Microprocessor Final Design Document

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Contents

1 Introduction

The objective of this course (CENG-3013, Integrated Circuit Design) is to design an 8-bit microprocessor, model and simulate it using the Verilog hardware description language, and finally to implement it in hardware using a programmable logic device (PLD). This document describes my microprocessor design, the test code used to verify it, and the physical hardware implementation.

Three things make my work unique:

- Rather than using ABEL test vectors to test each Verilog module, I wrote all of my testbench code in Verilog. This had several advantages.
  - Using an all-Verilog approach enabled me to use tools other than Lattice ispLEVER Classic, most of which were far superior. I primarily used Icarus Verilog (http://www.icarus.com/eda/verilog/) combined with a Bash build script to automate the build and test process for all of the modules. Rather than having to build and test each module independently, I was able to run all of the tests at once and see the pass/fail results immediately. The build script also performed macro substitution, so a test failure message could refer to a specific line of code, rather than merely printing out a simulation timestep.
  - Verilog testbenches are vastly more flexible and efficient for testing large and complex modules. The CPU testbench simulates a block of ROM, which is loaded from a separate file. This makes it very easy to write additional test vectors and to copy the test code into the physical EEPROM. Likewise, the control module test consists of a short segment of Verilog code coupled with an easy-to-read text file containing the test process. This type of high-level testing made it extremely easy to add and edit tests.
  - Both Icarus Verilog and Aldec ActiveHDL perform functional simulation rather than gate-level simulation. This let me focus first on whether the code worked correctly, rather than puzzling over why the optimizer had removed my registers or combined all of my signals. Once the code worked, I could synthesize it with Synplicity and work out synthesis bugs.
- I constructed my own board using a Lattice MachXO PLD instead of using an LSI5512. The latter are no longer available, and have been replaced by the costly and already-outdated Mach4000 series. The MachXO parts are much less expensive, and (until the upcoming release of the MachXO2) are Lattice's flagship CPLD, with solid tool support and documentation.
- To circumvent the painstaking process of creating hexadecimal opcodes for the final test program, I wrote an assembler for my microprocessor which parses an input file and creates output files for Verilog simulation and EEPROM programming.

1.1 Requirements

The requirements in this section are taken from the project specification posted at the beginning of the semester:

- 8-bit data bus
- 16-bit address bus
- Eight 8-bit general purpose registers which can be used in pairs as four 16-bit registers.
- Instructions formatted as shown in Table 1.
- Instruction set as shown in Table 2.
- Jump condition codes as shown in Table 3.

Table 1: Instruction format

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Opcode					Source type		Destination type	Source register			Destination register			Condition	

Table 2: Required instruction set

Instruction	Opcode	Operands
NOP	0x00	-
Add	0x01	reg, reg/imm
Subtract	0x02	reg, reg/imm
Multiply	0x03	reg, reg/imm
Logical AND	0x04	reg, reg/imm
Logical OR	0x05	reg, reg/imm
Logical shift right	0x06	reg
Logical shift left	0x07	reg
Complement bits	0x08	reg
Load	0x10	reg, imm/address
Store	0x11	address, reg
Move	0x12	address, address
Jump	0x0F	address, condition
Halt	0x1F	-

Table 3: Jump condition codes

Condition	Bit designation
Always	00
Carry	01
Zero	10
Negative	11

2 General Architecture Notes

Where multi-byte values are used, they are stored in big-endian format, with the bits ordered from most significant to least significant. The processor has an 8-bit internal data bus which transfers data between the individual modules and connects to external RAM and ROM.

2.1 Chip-level IO

- Clock - Square wave input from function generator
- Reset - Active low input from switch
- Address bus - 16-bit output bus
- Data bus - 8-bit bidirectional bus
- ROM enable - Active low signal which enables the EEPROM
- RAM enable - Active low signal which enables the SRAM
- Memory write - Active high signal which switches the direction of the bidirectional buffer
- $\overline{\text{Write}}$ - Active low signal which enables writing to SRAM

2.2 Instruction set

This section briefly describes each of the instructions. Operations are considered to be 8-bit operations with 8-bit results, except for the multiply, which produces a 16-bit result. For each operation, the zero flag is set if the result contains all zeros.

The negative flag mirrors the most significant bit in the result. In the two's complement number system, this is equivalent to telling whether the value is positive or negative. Mathematical operations are performed exactly the same as for unsigned values, and the programmer can even choose to ignore the negative flag and work with the unsigned values (Wakerly, J. "Digital Design Principles and Practices, 4th Ed.", pp 37-43). In the event that a subraction causes a borrow, the carry bit will be set, and this can be used to determine if a larger value was subtracted from a smaller value. This design is patterned after the operation of the negative flag in the Motorola M68HC11 (www.freescale.com/files/microcontrollers/doc/ref_manual/M68HC11RM.pdf, page 204).

2.2.1 NOP

No operation. After reading this instruction, the processor continues immediately to the next instruction without any extra clock cycles.

2.2.2 ADD

Adds a value to a register. The source value can be another register, a memory location, or an 8-bit immediate. The carry flag is set if a one was carried out of the highest bit. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.3 SUB

Subtracts a value from a register. The source value can be another register, a memory location, or an 8-bit immediate. The carry flag is set if a one was borrowed. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero. Note that because the values are only 8 bits wide, 0x00 - 0x81 gives 0x80, which is not a negative number. Thus, the negative flag will not be set, but the carry bit will.

2.2.4 MUL

Multiplies an 8-bit register by an 8-bit value, producing a 16-bit result. The source value can be another register, a memory location, or an immediate. The result will be written to the destination register and its 16-bit pair, i.e, multiplying register `a` by register `c` will replace both `a` and `b` with the result. Best practice is to load both operands into a single register pair, so that no registers with other data are accidentally overwritten.

2.2.5 AND

Performs a bitwise AND between a register and a value. The source value can be another register, a memory location, or an 8-bit immediate. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.6 OR

Performs a bitwise OR between a register and a value. The source value can be another register, a memory location, or an 8-bit immediate. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.7 LSR

Performs a logical right-shift on a register and stores the result in the same register. All eight bits are shifted, and a zero is shifted into the top bit position. The carry flag is set if a 1 was shifted out. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.8 LSL

Performs a logical left-shift on a register and stores the result in the same register. All eight bits are shifted, and a zero is shifted into the lowest bit position. The carry flag is set if a 1 was shifted out. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.9 ASR

Performs an arithmetic right-shift on a register. Only the lower seven bytes are shifted; a copy of the sign bit is shifted into the bit position below the sign bit. The carry flag is set if a 1 was shifted out. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.10 ASL

Performs an arithmetic left-shift on a register. Only the lower seven bytes are shifted; a zero is shifted into the lowest bit position. The carry flag is set if a 1 was shifted out. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.11 COMP

Complements all of the bits in a register and stores the result in the same register. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.12 NEG

Performs a 2's complement (binary negation) on a register and stores the result in the same register. The negative flag is set if the highest bit is a 1, and the zero flag is set if the result is zero.

2.2.13 LOAD

Loads a value into a register. The source value can be a memory location or an immediate. The source can also be another register, which is also handled internally with the LOAD opcode. The assembler uses the mnemonic "COPY" to refer to loading one register into another.

2.2.14 STORE

Stores a register to RAM. A memory address is required.

2.2.15 MOVE

Copies the contents of one memory address to another. Two addresses are required; the register contents are not affected.

2.2.16 Jump

A jump relocates the current program counter to the memory location specified. After the jump completes, the processor immediately continues executing instructions at the new memory location.

The processor can jump:

- Always, regardless of ALU flags. This uses the assembler mnemonic "JMP"
- If the ALU carry bit was set in the last ALU operation. This uses the assembler mnemonic "JCAR"
- If the ALU zero bit was set in the last ALU operation. This uses the assembler mnemonic "JZERO"
- If the ALU negative bit was set in the last ALU operation. This uses the assembler mnemonic "JNEG"

2.2.17 HALT

Halts the processor's operation. No more instructions are read and the processor stays in the HALT state until it is reset.

3 Module design

3.1 Generic 16-bit register

A 16-bit register is used three times in the design: the jump register, the memory address register, and the instruction register. The same module is instantiated in all three of these cases.

3.1.1 Design

The module has an 8-bit input, which in all three instantiations comes from the data bus. Two signals, `setHigh` and `setLow` determine whether this input is stored in the top half or bottom half of the register.

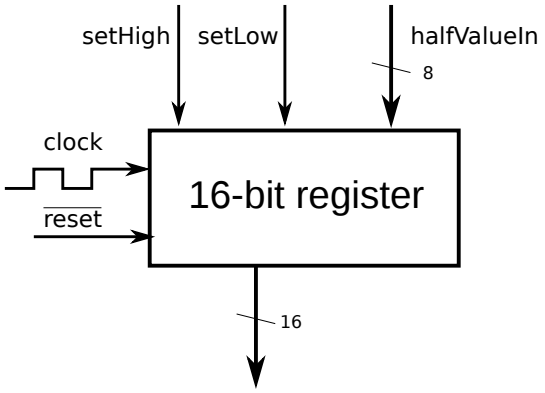


Figure 3.1: 16-bit register block diagram

The module code is shown in Appendix A.2 on page 26.

3.1.2 Testing

Since this was the first module coded, the test code was written in ABEL. It used the following procedure:

1. Reset the module, and ensure that the output is zero.
2. Load the high half of the register
3. Load the low half of the register
4. Load the high half while performing a reset. The reset should take precedence and the output should be zero.

The testbench code is shown in Appendix B.1 on page 43.

3.2 Program counter

3.2.1 Design

The program counter holds the address of the next instruction byte and is used to index ROM when fetching instructions. It increases the output count by on the rising edge of the clock when the `increment` signal is high. When the `set` signal is asserted, it loads the value from the jump register through the input `newCount`.

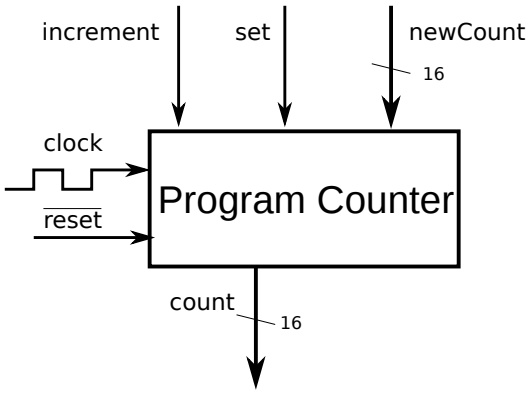


Figure 3.2: Program counter block diagram

The module code is shown in Appendix A.3 on page 27.

3.2.2 Testing

The test uses the following procedure:

1. Perform a reset and check that the output is zero.
2. Leave the increment signal low and ensure that the counter does not increment and remains at zero.
3. Load the value 0xFFFE into the counter and check that the output equals 0xFFFE and was not incremented on this clock cycle.
4. Increment the counter and check that it equals 0xFFFF.
5. Increment the counter again and check that it rolls over to 0x0000.

The testbench code is shown in Appendix B.2 on page 44.

3.3 General-purpose register block

The general-purpose register block contains 8 eight-bit registers which are used for data manipulation. They are grouped into pairs, creating 4 sixteen-bit registers which can receive the result of a multiply operation.

3.3.1 Design

Values are only stored on the rising edge of the clock, but the outputs are set via combinational logic. This means that the outputs are available immediately so register-to-register copies and ALU operations from the registers take place immediately without having to wait an additional clock cycle for the data to become available.

The register block has three 3-bit address inputs which are used to index the registers. The `input_select` input determines which register receives a value from the data bus if `read_data` is high; `output_select` determines which register is written when `write_data` is high. The `alu_output_value` bus goes directly to the ALU and is always active. The `alu_output_select` address determines which register is sent directly to the ALU on this bus.

The register pairing is not due to any hardware feature within the register block - the registers are implemented simply as an 8-element array of 8-bit registers. The pairing is performed by the control signals module, which

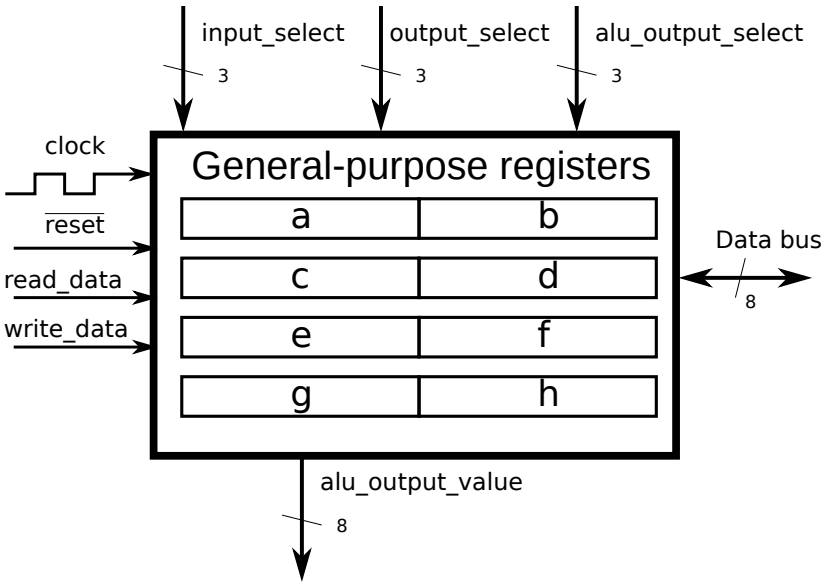


Figure 3.3: General-purpose registers block diagram

The module code is shown in Appendix A.6 on page 31.

3.3.2 Testing

The test uses the following procedure:

1. Perform a reset.
2. Read all of the registers out and check that they read zero.
3. Sequentially load values into each of the registers.
4. Iterate back through the registers, read out their values, and check that they match what was stored.

The testbench code is shown in Appendix B.5 on page 52

3.4 Arithmetic logic unit (ALU)

The arithmetic logic unit implements all of the arithmetic operations specified: addition, subtraction, multiplication, logical AND and OR, left and right logical shifts, left and right arithmetic shifts, bitwise complement, and negation. It also contains a passthrough instruction so that the ALU latch can be used as a temporary register for the MOVE operation. Output flags are set based on the results of the operation.

3.4.1 Design

The ALU consists entirely of combinational logic and operations are performed whenever the inputs change. This wastes a tiny bit of power due to unnecessary gate switching, but simplifies the design. The output is only 8 bits, except for the multiply, which is 16 bits. The zero flag is defined for every operation: if the result is all zeros, the flag is set. Likewise, the negative flag is set whenever the highest bit of the result is a 1, which indicates a negative number in the two's complement system. The behavior and meaning of the carry flag is dependant on the operation. For add and subtract, it indicates a carry out or borrow in; for shifts, it indicates the bit that was shifted out.

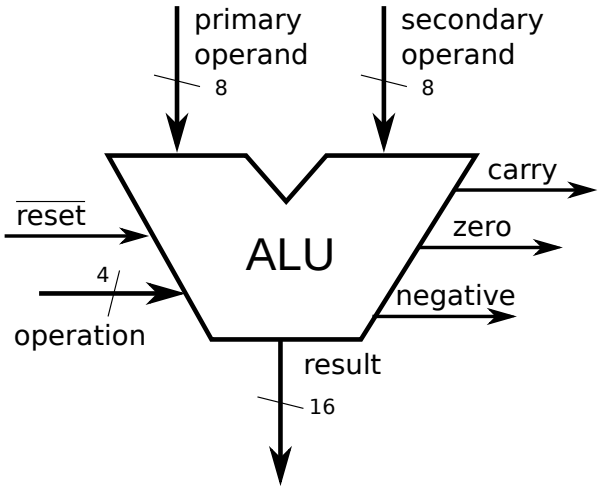


Figure 3.4: ALU block diagram

The ALU module code is shown in Appendix A.4 on page 27.

3.4.2 Testing

The ALU test consists of running a set of possible inputs and checking the result and the output flags. Each instruction is tested with several operations. The complete code is shown in Appendix B.3 on page 46.

3.5 ALU Latch

The ALU latch grabs the result of the ALU operation, holds it, and then puts it on the databus when the store signals are asserted. It also latches the flags, so that a jump operates based on the last time the result was grabbed.

3.5.1 Design

The ALU latch uses a simple sequential design. The `alu_result` and `flags` are stored on the rising edge of the clock if `grab` is high. Combinational logic is used to determine which half of the stored value is put out to the data bus. If neither store signal is high, the output is high-z. The `flags_out` output is always enabled.

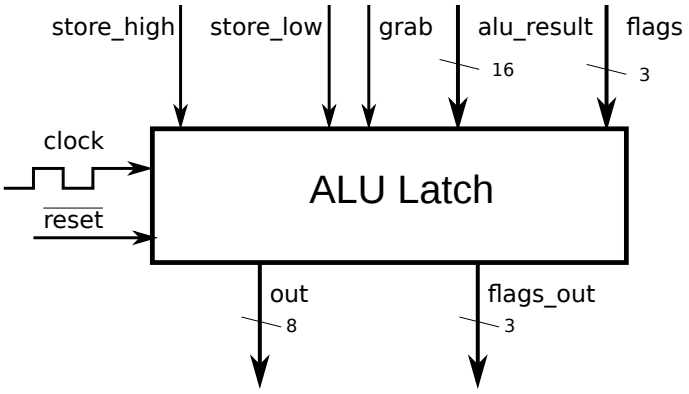


Figure 3.5: ALU latch block diagram

3.5.2 Testing

The test uses the following procedure:

1. Perform a reset.
2. Grab a value from the `alu_result` bus and hold it without putting the value on the data bus. The output should be high-z.
3. Put the high half of the value onto the data bus.
4. Put the low half of the value onto the data bus.
5. Grab a new value and put the result onto the data bus immediately.

Note that although the test passes as expected, the simulation ends as soon as the last test finishes so the final signal state is not shown on the waveform.

3.6 Datapath

3.6.1 Design

The datapath module combines the program counter, jump register, general-purpose registers, ALU, ALU latch, memory address register, and instruction register into a single unit connected by a data bus. The data bus is a bidirectional module port, so data can be brought in and out of the chip. A block diagram of the datapath is shown in Figure 3.6.

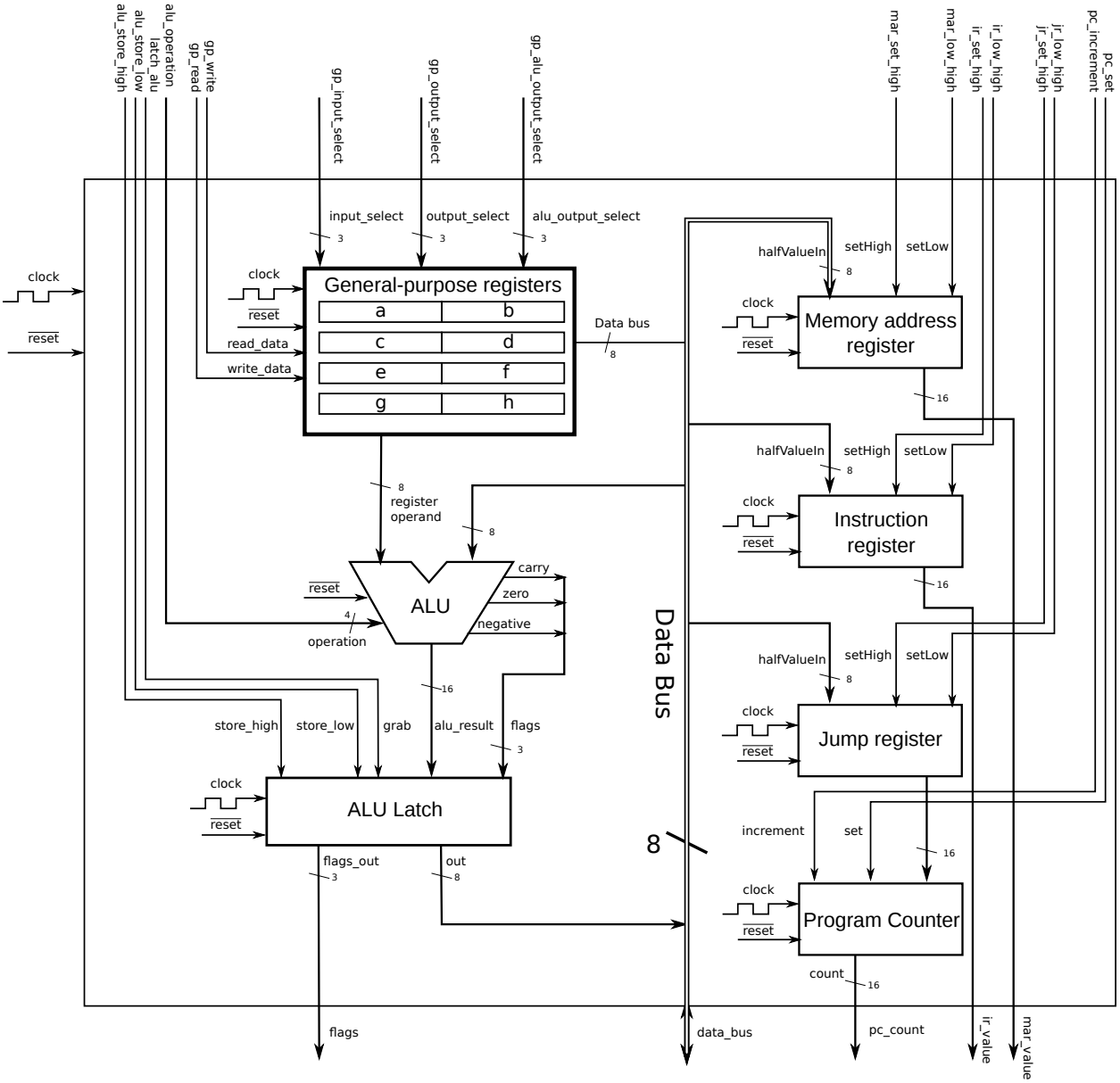


Figure 3.6: Datapath block diagram

3.6.2 Testing

The test uses the following procedure:

1. Perform a reset.
2. Load instruction register from the data bus (high and low).
3. Loading the jump register from the data bus (high and low).
4. Load program counter from jump register.
5. Iterate through each register and load a value from the data bus.
6. Iterate back through the registers and write it back to the data bus.

