236 wire sreg_en = mmu_addr[7] && ~mmu_addr[4] && ~mmu_addr[5];
237 wire intv_en = mmu_addr[8] && ~mmu_addr[3];
238 wire intm_en = mmu_addr[8] && mmu_addr[3];
239
240 wire apb_en    = !({tim0_en, sreg_en, intv_en, intm_en});
241 wire tim0_we   = (tim0_en && mmu_we);
242 wire intv_we   = (intv_en && mmu_we);
243 wire intm_we   = (intm_en && mmu_we);
244
245 // Special register selects
246 localparam SPECIAL_REGS = 8;
247 wire [MEM_WIDTH-1:0] sr_val;
248
249 // Interrupt vector and mask
250 initial ints_vector = 0;
251 initial ints_mask   = 0;
252 wire [2:0] intv_addr = mmu_addr[`clog2(`DEF_NUM_INT)-1:0];
253 always @(posedge clk)
254     if (intv_we)
255         ints_vector[intv_addr*`DATA_WIDTH +: `DATA_WIDTH] <= mmu_in;
256
257 always @(posedge clk)
258     if (intm_we)
259         ints_mask <= mmu_in;
260
261
262 always @(ints_vector)
263     $display($time,
264             "\tC%d\t\tints_vector W: | %h %h %h %h | %h %h %h %h |",
265             CORE_ID,
266             ints_vector[0*`DATA_WIDTH +: `DATA_WIDTH],
267             ints_vector[1*`DATA_WIDTH +: `DATA_WIDTH],
268             ints_vector[2*`DATA_WIDTH +: `DATA_WIDTH],
269             ints_vector[3*`DATA_WIDTH +: `DATA_WIDTH],
270             ints_vector[4*`DATA_WIDTH +: `DATA_WIDTH],
271             ints_vector[5*`DATA_WIDTH +: `DATA_WIDTH],
272             ints_vector[6*`DATA_WIDTH +: `DATA_WIDTH],
273             ints_vector[7*`DATA_WIDTH +: `DATA_WIDTH]
274             );
275
276 always @(intm_we)
277     $display($time, "\tC%d\t\tintm_we W: %b", CORE_ID, ints_mask);
278
279 // Output port
280 always @(*)
281     if (tim0_en) mmu_out = tim0_out;
282     else if (sreg_en) mmu_out = sr_val;
283     else if (intv_en) mmu_out = ints_vector[mmu_addr[2:0]*`DATA_WIDTH
284                                         +: `DATA_WIDTH];
285     else if (intm_en) mmu_out = ints_mask;
286     else mmu_out = per_out;
287
288 // APB master to slave interface
289 always @(posedge clk)
290     if (reset) begin
291         mmu_state <= MMU_STATE_T1;
292         M_PENABLE <= 0;
293         M_PADDR   <= 0;
294         M_PWDATA  <= 0;
295         M_PSELx   <= 0;
296         M_PWRITE  <= 0;
297     end
298     else
299         casex (mmu_state)
300             MMU_STATE_T1: begin
301                 if (req && apb_en) begin
302                     M_PADDR <= {mmu_lwex,
303                                 mmu_swex,
304                                 CORE_ID[CORE_ID_BITS-1:0],
305                                 mmu_addr[MEM_WIDTH-1:0]};
306
307                     M_PWDATA <= mmu_in;
308                     M_PSELx  <= 1;
309                     M_PWRITE <= mmu_we;
310
311                     mmu_state <= MMU_STATE_T2;
312                 end
313             end
314         `ifdef FIX_T3
315             MMU_STATE_T2: begin
316

```