7. Load the memory address register from the data bus.
8. Load memory address register from the general-purpose registers.
9. Perform an ALU binary operation using two general-purpose registers.
10. Perform an ALU binary operation with an immediate.
11. Perform an ALU unary operation with a general-purpose register.
12. Perform an ALU passthrough and latch the ALU result.
13. Store the ALU result to data bus.

Reset for the general purpose registers is not tested.

3.7 Control module

The control module consists of two separate modules: a state machine which reads the output of the instruction register and determines what to do on the next clock cycle, and a signal translation module which maps the control state into controls signals for all of the other modules.

3.7.1 State machine

Design The state diagram for the state machine is shown in Figure 3.8. The states are all defined as constants in a separate header file, shown in Appendix A.1 on page 25.

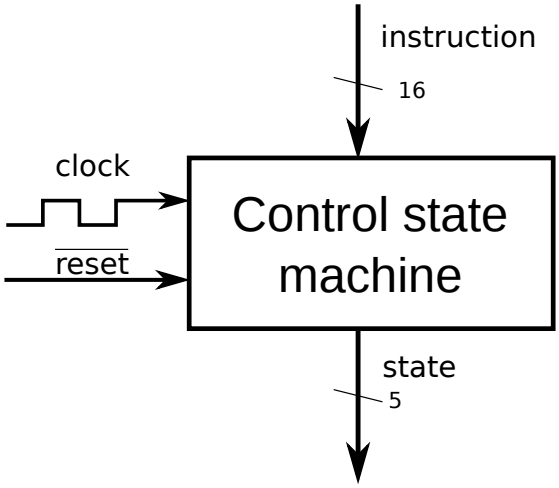


Figure 3.7: Block diagram of control module

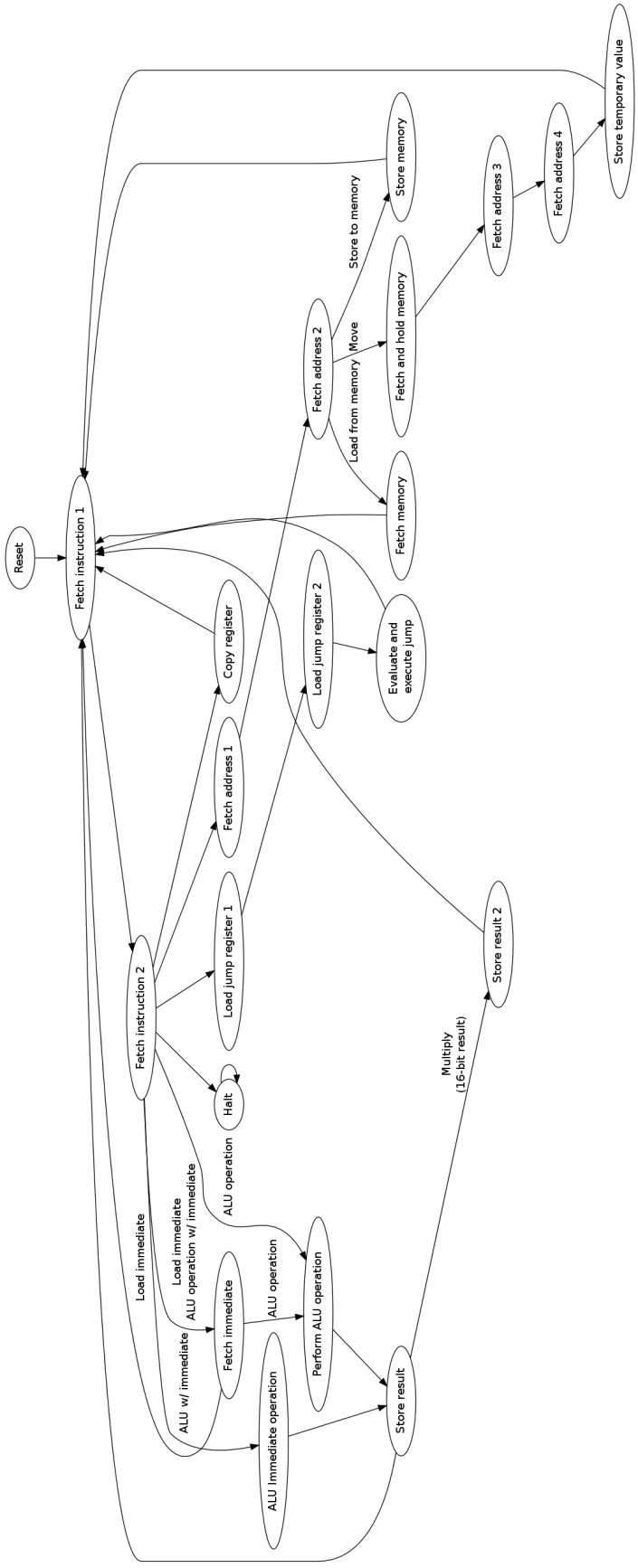


Figure 3.8: Control module state transition diagram. Each state takes exactly one clock cycle.

Testing The testbench for the control state machine uses an external file which contains instruction bytes interleaved with the sequence of states which the module must go through. The testbench reads a line of the file and checks that the current state matches the expected state. If the state is either FETCH_1 or FETCH_2, a hexadecimal byte is provided in the file and the testbench loads this into the simulated instruction register. Lines ending in a # symbol are comments and are ignored. A sample segment of the test file is shown below.

```
NOP#
FETCH_1
00
FETCH_2
00
Add#
FETCH_1
08
FETCH_2
20
ALU_OPERATION
STORE_RESULT_1
Multiply#
FETCH_1
18
FETCH_2
20
ALU_OPERATION
STORE_RESULT_1
STORE_RESULT_2
```

The test file checks every path of the state machine and ensures that each one works correctly.

3.7.2 Control signal translation

Design The state-to-control-vector matrix is shown in Table 4. Pure combinational logic with `assign` statements was used to produce the proper outputs. The general-purpose register addresses are taken directly from the opcode, except where the destination address is modified to produce a 16-bit store for the multiply operation. The ALU operation is taken directly from opcode bits [14:11].

Table 4: Mapping of states to control signals

	gp_read	gp_write	pc_set	pc_increment	mem_read	mem_write	latch_alu	alu_store_high	alu_store_low	ir_load_high	ir_load_low	jr_load_high	jr_load_low	mar_load_high	mar_load_low
RESET	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FETCH_1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0
FETCH_2	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0
FETCH_IMMEDIATE	?	0	0	1	1	0	0	0	0	0	0	0	0	0	0
ALU_OPERATION	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
ALU_IMMEDIATE	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
STORE_RESULT	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
STORE_RESULT_2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
COPY_REGISTER_1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
COPY_REGISTER_2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FETCH_ADDRESS_1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0
FETCH_ADDRESS_2	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1
FETCH_MEMORY	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
STORE_MEMORY	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
TEMP_FETCH	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
FETCH_ADDRESS_3	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0
FETCH_ADDRESS_4	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1
TEMP_STORE	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
LOAD_JUMP_1	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0
LOAD_JUMP_2	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0
EXECUTE_JUMP	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
HALT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The module also handles jump evaluation and execution. If the operation is a jump and the condition code is "always", then the program counter `set` signal is asserted. If the operation is a jump, the condition code is carry, and the carry flag is set, then the signal is asserted. The same logic is used for the carry and zero jumps. No additional clock cycles are necessary for evaluting the jump.

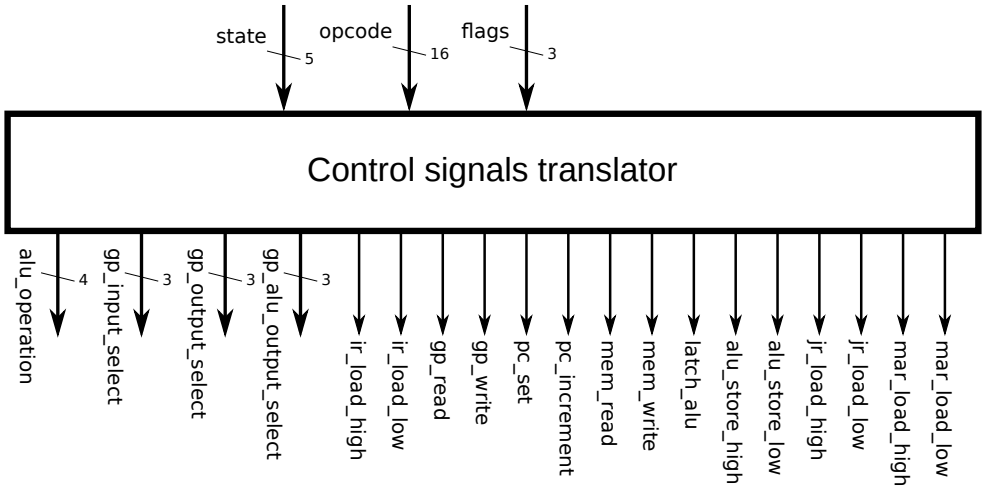


Figure 3.9: Control signal translation module block diagram

The module code for the control signal translation module is shown in Appendix A.11 on page 37.

Testing The testbench simply iterates through all of the states, setting the input state and then checking all of the outputs against those expected from the table. The testbench code is shown in B.8 on page 65.

3.8 Address multiplexer

The address multiplexer switches the output address between the program counter and memory address register based on the state. If the processor is performing a load or store using a memory location, the MAR address is used; otherwise, the program counter is used. The module code is shown in Appendix A.8 on page 33. The address multiplexer was tested as part of the CPU.

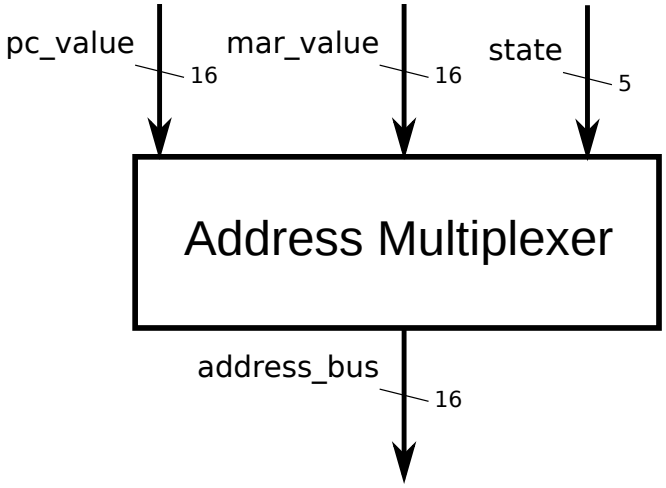


Figure 3.10: Address multiplexer block diagram

3.9 Memory IO

The memory IO module performs memory mapping to locate the ROM and RAM in address space, and translates the read and write signals into ROM and RAM chip enable signals.

3.9.1 Design

Because the program counter's reset is at 0x0000, it needs to find its first instruction at that memory location. This is done by memory-mapping the ROM to 0x0000 through 0x1FFF. The 8 by 8K RAM can occupy any portion of the address space; it was arbitrarily placed at 0x2000 through 0x3FFF. The module's operation is summarized in Table 5.

Table 5: Combinational operation of memory IO module

	Input address	
	0x0000 - 0x1FFFF	0x2000 - 0x13FFFF
`readmemory` = 1	`rom_enable` = 0, `ram_enable` = 1, `write` = 0	`rom_enable` = 1, `ram_enable` = 0, `write` = 0
`writememory` = 1	Invalid	`rom_enable` = 1, `ram_enable` = 0, `write` = 1
both low	`rom_enable` = 1, `ram_enable` = 1, `write` = 0	`rom_enable` = 1, `ram_enable` = 1, `write` = 0

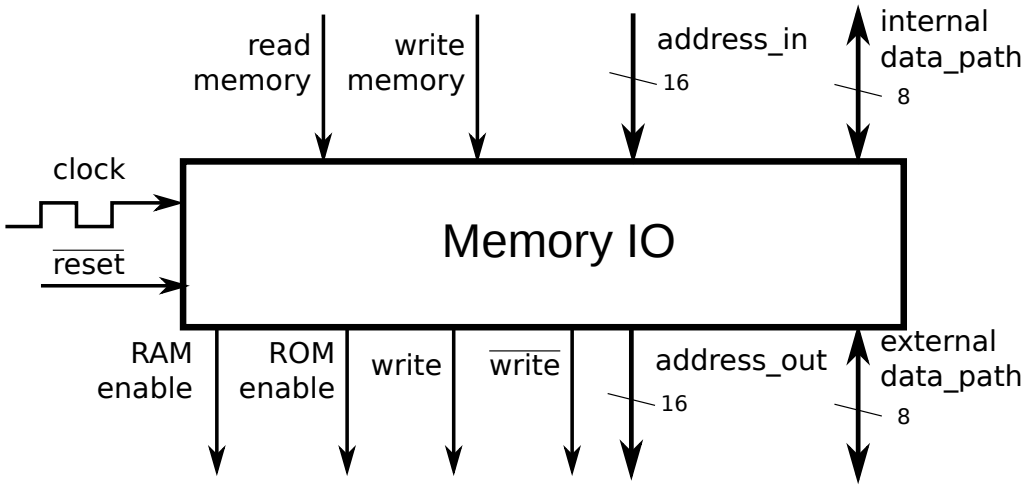


Figure 3.11: Block diagram of memory IO module

3.9.2 Testing

The memory IO unit was tested as part of the CPU.

3.10 Complete chip

3.10.1 Design

The CPU module includes all of the other modules. It connects the control state machine to the datapath via the state translation module, connects the datapath to the outside using the address multiplexer and memory IO module. A block diagram of the CPU is shown in Figure 3.12. For clarity, the datapath control signals are collapsed into a single representative bus.

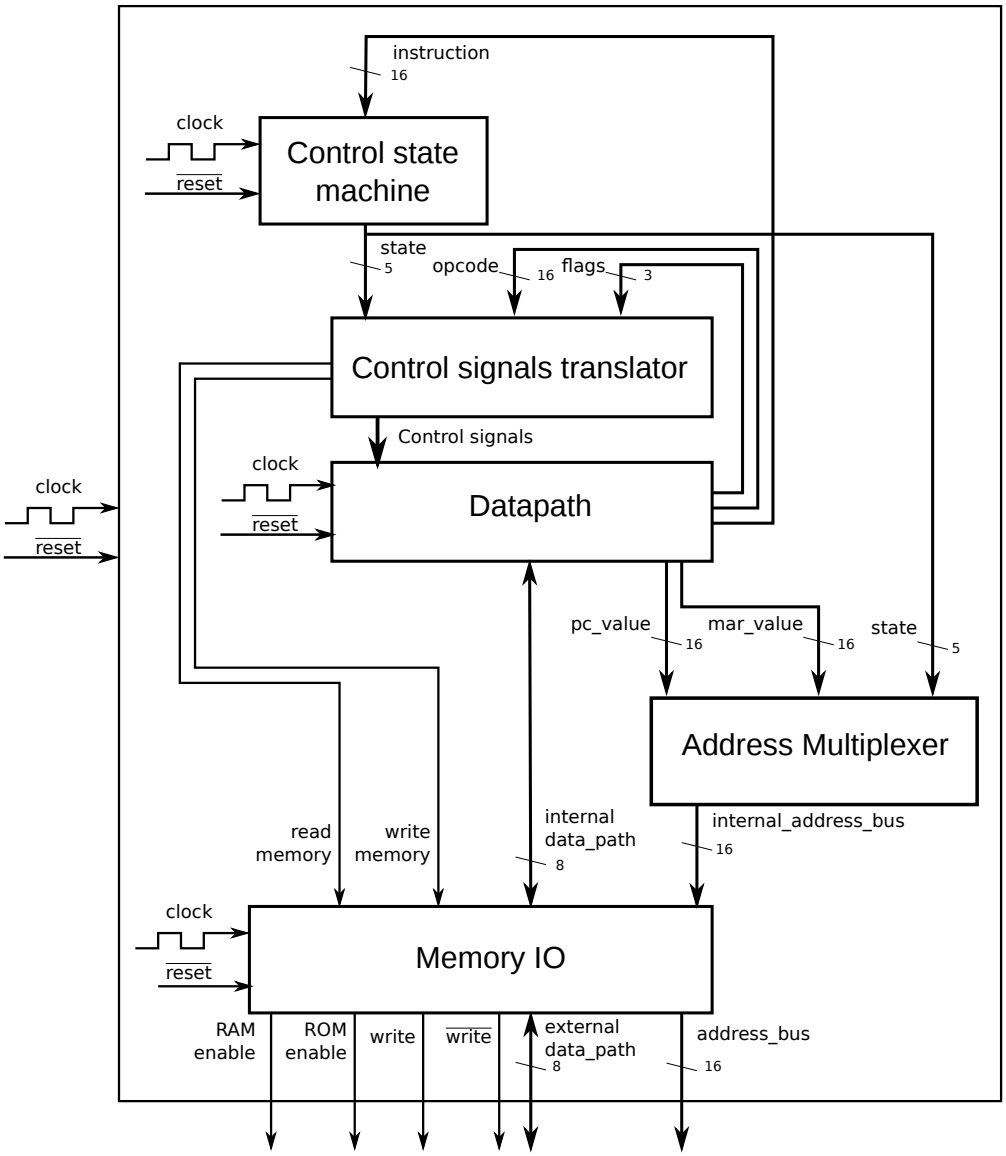


Figure 3.12: CPU block diagram

3.10.2 Testing

Rather than run a specific set of test vectors on the CPU, the testbench simulates RAM and ROM and effectively lets the chip run on its own. The inital ROM configuration is read in from a file produced by the assembler or by hand. The file contains a series of hexadecimal bytes, one per line. Lines beginning with the # symbol are comments and are ignored by the testbench.

After performing a reset, the testbench simply reads the address bus and memory enable lines and returns the appropriate value.

4 Hardware implementation

4.1 Motivation and design criteria

It was clear at the beginning of the class that many people would be competing for time on the implementation board, and its feature set and design are completely fixed. For these reasons, I decided early in the semester

to build my own board.

Two factors caused me to search for parts besides the LSI5512 provided in the class. There were relatively few chips and sockets available, and I assumed that other students would need them. Given that ours was the largest group of students to take this class at OC and that several graduate students would be building their own boards, a part shortage seemed imminent. More importantly, connecting wires to the 256-pin FPGBA socket is difficult and messy at best, and a debugging nightmare at worst. I desired some sort of breakout board which could interface easily with a breadboard.

4.2 Part selection

I researched several part familes from Lattice, Xilinx, and Altera, comparing logic capacity, prices, IDE support, and other factors.

- The Lattice 4000V series (specifically the LC4512V) is the nominal successor to the discontinued LSI5000 series. It is compatible with the Lattice download cables in the Digital lab and is similar to the LSI5000 series. However, chips are surprisingly expensive ($60), and is only supported by ispLEVER Classic, which compared to other tools is a very poor IDE.
- The Xilinx CoolRunner XC2C512 is moderately priced at $40, and comes with a very powerful and polished IDE (Xilix ISE WebPack), which Xilinx distributes for free. However, we do not have any download cables or programmers for the chip.
- In comparison to the CoolRunner CPLDs, Xilinx FPGAs are much cheaper and have an order of magnitude more gates. However, an FPGA is volatile, so it requires other hardware to be useful. Digilent makes several inexpensive ($100-$200) boards which contain a Xilinx Spartan FPGA and hardware to run them, including a USB-JTAG interface. This would be a simple and practical solution, but it is rather expensive and doesn't provide a simple interface to a breadboard.
- The Altera MAX II series is inexpensive ($20), and has a free and powerful IDE. However, it requires a $150 download cable.
- The Lattice MachXO series costs less than $20 and works with programming cables in the Digital lab. It is fully supported by Lattice's newest IDE, known as Lattice Diamond. Although it does not seem as powerful as Xilinx ISE, Diamond is far superior to ispLEVER Classic.

My final selection was to use a MachXO series chip with a custom PCB.

The MachXO series uses a different architecture than traditional CPLDs which uses lookup tables rather than macrocells. The LCMXO-2280 has 2,280 lookup tables, which Lattice equates to 1140 macrocells. Early synthesis reports of my datapath showed approximately 200 macrocells used, and previous designs fit in the 512 macrocell LSI5512, so I was confident that my design would fit easily within the logic constraints of the LCMXO-2280.

4.3 PCB Design

I designed a 2-layer breakout PCB for the LCMXO-2280 using Eagle and had it fabricated by Advanced Circuits (www.4pcb.com). The only other parts on the board were 16 eight-terminal female headers (Newark part #08N6773). One header is set up so that the ispDownload cable can be directly connected to the board (http://www.latticesemi.com/lit/docs/devtools/dlcable.pdf); a second header contains the V_{CC}, V_{IO}, and ground connections for the device. The remaining headers are connected directly to the PLD's IO pins. The Eagle schematic and PCB layout are shown in Appendix D on page 110.

4.4 Breadboard layout

The breadboard was laid out as shown in Figure 4.1. A pair of 74HC245 buffers was used in series on the data bus to ensure that the 5 V external signals did not damage the chip. The data bus connects to a buffer running at 3.3 V, which connects to a buffer at 5 V, which connects to the RAM and ROM. Because each

buffer has a delay of approximately 100ns, the maximum clock speed of the processor is reduced to about 2 MHz. 74HC244 unidirectional buffers were used on the address bus.

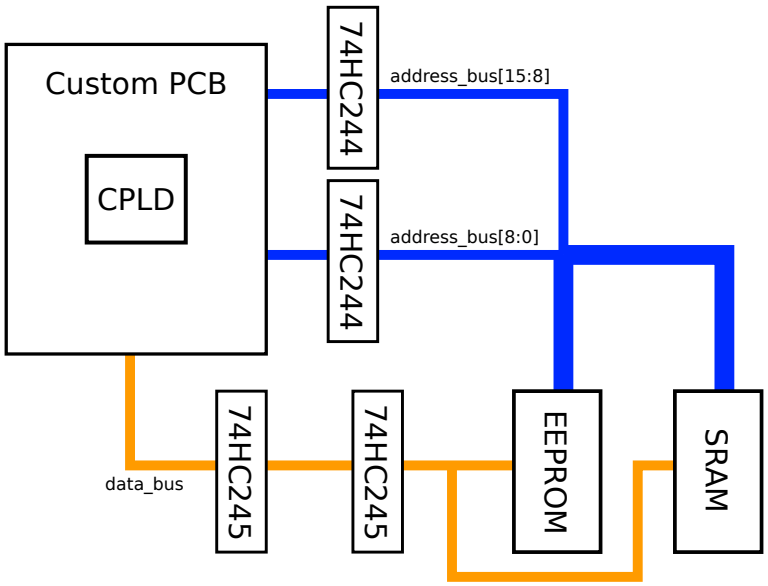


Figure 4.1: Block diagram of breadboard layout

Wires were color-coded using red for +3.3 V and +5 V, black for ground, blue for the address bus, orange for the data bus, green for other signals, and yellow for test points to the logic analyzer.

A photograph of the board is shown in Figure 4.2.

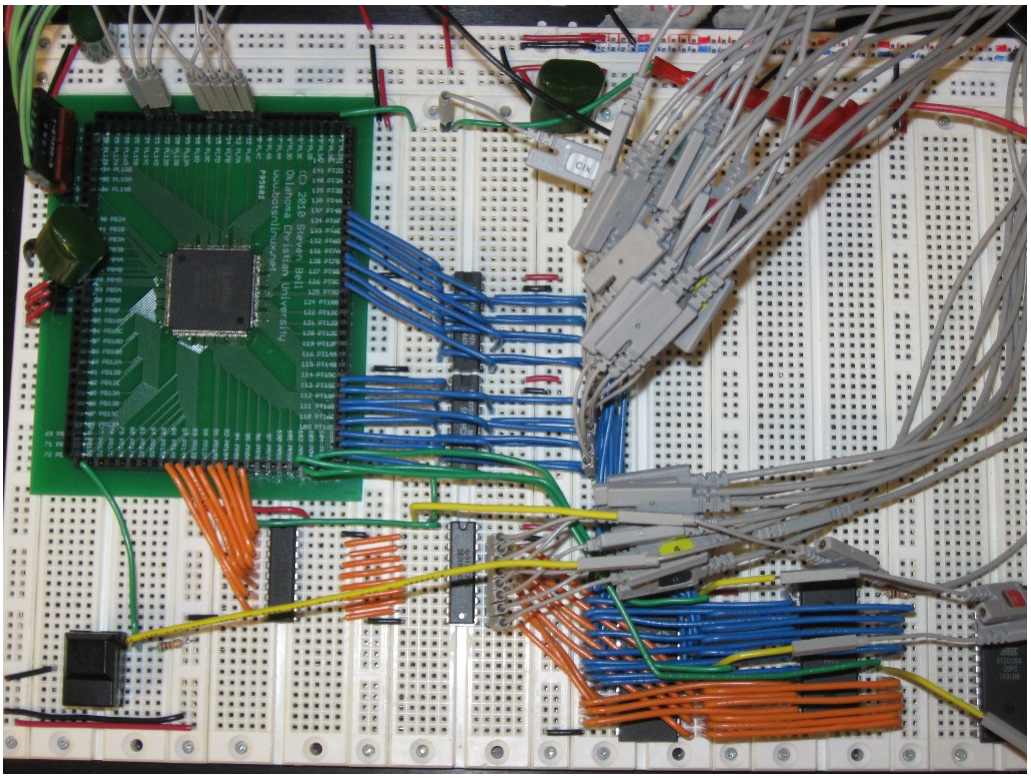


Figure 4.2: Photograph of the finished board

4.4.1 Pin mapping

The MachXO pins are mapped as shown in the table below. The clock input is routed specifically as a clock pin by Lattice Diamond.

Port	Type	Pin
clock	clock	1
reset	input	76
ram_enable	output	104
rom_enable	output	105
write	output	103
$\overline{\text{write}}$	output	102
external_data_bus_7	bidirectional	95
external_data_bus_6	bidirectional	94
external_data_bus_5	bidirectional	92
external_data_bus_4	bidirectional	91
external_data_bus_3	bidirectional	90
external_data_bus_2	bidirectional	89
external_data_bus_1	bidirectional	87
external_data_bus_0	bidirectional	86

Port	Direction	Pin
address_bus_15	output	134
address_bus_14	output	133
address_bus_13	output	132
address_bus_12	output	131
address_bus_11	output	130
address_bus_10	output	127
address_bus_9	output	126
address_bus_8	output	125
address_bus_7	output	113
address_bus_6	output	112
address_bus_5	output	111
address_bus_4	output	110
address_bus_3	output	109
address_bus_2	output	108
address_bus_1	output	107
address_bus_0	output	106

5 Assembler

The assembler is a command-line program written in C++ using the Qt framework. It takes an input file with assembly code based very loosely on Motorola 68HC11 assembly, and produces a Motorola SREC (.S19) file along with a hex dump which can be fed into the CPU simulation testbench. The assembler can handle labels as memory addresses, which is particularly useful for jump operations.

The assembler operates as follows:

1. The configuration is set up based on command-line parameters and the input file is opened.
2. One line of the file is read, broken up into individual tokens, and parsed.
3. If a label is encountered, the parser stores its memory address in a hash table for later reference.
4. If a label is referenced, the parser inserts the appropriate address.
5. If a label which has not yet been encountered is referenced, the parser adds the label to a table of unknown labels.
6. When the parser reaches the end of the file, it goes back through the unknown label list and fills in the remaining label references. If a label is still not defined, the assembler prints an error message.
7. The parser writes out the Motorola SREC file and, if requested, the simulation memory dump.

The complete assembler source code is given in Appendix E on page 112. Examples of the assembly source code which is parses are given in Appendix F on page 130.

6 Conclusion

6.1 Current status

The required test program detailed in F on page 130 works correctly in simulation and in hardware. Captured waveforms from the logic analyzer are shown in Appendix G on page 135.

There is a bug in the ALU on certain multiplications: When a positive value is multiplied by a negative value to give a (e.g, -10 and 6, equivalent to 0xF5 and 0x06), the result is effectively treated as an 8-bit value but is put into the 16-bit register. Thus, rather than giving a 16-bit signed value, it returns an 8-bit signed value.

Arithmetic shifts are not working properly in the ALU, due to the way Verilog handles the arithmetic shift operator. The solution is to write a bit-level assignment to perform the arithmetic shift.

6.2 Future improvements

Several things could be improved on the current design. As my understanding of the Verilog language grew over the course of the semester, my coding style and practices evolved slightly. Were I to start again from scratch, I would:

- Be more careful in my differentiation of blocking and non-blocking assignments. Although my code works, it could probably be improved by using better logic design practices.
- Watch more closely for inferred latches and make sure to clock every module with storage. During the implementation phase, I had to fix several bugs related to inferred latches and unclocked operation.
- Run all of my testbenches based on the positive clock edges. Ultimately, my entire chip operates on the rising edge of the clock; nothing happens on the falling edge. However, I initially tested all of my modules assuming that inputs changed on the negative edges and that they did their work on the rising edge. This obscured my understanding of what was actually happening when I assembled the complete chip.
- Use port names to connect modules rather than argument order. This small syntactical feature was particularly useful at the CPU level, but would have been advantagous even for small modules.
- Define all constants in a single header file (with a .h extension) before writing my ALU and control state machine. I went through several iterations of merging and renaming files as I added new constants and switched build environments.

A Verilog module code

A.1 Global constants

```
/* constants.vh  Definition file for chip-wide opcodes and other parameters
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 4 November 2010
 * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
 */

`ifndef _CONSTANTS_V_
`define _CONSTANTS_V_

`define ZEROFLAG 2
`define CARRYFLAG 1
`define NEGFLAG 0

// ALU Opcodes
// These are the four lower bits from the opcode (instruction bits 14-11)
`define ALU_PASSTHROUGH 4'b1100
`define ALU_ADD 4'b0001
`define ALU_SUBTRACT 4'b0010
`define ALU_MULTIPLY 4'b0011
`define ALU_AND 4'b0100
`define ALU_OR 4'b0101
`define ALU_LOGICAL_SHIFT_RIGHT 4'b0110
`define ALU_LOGICAL_SHIFT_LEFT 4'b0111
`define ALU_ARITH_SHIFT_RIGHT 4'b1001
`define ALU_ARITH_SHIFT_LEFT 4'b1010
`define ALU_TWOS_COMPLEMENT 4'b1011
`define ALU_COMPLEMENT 4'b1000
// Room for 2 more, 4'b1101 and 4'b1110
// 4'b0000 is taken for NOP 4'b1111 for JUMP - these will give a 0 result

// Control module opcodes
// These are the complete 5-bit opcodes used in the control module
`define NOP 5'b00000
`define ADD 5'b00001
`define SUBTRACT 5'b00010
`define MULTIPLY 5'b00011
`define AND 5'b00100
`define OR 5'b00101
`define LOGICAL_SHIFT_RIGHT 5'b00110
`define LOGICAL_SHIFT_LEFT 5'b00111
`define COMPLEMENT 5'b01000
`define ARITH_SHIFT_RIGHT 5'b01001
`define ARITH_SHIFT_LEFT 5'b01010
`define TWOS_COMPLEMENT 5'b01011
`define PASSTHROUGH 5'b01100
`define LOAD 5'b10000
`define STORE 5'b10001
`define MOVE 5'b10010
`define JUMP 5'b01111
`define HALT 5'b11111
```

```
51
52 `define SOURCE_REGISTER 2'b00
53 `define SOURCE_IMMEDIATE 2'b10
54 `define SOURCE_MEMORY 2'b01
55
56 // Control module states
57 // Used in the control module and the control_signals module
58 `define S_RESET 5'd0
59 `define S_FETCH_1 5'd1
60 `define S_FETCH_2 5'd2
61 `define S_ALU_OPERATION 5'd3
62 `define S_STORE_RESULT_1 5'd4
63 `define S_STORE_RESULT_2 5'd5
64 `define S_FETCH_IMMEDIATE 5'd6
65 `define S_COPY_REGISTER 5'd7
66 `define S_FETCH_ADDRESS_1 5'd8
67 `define S_FETCH_ADDRESS_2 5'd9
68 `define S_FETCH_MEMORY 5'd10
69 `define S_STORE_MEMORY 5'd11
70 `define S_TEMP_FETCH 5'd12
71 `define S_FETCH_ADDRESS_3 5'd13
72 `define S_FETCH_ADDRESS_4 5'd14
73 `define S_TEMP_STORE 5'd15
74 `define S_LOAD_JUMP_1 5'd16
75 `define S_LOAD_JUMP_2 5'd17
76 `define S_EXECUTE_JUMP 5'd18
77 `define S_HALT 5'd19
78 `define S_ALU_IMMEDIATE 5'd20
79
80 `endif
```

A.2 Generic 16-bit register

```
1  /* register_16bit.v
2   * Implements a generic 16-bit register which is loaded in two
3   * sequential 8-byte actions.
4   * Author: Steven Bell <steven.bell@student.oc.edu>
5   * Date: 16 September 2010
6   * $LastChangedDate: 2010-09-23 08:44:58 -0500 (Thu, 23 Sep 2010) $
7   */
8
9  module register_16bit(clock, reset, setHigh, setLow, halfValueIn, valueOut);
10   input clock;
11   input reset; // Synchronous reset; active low
12   input setHigh; // When this signal is high, the top half of the value is
         loaded from the input line (data bus)
13   input setLow;
14   input [7:0] halfValueIn;
15   output reg [15:0] valueOut; // Output value containing both bytes
16
17   always @(posedge clock) begin
18     if(~reset) begin // If the reset line is low, then zero the register
19       valueOut = 0;
20     end
```

```
    else if(setHigh) begin
      valueOut[15:8] = halfValueIn; // Load the top half
      // Leave the bottom half the same
    end
    else if(setLow) begin
      // Leave the top half the same
      valueOut[7:0] = halfValueIn; // Load the bottom half
    end
  end // END always

endmodule
```

A.3 Program counter

```
/* program_counter.v
 * Implements the 16-bit loadable program counter.
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 11 September 2010
 * $LastChangedDate: 2010-11-23 09:34:58 -0600 (Tue, 23 Nov 2010) $
 */

/* Program counter which is used to index memory to load instructions.
 * It can be set to new values to implement a jump.  We have to do the set
 * in one shot, because otherwise we jump partway and can't get the next byte.
 */
module program_counter(clock, reset, increment, set, new_count, count);
  input clock;
  input reset; // Synchronous reset; active low
  input increment; // Only increment the counter when this signal is high
  input set; // When this signal is high, the counter loads new_count into the
      counter
  input [15:0] new_count; // New value to set the counter to
  output reg [15:0] count; // Output address of the program counter

  // Clocked operation
  always @(posedge clock) begin
    if(~reset) begin // If the reset line is low, then zero the counter
      count <= 0;
    end
    else if(set) begin // If set is high, then load a new value into the
        counter
      count <= new_count;
    end
    else if(increment) begin // Otherwise, if increment is high, add one to
        the counter
      count <= count + 1;
    end
  end // END always

endmodule
```

A.4 ALU

```
/* alu.v
 * Arithmetic logic unit.
```

```
3  * Author: Steven Bell <steven.bell@student.oc.edu>
4  * Date: 30 September 2010
5  * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
6  */
7
8  `include "constants.v"
9
10 module alu(clock, reset, primaryOperand, secondaryOperand, operation, result,
       flags);
11   input clock; // TODO: remove the clock from the port list, since we're not
         using it anymore
12   input reset; // Asynchronous reset; active low
13   input[7:0] primaryOperand; // Used for all operations except passthrough
14   input[7:0] secondaryOperand; // Used for two-operand operations
15   input[3:0] operation; // Up to 16 operations
16   output[15:0] result;
17   reg[15:0] result;
18   output[2:0] flags;
19   reg[2:0] flags; // Zero, carry, negative
20
21   always @(*) begin
22     result[15:0] = 16'd0; // Reset all of the bits so we don't infer any
         latches
23                           // But does the assignment (= rather than <=) cause
                                extra logic?
24     // Do the requested operation
25     case(operation)
26       `ALU_PASSTHROUGH: begin
27         result[7:0] = secondaryOperand; // Send the data bus input directly to
               the result
28         // It's pointless to pass the register operand through. If we need to
              move it from
29         // one register to another, we can just put it on the data bus.
30         flags[`CARRYFLAG] = 1'b0; // There is never a carry on a passthrough
31         flags[`NEGFLAG] = result[7];
32       end
33       `ALU_ADD: begin
34         result[8:0] = primaryOperand + secondaryOperand;
35         flags[`CARRYFLAG] = result[8]; // See if a bit was carried
36         flags[`NEGFLAG] = result[7];
37       end
38       `ALU_SUBTRACT: begin
39         result[8:0] = primaryOperand - secondaryOperand;
40         flags[`CARRYFLAG] = result[8]; // If the bit is a 1, then we had to
              borrow
41         flags[`NEGFLAG] = result[7];
42       end
43       `ALU_MULTIPLY: begin
44         result[15:0] = primaryOperand * secondaryOperand;
45         flags[`CARRYFLAG] = 1'b0;
46         flags[`NEGFLAG] = result[15];
47       end
48       `ALU_AND: begin
49         result[7:0] = primaryOperand & secondaryOperand;
```

```
50          flags[`CARRYFLAG] = 1'b0;
51          flags[`NEGFLAG] = result[7];
52        end
53        `ALU_OR: begin
54          result[7:0] = primaryOperand | secondaryOperand;
55          flags[`CARRYFLAG] = 1'b0;
56          flags[`NEGFLAG] = result[7];
57        end
58        `ALU_LOGICAL_SHIFT_RIGHT: begin
59          result[7:0] = primaryOperand >> 1;
60          flags[`CARRYFLAG] = primaryOperand[0]; // Set the carry to be the bit
                that got shifted out
61          flags[`NEGFLAG] = result[7]; // This will always be 0; perhaps we
                should set it explicitly?
62        end
63        `ALU_LOGICAL_SHIFT_LEFT: begin
64          result[7:0] = primaryOperand << 1;
65          flags[`CARRYFLAG] = primaryOperand[7]; // Set the carry to be the bit
                that got shifted out
66          flags[`NEGFLAG] = result[7];
67        end
68        `ALU_ARITH_SHIFT_RIGHT: begin
69          result[7:0] = primaryOperand >>> 1;
70          flags[`CARRYFLAG] = primaryOperand[0]; // Set the carry to be the bit
                that got shifted out
71          flags[`NEGFLAG] = result[7];
72        end
73        `ALU_ARITH_SHIFT_LEFT: begin
74          result[7:0] = primaryOperand <<< 1;
75          flags[`CARRYFLAG] = primaryOperand[7]; // Set the carry to be the bit
                that got shifted out
76          flags[`NEGFLAG] = result[7];
77        end
78        `ALU_TWOS_COMPLEMENT: begin
79          result = ~primaryOperand; // Complement
80          result = result + 8'd1; // and add one
81          flags[`CARRYFLAG] = 1'b0;
82          flags[`NEGFLAG] = result[7];
83        end
84        `ALU_COMPLEMENT: begin
85          result = ~primaryOperand;
86          flags[`CARRYFLAG] = 1'b0;
87          flags[`NEGFLAG] = result[7];
88        end
89        default: begin
90          result[15:0] = 15'd0;
91          flags[`CARRYFLAG] = 1'b0;
92          flags[`NEGFLAG] = 1'b0;
93        end
94      endcase
95
96      if(operation == `ALU_MULTIPLY) begin
97        flags[`ZEROFLAG] = (result[15:0] == 16'h0000) ? 1'b1 : 1'b0;
98      end
```

```
99      else begin
100       flags[`ZEROFLAG] = (result[7:0] == 8'h00) ? 1'b1 : 1'b0;
101     end // if(operation == `MULTIPLY)
102    end //always @(posedge clock)
103
104 endmodule
```

A.5 ALU latch

```
1  /* alu_latch.v
2   * Grabs the result from the ALU and puts it on the data bus
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 11 October 2010
5   * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
6   */
7
8  module alu_latch(
9    input clock,
10   input reset,
11   input[15:0] alu_result, // Result from the ALU
12   input[2:0] flags, // ALU flags which must also be latched
13   input grab, // Active-high signal telling us whether or not to latch the
       value
14   input store_high, // Put the top 8 bytes on the data bus (only used for
       multiply)
15   input store_low, // Put the low 8 bytes on the data bus
16   output reg[7:0] out,
17   output reg[2:0] flags_out
18 );
19
20   reg[15:0] value; // Stores the full-length output value
21
22   always @(posedge clock) begin
23     if(reset == 1'b0) begin
24       value <= 16'b0;
25     end
26     if(grab == 1'b1) begin // Latch the ALU value when the grab signal is high
27       value <= alu_result;
28       flags_out <= flags;
29     end
30   end // always
31
32   /* This part will synthesize into combinational logic which puts
33    * the appropriate set of signals onto the data bus. */
34   always @(*) begin
35     if(store_low == 1'b1) begin
36       out <= value[7:0];
37     end
38     else if(store_high == 1'b1) begin
39       out <= value[15:8];
40     end
41     else begin
42       out <= 8'hzz;
43     end
```

```
44   end
45
46 endmodule
```

A.6 General-purpose register block

```
1  /* gp_registers.v
2   * 8x8 bit general purpose register set.
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 23 September 2010
5   * $LastChangedDate: 2010-12-14 09:01:55 -0600 (Tue, 14 Dec 2010) $
6   */
7
8  module gp_registers
9  (
10   input clock,
11   input reset, // Active-low synchronous reset
12   input read_data, // Flag telling us whether or not to load a register value
        from the data bus (active high)
13   input write_data, // Flag telling us whether or not to write a register to
        the data bus (active high)
14   // We'll just leave the ALU output always enabled, since it can't mess
        things up and we
15   // don't care about the slight increase in power consumption due to flipping
         unnecessary gates.
16
17   input[2:0] input_select, // Register to put the input value into
18   input[2:0] output_select, // Index of the register we want to put on the
        data bus output
19   input[2:0] alu_output_select, // Index of the register we want to put on the
         ALU output
20
21   inout[7:0] data_bus, // Contains the input value to store, or the ouput we
        write
22   output[7:0] alu_output_value // Output bus to the ALU
23 );
24
25   reg[7:0] register_data[7:0]; // Data array, 8 bits x 8 registers
26   wire[7:0] output_value; // Temporary latch, because the data_bus is a wire
        and not a reg
27
28   integer i; // Used for iterating through the registers when resetting them
29
30   always@(posedge clock) begin
31     if(reset == 1'b0) begin
32       // Remember that this code produces hardware, and all of the registers
            will be reset simultaneously
33       for(i = 0; i < 8; i = i+1) begin
34         register_data[i] <= 8'd0;
35       end
36     end
37
38     if(read_data == 1'b1) begin
39       register_data[input_select] <= data_bus;
```

```
40      end
41    end // always
42
43    // Combinational logic to interface with the data bus
44
45    assign output_value = register_data[output_select];
46    assign data_bus = write_data ? output_value : 8'hzz;
47    assign alu_output_value = register_data[alu_output_select];
48
49  endmodule
```