```

317         M_PENABLE <= 1;
318
319         if (M_PREADY == 1'b1) begin
320             mmu_state <= MMU_STATE_T3;
321         end
322     end
323
324     MMU_STATE_T3: begin
325         // Slave has output a ready signal (finished)
326         M_PENABLE <= 0;
327         M_PADDR <= 0;
328         M_PWDATA <= 0;
329         M_PSELx <= 0;
330         M_PWRITE <= 0;
331         // Clock the peripheral output into a reg,
332         // to output on the next clock cycle
333         per_out <= M_PRDATA;
334
335         mmu_state <= MMU_STATE_T1;
336     end
337 `else
338     // No FIX_T3
339     MMU_STATE_T2: begin
340         if (M_PREADY == 1'b1) begin
341             M_PENABLE <= 0;
342             M_PADDR <= 0;
343             M_PWDATA <= 0;
344             M_PSELx <= 0;
345             M_PWRITE <= 0;
346             // Clock the peripheral output into a reg,
347             // to output on the next clock cycle
348             per_out <= M_PRDATA;
349
350             mmu_state <= MMU_STATE_T1;
351         end else begin
352             M_PENABLE <= 1;
353         end
354     end
355 `endif
356 endcase
357
358 (* ram_style = "block" *)
359 vmicro16_bram # (
360     .MEM_WIDTH (MEM_WIDTH),
361     .MEM_DEPTH (SPECIAL_REGS),
362     .USE_INITS (0),
363     .PARAM_DEFAULTS_R0 (CORE_ID),
364     .PARAM_DEFAULTS_R1 (`CORES),
365     .PARAM_DEFAULTS_R2 (`APB_BRAMO_CELLS),
366     .PARAM_DEFAULTS_R3 (`SLAVES),
367     .NAME ("ram_sr")
368 ) ram_sr (
369     .clk (clk),
370     .reset (reset),
371     .mem_addr (mmu_addr[`clog2(SPECIAL_REGS)-1:0]),
372     .mem_in (),
373     .mem_we (),
374     .mem_out (sr_val)
375 );
376
377 // Each M core has a TIMO scratch memory
378 (* ram_style = "block" *)
379 vmicro16_bram # (
380     .MEM_WIDTH (MEM_WIDTH),
381     .MEM_DEPTH (MEM_DEPTH),
382     .USE_INITS (0),
383     .NAME ("TIMO")
384 ) TIMO (
385     .clk (clk),
386     .reset (reset),
387     .mem_addr (mmu_addr[7:0]),
388     .mem_in (mmu_in),
389     .mem_we (tim0_we),
390     .mem_out (tim0_out)
391 );
392 endmodule
393
394
395 module vmicro16_regs # (
396     parameter CELL_WIDTH = 16,
397     parameter CELL_DEPTH = 8,
398     parameter CELL_SEL_BITS = `clog2(CELL_DEPTH),
399     parameter CELL_DEFAULTS = 0,
400     parameter DEBUG_NAME = "",
401     parameter CORE_ID = 0,
402     parameter PARAM_DEFAULTS_R0 = 16'h0000,
403     parameter PARAM_DEFAULTS_R1 = 16'h0000
404 ) (
405     input clk,

```

```

407     input reset,
408     // Dual port register reads
409     input [CELL_SEL_BITS-1:0] rs1, // port 1
410     output [CELL_WIDTH-1:0] rd1,
411     //input [CELL_SEL_BITS-1:0] rs2, // port 2
412     //output [CELL_WIDTH-1:0] rd2,
413     // EX/WB final stage write back
414     input we,
415     input [CELL_SEL_BITS-1:0] ws1,
416     input [CELL_WIDTH-1:0] wd
417 );
418 (* ram_style = "distributed" *)
419 reg [CELL_WIDTH-1:0] regs [0:CELL_DEPTH-1] /*verilator public_flat*/;
420
421 // Initialise registers with default values
422 // Really only used for special registers used by the soc
423 // TODO: How to do this on reset?
424 integer i;
425 initial
426     if (CELL_DEFAULTS)
427         $readmemh(CELL_DEFAULTS, regs);
428     else begin
429         for(i = 0; i < CELL_DEPTH; i = i + 1)
430             regs[i] = 0;
431         regs[0] = PARAM_DEFAULTS_R0;
432         regs[1] = PARAM_DEFAULTS_R1;
433     end
434
435 `ifdef ICARUS
436     always @(regs)
437         $display($time, "\tC%02h\t\t| %h %h %h %h | %h %h %h %h |",
438             CORE_ID,
439             regs[0], regs[1], regs[2], regs[3],
440             regs[4], regs[5], regs[6], regs[7]);
441 `endif
442
443 always @(posedge clk)
444     if (reset) begin
445         for(i = 0; i < CELL_DEPTH; i = i + 1)
446             regs[i] <= 0;
447         regs[0] <= PARAM_DEFAULTS_R0;
448         regs[1] <= PARAM_DEFAULTS_R1;
449     end
450     else if (we) begin
451         $display($time, "\tC%02h: REGS #s: Writing %h to reg[%d]",
452             CORE_ID, DEBUG_NAME, wd, ws1);
453
454         // Perform the write
455         regs[ws1] <= wd;
456     end
457
458 // sync writes, async reads
459 assign rd1 = regs[rs1];
460 //assign rd2 = regs[rs2];
461 endmodule
462
463 module vmicro16_dec # (
464     parameter INSTR_WIDTH = 16,
465     parameter INSTR_OP_WIDTH = 5,
466     parameter INSTR_RS_WIDTH = 3,
467     parameter ALU_OP_WIDTH = 5
468 ) (
469     //input clk, // not used yet (all combinational)
470     //input reset, // not used yet (all combinational)
471
472     input [INSTR_WIDTH-1:0] instr,
473
474     output [INSTR_OP_WIDTH-1:0] opcode,
475     output [INSTR_RS_WIDTH-1:0] rd,
476     output [INSTR_RS_WIDTH-1:0] ra,
477     output [3:0] imm4,
478     output [7:0] imm8,
479     output [11:0] imm12,
480     output [4:0] simm5,
481
482     // This can be freely increased without affecting the isa
483     output reg [ALU_OP_WIDTH-1:0] alu_op,
484
485     output reg has_imm4,
486     output reg has_imm8,
487     output reg has_imm12,
488     output reg has_we,
489     output reg has_br,
490     output reg has_mem,
491     output reg has_mem_we,
492     output reg has_cmp,
493
494     output halt,
495     output intr,
496

```