A.7 Datapath

```
1   /* datapath.v
2    * Datapath which includes the general purpose registers, special purpose
3    * registers, ALU, and the connections between them.
4    * Author: Steven Bell <steven.bell@student.oc.edu>
5    * Date: 6 October 2010
6    * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
7    */
8
9   module datapath(
10    input clock,
11    input reset,
12    input pc_increment,
13    input pc_set,
14    input gp_read,
15    input gp_write,
16    input[2:0] gp_input_select,
17    input[2:0] gp_output_select,
18    input[2:0] gp_alu_output_select,
19    input[3:0] alu_operation,
20    input latch_alu,
21    input alu_store_high,
22    input alu_store_low,
23    input mar_set_high,
24    input mar_set_low,
25    input ir_set_high,
26    input ir_set_low,
27    input jr_set_high,
28    input jr_set_low,
29
30    output wire[15:0] pc_count, // Program counter output
31    output wire[15:0] mar_value, // Memory address register output
32    output wire[15:0] ir_value, // Instruction register output
33    output wire[2:0] flags, // ALU flags
34
35    inout[7:0] data_bus
36  );
37
38    // Shared connections
39    wire[7:0] register_operand; // Bus from the general-purpose registers to the
          ALU
```

```
40   wire[15:0] pc_jump_count; // Bus from the jump register to the program
        counter (value to jump to)
41   wire[15:0] alu_result;
42   wire[2:0] flags_temp;
43
44   // Program counter (only reads from jump register, not data bus)
45   program_counter m_program_counter(clock, reset, pc_increment, pc_set,
        pc_jump_count, pc_count);
46
47   // Jump register which holds the value for the program counter to jump to
48   register_16bit m_jump_register(clock, reset, jr_set_high, jr_set_low,
        data_bus, pc_jump_count);
49
50   // General-purpose registers
51   gp_registers m_gp_registers(clock, reset, gp_read, gp_write, gp_input_select
        , gp_output_select, gp_alu_output_select, data_bus, register_operand);
52
53   // ALU and ALU latch
54   alu m_alu(clock, reset, register_operand, data_bus, alu_operation,
        alu_result, flags_temp);
55   alu_latch m_alu_latch(clock, reset, alu_result, flags_temp, latch_alu,
        alu_store_high, alu_store_low, data_bus, flags);
56
57   // Memory address register
58   register_16bit m_address_register(clock, reset, mar_set_high, mar_set_low,
        data_bus, mar_value);
59
60   // Instruction register
61   register_16bit m_instruction_register(clock, reset, ir_set_high, ir_set_low,
         data_bus, ir_value);
62
63
64
65 endmodule
```

A.8 Address Multiplexer

```
1  /* address_mux.v  Multiplexer that picks the output address bus value from
      either the MAR or
2   *                the program counter based the control module state.
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 6 December 2010
5   * $LastChangedDate: 2010-12-16 17:48:32 -0600 (Thu, 16 Dec 2010) $
6   */
7
8  `include "constants.v"
9
10 module address_mux(
11   input[15:0] pc_value,
12   input[15:0] mar_value,
13   input[4:0] state,
14   output[15:0] address_bus
15 );
16
```

```
17   assign address_bus = (state === `S_FETCH_MEMORY || state === `S_STORE_MEMORY
         ||
18                         state === `S_TEMP_FETCH || state === `S_TEMP_STORE) ?
                              mar_value : pc_value;
19 endmodule
```

A.9 Memory IO

```
1  /* memio.v  Memory IO module which performs memory mapping and holds the
2   * digital IO banks.
3   *
4   * Author: Steven Bell <steven.bell@student.oc.edu>
5   * Date: 5 December 2010
6   * $LastChangedDate$
7   */
8
9  module memio(
10   input read_memory,
11   input write_memory,
12   inout[7:0] internal_data_path,
13   inout[7:0] external_data_path,
14
15   input[15:0] address_in, // Full 16-bit address input
16   output[15:0] address_out, // Output address; not all 16 bits may be used
17   // TODO: digital inputs/outputs
18   output ram_enable, // Active low signal which turns the RAM on
19   output rom_enable, // Active low signal which turns the ROM on
20   output write, // Active high signal which tells the bidirectional buffers we
        're writing
21   output write_bar // Opposite of write; active low signal which tells the RAM
         we're writing
22 );
23   // TODO: use this to make sure we don't crash and burn if both read and
        write are asserted
24   wire enabled;
25   assign enabled = read_memory ^ write_memory;
26
27   assign internal_data_path = read_memory ? external_data_path : 8'hzz;
28   assign external_data_path = write_memory ? internal_data_path : 8'hzz;
29
30
31   // Map the ROM to 0000 - 1FFF
32   // Output is active low
33   assign rom_enable = !(address_in[15:13] === 3'b000);
34
35   // Map the RAM to 2000 - 3FFF
36   // Output is active low
37   assign ram_enable = !(address_in[15:13] === 3'b001);
38
39   assign address_out = address_in; // Passthrough for now
40   assign write = write_memory;
41   assign write_bar = !write_memory;
42
43 endmodule
```

A.10 Control module state machine

```
/* control.v
 * Control module which fetches instructions and drives all of the other
 * modules.
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 28 October 2010
 * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
 */

`include "constants.v"

module control
(
  input clock,
  input reset,
  input[15:0] instruction, // Value from the instruction register
  output reg[4:0] state // Current control state
);

  always @(posedge clock) begin

    // Moving into reset is handled by an if statement at the end
    case(state)
      `S_RESET:
        // Everything is zero
        if(reset != 1'b0) begin // If reset is no longer asserted, it's time to start!
          state <= `S_FETCH_1;
        end
      `S_FETCH_1:
        // Always to go to fetch 2, since every opcode is two bytes
        state <= `S_FETCH_2;
      `S_FETCH_2:
        // Figure out what to do next based on the first half of the opcode
        // We won't have the second half until the end of the clock
        if(instruction[15:11] == `NOP) begin
          state <= `S_FETCH_1;
        end
        else if(instruction[15:11] == `JUMP) begin
          state <= `S_LOAD_JUMP_1;
        end
        // If the opcode begins with a zero, then it's an ALU operation, except if it's
        // 01101 or 01110, which are not used (JUMP and NOP are already handled)
        else if(instruction[15] == 1'b0 && instruction[15:11] != 5'b01101 && instruction != 5'b01110) begin
          if(instruction[10:9] == `SOURCE_REGISTER) begin
            state <= `S_ALU_OPERATION;
          end
          else begin // TODO: Crash gracefully if it's invalid
            state <= `S_ALU_IMMEDIATE;
          end
```

```
49          end
50          else if(instruction[15:11] == `LOAD) begin
51            if(instruction[10:9] == `SOURCE_REGISTER) begin
52              state <= `S_COPY_REGISTER;
53            end
54            else if(instruction[10:9] == `SOURCE_IMMEDIATE) begin
55              state <= `S_FETCH_IMMEDIATE;
56            end
57            else if(instruction[10:9] == `SOURCE_MEMORY) begin
58              state <= `S_FETCH_ADDRESS_1;
59            end
60          end
61          else if(instruction[15:11] == `STORE ||
62                  instruction[15:11] == `MOVE) begin
63            state <= `S_FETCH_ADDRESS_1;
64          end
65          else if(instruction[15:11] == `S_HALT) begin
66            state <= `S_HALT;
67          end
68          else begin
69            state <= `S_HALT;
70          end
71
72        `S_ALU_OPERATION:
73          state <= `S_STORE_RESULT_1;
74
75        `S_ALU_IMMEDIATE:
76          state <= `S_STORE_RESULT_1;
77
78        `S_STORE_RESULT_1:
79          // If the operation was a multiply, we have to do 2 stores
80          if(instruction[15:11] == `MULTIPLY) begin
81            state <= `S_STORE_RESULT_2;
82          end
83          // Otherwise, we're ready for the next operation
84          else begin
85            state <= `S_FETCH_1;
86          end
87        `S_STORE_RESULT_2:
88          state <= `S_FETCH_1;
89        `S_FETCH_IMMEDIATE:
90          // Because this state is used both for storing immediates into the
                registers
91          // and for grabbing immediate values for the ALU, this state loads the
                immediate
92          // value into the register.  It will be overwritten by the ALU result
                if there is one.
93          // This could be fixed by creating a separate state for loading
                immediates.
94          if(instruction[15:11] == `LOAD) begin
95            state <= `S_FETCH_1;
96          end
97          else begin
98            state <= `S_ALU_OPERATION;
```

```
99          end
100       `S_COPY_REGISTER:
101         state <= `S_FETCH_1;
102       `S_FETCH_ADDRESS_1:
103         state <= `S_FETCH_ADDRESS_2;
104       `S_FETCH_ADDRESS_2:
105         if(instruction[15:11] == `LOAD) begin
106           state <= `S_FETCH_MEMORY;
107         end
108         else if(instruction[15:11] == `STORE) begin
109           state <= `S_STORE_MEMORY;
110         end
111         else if(instruction[15:11] == `MOVE) begin
112           state <= `S_TEMP_FETCH;
113         end
114       `S_FETCH_MEMORY:
115         state <= `S_FETCH_1;
116       `S_STORE_MEMORY:
117         state <= `S_FETCH_1;
118       `S_TEMP_FETCH:
119         state <= `S_FETCH_ADDRESS_3;
120       `S_FETCH_ADDRESS_3:
121         state <= `S_FETCH_ADDRESS_4;
122       `S_FETCH_ADDRESS_4:
123         state <= `S_TEMP_STORE;
124       `S_TEMP_STORE:
125         state <= `S_FETCH_1;
126       `S_LOAD_JUMP_1:
127         state <= `S_LOAD_JUMP_2;
128       `S_LOAD_JUMP_2:
129         state <= `S_EXECUTE_JUMP;
130       `S_EXECUTE_JUMP:
131         state <= `S_FETCH_1;
132       `S_HALT:
133         state <= `S_HALT; // Just stay put!
134     endcase
135
136     if(reset == 0) begin
137       state <= `S_RESET;
138     end
139
140   end
141
142
143 endmodule
```

A.11 Control signals translator

```
1  /* control_signals.v
2   * Module which translates the control module state into the set of control
        signals
3   * for the rest of the chip.
4   * Author: Steven Bell <steven.bell@student.oc.edu>
5   * Date: 24 November 2010
```

```
 * $LastChangedDate$
 */

`include "constants.v"

module control_signals(
  input[4:0] state, // State from the control state machine
  input[15:0] opcode, // Full 16-bit opcode from the instruction register
  input[2:0] alu_flags, // Carry/Zero/Negative flags from ALU

  output ir_load_high, // Load the high 8 bits of the instruction from the data bus
  output ir_load_low, // Load the low 8 bits of the instruction
  output gp_read, // Read a value from the data bus into a register
  output gp_write, // Write a value from the register onto the data bus
  output pc_set, // Set the program counter from the jump register
  output pc_increment, // Increment the program counter
  output mem_read, // Read a value from memory onto the data bus
  output mem_write, // Write a value from the data bus out to memory (RAM)
  output latch_alu,
  output alu_store_high, // Write the high 8 bits of the ALU result to the data bus
  output alu_store_low, // Write the low 8 bits of the ALU result to the data bus
  output jr_load_high, // Load the high 8 bits of the jump destination into the jump register
  output jr_load_low, // Load the low 8 bits of the jump destination
  output mar_load_high, // Load the high 8 bits of the memory address into the MAR
  output mar_load_low, // Load the low 8 bits of the memory address

  output[3:0] alu_operation,
  output[2:0] gp_input_select,
  output[2:0] gp_output_select, // Register select for GP registers to data bus
  output[2:0] gp_alu_output_select // Register select for GP registers directly to ALU
);

  // Signals directly from the opcode
  assign alu_operation = (opcode[15:11] === `MOVE) ? `ALU_PASSTHROUGH : opcode[14:11];
  // The assignments below assume that the ALU operand directly from the GP registers
  // is the "primary operand" used for unary operations.
  assign gp_input_select[2:1] = opcode[4:3]; // GP registers from data bus

  wire gp_address_force; // Bit used to force a particular address when using a multiply
  assign gp_address_force = (state === `S_STORE_RESULT_2) ? 1'b1 : 1'b0;
  assign gp_input_select[0] = (opcode[15:11] === `MULTIPLY) ? gp_address_force : opcode[2];
  assign gp_output_select = opcode[7:5]; // GP registers to the data bus
  assign gp_alu_output_select = opcode[4:2]; // GP registers to the ALU
```

```
49
50  // Signals from the state machine
51  assign ir_load_high = (state === `S_FETCH_1);
52  assign ir_load_low = (state === `S_FETCH_2);
53  // Read into the registers if we have a store, a copy, or are loading an
        immediate into a register
54  assign gp_read = (state === `S_STORE_RESULT_1 || state === `S_STORE_RESULT_2
        ||
55                    state === `S_COPY_REGISTER || state === `S_FETCH_MEMORY ||
56                    (state === `S_FETCH_IMMEDIATE && opcode[15:11] === `LOAD))
                          ;
57  // Write from the registers if we have a register ALU operation or a store
58  assign gp_write = ((state === `S_ALU_OPERATION && opcode[10:9] === 2'b00) ||
59                     state === `S_STORE_MEMORY || state === `S_COPY_REGISTER);
60  // Jump only if the code from the ALU tells us to
61  assign pc_set = (state === `S_EXECUTE_JUMP &&
62                  (opcode[1:0] === 2'b00 ||
63                  (opcode[1:0] === 2'b01 && alu_flags[`CARRYFLAG] == 1'b1) ||
64                  (opcode[1:0] === 2'b10 && alu_flags[`ZEROFLAG] == 1'b1) ||
65                  (opcode[1:0] === 2'b11 && alu_flags[`NEGFLAG] == 1'b1)));
66
67  assign pc_increment = (state === `S_FETCH_1 || state === `S_FETCH_2 ||
68                         state === `S_FETCH_IMMEDIATE || state ===
                               `S_ALU_IMMEDIATE ||
69                         state === `S_FETCH_ADDRESS_1 || state ===
                               `S_FETCH_ADDRESS_2 ||
70                         state === `S_FETCH_ADDRESS_3 || state ===
                               `S_FETCH_ADDRESS_4 ||
71                         state === `S_LOAD_JUMP_1 || state === `S_LOAD_JUMP_2)
                              ;
72  assign mem_read = (state === `S_FETCH_1 || state === `S_FETCH_2 ||
73                     state === `S_FETCH_IMMEDIATE || state ===
                           `S_ALU_IMMEDIATE ||
74                     state === `S_FETCH_ADDRESS_1 || state ===
                           `S_FETCH_ADDRESS_2 ||
75                     state === `S_FETCH_MEMORY || state === `S_TEMP_FETCH ||
76                     state === `S_FETCH_ADDRESS_3 || state ===
                           `S_FETCH_ADDRESS_4 ||
77                     state === `S_LOAD_JUMP_1 || state === `S_LOAD_JUMP_2);
78
79  assign mem_write = (state === `S_STORE_MEMORY || state === `S_TEMP_STORE);
80  assign latch_alu = (state === `S_ALU_OPERATION || state === `S_ALU_IMMEDIATE
        ||
81                      state === `S_TEMP_FETCH);
82  // On store 1, store the lower half, unless there is a multiply.
83  assign alu_store_high = (state === `S_STORE_RESULT_1 && opcode[15:11] ===
        `MULTIPLY);
84  assign alu_store_low = ((state === `S_STORE_RESULT_1 && opcode[15:11] !==
        `MULTIPLY) ||
85                          state === `S_STORE_RESULT_2 || state ===
                                `S_TEMP_STORE);
86  assign jr_load_high = (state === `S_LOAD_JUMP_1);
87  assign jr_load_low = (state === `S_LOAD_JUMP_2);
```

```
88    assign mar_load_high = (state === `S_FETCH_ADDRESS_1 || state ===
          `S_FETCH_ADDRESS_3);
89    assign mar_load_low = (state === `S_FETCH_ADDRESS_2 || state ===
          `S_FETCH_ADDRESS_4);
90
91
92  endmodule
```

A.12 CPU

```
1   /* cpu.v  Top level module for IC design project
2    * Author: Steven Bell <steven.bell@student.oc.edu>
3    * Date: 5 December 2010
4    * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
5    */
6
7   module cpu(
8     input clock,
9     input reset,
10    inout[7:0] external_data_bus,
11    output[15:0] address_bus,
12    output ram_enable,
13    output rom_enable,
14    output write,
15    output write_bar,
16    output[4:0] state
17  );
18
19    // Signals from control module to datapath
20    wire pc_increment;
21    wire pc_set;
22    wire gp_read;
23    wire gp_write;
24    wire[2:0] gp_input_select;
25    wire[2:0] gp_output_select;
26    wire[2:0] gp_alu_output_select;
27    wire[3:0] alu_operation;
28    wire latch_alu;
29    wire alu_store_high;
30    wire alu_store_low;
31    wire mar_set_high;
32    wire mar_set_low;
33    wire ir_set_high;
34    wire ir_set_low;
35    wire jr_set_high;
36    wire jr_set_low;
37
38    // Signals from datapath to control module
39    wire[15:0] ir_value; // Instruction register
40    wire[2:0] alu_flags;
41
42    // Other signals from datapath
43    wire[15:0] pc_count;
44    wire[15:0] mar_value;
```

```
45  wire[7:0] data_bus; // Internal data bus
46
47  //wire[4:0] state;
48  wire[15:0] address_mux_out;
49
50  datapath dp(.clock(clock),
51              .reset(reset),
52              .pc_increment(pc_increment),
53              .pc_set(pc_set),
54              .gp_read(gp_read),
55              .gp_write(gp_write),
56              .gp_input_select(gp_input_select),
57              .gp_output_select(gp_output_select),
58              .gp_alu_output_select(gp_alu_output_select),
59              .alu_operation(alu_operation),
60              .latch_alu(latch_alu),
61              .alu_store_high(alu_store_high),
62              .alu_store_low(alu_store_low),
63              .mar_set_high(mar_set_high),
64              .mar_set_low(mar_set_low),
65              .ir_set_high(ir_set_high),
66              .ir_set_low(ir_set_low),
67              .jr_set_high(jr_set_high),
68              .jr_set_low(jr_set_low),
69              .pc_count(pc_count),
70              .mar_value(mar_value),
71              .ir_value(ir_value),
72              .flags(alu_flags),
73              .data_bus(data_bus));
74
75  control cm(.clock(clock),
76             .reset(reset),
77             .instruction(ir_value),
78             .state(state));
79
80  control_signals cs(.state(state),
81                     .opcode(ir_value),
82                     .alu_flags(alu_flags),
83                     .ir_load_high(ir_set_high),
84                     .ir_load_low(ir_set_low),
85                     .gp_read(gp_read),
86                     .gp_write(gp_write),
87                     .pc_set(pc_set),
88                     .pc_increment(pc_increment),
89                     .mem_read(mem_read),
90                     .mem_write(mem_write),
91                     .latch_alu(latch_alu),
92                     .alu_store_high(alu_store_high),
93                     .alu_store_low(alu_store_low),
94                     .jr_load_high(jr_set_high),
95                     .jr_load_low(jr_set_low),
96                     .mar_load_high(mar_set_high),
97                     .mar_load_low(mar_set_low),
98                     .alu_operation(alu_operation),
```

```
99                      .gp_input_select(gp_input_select),
100                     .gp_output_select(gp_output_select),
101                     .gp_alu_output_select(gp_alu_output_select));
102
103   address_mux am(.pc_value(pc_count),
104                  .mar_value(mar_value),
105                  .state(state),
106                  .address_bus(address_mux_out));
107
108
109   memio mem(.read_memory(mem_read),
110             .write_memory(mem_write),
111             .internal_data_path(data_bus),
112             .external_data_path(external_data_bus),
113             .address_in(address_mux_out),
114             .address_out(address_bus),
115             .ram_enable(ram_enable),
116             .rom_enable(rom_enable),
117                         .write(write),
118                         .write_bar(write_bar));
119
120 endmodule
```

B Verilog testbench code

B.1 Generic 16-bit register

```
1  // register_16bit_test.abv
2  // ABEL test vector file for register_16_bit.v
3  // Author: Steven Bell <steven.bell@student.oc.edu>
4  // Date: 16 September 2010
5  // $LastChangedDate: 2010-09-23 08:44:58 -0500 (Thu, 23 Sep 2010) $
6
7  MODULE register_16bit
8
9  // Inputs
10     clock pin;
11     reset pin;
12     setHigh pin;
13     setLow pin;
14     instructionByteIn_7_ pin;
15     instructionByteIn_6_ pin;
16     instructionByteIn_5_ pin;
17     instructionByteIn_4_ pin;
18     instructionByteIn_3_ pin;
19     instructionByteIn_2_ pin;
20     instructionByteIn_1_ pin;
21     instructionByteIn_0_ pin;
22
23
24 // Outputs
25     instructionOut_15_ pin;
26     instructionOut_14_ pin;
27     instructionOut_13_ pin;
28     instructionOut_12_ pin;
29     instructionOut_11_ pin;
30     instructionOut_10_ pin;
31     instructionOut_9_ pin;
32     instructionOut_8_ pin;
33     instructionOut_7_ pin;
34     instructionOut_6_ pin;
35     instructionOut_5_ pin;
36     instructionOut_4_ pin;
37     instructionOut_3_ pin;
38     instructionOut_2_ pin;
39     instructionOut_1_ pin;
40     instructionOut_0_ pin;
41
42 // Buses
43     instructionByteIn = [instructionByteIn_7_,instructionByteIn_6_,
           instructionByteIn_5_,instructionByteIn_4_,instructionByteIn_3_,
           instructionByteIn_2_,instructionByteIn_1_,instructionByteIn_0_];
44     instructionOut = [instructionOut_15_,instructionOut_14_,instructionOut_13_
           ,instructionOut_12_,instructionOut_11_,instructionOut_10_,
           instructionOut_9_,instructionOut_8_,instructionOut_7_,
           instructionOut_6_,instructionOut_5_,instructionOut_4_,
           instructionOut_3_,instructionOut_2_,instructionOut_1_,
```

```
        instructionOut_0_];
45
46      u = .u.; // Rising edge
47      d = .d.; // Falling edge
48      x = .x.; // Don't care
49
50  Test_vectors
51  ([clock,reset,setHigh,setLow,instructionByteIn] -> [instructionOut])
52    [u, 0, 0, 0, ^hde] -> [^h0000]; // Reset
53    [u, 1, 1, 0, ^hde] -> [^hde00]; // Set high
54    [u, 1, 0, 1, ^had] -> [^hdead]; // Set low
55    [u, 0, 1, 0, ^hfa] -> [^h0000]; // Reset while setting high; reset should
        take precedence
56    [u, 1, 1, 1, ^hfa] -> [^hfa00]; // Set both high and low; high should should
        take precedence, low will not be set
57    [u, 1, 0, 1, ^hce] -> [^hface]; // Set low
58  END
```