```

497     output reg has_lwex,
498     output reg has_swex
499
500     // TODO: Use to identify bad instruction and
501     //       raise exceptions
502     //, output is_bad
503 );
504 assign opcode = instr[15:11];
505 assign rd     = instr[10:8];
506 assign ra     = instr[7:5];
507 assign imm4   = instr[3:0];
508 assign imm8   = instr[7:0];
509 assign imm12  = instr[11:0];
510 assign simm5  = instr[4:0];
511
512 // exme_op
513 always @(*) case (opcode)
514     `VMICRO16_OP_SPCL: casez(instr[11:0])
515         `VMICRO16_OP_SPCL_NOP,
516         `VMICRO16_OP_SPCL_HALT,
517         `VMICRO16_OP_SPCL_INTR: alu_op = `VMICRO16_ALU_NOP;
518         default: alu_op = `VMICRO16_ALU_NOP; endcase
519
520     `VMICRO16_OP_LW: alu_op = `VMICRO16_ALU_LW;
521     `VMICRO16_OP_SW: alu_op = `VMICRO16_ALU_SW;
522     `VMICRO16_OP_LWEX: alu_op = `VMICRO16_ALU_LW;
523     `VMICRO16_OP_SWEX: alu_op = `VMICRO16_ALU_SW;
524
525     `VMICRO16_OP_MOV: alu_op = `VMICRO16_ALU_MOV;
526     `VMICRO16_OP_MOVI: alu_op = `VMICRO16_ALU_MOVI;
527
528     `VMICRO16_OP_BR: alu_op = `VMICRO16_ALU_BR;
529     `VMICRO16_OP_MULT: alu_op = `VMICRO16_ALU_MULT;
530
531     `VMICRO16_OP_CMP: alu_op = `VMICRO16_ALU_CMP;
532     `VMICRO16_OP_SETC: alu_op = `VMICRO16_ALU_SETC;
533
534     `VMICRO16_OP_BIT: casez (simm5)
535         `VMICRO16_OP_BIT_OR: alu_op = `VMICRO16_ALU_BIT_OR;
536         `VMICRO16_OP_BIT_XOR: alu_op = `VMICRO16_ALU_BIT_XOR;
537         `VMICRO16_OP_BIT_AND: alu_op = `VMICRO16_ALU_BIT_AND;
538         `VMICRO16_OP_BIT_NOT: alu_op = `VMICRO16_ALU_BIT_NOT;
539         `VMICRO16_OP_BIT_LSHFT: alu_op = `VMICRO16_ALU_BIT_LSHFT;
540         `VMICRO16_OP_BIT_RSHFT: alu_op = `VMICRO16_ALU_BIT_RSHFT;
541         default: alu_op = `VMICRO16_ALU_BAD; endcase
542
543     `VMICRO16_OP_ARITH_U: casez (simm5)
544         `VMICRO16_OP_ARITH_UADD: alu_op = `VMICRO16_ALU_ARITH_UADD;
545         `VMICRO16_OP_ARITH_USUB: alu_op = `VMICRO16_ALU_ARITH_USUB;
546         `VMICRO16_OP_ARITH_UADDI: alu_op = `VMICRO16_ALU_ARITH_UADDI;
547         default: alu_op = `VMICRO16_ALU_BAD; endcase
548
549     `VMICRO16_OP_ARITH_S: casez (simm5)
550         `VMICRO16_OP_ARITH_SADD: alu_op = `VMICRO16_ALU_ARITH_SADD;
551         `VMICRO16_OP_ARITH_SSUB: alu_op = `VMICRO16_ALU_ARITH_SSUB;
552         `VMICRO16_OP_ARITH_SSUBI: alu_op = `VMICRO16_ALU_ARITH_SSUBI;
553         default: alu_op = `VMICRO16_ALU_BAD; endcase
554
555     default: begin
556         alu_op = `VMICRO16_ALU_NOP;
557         $display($time, "\tDEC: unknown opcode: %h ... NOPPING", opcode);
558     end
559 endcase
560
561 // Special opcodes
562 //assign nop == ((opcode == `VMICRO16_OP_SPCL) & (~instr[0]));
563 assign halt = ((opcode == `VMICRO16_OP_SPCL) & instr[0]);
564 assign intr = ((opcode == `VMICRO16_OP_SPCL) & instr[1]);
565
566 // Register writes
567 always @(*) case (opcode)
568     `VMICRO16_OP_LWEX,
569     `VMICRO16_OP_SWEX,
570     `VMICRO16_OP_LW,
571     `VMICRO16_OP_MOV,
572     `VMICRO16_OP_MOVI,
573     // `VMICRO16_OP_MOVI_L,
574     `VMICRO16_OP_ARITH_U,
575     `VMICRO16_OP_ARITH_S,
576     `VMICRO16_OP_SETC,
577     `VMICRO16_OP_BIT,
578     `VMICRO16_OP_MULT: has_we = 1'b1;
579     default: has_we = 1'b0;
580 endcase
581
582 // Contains 4-bit immediate
583 always @(*)
584     if( ((opcode == `VMICRO16_OP_ARITH_U) && (simm5[4] == 0)) ||
585         ((opcode == `VMICRO16_OP_ARITH_S) && (simm5[4] == 0)) )
586         has_imm4 = 1'b1;

```

```

587         else
588             has_imm4 = 1'b0;
589
590         // Contains 8-bit immediate
591         always @(*) case (opcode)
592             `VMICRO16_OP_MOVI,
593             `VMICRO16_OP_BR:      has_imm8 = 1'b1;
594             default:              has_imm8 = 1'b0;
595         endcase
596
597         /// Contains 12-bit immediate
598         //always @(*) case (opcode)
599         //    `VMICRO16_OP_MOVI_L:  has_imm12 = 1'b1;
600         //    default:              has_imm12 = 1'b0;
601         //endcase
602
603         // Will branch the pc
604         always @(*) case (opcode)
605             `VMICRO16_OP_BR:      has_br = 1'b1;
606             default:              has_br = 1'b0;
607         endcase
608
609         // Requires external memory
610         always @(*) case (opcode)
611             `VMICRO16_OP_LW,
612             `VMICRO16_OP_SW,
613             `VMICRO16_OP_LWEX,
614             `VMICRO16_OP_SWEX:    has_mem = 1'b1;
615             default:              has_mem = 1'b0;
616         endcase
617
618         // Requires external memory write
619         always @(*) case (opcode)
620             `VMICRO16_OP_SW,
621             `VMICRO16_OP_SWEX:    has_mem_we = 1'b1;
622             default:              has_mem_we = 1'b0;
623         endcase
624
625         // Affects status registers (cmp instructions)
626         always @(*) case (opcode)
627             `VMICRO16_OP_CMP:      has_cmp = 1'b1;
628             default:              has_cmp = 1'b0;
629         endcase
630
631         // Performs exclusive checks
632         always @(*) case (opcode)
633             `VMICRO16_OP_LWEX:      has_lwex = 1'b1;
634             default:              has_lwex = 1'b0;
635         endcase
636
637         always @(*) case (opcode)
638             `VMICRO16_OP_SWEX:      has_swex = 1'b1;
639             default:              has_swex = 1'b0;
640         endcase
641     endmodule
642
643
644     module vmicro16_alu # (
645         parameter OP_WIDTH   = 5,
646         parameter DATA_WIDTH = 16,
647         parameter CORE_ID    = 0
648     ) (
649         // input clk, // TODO: make clocked
650
651         input      [OP_WIDTH-1:0] op,
652         input      [DATA_WIDTH-1:0] a, // rs1/dst
653         input      [DATA_WIDTH-1:0] b, // rs2
654         input      [3:0] flags,
655         output reg [DATA_WIDTH-1:0] c
656     );
657     localparam TOP_BIT = (DATA_WIDTH-1);
658     // 17-bit register
659     reg [DATA_WIDTH:0] cmp_tmp = 0; // = {carry, [15:0]}
660     wire r_setc;
661
662     always @(*) begin
663         cmp_tmp = 0;
664         case (op)
665             // branch/nop, output nothing
666             `VMICRO16_ALU_BR,
667             `VMICRO16_ALU_NOP:      c = {DATA_WIDTH{1'b0}};
668             // load/store addresses (use value in rd2)
669             `VMICRO16_ALU_LW,
670             `VMICRO16_ALU_SW:      c = b;
671             // bitwise operations
672             `VMICRO16_ALU_BIT_OR:   c = a | b;
673             `VMICRO16_ALU_BIT_XOR:  c = a ^ b;
674             `VMICRO16_ALU_BIT_AND:  c = a & b;
675             `VMICRO16_ALU_BIT_NOT:  c = ~(b);
676             `VMICRO16_ALU_BIT_LSHFT: c = a << b;

```