B.2 Program counter

```
1  /* program_counter_test.v
2   * Verilog testbench for program_counter.v
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 11 September 2010
5   * $LastChangedDate: 2010-11-23 09:34:58 -0600 (Tue, 23 Nov 2010) $
6   */
7
8  // Expected clock frequency is ~10 MHz = 100ns
9  // Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
10 `timescale 1 ns / 10 ps
11
12 module program_counter_test();
13
14   reg reset = 1'b1; // Active low reset for the part
15   reg increment = 1'b0;
16   reg set = 1'b0; // Set the count from the external source
17   reg[15:0] counterIn = 16'hfffe; // Input value to the counter
18   wire[15:0] counterOut; // Counter output for accessing memory
19
20   // Clock
21   reg clock = 1'b0;
22   always #50 clock = !clock; // 100 time ticks per cycle = 10 MHz clock
23
24   program_counter pc_dut(clock, reset, increment, set, counterIn, counterOut);
25
26   // Test
27   initial begin
28     // Reset
29     @(negedge clock) begin
30       reset = 1'b0;
31     end
32     checkCount(16'b0, __LINE__);
33
34     // Check that counter doesn't increment without the signal being asserted
```

```
35      @(negedge clock) begin
36        reset = 1'b1;
37      end
38      checkCount(16'b0, __LINE__);
39
40      // Load a value
41      @(negedge clock) begin
42        set = 1'b1;
43      end
44      checkCount(16'hfffe, __LINE__);
45
46      // Load a value while incrementing, the new value should take precendence
47      @(negedge clock) begin
48        set = 1'b1;
49        increment = 1'b1;
50      end
51      checkCount(16'hfffe, __LINE__);
52
53      // Increment
54      @(negedge clock) begin
55        set = 1'b0;
56        increment = 1'b1;
57      end
58      checkCount(16'hffff, __LINE__);
59
60      // Test rollover
61      @(negedge clock) begin
62        increment = 1'b1;
63      end
64      checkCount(16'h0000, __LINE__);
65
66      $finish;
67    end
68
69
70    // Waveform log file and monitoring
71    initial begin
72      $dumpfile("program_counter.vcd");
73      $dumpvars();
74      //$monitor("time: %d, value: %h", $time, counterOut);
75    end
76
77    task checkCount(input[15:0] expected, input integer lineNum);
78    begin
79      @(posedge clock) #5 begin
80        if(counterOut === expected) begin
81          $display("%3d - Test passed", lineNum);
82        end
83        else begin
84          $display("%3d - Test failed, expected %h, got %h", lineNum, expected,
              counterOut);
85        end
86      end
87    end
```

```
88    endtask
89
90  endmodule
```

B.3 ALU

```
1   /* alu_test.v
2    * Testbench for the arithmetic logic unit
3    * Author: Steven Bell <steven.bell@student.oc.edu>
4    * Date: 30 September 2010
5    * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
6    */
7
8   // Expected clock frequency is ~10 MHz = 100ns
9   // Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
10  `timescale 1 ns / 10 ps
11
12  module alu_test();
13
14    reg reset = 1;
15    reg[7:0] registerParam; // Parameter from the general purpose registers (
          primary)
16    reg[7:0] databusParam; // Parameter from the data bus (secondary)
17    reg[3:0] operation; // Operation to perform
18    wire[15:0] result; // ALU result
19    wire[2:0] flags;
20
21    // Clock
22    reg clock = 0;
23    always #50 clock = !clock; //100 time ticks per cycle = 10 MHz clock
24
25    // DUT
26    alu aluDUT(clock, reset, registerParam, databusParam, operation, result,
          flags);
27
28    // Waveform file and monitoring
29    initial begin
30      $dumpfile("alu.vcd");
31      $dumpvars; // Dump everything
32      //$monitor("%d + %d = %d  ", registerParam, databusParam, result);
33    end
34
35
36    initial begin
37      perform_reset();
38      // Test PASSTHROUGH
39      // Passthrough uses the secondary input (data bus) rather than the primary
            (GP registers)
40      test_operation(8'd0, 8'd2, `ALU_PASSTHROUGH, 8'd2, 3'b000, __LINE__); // "
          Normal" passthrough
41      test_operation(8'd1, 8'd0, `ALU_PASSTHROUGH, 8'd0, 3'b100, __LINE__); //
          Test zero
42      test_operation(8'd0, -8'd1, `ALU_PASSTHROUGH, -8'd1, 3'b001, __LINE__); //
            Test negative
```

```
43
44      // Test ADD
45      test_operation(8'd1, 8'd2, `ALU_ADD, 8'd3, 3'b000, __LINE__); // Normal
            add
46      test_operation(8'd255, 8'd2, `ALU_ADD, 8'd1, 3'b010, __LINE__); // Test
            carry
47      test_operation(8'd125, 8'd10, `ALU_ADD, 8'd135, 3'b001, __LINE__); // Test
             negative
48      test_operation(-8'd15, 8'd10, `ALU_ADD, -8'd5, 3'b001, __LINE__); // Test
            negative another way
49      test_operation(8'd250, 8'd6, `ALU_ADD, 8'd0, 3'b110, __LINE__); // Test
            carry and zero
50
51      // Test SUBTRACT
52      // Note that the subtraction of a negative number causes a borrow because
            of the sign bit. This
53      // is not exactly the desired behavior, but it is the simplest logically
            consistent behavior.
54      test_operation(8'd10, 8'd6, `ALU_SUBTRACT, 8'd4, 3'b000, __LINE__); //
            Normal subtract
55      test_operation(8'd10, 8'd10, `ALU_SUBTRACT, 8'd0, 3'b100, __LINE__); //
            Test zero
56      test_operation(8'd10, 8'd15, `ALU_SUBTRACT, -8'd5, 3'b011, __LINE__); //
            Test borrow and negative
57      test_operation(8'd2, -8'd6, `ALU_SUBTRACT, 8'd8, 3'b010, __LINE__); //
            Subtraction of negative number
58      test_operation(-8'd128, 8'd1, `ALU_SUBTRACT, 8'd127, 3'b000, __LINE__); //
             Test underflow (no borrow)
59
60      // Test MULTIPLY
61      test_operation16(8'd10, 8'd6, `ALU_MULTIPLY, 16'd60, 3'b000, __LINE__); //
             Small multiply
62      test_operation16(8'd100, 8'd60, `ALU_MULTIPLY, 16'd6000, 3'b000, __LINE__)
            ; // Large multiply
63      test_operation16(-8'd1, -8'd1, `ALU_MULTIPLY, 16'd1, 3'b000, __LINE__); //
             Huge multiply
64      test_operation16(-8'd10, 8'd6, `ALU_MULTIPLY, -16'd60, 3'b000, __LINE__);
            // Normal multiply
65      // BUG: Signed multiplication doesn't work exactly as I expect, due to the
             input values having only
66      // 8 bits but producing a 16-bit result.
67
68      // Test AND
69      test_operation(8'b10101010, 8'b01100110, `ALU_AND, 8'b00100010, 3'b000,
            __LINE__); // Normal AND
70      test_operation(8'b10101010, 8'b01010101, `ALU_AND, 8'b00000000, 3'b100,
            __LINE__); // Test zero
71      test_operation(8'b10101010, 8'b11100110, `ALU_AND, 8'b10100010, 3'b001,
            __LINE__); // Test negative
72
73      // Test OR
74      test_operation(8'b00101010, 8'b01100110, `ALU_OR, 8'b01101110, 3'b000,
            __LINE__); // Normal OR
```

```
75      test_operation(8'b10101010, 8'b01100110, `ALU_OR, 8'b11101110, 3'b001,
            __LINE__); // Test negative
76      test_operation(8'b00000000, 8'b00000000, `ALU_OR, 8'b00000000, 3'b100,
            __LINE__); // Test zero
77
78      // Test LOGICAL_SHIFT_RIGHT
79      test_operation(8'b10101010, 8'b11111111, `ALU_LOGICAL_SHIFT_RIGHT, 8'
            b01010101, 3'b000, __LINE__); // Shift out a 0
80      test_operation(8'b10101011, 8'b11111111, `ALU_LOGICAL_SHIFT_RIGHT, 8'
            b01010101, 3'b010, __LINE__); // Shift out a 1
81      test_operation(8'b00000000, 8'b11111111, `ALU_LOGICAL_SHIFT_RIGHT, 8'
            b00000000, 3'b100, __LINE__); // Test zero
82
83      // Test LOGICAL_SHIFT_LEFT
84      test_operation(8'b00101010, 8'b11111111, `ALU_LOGICAL_SHIFT_LEFT, 8'
            b01010100, 3'b000, __LINE__); // Shift out a 0
85      test_operation(8'b10101010, 8'b11111111, `ALU_LOGICAL_SHIFT_LEFT, 8'
            b01010100, 3'b010, __LINE__); // Shift out a 1
86      test_operation(8'b00000000, 8'b11111111, `ALU_LOGICAL_SHIFT_LEFT, 8'
            b00000000, 3'b100, __LINE__); // Test zero
87      test_operation(8'b11000000, 8'b11111111, `ALU_LOGICAL_SHIFT_LEFT, 8'
            b10000000, 3'b011, __LINE__); // Test carry and negative
88
89      // Test ARITH_SHIFT_RIGHT
90      test_operation(8'b00101010, 8'b11111111, `ALU_ARITH_SHIFT_RIGHT, 8'
            b00010101, 3'b000, __LINE__); // Shift out a 0
91      test_operation(8'b00101011, 8'b11111111, `ALU_ARITH_SHIFT_RIGHT, 8'
            b00010101, 3'b010, __LINE__); // Shift out a 1
92      test_operation(8'b00000000, 8'b11111111, `ALU_ARITH_SHIFT_RIGHT, 8'
            b00000000, 3'b100, __LINE__); // Test zero
93      test_operation(8'b10101010, 8'b11111111, `ALU_ARITH_SHIFT_RIGHT, 8'
            b11010101, 3'b001, __LINE__); // Test sign bit shift
94      // BUG: The test above fails - apparently Verilog only does an arithmetic
            shift if the value is signed
95      // so it seems to just be doing a logical shift.  I could hack an
            arithmetic shift, or maybe there is
96      // a way to treat the input as a signed value?
97
98      // Test ARITH_SHIFT_LEFT
99      test_operation(8'b00101010, 8'b11111111, `ALU_ARITH_SHIFT_LEFT, 8'
            b01010100, 3'b000, __LINE__); // Shift out a 0
100     test_operation(8'b10101010, 8'b11111111, `ALU_ARITH_SHIFT_LEFT, 8'
            b01010100, 3'b010, __LINE__); // Shift out a 1
101     test_operation(8'b01101010, 8'b11111111, `ALU_ARITH_SHIFT_LEFT, 8'
            b11010100, 3'b001, __LINE__); // Test overflow
102     test_operation(8'b00000000, 8'b11111111, `ALU_ARITH_SHIFT_LEFT, 8'
            b00000000, 3'b100, __LINE__); // Test zero
103
104     // Test TWOS_COMPLEMENT
105     test_operation(8'b00000001, 8'b11111111, `ALU_TWOS_COMPLEMENT, 8'b11111111
            , 3'b001, __LINE__); // 1 -> -1
106     test_operation(8'b10000000, 8'b11111111, `ALU_TWOS_COMPLEMENT, 8'b10000000
            , 3'b001, __LINE__); // 128 -> -128
```

```
107     test_operation(8'd50, 8'b11111111, `ALU_TWOS_COMPLEMENT, -8'd50, 3'b001,
            __LINE__); // 50 -> -50
108     test_operation(-8'd50, 8'b11111111, `ALU_TWOS_COMPLEMENT, 8'd50, 3'b000,
            __LINE__); // -50 -> 50
109     test_operation(8'd0, 8'b11111111, `ALU_TWOS_COMPLEMENT, 8'd0, 3'b100,
            __LINE__); // 50 -> -50
110
111     // Test COMPLEMENT
112     test_operation(8'b10000001, 8'b11111111, `ALU_COMPLEMENT, 8'b01111110, 3'
            b000, __LINE__); // Test positive
113     test_operation(8'b00000001, 8'b11111111, `ALU_COMPLEMENT, 8'b11111110, 3'
            b001, __LINE__); // Test negative
114     test_operation(8'b11111111, 8'b11111111, `ALU_COMPLEMENT, 8'b00000000, 3'
            b100, __LINE__); // Test zero
115
116
117     @(negedge clock) begin
118       $finish;
119     end
120   end
121
122 /* Cycles the reset input to the ALU to put it into a known state.
123  * Takes no parameters. */
124 task perform_reset();
125   begin
126     @(negedge clock) begin
127       reset = 0;
128     end
129     @(negedge clock) begin
130       reset = 1;
131     end
132   end
133 endtask
134
135
136 /* Performs an ALU operation giving an 8 bit result and determines whether the
137  * result and flags match the expected results and flags.
138  *
139  * tParam1 - First operand for the ALU; typically from the general purpose
        registers
140  * tParam2 - Second operand for the ALU; typically from the data bus
141  * tOperation - Operation to perform on the two operands
142  * tExpectedValue - Expected result of the operation
143  * tExpectedFlags - Expected zero, carry, and negative flags from the
        operation
144  * lineNum - Line number the test is on.  This should generally be a
        preprocessor macro.
145  */
146 task test_operation(input[7:0] tParam1, input[7:0] tParam2, input[3:0]
      tOperation,
147                     input[7:0] tExpectedValue, input[2:0] tExpectedFlags,
                            input integer lineNum);
148   begin
149     @(negedge clock) begin // Wait for falling edge
```

```
150       registerParam = tParam1; // Set the inputs
151       databusParam = tParam2;
152       operation = tOperation; // Select the operation
153     end
154     @(posedge clock) begin // Wait for rising edge, and delay so the values
            are stable
155       #5;
156       if(result[7:0] != tExpectedValue) begin // Check the outputs
157         $display("%3d␣-␣Test␣failed!␣Expected␣result␣%d,␣got␣%d", lineNum,
              tExpectedValue, result[7:0]);
158       end
159       else if(flags != tExpectedFlags) begin
160         $display("%3d␣-␣Test␣failed!␣Expected␣flags␣%b,␣got␣%b", lineNum,
              tExpectedFlags, flags);
161       end
162       else begin
163         $display("%3d␣-␣Test␣passed", lineNum);
164       end
165     end // @(posedge clock)
166   end // task
167 endtask
168
169
170 /* Performs an ALU operation giving a 16-bit result and determines whether the
171  * result and flags match the expected results and flags.
172  *
173  * tParam1 - First operand for the ALU; typically from the general purpose
        registers
174  * tParam2 - Second operand for the ALU; typically from the data bus
175  * tOperation - Operation to perform on the two operands
176  * tExpectedValue - Expected result of the operation
177  * tExpectedFlags - Expected zero, carry, and negative flags from the
        operation
178  * lineNum - Line number the test is on.  This should generally be a
        preprocessor macro.
179  */
180 task test_operation16(input[7:0] tParam1, input[7:0] tParam2, input[3:0]
       tOperation,
181                       input[15:0] tExpectedValue, input[2:0] tExpectedFlags,
                            input integer lineNum);
182   begin
183     @(negedge clock) begin // Wait for falling edge
184       registerParam = tParam1; // Set the inputs
185       databusParam = tParam2;
186       operation = tOperation; // Select the operation
187     end
188     @(posedge clock) begin // Wait for rising edge, and delay so the values
            are stable
189       #5;
190       if(result[15:0] != tExpectedValue) begin // Check the outputs
191         $display("%3d␣-␣Test␣failed!␣Expected␣result␣%d,␣got␣%d", lineNum,
              tExpectedValue, result[7:0]);
192       end
193       else if(flags != tExpectedFlags) begin
```

```
194         $display("%3d - Test failed! Expected flags %b, got %b", lineNum,
               tExpectedFlags, flags);
195       end
196       else begin
197         $display("%3d - Test passed", lineNum);
198       end
199     end
200   // Print the result
201   end
202 endtask
203
204
205 endmodule
```

B.4 ALU latch

```
1  /* alu_latch_test.v
2   * Testbench for the ALU latch
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 14 October 2010
5   * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
6   */
7
8  // Expected clock frequency is ~10 MHz = 100ns
9  // Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
10 `timescale 1 ns / 10 ps
11
12 module alu_latch_test();
13   reg reset = 1;
14   reg[15:0] alu_result;
15   reg grab;
16   reg store_high;
17   reg store_low;
18   wire[7:0] databus; // Output of ALU latch goes to data bus (for now)
19
20   // Clock
21   reg clock = 0;
22   always #50 clock = ~clock; // 100 time ticks per cycle = 10 MHz clock
23
24   // DUT
25   alu_latch latchDUT(.clock(clock),
26                      .reset(reset),
27                      .alu_result(alu_result),
28                      .grab(grab),
29                      .store_high(store_high),
30                      .store_low(store_low),
31                      .out(databus));
32
33   // Monitoring and dumpfile
34   initial begin
35     $dumpfile("alu_latch.vcd");
36     $dumpvars; // Dump everything
37   end
38
```

```
39   // Beginning of test
40   initial begin
41     @(negedge clock) begin
42       reset = 0;
43     end
44     @(negedge clock) begin
45       reset = 1;
46     end
47
48     //      input     grab  high  low   expected
49     do_test(16'hbeef, 1'b1, 1'b0, 1'b0, 8'hzz, __LINE__); // Latch a value,
          but don't put it out
50     do_test(16'hdead, 1'b0, 1'b1, 1'b0, 8'hbe, __LINE__); // Hold the value
          and put the high half out
51     do_test(16'hdead, 1'b0, 1'b0, 1'b1, 8'hef, __LINE__); // Hold the value
          and put the low half out
52     do_test(16'hface, 1'b1, 1'b0, 1'b1, 8'hce, __LINE__); // Load a new value
          and put it's low half out
53
54     $finish; // End the simulation
55   end
56
57   task do_test(input[15:0] r, input g, input h, input l, input[7:0] expected,
        input integer line);
58   begin
59     @(negedge clock) begin
60       alu_result = r;
61       grab = g;
62       store_high = h;
63       store_low = l;
64     end
65     @(posedge clock) begin
66       #5; // Wait for the bits to flip, then check them
67       if(databus === expected) begin
68         $display("%3d - Test passed", line);
69       end
70       else begin
71         $display("%3d - Test failed!  Expected %h, got %h", line, expected,
              databus);
72       end
73     end
74   end
75   endtask
76
77
78 endmodule
```