```

677     `VMICRO16_ALU_BIT_RSHFT:    c = a >> b;
678
679     `VMICRO16_ALU_MOV:         c = b;
680     `VMICRO16_ALU_MOVI:       c = b;
681     `VMICRO16_ALU_MOVI_L:     c = b;
682
683     `VMICRO16_ALU_ARITH_UADD:  c = a + b;
684     `VMICRO16_ALU_ARITH_USUB: c = a - b;
685     // TODO: ALU should have simm5 as input
686     `VMICRO16_ALU_ARITH_UADDI: c = a + b;
687
688     `ifdef DEF_ALU_HW_MULT
689         `VMICRO16_ALU_MULT:    c = a * b;
690     `endif
691
692     `VMICRO16_ALU_ARITH_SADD:  c = $signed(a) + $signed(b);
693     `VMICRO16_ALU_ARITH_SSUB:  c = $signed(a) - $signed(b);
694     // TODO: ALU should have simm5 as input
695     `VMICRO16_ALU_ARITH_SSUBI: c = $signed(a) - $signed(b);
696
697     `VMICRO16_ALU_CMP: begin
698         // TODO: Do a-b in 17-bit register
699         // Set zero, overflow, carry, signed bits in result
700         cmp_tmp = a - b;
701         c = 0;
702
703         // N Negative condition code flag
704         // Z Zero condition code flag
705         // C Carry condition code flag
706         // V Overflow condition code flag
707         c[`VMICRO16_SFLAG_N] = cmp_tmp[TOP_BIT];
708         c[`VMICRO16_SFLAG_Z] = (cmp_tmp == 0);
709         c[`VMICRO16_SFLAG_C] = 0; //cmp_tmp[TOP_BIT+1]; // not used
710
711         // Overflow flag
712         // https://stackoverflow.com/questions/30957188/
713         // https://github.com/bendl/prco304/blob/master/prco_core/rtl/prco_alu.v#L50
714         case(cmp_tmp[TOP_BIT+1:TOP_BIT])
715             2'b01: c[`VMICRO16_SFLAG_V] = 1;
716             2'b10: c[`VMICRO16_SFLAG_V] = 1;
717             default: c[`VMICRO16_SFLAG_V] = 0;
718         endcase
719
720         $display($time, "\t%c%02h: ALU CMP: %h %h = %h = %b", CORE_ID, a, b, cmp_tmp, c[3:0]);
721     end
722
723     `VMICRO16_ALU_SETC: c = { {15{1'b0}}, r_setc };
724
725     // TODO: Parameterise
726     default: begin
727         $display($time, "\tALU: unknown op: %h", op);
728         c = 0;
729         cmp_tmp = 0;
730     end
731     endcase
732 end
733
734 branch setc_check (
735     .flags      (flags),
736     .cond       (b[7:0]),
737     .en         (r_setc)
738 );
739 endmodule
740
741 // flags = 4 bit r_cmp_flags register
742 // cond = 8 bit VMICRO16_OP_BR_? value. See vmicro16_isa.v
743 module branch (
744     input [3:0] flags,
745     input [7:0] cond,
746     output reg en
747 );
748     always @(*)
749         case (cond)
750             `VMICRO16_OP_BR_U: en = 1;
751             `VMICRO16_OP_BR_E: en = (flags[`VMICRO16_SFLAG_Z] == 1);
752             `VMICRO16_OP_BR_NE: en = (flags[`VMICRO16_SFLAG_Z] == 0);
753             `VMICRO16_OP_BR_G: en = (flags[`VMICRO16_SFLAG_Z] == 0) &&
754                 (flags[`VMICRO16_SFLAG_N] == flags[`VMICRO16_SFLAG_V]);
755             `VMICRO16_OP_BR_L: en = (flags[`VMICRO16_SFLAG_Z] != flags[`VMICRO16_SFLAG_N]);
756             `VMICRO16_OP_BR_GE: en = (flags[`VMICRO16_SFLAG_Z] == flags[`VMICRO16_SFLAG_N]);
757             `VMICRO16_OP_BR_LE: en = (flags[`VMICRO16_SFLAG_Z] == 1) ||
758                 (flags[`VMICRO16_SFLAG_N] != flags[`VMICRO16_SFLAG_V]);
759             default: en = 0;
760         endcase
761 endmodule
762
763
764
765 module vmicro16_core # (
766     parameter DATA_WIDTH = 16,

```

```

767     parameter MEM_INSTR_DEPTH   = 64,
768     parameter MEM_SCRATCH_DEPTH = 64,
769     parameter MEM_WIDTH        = 16,
770
771     parameter CORE_ID          = 3'h0
772 ) (
773     input      clk,
774     input      reset,
775
776     output [7:0] dbug,
777
778     output      halt,
779
780     // interrupt sources
781     input  [`DEF_NUM_INT-1:0]      ints,
782     input  [`DEF_NUM_INT*`DATA_WIDTH-1:0] ints_data,
783     output [`DEF_NUM_INT-1:0]      ints_ack,
784
785     // APB master to slave interface (apb_intercon)
786     output [`APB_WIDTH-1:0]        w_PADDR,
787     output                                w_PWRITE,
788     output                                w_PSELx,
789     output                                w_PENABLE,
790     output [DATA_WIDTH-1:0]         w_PWDATA,
791     input  [DATA_WIDTH-1:0]         w_PRDATA,
792     input                                w_PREADY
793
794     `ifndef DEF_CORE_HAS_INSTR_MEM
795     , // APB master interface to slave instruction memory
796     output reg  [`APB_WIDTH-1:0]      w2_PADDR,
797     output reg  w2_PWRITE,
798     output reg  w2_PSELx,
799     output reg  w2_PENABLE,
800     output reg  [DATA_WIDTH-1:0]      w2_PWDATA,
801     input  [DATA_WIDTH-1:0]           w2_PRDATA,
802     input                                w2_PREADY
803     `endif
804 );
805     localparam STATE_IF = 0;
806     localparam STATE_R1 = 1;
807     localparam STATE_R2 = 2;
808     localparam STATE_ME = 3;
809     localparam STATE_WB = 4;
810     localparam STATE_FE = 5;
811     localparam STATE_IDLE = 6;
812     localparam STATE_HALT = 7;
813     reg [2:0] r_state = STATE_IF;
814
815     reg [DATA_WIDTH-1:0] r_pc      = 16'h0000;
816     reg [DATA_WIDTH-1:0] r_pc_saved = 16'h0000;
817     reg [DATA_WIDTH-1:0] r_instr   = 16'h0000;
818     wire [DATA_WIDTH-1:0] w_mem_instr_out;
819     wire                    w_halt;
820
821     assign dbug = {7'h00, w_halt};
822     assign halt = w_halt;
823
824     wire [4:0]      r_instr_opcode;
825     wire [4:0]      r_instr_alu_op;
826     wire [2:0]      r_instr_rsd;
827     wire [2:0]      r_instr_rsa;
828     reg [DATA_WIDTH-1:0] r_instr_rdd = 0;
829     reg [DATA_WIDTH-1:0] r_instr_rda = 0;
830     wire [3:0]      r_instr_imm4;
831     wire [7:0]      r_instr_imm8;
832     wire [4:0]      r_instr_simm5;
833     wire            r_instr_has_imm4;
834     wire            r_instr_has_imm8;
835     wire            r_instr_has_we;
836     wire            r_instr_has_br;
837     wire            r_instr_has_cmp;
838     wire            r_instr_has_mem;
839     wire            r_instr_has_mem_we;
840     wire            r_instr_halt;
841     wire            r_instr_has_lwex;
842     wire            r_instr_has_swex;
843
844     wire [DATA_WIDTH-1:0] r_alu_out;
845
846     wire [DATA_WIDTH-1:0] r_mem_scratch_addr = $signed(r_alu_out) + $signed(r_instr_simm5);
847     wire [DATA_WIDTH-1:0] r_mem_scratch_in  = r_instr_rdd;
848     wire [DATA_WIDTH-1:0] r_mem_scratch_out;
849     wire                    r_mem_scratch_we = r_instr_has_mem_we && (r_state == STATE_ME);
850     reg                    r_mem_scratch_req = 0;
851     wire                    r_mem_scratch_busy;
852
853     reg [2:0]      r_reg_rs1 = 0;
854     wire [DATA_WIDTH-1:0] r_reg_rd1_s;
855     wire [DATA_WIDTH-1:0] r_reg_rd1_i;
856     wire [DATA_WIDTH-1:0] r_reg_rd1 = regs_use_int ? r_reg_rd1_i : r_reg_rd1_s;

```

```

857 //wire [15:0] r_reg_rd2;
858 wire [DATA_WIDTH-1:0] r_reg_wd = (r_instr_has_mem) ? r_mem_scratch_out : r_alu_out;
859 wire r_reg_we = r_instr_has_we && (r_state == STATE_WB);
860
861 // branching
862 wire w_intr;
863 wire w_branch_en;
864 wire w_branching = r_instr_has_br && w_branch_en;
865 reg [3:0] r_cmp_flags = 4'h00; // N, Z, C, V
866
867 always @(r_cmp_flags)
868     $display($time, "\tC%02h:\tALU CMP: %b", CORE_ID, r_cmp_flags);
869
870 // 2 cycle register fetch
871 always @(*) begin
872     r_reg_rs1 = 0;
873     if (r_state == STATE_R1)
874         r_reg_rs1 = r_instr_rsd;
875     else if (r_state == STATE_R2)
876         r_reg_rs1 = r_instr_rsa;
877     else
878         r_reg_rs1 = 3'h0;
879 end
880
881 reg regs_use_int = 0;
882 `ifdef DEF_ENABLE_INT
883 wire [`DEF_NUM_INT*`DATA_WIDTH-1:0] ints_vector;
884 wire [`DEF_NUM_INT-1:0] ints_mask;
885 wire has_int = ints & ints_mask;
886
887 reg int_pending = 0;
888 reg int_pending_ack = 0;
889 always @(posedge clk)
890     if (int_pending_ack)
891         // We've now branched to the isr
892         int_pending <= 0;
893     else if (has_int)
894         // Notify fsm to switch to the ints_vector at the last stage
895         int_pending <= 1;
896     else if (w_intr)
897         // Return to Interrupt instruction called,
898         // so we've finished with the interrupt
899         int_pending <= 0;
900 `endif
901
902 // Next program counter logic
903 reg [`DATA_WIDTH-1:0] next_pc = 0;
904 always @(posedge clk)
905     if (reset)
906         r_pc <= 0;
907     else if (r_state == STATE_WB) begin
908         `ifdef DEF_ENABLE_INT
909         if (int_pending) begin
910             $display($time, "\tC%02h: Jumping to ISR: %h",
911                     CORE_ID,
912                     ints_vector[0 +: `DATA_WIDTH]);
913             // TODO: check bounds
914             // Save state
915             r_pc_saved <= r_pc + 1;
916             regs_use_int <= 1;
917             int_pending_ack <= 1;
918             // Jump to ISR
919             r_pc <= ints_vector[0 +: `DATA_WIDTH];
920         end else if (w_intr) begin
921             $display($time, "\tC%02h: Returning from ISR: %h",
922                     CORE_ID, r_pc_saved);
923             // Restore state
924             r_pc <= r_pc_saved;
925             regs_use_int <= 0;
926             int_pending_ack <= 0;
927         end else
928         `endif
929         if (w_branching) begin
930             $display($time, "\tC%02h: branching to %h", CORE_ID, r_instr_rdd);
931             r_pc <= r_instr_rdd;
932
933             `ifdef DEF_ENABLE_INT
934             int_pending_ack <= 0;
935             `endif
936         end else if (r_pc < (MEM_INSTR_DEPTH-1)) begin
937             // normal increment
938             // pc <= pc + 1
939             r_pc <= r_pc + 1;
940
941             `ifdef DEF_ENABLE_INT
942             int_pending_ack <= 0;
943             `endif
944         end
945     end // end r_state == STATE_WB
946     else if (r_state == STATE_HALT) begin

```