B.5 General-purpose register block

```
1  /* gp_registers_test.v
2   * Testbench for the general purpose register set.
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 23 September 2010
5   * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
```

```
 */

// Expected clock frequency is ~10 MHz = 100ns
// Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
`timescale 1 ns / 10 ps

module gp_registers_test;

  reg reset;
  reg read_data; // save data to register
  reg write_data; // write data from register
  reg[2:0] input_select; // Register to put the input value into
  reg[2:0] output_select; // Index of the register we want to put on the data bus output
  reg[2:0] alu_output_select; // Index of the register we want to put on the ALU output

  wire[7:0] data_bus; // Contains the input value to store, or the ouput we write
  wire[7:0] alu_output_value; // Output bus to the ALU

  // Data bus
  reg[7:0] data_bus_driver; // Simulation of another device driving the data bus
  reg data_bus_driven; // Whether or not something else is driving the data bus
  assign data_bus = data_bus_driven ? data_bus_driver : 8'hzz;

  // Test variables
  parameter NUM_REGISTERS = 8; // Number of registers we have
  integer regidx; // Used to cycle through the registers

  // Clock
  reg clock = 0;
  always #50 clock = !clock; //100 time ticks per cycle = 10 MHz clock

  // DUT
  gp_registers registers(clock, reset, read_data, write_data,
                         input_select, output_select, alu_output_select,
                         data_bus, alu_output_value);

  // Waveform log file
  initial begin
    $dumpfile("gp_registers.vcd");
    $dumpvars; // Dump everything
    //$monitor("time: %5d, clock: %d, reset: %d ", $time, clock, reset);
  end

  // Test code
  initial begin
    // Reset the registers
    @(negedge clock)
      reset = 0;
    @(negedge clock)
```

```
55        reset = 1;
56
57
58      // Iterate through the registers and check that they were reset
59      for(regidx = 0; regidx < NUM_REGISTERS; regidx = regidx + 1) begin
60        // On the negative edge of the clock, request the value out both ports
61        @(negedge clock) begin
62          write_data = 1'b1; // The registers will be writing data out to the
                bus
63          read_data = 1'b0;
64          output_select = regidx;
65          alu_output_select = regidx;
66        end
67        // On the positive edge, read the output and check it
68        @(posedge clock) begin
69          #30; // Wait for the value to change - is there a better way?
70          if(data_bus != 8'h00 || alu_output_value != 8'h00) begin
71            $display("Register␣%d␣not␣reset!␣Value␣is␣%d/%d", regidx, data_bus,
                  alu_output_value);
72          end // if
73        end // posedge clock
74      end // checking reset
75
76
77      // Iterate throught the registers and assign values that we will read
          later
78      for(regidx = 0; regidx < NUM_REGISTERS; regidx = regidx + 1) begin
79        // On the negative edge of the clock, set up the inputs
80        @(negedge clock) begin
81          write_data = 1'b0;
82          read_data = 1'b1; // The registers will now be reading data in
83          data_bus_driven = 1'b1; // And we will be driving the data bus
84          data_bus_driver = regidx + 10; // Store a unique nonzero value for
                each register
85          input_select = regidx;
86          output_select = (regidx + 1) % NUM_REGISTERS; // Read out a different
                register than
87          alu_output_select = (regidx + 1) % NUM_REGISTERS; // the one we are
                writing to
88        end
89        // On the positive edge, read the output and check it
90        @(posedge clock) begin
91          #30; // Wait for the value to change - is there a better way?
92          // BUG: This will fail on the last loop
93          //if(data_bus != 8'hzz || alu_output_value != 8'h00) begin
94          //  $display("Register %d not writing properly! Output is %d/%d",
                regidx, data_bus, alu_output_value);
95          //end // if
96        end // posedge clock
97      end // assigning test values
98
99
100     // Iterate through the registers and check that we cna read the test
          values out again
```

```
101     for(regidx = 0; regidx < NUM_REGISTERS; regidx = regidx + 1) begin
102       // On the negative edge of the clock, request the value out both ports
103       @(negedge clock) begin
104         write_data = 1'b1; // The registers will be writing data out to the
                bus
105         read_data = 1'b0;
106         data_bus_driven = 1'b0; // The registers will be driving the bus
107         output_select = regidx;
108         alu_output_select = regidx;
109       end
110       // On the positive edge, read the output and check it
111       @(posedge clock) begin
112         #30; // Wait for the value to change - is there a better way?
113         if(data_bus != regidx + 10 || alu_output_value != regidx + 10) begin
114           $display("Register␣%d␣failed!␣Expected␣%d,␣got␣%d␣and␣%d", regidx,
                regidx + 10, data_bus, alu_output_value);
115         end // if
116       end // posedge clock
117     end // checking reset
118
119     @(negedge clock)
120       $finish;
121
122   end
123
124 endmodule
```

B.6 Datapath

```
1  /* datapath_test.v
2   * Testbench for the arithmetic logic unit
3   * Author: Steven Bell <steven.bell@student.oc.edu>
4   * Date: 6 October 2010
5   * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
6   */
7
8  // Expected clock frequency is ~10 MHz = 100ns
9  // Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
10 `timescale 1 ns / 10 ps
11
12 `include "constants.v"
13
14 module datapath_test();
15
16   parameter NAME_LEN = 239; // Length of the string in bytes, minus one (30 *
         8 - 1)
17
18   reg reset;
19   reg gp_read;
20   reg gp_write;
21   reg pc_increment;
22   reg pc_set;
23   reg[2:0] gp_input_select;
24   reg[2:0] gp_output_select;
```

```
25  reg[2:0] gp_alu_output_select;
26  reg[3:0] alu_operation;
27  reg latch_alu;
28  reg alu_store_high;
29  reg alu_store_low;
30  reg mar_set_high;
31  reg mar_set_low;
32  reg ir_set_high;
33  reg ir_set_low;
34  reg jr_set_high;
35  reg jr_set_low;
36
37  wire[15:0] pc_count; // Program counter output
38  wire[15:0] mar_value; // Memory address register output
39  wire[15:0] ir_value; // Instruction register output
40  wire[2:0] alu_flags; // ALU flags
41
42  /* Data bus
43   * Because the data bus is a bidirectional port, we can't treat it as a wire
44   * (which must have continuous assignment) or a reg (which can't be
        continuously
45   * assigned).  We have to create a reg which holds the value, and then use
        an
46   * assign statement to pick what we want. */
47  reg[7:0] data_bus_driver; // Holds the value we want to put onto the bus
48  reg data_bus_input; // When true, the data bus reads from data_bus_driver,
       when false, it's an output
49  wire[7:0] data_bus; // Wire connected to the DUT
50
51  assign data_bus = data_bus_input ? data_bus_driver : 8'hzz;
52
53  // Testbench variables
54  integer regIdx; // Index variable for the general purpose registers
55  reg[NAME_LEN:0] testName; // Holds the printed name for some tests
56
57  // Clock
58  reg clock = 0;
59  always #50 clock = !clock; // 100 time ticks per cycle = 10 MHz clock
60
61  // DUT
62  datapath dp(
63              .clock(clock),
64              .reset(reset),
65              .pc_increment(pc_increment),
66              .pc_set(pc_set),
67              .gp_read(gp_read),
68              .gp_write(gp_write),
69              .gp_input_select(gp_input_select),
70              .gp_output_select(gp_output_select),
71              .gp_alu_output_select(gp_alu_output_select),
72              .alu_operation(alu_operation),
73              .latch_alu(latch_alu),
74              .alu_store_high(alu_store_high),
75              .alu_store_low(alu_store_low),
```

```
76                .mar_set_high(mar_set_high),
77                .mar_set_low(mar_set_low),
78                .ir_set_high(ir_set_high),
79                .ir_set_low(ir_set_low),
80                .jr_set_high(jr_set_high),
81                .jr_set_low(jr_set_low),
82                .pc_count(pc_count),
83                .mar_value(mar_value),
84                .ir_value(ir_value),
85                .flags(alu_flags),
86                .data_bus(data_bus));
87
88  // Waveform log file and monitoring
89  initial begin
90    $dumpfile("datapath.vcd");
91    $dumpvars;
92    $monitor();
93  end
94
95  // Beginning of the test
96  initial begin
97    // Reset
98    @(negedge clock)
99    resetSignals();
100   reset = 1'b0;
101   @(posedge clock) #5
102   check16("Program counter reset", pc_count, 16'b0, __LINE__);
103   check16("MAR reset", mar_value, 16'b0, __LINE__);
104   check16("Instruction register reset", ir_value, 16'b0, __LINE__);
105
106   // Load instruction register from the data bus
107   @(negedge clock)
108   resetSignals();
109   data_bus_driver = 8'hef;
110   data_bus_input = 1'b1;
111   ir_set_low = 1'b1;
112   @(posedge clock) #5
113   check16("Instruction register load low", ir_value, 16'h00ef, __LINE__);
114   @(negedge clock)
115   resetSignals();
116   data_bus_driver = 8'hbe;
117   data_bus_input = 1'b1;
118   ir_set_high = 1'b1;
119   @(posedge clock) #5
120   check16("Instruction register load high", ir_value, 16'hbeef, __LINE__);
121
122   // Load the jump register from the data bus
123   // The jump register doesn't have an output except to the program counter
124   @(negedge clock)
125     resetSignals();
126     data_bus_driver = 8'hce;
127     data_bus_input = 1'b1;
128     jr_set_low = 1'b1;
129   @(negedge clock)
```

```
130       resetSignals();
131       data_bus_driver = 8'hfa;
132       data_bus_input = 1'b1;
133       jr_set_high = 1'b1;
134     // Put the jump register value into the program counter and check it
135     @(negedge clock)
136       resetSignals();
137       pc_set = 1'b1;
138     @(posedge clock) #5
139       check16("Jump register", pc_count, 16'hface, __LINE__);
140
141     // Increment the program counter
142     @(negedge clock)
143       resetSignals();
144       pc_increment = 1'b1;
145     @(posedge clock) #5
146       check16("Program counter increment", pc_count, 16'hfacf, __LINE__);
147
148     // Load each general purpose register from the data bus
149     resetSignals();
150     for(regIdx = 0; regIdx < 8; regIdx = regIdx + 1) begin
151       @(negedge clock)
152         data_bus_driver = regIdx; // Load each register with its index
153         data_bus_input = 1'b1; // We are driving the data bus
154         gp_input_select = regIdx; // regIdx will never be more than 7, so this
              is safe
155         gp_read = 1'b1; // Read from the data bus into the register
156     end
157
158     // Put each general purpose register back on the data bus and check it
159     for(regIdx = 0; regIdx < 8; regIdx = regIdx + 1) begin
160       @(negedge clock)
161         resetSignals();
162         gp_output_select = regIdx;
163         gp_write = 1'b1;
164       @(posedge clock) #5
165         $sformat(testName, "General-purpose reg #%1d", regIdx);
166         checkDatabus(testName, regIdx, __LINE__);
167     end
168
169     // Load memory address register from the data bus
170     @(negedge clock)
171       resetSignals();
172       data_bus_driver = 8'had;
173       data_bus_input = 1'b1;
174       mar_set_low = 1'b1;
175     @(posedge clock) #5
176       check16("MAR load low", mar_value, 16'h00ad, __LINE__);
177     @(negedge clock)
178       resetSignals();
179       data_bus_driver = 8'hde;
180       data_bus_input = 1'b1;
181       mar_set_high = 1'b1;
182     @(posedge clock) #5
```

```
183       check16("MAR load high", mar_value, 16'hdead, __LINE__);
184
185     // Load memory address register from the GP registers
186     // This loads the high byte and then the low byte, to ensure that that
          works just
187     // as well as loading low and then high.
188     // This code assumes that the register values are equal to their addresses
189     @(negedge clock)
190       resetSignals();
191       gp_output_select = 3'h4;
192       gp_write = 1'b1;
193       mar_set_high = 1'b1;
194     @(negedge clock)
195       resetSignals();
196       gp_output_select = 3'h5;
197       gp_write = 1'b1;
198       mar_set_low = 1'b1;
199     @(posedge clock) #5
200       check16("MAR load from GPR", mar_value, 16'h0405, __LINE__);
201
202     // Perform 2-operand ALU operation using GP registers
203     // Add registers 5 and 6, and check that the result is 11
204     @(negedge clock)
205     resetSignals();
206     gp_alu_output_select = 3'h6; // Register 6 directly to ALU
207     gp_output_select = 3'h5; // Register 5 on data bus
208     gp_write = 1'b1;
209     alu_operation = `ALU_ADD;
210     latch_alu = 1'b1; // Latch this result so we can put it on the data bus
211     // There's no way to see the ALU output except to put it on the data bus,
212     // so that's what we do next.
213     @(negedge clock)
214     resetSignals();
215     alu_store_low = 1'b1;
216     @(posedge clock)
217     checkDatabus("ALU binary from GP", 8'd11, __LINE__);
218
219     // Perform 2-operand ALU operation using an immediate
220     // Multiply 6 by 100 and check that the result is 0x0258 (600)
221     @(negedge clock)
222     resetSignals();
223     gp_alu_output_select = 3'h6; // Register 6 directly to ALU
224     data_bus_driver = 8'd100; // Immediate value of 100
225     data_bus_input = 1'b1;
226     alu_operation = `ALU_MULTIPLY;
227     latch_alu = 1'b1; // Latch this result so we can put it on the data bus
228     @(negedge clock)
229     resetSignals();
230     alu_store_high = 1'b1;
231     @(negedge clock)
232     checkDatabus("ALU binary with immediate high", 8'h02, __LINE__);
233     @(negedge clock)
234     resetSignals();
235     alu_store_low = 1'b1;
```

```
236     @(posedge clock)
237     checkDatabus("ALU binary with immediate low", 8'h58, __LINE__);
238
239
240     // Perform 1-operand ALU operation using GP register
241     // Invert register 1 to get 0b11111110 (0xFE)
242     @(negedge clock)
243     resetSignals();
244     gp_alu_output_select = 3'h1; // Register 6 directly to ALU
245     alu_operation = `ALU_COMPLEMENT;
246     latch_alu = 1'b1; // Latch this result so we can put it on the data bus
247     @(negedge clock)
248     resetSignals();
249     alu_store_low = 1'b1;
250     @(posedge clock)
251     checkDatabus("ALU unary from GP", 8'hfe, __LINE__);
252
253     // Perform ALU passthrough
254     // Copy the value 125 into the ALU latch and write it back out to the
          databus
255     @(negedge clock)
256     resetSignals();
257     data_bus_driver = 8'd125;
258     data_bus_input = 1'b1;
259     alu_operation = `ALU_PASSTHROUGH;
260     latch_alu = 1'b1; // Latch this result so we can put it on the data bus
261     @(negedge clock)
262     resetSignals();
263     alu_store_low = 1'b1;
264     @(negedge clock)
265     checkDatabus("ALU passthrough", 8'd125, __LINE__);
266
267
268
269     @(negedge clock)
270     $finish;
271   end // End of the test
272
273   // Sets all of the signals to their inactive state.
274   task resetSignals();
275   begin
276     reset = 1;
277     data_bus_input = 1'b0;
278     pc_increment = 1'b0;
279     pc_set = 1'b0;
280     gp_read = 0;
281     gp_write = 0;
282     gp_input_select = 0;
283     gp_output_select = 0;
284     gp_alu_output_select = 0;
285     alu_operation = 0;
286     latch_alu = 1'b0;
287     alu_store_high = 1'b0;
288     alu_store_low = 1'b0;
```

```
289     mar_set_high = 0;
290     mar_set_low = 0;
291     ir_set_high = 0;
292     ir_set_low = 0;
293     jr_set_high = 0;
294     jr_set_low = 0;
295  end
296   endtask
297
298   task check16(input[NAME_LEN:0] name, input[15:0] value, input[15:0] expected
          , input integer lineNum);
299   begin
300     if(value === expected) begin
301       $display("%3d␣-␣Test␣passed␣:␣%s", lineNum, name);
302     end
303     else begin
304       $display("%3d␣-␣Test␣failed,␣expected␣%h,␣got␣%h␣:␣%s", lineNum,
              expected, value, name);
305     end
306   end
307   endtask
308
309   task checkDatabus(input [NAME_LEN:0] name, input[7:0] expected, input
          integer lineNum);
310   begin
311     if(data_bus === expected) begin
312        $display("%3d␣-␣Test␣passed␣:␣%s", lineNum, name);
313     end
314     else begin
315       $display("%3d␣-␣Test␣failed,␣expected␣%h,␣got␣%h␣:␣%s", lineNum,
              expected, data_bus, name);
316     end
317   end
318   endtask
319
320 endmodule
```

B.7 Control module state machine

```
1  /* control_test.v
2   * Testbench for the control module.  This code uses an external text file,
3   * control_vectors, which contains a series of control module states and
        opcodes
4   * where necessary.  After performing a reset, the code reads a line from the
5   * file, executes a clock cycle, and checks that the control module entered
        the
6   * specified state.
7   * This code does not check that the state vectors are outputted properly. It
        only
8   * checks that the state sequence is correct.
9   * Author: Steven Bell <steven.bell@student.oc.edu>
10  * Date: 23 November 2010
11  * $LastChangedDate: 2010-12-13 18:04:13 -0600 (Mon, 13 Dec 2010) $
12  */
```

```
13
14 // Expected clock frequency is ~10 MHz = 100ns
15 // Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
16 `timescale 1 ns / 10 ps
17
18 module control_test();
19   parameter STRING_LEN = 239; // Maximum length of the strings we read in bits
         (minus one)
20   reg reset = 1; // Reset signal for the part
21   reg[15:0] instruction_register; // Dummy instruction register which we load
        from the file
22
23   wire[4:0] control_state; // Current state of the control module
24
25   // Clock
26   reg clock = 0;
27   always #50 clock = ~clock;
28
29   // DUT
30   control controlDUT(.clock(clock),
31                      .reset(reset),
32                      .instruction(instruction_register),
33                      .state(control_state));
34
35   // Logging
36   initial begin
37     $dumpfile("control.vcd");
38     $dumpvars(); // Dump everything
39   end
40
41   // Variables for reading the file
42   integer file;
43   integer r; // Result from scanf; required by verilog spec, but not used
44   reg[STRING_LEN:0] stateString;
45   reg[7:0] opcodeByte;
46
47
48   // Beginning of test
49   initial begin
50     // Perform reset
51     @(negedge clock)
52     reset = 1'b0;
53     @(negedge clock)
54     reset = 1'b1;
55
56     // Start reading the file
57     file = $fopen("control_vectors", "r");
58
59     // Loop until we get to the end of the file
60     while(!$feof(file)) begin
61       // Read a line with a desired state
62       r = $fscanf(file, "%s", stateString);
63       while(isComment(stateString)) begin // Keep reading and printing
           comments until we get an instruction
```

```
64          $display("%s", stateString);
65          r = $fscanf(file, "%s", stateString);
66        end
67
68        // On the rising edge of the clock, the module should be in that state
69        @(posedge clock) #5
70        testOpcode(stateString, control_state);
71
72        // If the state is a fetch, then read the opcode byte from the file and
73        // set the instruction register appropriately
74        if(stateString == "FETCH_1") begin
75          r = $fscanf(file, "%2h", opcodeByte);
76          instruction_register[15:8] = opcodeByte;
77        end
78        else if(stateString == "FETCH_2") begin
79          r = $fscanf(file, "%2h", opcodeByte);
80          instruction_register[7:0] = opcodeByte;
81        end
82
83      end
84
85
86      // How do we test jumps??
87
88      // End of the test
89      $display("Test completed successfully!");
90      $finish;
91    end
92
93    /* Compares a state string (e.g, "FETCH_2") to a state number (e.g, 2) to
94     * see if they match.  If so, it prints the state string.  If not, it prints
95     * an error message and quits the simulation */
96    task testOpcode(input[20*8-1:0] string, input[4:0] state);
97      reg[4:0] desiredState; // State value determined from the string
98    begin
99
100     case(string)
101       "RESET":
102         desiredState = `S_RESET;
103       "FETCH_1":
104         desiredState = `S_FETCH_1;
105       "FETCH_2":
106         desiredState = `S_FETCH_2;
107       "ALU_OPERATION":
108         desiredState = `S_ALU_OPERATION;
109       "ALU_IMMEDIATE":
110         desiredState = `S_ALU_IMMEDIATE;
111       "STORE_RESULT_1":
112         desiredState = `S_STORE_RESULT_1;
113       "STORE_RESULT_2":
114         desiredState = `S_STORE_RESULT_2;
115       "FETCH_IMMEDIATE":
116         desiredState = `S_FETCH_IMMEDIATE;
117       "COPY_REGISTER":
```

```
118         desiredState = `S_COPY_REGISTER;
119       "FETCH_ADDRESS_1":
120         desiredState = `S_FETCH_ADDRESS_1;
121       "FETCH_ADDRESS_2":
122         desiredState = `S_FETCH_ADDRESS_2;
123       "FETCH_MEMORY":
124         desiredState = `S_FETCH_MEMORY;
125       "STORE_MEMORY":
126         desiredState = `S_STORE_MEMORY;
127       "TEMP_FETCH":
128         desiredState = `S_TEMP_FETCH;
129       "FETCH_ADDRESS_3":
130         desiredState = `S_FETCH_ADDRESS_3;
131       "FETCH_ADDRESS_4":
132         desiredState = `S_FETCH_ADDRESS_4;
133       "TEMP_STORE":
134         desiredState = `S_TEMP_STORE;
135       "LOAD_JUMP_1":
136         desiredState = `S_LOAD_JUMP_1;
137       "LOAD_JUMP_2":
138         desiredState = `S_LOAD_JUMP_2;
139       "EXECUTE_JUMP":
140         desiredState = `S_EXECUTE_JUMP;
141       "HALT":
142         desiredState = `S_HALT;
143       default:
144         desiredState = 5'b00000;
145     endcase
146
147     if(state == desiredState) begin
148       $display("%h, %s", instruction_register, string);
149     end
150     else begin
151       $display("Test failed! Expected state %s, but got %d", string, state);
152       $display("Instruction register contained %h at failure",
              instruction_register);
153       $finish; // quit the simulation
154     end
155   end
156   endtask
157
158   function isComment(input[STRING_LEN:0] str);
159   begin
160     if(str[7:0] == "#") begin
161       isComment = 1'b1;
162     end
163     else begin
164       isComment = 1'b0;
165     end
166   end
167   endfunction
168
169
170 endmodule
```

B.8 Control signals translator

```
/* control_signals_test.v  Testbench for control signals module, which
 * translates the control module state into the vector of control signals.
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 2 December 2010
 * $LastChangedDate$
 */

// Expected clock frequency is ~10 MHz = 100ns
// Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
`timescale 1 ns / 10 ps

// Need to see if there's something like C's #ifndef for headers
//`include "constants.vh"

module control_signals_test();
  // Inputs to the DUT
  reg[4:0] state;
  reg[15:0] opcode;
  reg[2:0] alu_flags;

  // Outputs from the DUT
  wire ir_load_high;
  wire ir_load_low;
  wire gp_read;
  wire gp_write;
  wire pc_set;
  wire pc_increment;
  wire mem_read;
  wire mem_write;
  wire latch_alu;
  wire alu_store_high;
  wire alu_store_low;
  wire jr_load_high;
  wire jr_load_low;
  wire mar_load_high;
  wire mar_load_low;
  wire[3:0] alu_operation;
  wire[2:0] gp_input_select;
  wire[2:0] gp_output_select;
  wire[2:0] gp_alu_output_select;

  // Variables representing the desired values for the outputs
  reg d_ir_load_high;
  reg d_ir_load_low;
  reg d_gp_primary_addr;
  reg d_gp_alu_addr;
  reg d_gp_read;
  reg d_gp_write;
  reg d_pc_set;
  reg d_pc_increment;
  reg d_mem_read;
  reg d_mem_write;
```

```
53  reg d_latch_alu;
54  reg d_alu_store_high;
55  reg d_alu_store_low;
56  reg d_jr_load_high;
57  reg d_jr_load_low;
58  reg d_mar_load_high;
59  reg d_mar_load_low;
60  reg[3:0] d_alu_operation;
61  reg[2:0] d_gp_input_select;
62  reg[2:0] d_gp_output_select;
63  reg[2:0] d_gp_alu_output_select;
64
65  // Variables for module tasks
66  reg passed = 1'b1;
67
68  // DUT
69  control_signals csDUT(.state(state),
70                        .opcode(opcode),
71                        .alu_flags(alu_flags),
72                        .ir_load_high(ir_load_high),
73                        .ir_load_low(ir_load_low),
74                        .gp_read(gp_read),
75                        .gp_write(gp_write),
76                        .pc_set(pc_set),
77                        .pc_increment(pc_increment),
78                        .mem_read(mem_read),
79                        .mem_write(mem_write),
80                        .latch_alu(latch_alu),
81                        .alu_store_high(alu_store_high),
82                        .alu_store_low(alu_store_low),
83                        .jr_load_high(jr_load_high),
84                        .jr_load_low(jr_load_low),
85                        .mar_load_high(mar_load_high),
86                        .mar_load_low(mar_load_low),
87                        .alu_operation(alu_operation),
88                        .gp_input_select(gp_input_select),
89                        .gp_output_select(gp_output_select),
90                        .gp_alu_output_select(gp_alu_output_select));
91
92  // Monitoring and dumpfile
93  initial begin
94    $dumpfile("control_signals.vcd");
95    $dumpvars; // Dump everything
96  end
97
98  // Beginning of test
99  initial begin
100   // Reset
101   state = `S_RESET;
102   opcode = 16'hbeef;
103   zeroDesired();
104
105   checkSignals(__LINE__);
106
```

```
107
108     // Fetch 1
109     state = `S_FETCH_1;
110     opcode = 16'hface;
111     zeroDesired();
112     d_ir_load_high = 1;
113     d_mem_read = 1;
114     d_pc_increment = 1;
115
116     checkSignals(__LINE__);
117
118
119     // Fetch 2
120     state = `S_FETCH_2;
121     opcode = 16'hface;
122     zeroDesired();
123     d_ir_load_low = 1;
124     d_mem_read = 1;
125     d_pc_increment = 1;
126
127     checkSignals(__LINE__);
128
129
130     // ALU operation with immediate, no write from register
131     state = `S_ALU_OPERATION;
132     opcode = 16'h0c00;
133     zeroDesired();
134     d_latch_alu = 1;
135
136     checkSignals(__LINE__);
137
138
139     // ALU operation with two registers
140     state = `S_ALU_OPERATION;
141     opcode = 16'h0800;
142     zeroDesired();
143     d_gp_write = 1;
144     d_latch_alu = 1;
145
146     checkSignals(__LINE__);
147
148
149     // Store result
150     state = `S_STORE_RESULT_1;
151     opcode = 16'h0c00;
152     zeroDesired();
153     d_gp_read = 1;
154     d_alu_store_low = 1;
155
156     checkSignals(__LINE__);
157
158
159     // Store a multiply
160     state = `S_STORE_RESULT_1;
```

```
161     opcode = 16'h1820;
162     zeroDesired();
163     d_gp_read = 1;
164     d_alu_store_high = 1;
165     checkSignals(__LINE__);
166
167     // Store the second half of the multiply
168     state = `S_STORE_RESULT_2;
169     opcode = 16'h1820;
170     zeroDesired();
171     d_gp_read = 1;
172     d_alu_store_low = 1;
173     checkSignals(__LINE__);
174
175     // Do a copy
176     state = `S_COPY_REGISTER;
177     opcode = 16'h0000;
178     zeroDesired();
179     d_gp_read = 1;
180     d_gp_write = 1;
181     checkSignals(__LINE__);
182
183     // Do an address fetch
184     state = `S_FETCH_ADDRESS_1;
185     opcode = 16'h0000;
186     zeroDesired();
187     d_pc_increment = 1;
188     d_mem_read = 1;
189     d_mar_load_high = 1;
190     checkSignals(__LINE__);
191
192     state = `S_FETCH_ADDRESS_2;
193     opcode = 16'h0000;
194     zeroDesired();
195     d_pc_increment = 1;
196     d_mem_read = 1;
197     d_mar_load_low = 1;
198     checkSignals(__LINE__);
199
200     // Memory fetch
201     state = `S_FETCH_MEMORY;
202     opcode = 16'h0000;
203     zeroDesired();
204     d_gp_read = 1;
205     d_mem_read = 1;
206     checkSignals(__LINE__);
207
208     // Memory store
209     state = `S_STORE_MEMORY;
210     opcode = 16'h0000;
211     zeroDesired();
212     d_gp_write = 1;
213     d_mem_write = 1;
214     checkSignals(__LINE__);
```

```
215
216     // Do a move starting with the temp fetch
217     state = `S_TEMP_FETCH;
218     opcode = 16'h9000;
219     zeroDesired();
220     d_latch_alu = 1;
221     d_mem_read = 1;
222     checkSignals(__LINE__);
223
224     // Continue move; get the destination address
225     state = `S_FETCH_ADDRESS_3;
226     opcode = 16'h9000;
227     zeroDesired();
228     d_pc_increment = 1;
229     d_mem_read = 1;
230     d_mar_load_high = 1;
231     checkSignals(__LINE__);
232
233     state = `S_FETCH_ADDRESS_4;
234     opcode = 16'h9000;
235     zeroDesired();
236     d_pc_increment = 1;
237     d_mem_read = 1;
238     d_mar_load_low = 1;
239     checkSignals(__LINE__);
240
241     // Do the temp store
242     state = `S_TEMP_STORE;
243     opcode = 16'h9000;
244     zeroDesired();
245     d_alu_store_low = 1;
246     d_mem_write = 1;
247     checkSignals(__LINE__);
248
249     // Load the jump register
250     state = `S_LOAD_JUMP_1;
251     opcode = 16'h7800;
252     zeroDesired();
253     d_pc_increment = 1;
254     d_mem_read = 1;
255     d_jr_load_high = 1;
256     checkSignals(__LINE__);
257
258     state = `S_LOAD_JUMP_2;
259     opcode = 16'h7800;
260     zeroDesired();
261     d_pc_increment = 1;
262     d_mem_read = 1;
263     d_jr_load_low = 1;
264     checkSignals(__LINE__);
265
266     // Test jump always
267     state = `S_EXECUTE_JUMP;
268     opcode = 16'h7800;
```

```
269     zeroDesired();
270     d_pc_set = 1;
271     checkSignals(__LINE__);
272 
273     // Test jump if carry - don't jump
274     state = `S_EXECUTE_JUMP;
275     opcode = 16'h7801;
276     alu_flags = 3'b000;
277     zeroDesired();
278     d_pc_set = 0;
279     checkSignals(__LINE__);
280 
281     // Jump if carry - do jump
282     state = `S_EXECUTE_JUMP;
283     opcode = 16'h7801;
284     alu_flags = 3'b010;
285     zeroDesired();
286     d_pc_set = 1;
287     checkSignals(__LINE__);
288 
289     // Test jump if zero - don't jump
290     state = `S_EXECUTE_JUMP;
291     opcode = 16'h7802;
292     alu_flags = 3'b000;
293     zeroDesired();
294     d_pc_set = 0;
295     checkSignals(__LINE__);
296 
297     // Jump if zero - do jump
298     state = `S_EXECUTE_JUMP;
299     opcode = 16'h7802;
300     alu_flags = 3'b100;
301     zeroDesired();
302     d_pc_set = 1;
303     checkSignals(__LINE__);
304 
305     // Test jump if negative - don't jump
306     state = `S_EXECUTE_JUMP;
307     opcode = 16'h7803;
308     alu_flags = 3'b000;
309     zeroDesired();
310     d_pc_set = 0;
311     checkSignals(__LINE__);
312 
313     // Jump if negative - do jump
314     state = `S_EXECUTE_JUMP;
315     opcode = 16'h7803;
316     alu_flags = 3'b001;
317     zeroDesired();
318     d_pc_set = 1;
319     checkSignals(__LINE__);
320 
321 
322   // Check halt
```

```
323     state = `HALT;
324     opcode = 16'hff00;
325     zeroDesired();
326     checkSignals(__LINE__);
327
328
329
330
331
332
333     $finish;
334   end
335
336   task checkSignals(input integer lineNum);
337   begin
338     #100
339     if(ir_load_high !== d_ir_load_high) begin
340       $display("%4d : IR high test failed; expected %h but got %h", lineNum,
            d_ir_load_high, ir_load_high);
341       passed = 1'b0;
342     end
343     if(ir_load_low !== d_ir_load_low) begin
344       $display("%4d : IR low test failed; expected %h but got %h", lineNum,
            d_ir_load_low, ir_load_low);
345       passed = 1'b0;
346     end
347     if(gp_read !== d_gp_read) begin
348       $display("%4d : GP read test failed; expected %h but got %h", lineNum,
            d_gp_read, gp_read);
349       passed = 1'b0;
350     end
351     if(gp_write !== d_gp_write) begin
352       $display("%4d : GP write test failed; expected %h but got %h", lineNum,
            d_gp_write, gp_write);
353       passed = 1'b0;
354     end
355     if(pc_set !== d_pc_set) begin
356       $display("%4d : PC set test failed; expected %h but got %h", lineNum,
            d_pc_set, pc_set);
357       passed = 1'b0;
358     end
359     if(pc_increment !== d_pc_increment) begin
360       $display("%4d : PC increment test failed; expected %h but got %h",
            lineNum, d_pc_increment, pc_increment);
361       passed = 1'b0;
362     end
363     if(mem_read !== d_mem_read) begin
364       $display("%4d : Memory read test failed; expected %h but got %h",
            lineNum, d_mem_read, mem_read);
365       passed = 1'b0;
366     end
367     if(mem_write !== d_mem_write) begin
368       $display("%4d : Memory write test failed; expected %h but got %h",
            lineNum, d_mem_write, mem_write);
```

```
369       passed = 1'b0;
370     end
371     if(latch_alu !== d_latch_alu) begin
372       $display("%4d : ALU latch test failed; expected %h but got %h", lineNum,
              d_latch_alu, latch_alu);
373       passed = 1'b0;
374     end
375     if(alu_store_high !== d_alu_store_high) begin
376       $display("%4d : ALU store high test failed; expected %h but got %h",
              lineNum, d_alu_store_high, alu_store_high);
377       passed = 1'b0;
378     end
379     if(alu_store_low !== d_alu_store_low) begin
380       $display("%4d : ALU store low test failed; expected %h but got %h",
              lineNum, d_alu_store_low, alu_store_low);
381       passed = 1'b0;
382     end
383     if(jr_load_high !== d_jr_load_high) begin
384       $display("%4d : JR high test failed; expected %h but got %h", lineNum,
              d_jr_load_high, jr_load_high);
385       passed = 1'b0;
386     end
387     if(ir_load_low !== d_ir_load_low) begin
388       $display("%4d : JR low test failed; expected %h but got %h", lineNum,
              d_jr_load_low, jr_load_low);
389       passed = 1'b0;
390     end
391     if(mar_load_high !== d_mar_load_high) begin
392       $display("%4d : MAR high test failed; expected %h but got %h", lineNum,
              d_mar_load_high, mar_load_high);
393       passed = 1'b0;
394     end
395     if(mar_load_low !== d_mar_load_low) begin
396       $display("%4d : MAR low test failed; expected %h but got %h", lineNum,
              d_mar_load_low, mar_load_low);
397       passed = 1'b0;
398     end
399     if(passed === 1'b1) begin
400       $display("%4d : Test passed", lineNum);
401     end
402
403
404   end
405   endtask
406
407   task zeroDesired();
408   begin
409     d_ir_load_high = 1'b0;
410     d_ir_load_low = 1'b0;
411     d_gp_primary_addr = 1'b0;
412     d_gp_alu_addr = 1'b0;
413     d_gp_read = 1'b0;
414     d_gp_write = 1'b0;
415     d_pc_set = 1'b0;
```

```
    d_pc_increment = 1'b0;
    d_mem_read = 1'b0;
    d_mem_write = 1'b0;
    d_latch_alu = 1'b0;
    d_alu_store_high = 1'b0;
    d_alu_store_low = 1'b0;
    d_jr_load_high = 1'b0;
    d_jr_load_low = 1'b0;
    d_mar_load_high = 1'b0;
    d_mar_load_low = 1'b0;
    d_alu_operation = 4'd0;
    d_gp_input_select = 3'd0;
    d_gp_output_select = 3'd0;
    d_gp_alu_output_select = 3'd0;
  end
  endtask


endmodule
```

B.9 CPU

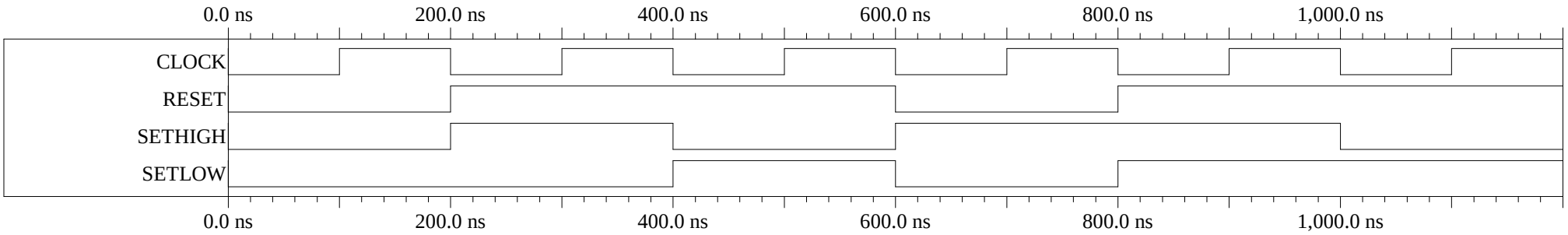
```
/* cpu_test.v  Testbench for full CPU
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 6 December 2010
 * $LastChangedDate: 2010-12-16 17:48:32 -0600 (Thu, 16 Dec 2010) $
 */

// Expected clock frequency is ~10 MHz = 100ns
// Tick freq is 1 GHz => 100 ticks is one clock cycle; resolution is 10 ps
`timescale 1 ns / 10 ps

module cpu_test();
  parameter RAM_SIZE = 16; // Size of the RAM in bytes
  parameter RAM_ADDRESS_BITS = 4; // How many address bits the RAM needs
  parameter ROM_SIZE = 1024; // Size of the ROM in bytes
  parameter ROM_ADDRESS_BITS = 10; // How many address bits the ROM needs
  parameter MAX_LINE_LENGTH = 200; // Maximum length of line in input file

  // Signals for DUT
  reg reset;
  reg[7:0] data_bus_driver; // Value from the memory to drive the bus
  reg memory_drives_bus; // True if the memory is driving the data bus
  wire[7:0] data_bus; // Bidirectional data bus
  wire[15:0] address_bus; // Address bus coming out of the chip
  wire ram_enable;
  wire rom_enable;
  wire write;

  // Variables for file processing and simulation
  integer clock_cycles; // Number of clock cycles we've stepped through
  reg[7:0] rom[0:ROM_SIZE-1]; // Simulated EEPROM
  reg[7:0] ram[0:RAM_SIZE-1]; // Simulated RAM
  integer i; // Index for ROM
```

```
33  integer file; // File handle
34  integer c; // Test character for seeing if the a line begins with a comment
35  integer r; // Unused placeholder for return values from file parsing
36  reg[8*MAX_LINE_LENGTH:0] line; // Unused placeholder for string comments
        that get read
37
38  // Clock
39  reg clock = 0;
40  always #50 clock = ~clock;
41
42  // DUT
43  cpu cpuDUT(.clock(clock),
44             .reset(reset),
45             .external_data_bus(data_bus),
46             .address_bus(address_bus),
47             .ram_enable(ram_enable),
48             .rom_enable(rom_enable),
49             .write(write));
50
51  // Waveform log file
52  initial begin
53    $dumpfile("cpu.vcd");
54    $dumpvars;
55  end
56
57  // Bidirectional driver code for data bus
58  assign data_bus = memory_drives_bus ? data_bus_driver : 16'hzz;
59
60  // Beginning of test
61  initial begin
62    // Initialize ROM to all zeros
63    for(i = 0; i < ROM_SIZE; i = i + 1) begin
64      rom[i] = 8'd0;
65    end
66
67    $display("Loading␣instructions␣into␣simulated␣ROM␣from␣\"cpu_code\"");
68    // Start reading the file
69    file = $fopen("cpu_code", "r");
70
71    // Loop until we get to the end of the file and initialize ROM with the
          contents
72    i = 0; // Start back at the beginning of ROM
73    while(! $feof(file)) begin
74      // Check if the first character is a '#', signifiying a comment
75      c = $fgetc(file);
76      if(c == "#") begin
77        // If we've got a comment, skip to the next line
78        r = $fgets(line, file);
79      end
80      else begin
81        // Otherwise, assume that it's a hex value and try to read it
82        r = $ungetc(c, file);
83        r = $fscanf(file, "%h\n", rom[i]);
84        i = i + 1;
```

```
85        end
86      end
87
88      // Test: print out the contents of ROM
89      for(i = 0; i < 20; i = i + 1) begin
90        $write("%h ", rom[i]);
91        if(i % 8 == 7) begin
92          $write("\n");
93        end
94      end
95
96      // Perform a reset
97      @(negedge clock)
98        reset = 1'b0;
99      @(negedge clock)
100       reset = 1'b1;
101
102     // And off we go!
103     for(clock_cycles = 0; clock_cycles < 500; clock_cycles = clock_cycles + 1)
            begin
104       @(posedge clock)
105       memory_drives_bus = 1'b0; // Relinquish control of the data bus until we
              're told to keep using it
106       #10 // Wait for the memory address to be set before we try to give back
              data!
107       if(rom_enable == 1'b0) begin // ROM output-enable is active low
108         data_bus_driver = rom[address_bus];
109       end
110       else if(ram_enable == 1'b0) begin // RAM output-enable is also active
              low
111         if(write == 1'b1) begin // CPU is writing to RAM
112           ram[address_bus[RAM_ADDRESS_BITS-1:0]] = data_bus;
113         end
114         else begin // CPU is reading from RAM
115           data_bus_driver = ram[address_bus[RAM_ADDRESS_BITS-1:0]];
116         end
117       end // if(rom/ram enable)
118       memory_drives_bus = !write;
119
120
121       //$display("%h %h", address_bus, data_bus);
122     end // for(clock_cycles)
123     $finish;
124   end // initial
125
126 endmodule
```

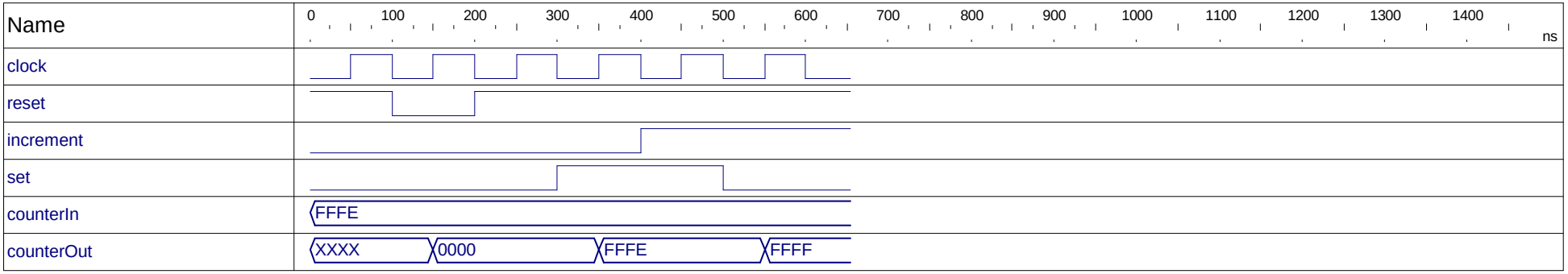
C Output waveforms

Waveforms were created by dumping the signals to a VCD file directly from Verilog, converting them to Aldec's .abf file format using the Aldec command-line utilities `vcd2asdb` and `awfconv`, and viewing them in ActiveHDL's waveform viewer.