```

947     `ifdef DEF_ENABLE_INT
948     // Only an interrupt can return from halt
949     // duplicate code form STATE_ME!
950     if (int_pending) begin
951         $display($time, "\tC%02h: Jumping to ISR: %h", CORE_ID, ints_vector[0 +: `DATA_WIDTH]);
952         // TODO: check bounds
953         // Save state
954         r_pc_saved    <= r_pc; // + 1; HALT = stay with same PC
955         regs_use_int   <= 1;
956         int_pending_ack <= 1;
957         // Jump to ISR
958         r_pc          <= ints_vector[0 +: `DATA_WIDTH];
959     end else if (w_intr) begin
960         $display($time, "\tC%02h: Returning from ISR: %h", CORE_ID, r_pc_saved);
961         r_pc          <= r_pc_saved;
962         regs_use_int   <= 0;
963         int_pending_ack <= 0;
964     end
965     `endif
966 end
967
968 `ifndef DEF_CORE_HAS_INSTR_MEM
969     initial w2_PSELx  = 0;
970     initial w2_PENABLE = 0;
971     initial w2_PADDR   = 0;
972 `endif
973
974 // cpu state machine
975 always @(posedge clk)
976     if (reset) begin
977         r_state    <= STATE_IF;
978         r_instr     <= 0;
979         r_mem_scratch_req <= 0;
980         r_instr_rdd <= 0;
981         r_instr_rda <= 0;
982     end
983     else begin
984
985     `ifdef DEF_CORE_HAS_INSTR_MEM
986         if (r_state == STATE_IF) begin
987             r_instr <= w_mem_instr_out;
988
989             $display("");
990             $display($time, "\tC%02h: PC: %h", CORE_ID, r_pc);
991             $display($time, "\tC%02h: INSTR: %h", CORE_ID, w_mem_instr_out);
992
993             r_state <= STATE_R1;
994         end
995     `else
996         // wait for global instruction rom to give us our instruction
997         if (r_state == STATE_IF) begin
998             // wait for ready signal
999             if (!w2_PREADY) begin
1000                 w2_PSELx    <= 1;
1001                 w2_PWRITE    <= 0;
1002                 w2_PENABLE   <= 1;
1003                 w2_PWDATA    <= 0;
1004                 w2_PADDR     <= r_pc;
1005             end else begin
1006                 w2_PSELx    <= 0;
1007                 w2_PWRITE    <= 0;
1008                 w2_PENABLE   <= 0;
1009                 w2_PWDATA    <= 0;
1010
1011                 r_instr <= w2_PRDATA;
1012
1013                 $display("");
1014                 $display($time, "\tC%02h: PC: %h", CORE_ID, r_pc);
1015                 $display($time, "\tC%02h: INSTR: %h", CORE_ID, w2_PRDATA);
1016
1017                 r_state <= STATE_R1;
1018             end
1019         end
1020     `endif
1021
1022     else if (r_state == STATE_R1) begin
1023         if (w_halt) begin
1024             $display("");
1025             $display($time, "\tC%02h: PC: %h HALT", CORE_ID, r_pc);
1026             r_state <= STATE_HALT;
1027         end else begin
1028             // primary operand
1029             r_instr_rdd <= r_reg_rd1;
1030             r_state     <= STATE_R2;
1031         end
1032     end
1033     else if (r_state == STATE_R2) begin
1034         // Choose secondary operand (register or immediate)
1035         if (r_instr_has_imm8) r_instr_rda <= r_instr_imm8;
1036     end

```

```

1037         else if (r_instr_has_imm4) r_instr_rda <= r_reg_rd1 + r_instr_imm4;
1038         else r_instr_rda <= r_reg_rd1;
1039
1040         if (r_instr_has_mem) begin
1041             r_state <= STATE_ME;
1042             // Pulse req
1043             r_mem_scratch_req <= 1;
1044         end else
1045             r_state <= STATE_WB;
1046     end
1047     else if (r_state == STATE_ME) begin
1048         // Pulse req
1049         r_mem_scratch_req <= 0;
1050         // Wait for MMU to finish
1051         if (!r_mem_scratch_busy)
1052             r_state <= STATE_WB;
1053     end
1054     else if (r_state == STATE_WB) begin
1055         if (r_instr_has_cmp) begin
1056             $display($time, "\tC%02h: CMP: %h", CORE_ID, r_alu_out[3:0]);
1057             r_cmp_flags <= r_alu_out[3:0];
1058         end
1059         r_state <= STATE_FE;
1060     end
1061     else if (r_state == STATE_FE)
1062         r_state <= STATE_IF;
1063     else if (r_state == STATE_HALT) begin
1064         `ifdef DEF_ENABLE_INT
1065             if (int_pending) begin
1066                 r_state <= STATE_FE;
1067             end
1068         `endif
1069     end
1070 end
1071
1072 `ifndef DEF_CORE_HAS_INSTR_MEM
1073 // Instruction ROM
1074 (* rom_style = "distributed" *)
1075 vmicro16_bram # (
1076     .MEM_WIDTH      (DATA_WIDTH),
1077     .MEM_DEPTH      (MEM_INSTR_DEPTH),
1078     .CORE_ID        (CORE_ID),
1079     .USE_INITS      (1),
1080     .NAME           ("INSTR_MEM")
1081 ) mem_instr (
1082     .clk            (clk),
1083     .reset          (reset),
1084     // port 1
1085     .mem_addr       (r_pc),
1086     .mem_in         (0),
1087     .mem_we         (1'b0), // ROM
1088     .mem_out        (w_mem_instr_out)
1089 );
1090 `endif
1091
1092 // MMU
1093 vmicro16_core_mmu # (
1094     .MEM_WIDTH      (DATA_WIDTH),
1095     .MEM_DEPTH      (MEM_SCRATCH_DEPTH),
1096     .CORE_ID        (CORE_ID)
1097 ) mmu (
1098     .clk            (clk),
1099     .reset          (reset),
1100     .req            (r_mem_scratch_req),
1101     .busy           (r_mem_scratch_busy),
1102     // interrupts
1103     .ints_vector    (ints_vector),
1104     .ints_mask      (ints_mask),
1105     // port 1
1106     .mmu_addr       (r_mem_scratch_addr),
1107     .mmu_in         (r_mem_scratch_in),
1108     .mmu_we         (r_mem_scratch_we),
1109     .mmu_lwex       (r_instr_has_lwex),
1110     .mmu_swex       (r_instr_has_swex),
1111     .mmu_out        (r_mem_scratch_out),
1112     // APB master to slave
1113     .M_PADDR        (w_PADDR),
1114     .M_PWRITE       (w_PWRITE),
1115     .M_PSELx        (w_PSELx),
1116     .M_PENABLE      (w_PENABLE),
1117     .M_PWDATA       (w_PWDATA),
1118     .M_PRDATA       (w_PRDATA),
1119     .M_PREADY       (w_PREADY)
1120 );
1121
1122 // Instruction decoder
1123 vmicro16_dec dec (
1124     // input
1125
```

```

1126     .instr          (r_instr),
1127     // output async
1128     .opcode         (),
1129     .rd              (r_instr_rsd),
1130     .ra              (r_instr_rsa),
1131     .imm4            (r_instr_imm4),
1132     .imm8            (r_instr_imm8),
1133     .imm12          (),
1134     .simm5           (r_instr_simm5),
1135     .alu_op          (r_instr_alu_op),
1136     .has_imm4        (r_instr_has_imm4),
1137     .has_imm8        (r_instr_has_imm8),
1138     .has_we          (r_instr_has_we),
1139     .has_br          (r_instr_has_br),
1140     .has_cmp         (r_instr_has_cmp),
1141     .has_mem         (r_instr_has_mem),
1142     .has_mem_we      (r_instr_has_mem_we),
1143     .halt            (w_halt),
1144     .intr            (w_intr),
1145     .has_lwex        (r_instr_has_lwex),
1146     .has_swex        (r_instr_has_swex)
1147 );
1148
1149 // Software registers
1150 vmicro16_regs # (
1151     .CORE_ID        (CORE_ID),
1152     .CELL_WIDTH     (`DATA_WIDTH)
1153 ) regs (
1154     .clk             (clk),
1155     .reset           (reset),
1156     // async port 0
1157     .rs1             (r_reg_rs1),
1158     .rd1             (r_reg_rd1_s),
1159     // async port 1
1160     // .rs2           (),
1161     // .rd2           (),
1162     // write port
1163     .we              (r_reg_we && ~regs_use_int),
1164     .ws1             (r_instr_rsd),
1165     .wd              (r_reg_wd)
1166 );
1167
1168 // Interrupt replacement registers
1169 `ifdef DEF_ENABLE_INT
1170 vmicro16_regs # (
1171     .CORE_ID        (CORE_ID),
1172     .CELL_WIDTH     (`DATA_WIDTH),
1173     .DEBUG_NAME     ("REGSINT")
1174 ) regs_intr (
1175     .clk             (clk),
1176     .reset           (reset),
1177     // async port 0
1178     .rs1             (r_reg_rs1),
1179     .rd1             (r_reg_rd1_i),
1180     // async port 1
1181     // .rs2           (),
1182     // .rd2           (),
1183     // write port
1184     .we              (r_reg_we && regs_use_int),
1185     .ws1             (r_instr_rsd),
1186     .wd              (r_reg_wd)
1187 );
1188 `endif
1189
1190 // ALU
1191 vmicro16_alu # (
1192     .CORE_ID(CORE_ID)
1193 ) alu (
1194     .op              (r_instr_alu_op),
1195     .a               (r_instr_rdd),
1196     .b               (r_instr_rda),
1197     .flags           (r_cmp_flags),
1198     // async output
1199     .c               (r_alu_out)
1200 );
1201
1202 branch branch_check (
1203     .flags           (r_cmp_flags),
1204     .cond            (r_instr_imm8),
1205     .en              (w_branch_en)
1206 );
1207
1208 endmodule

```