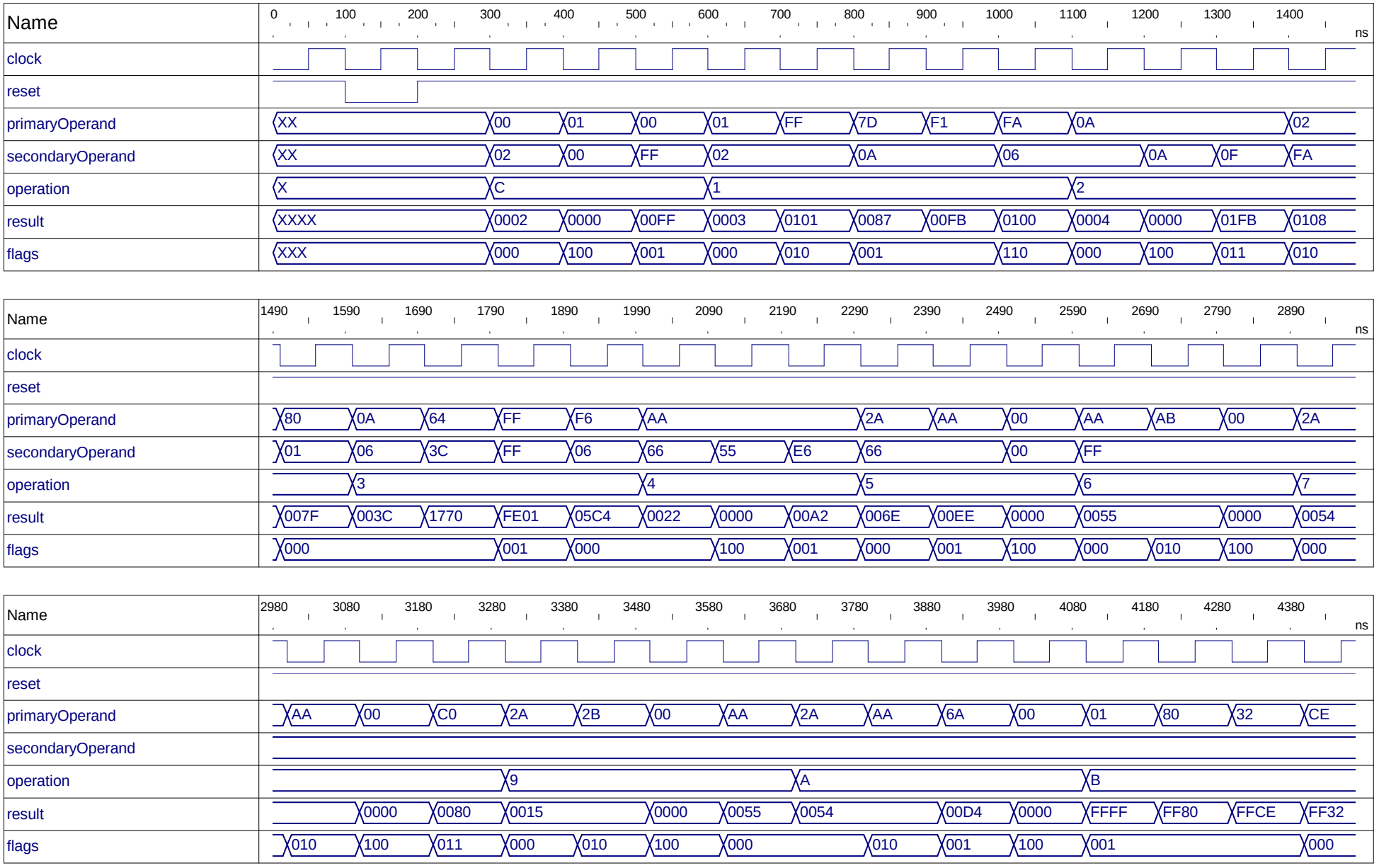

0.0 ns
200.0 ns
400.0 ns
600.0 ns
800.0 ns
1,000.0 ns
CLOCK
RESET
SETHIGH
SETLOW
0.0 ns
200.0 ns
400.0 ns
600.0 ns
800.0 ns
1,000.0 ns

77

Program Counter

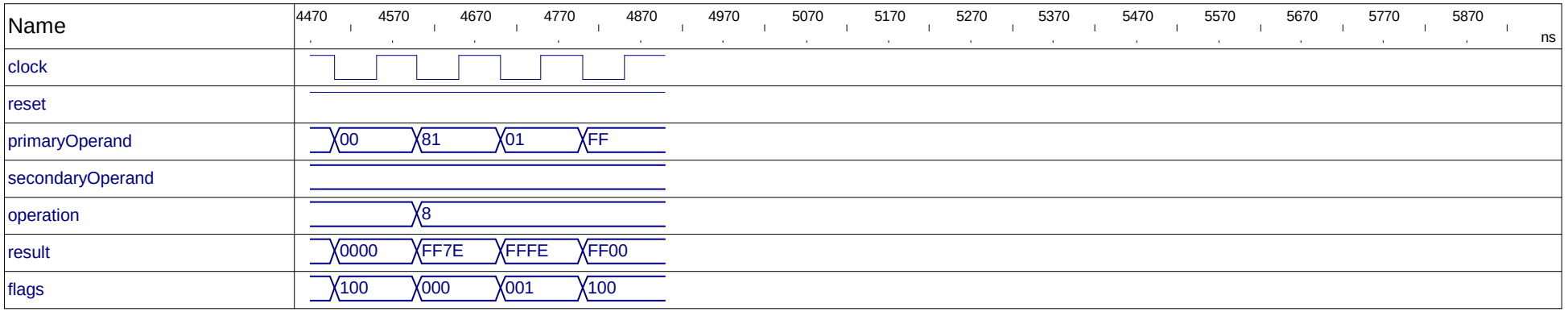


ALU

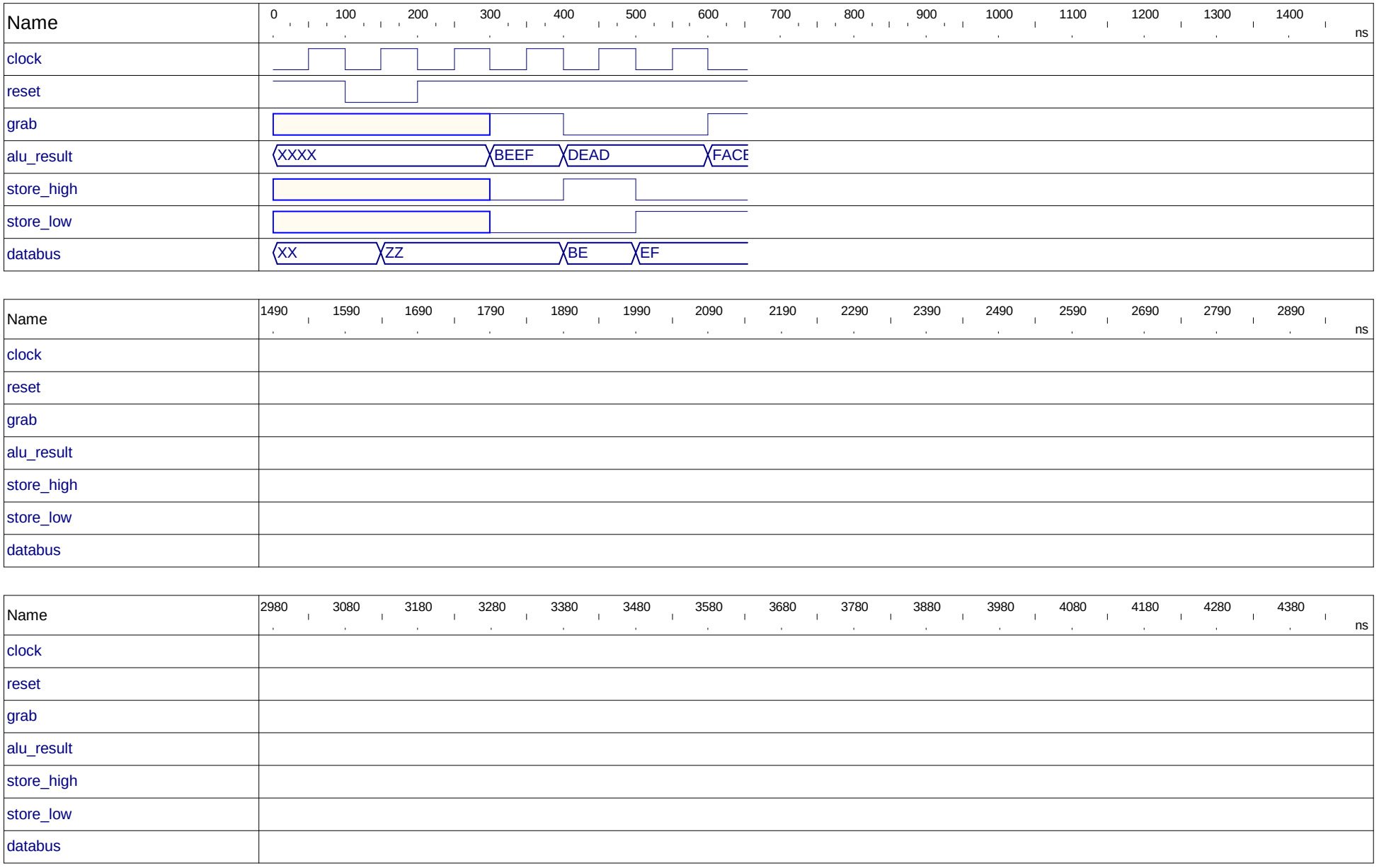

Name
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 ns
clock
reset
primaryOperand
XX 00 01 00 01 FF 7D F1 FA 0A 02
secondaryOperand
XX 02 00 FF 02 0A 06 0A 0F FA
operation
X C 1 2
result
XXXX 0002 0000 00FF 0003 0101 0087 00FB 0100 0004 0000 01FB 0108
flags
XXX 000 100 001 000 010 001 110 000 100 011 010
Name
1490 1590 1690 1790 1890 1990 2090 2190 2290 2390 2490 2590 2690 2790 2890 ns
clock
reset
primaryOperand
80 0A 64 FF F6 AA 2A AA 00 AA AB 00 2A
secondaryOperand
01 06 3C FF 06 66 55 E6 66 00 FF
operation
3 4 5 6 7
result
007F 003C 1770 FE01 05C4 0022 0000 00A2 006E 00EE 0000 0055 0000 0054
flags
000 001 000 100 001 000 001 100 000 010 100 000
Name
2980 3080 3180 3280 3380 3480 3580 3680 3780 3880 3980 4080 4180 4280 4380 ns
clock
reset
primaryOperand
AA 00 C0 2A 2B 00 AA 2A AA 6A 00 01 80 32 CE
secondaryOperand
operation
9 A B
result
0000 0080 0015 0000 0055 0054 00D4 0000 FFFF FF80 FFCE FF32
flags
010 100 011 000 010 100 000 010 001 100 001 000

79

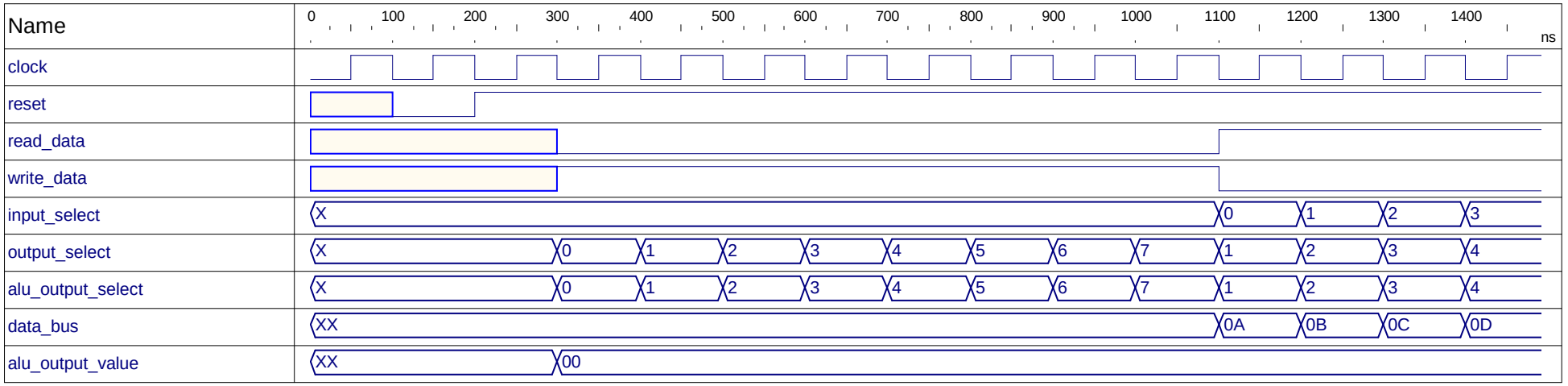
ALU

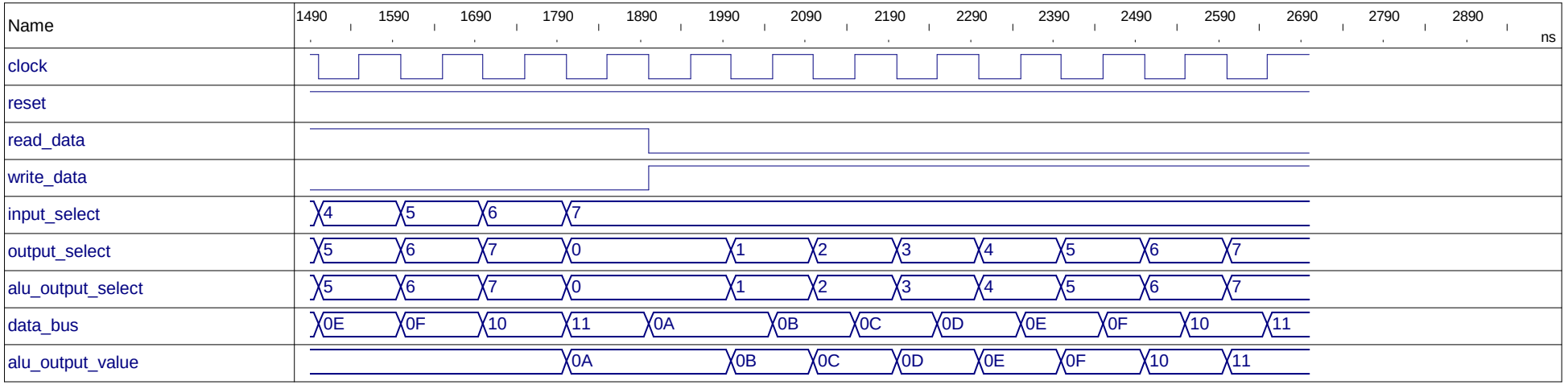

Name
4470
4570
4670
4770
4870
4970
5070
5170
5270
5370
5470
5570
5670
5770
5870
ns
clock
reset
primaryOperand
00
81
01
FF
secondaryOperand
operation
8
result
0000
FF7E
FFFE
FF00
flags
100
000
001
100

ALU Latch

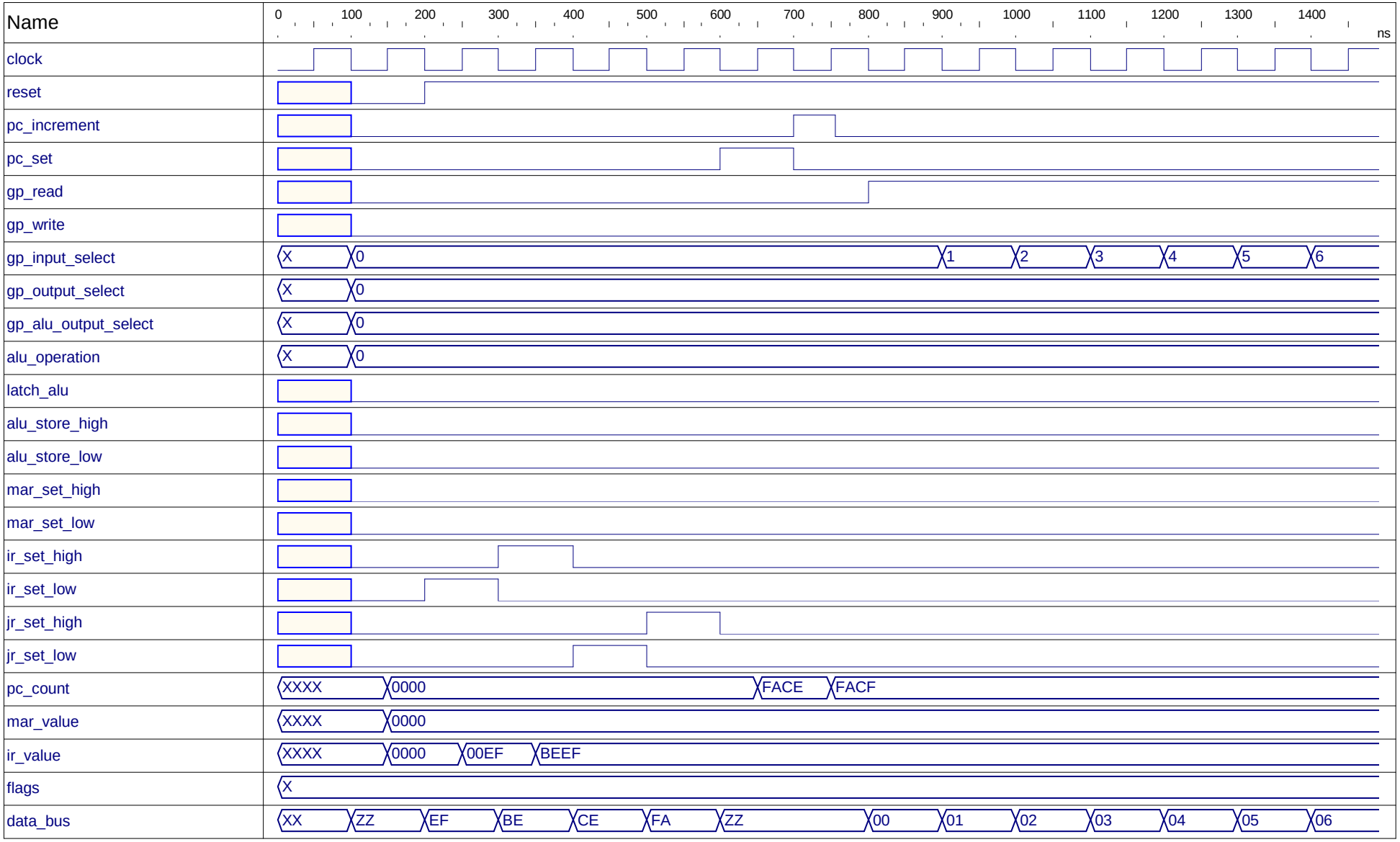

Name
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
ns
clock
reset
grab
alu_result
XXXX
BEEF
DEAD
FACE
store_high
store_low
databus
XX
ZZ
BE
EF
Name
1490
1590
1690
1790
1890
1990
2090
2190
2290
2390
2490
2590
2690
2790
2890
ns
clock
reset
grab
alu_result
store_high
store_low
databus
Name
2980
3080
3180
3280
3380
3480
3580
3680
3780
3880
3980
4080
4180
4280
4380
ns
clock
reset
grab
alu_result
store_high
store_low
databus

General purpose registers

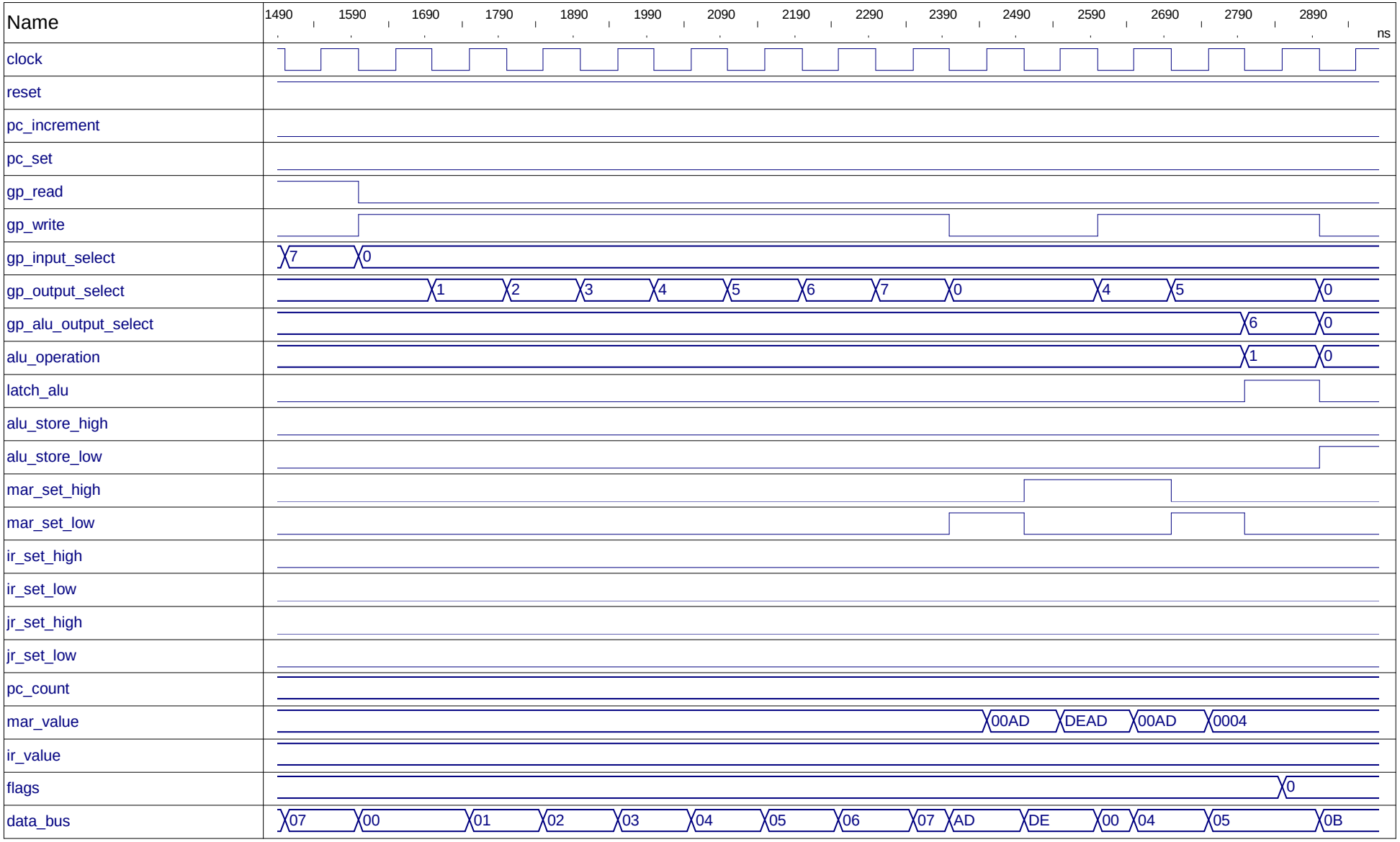




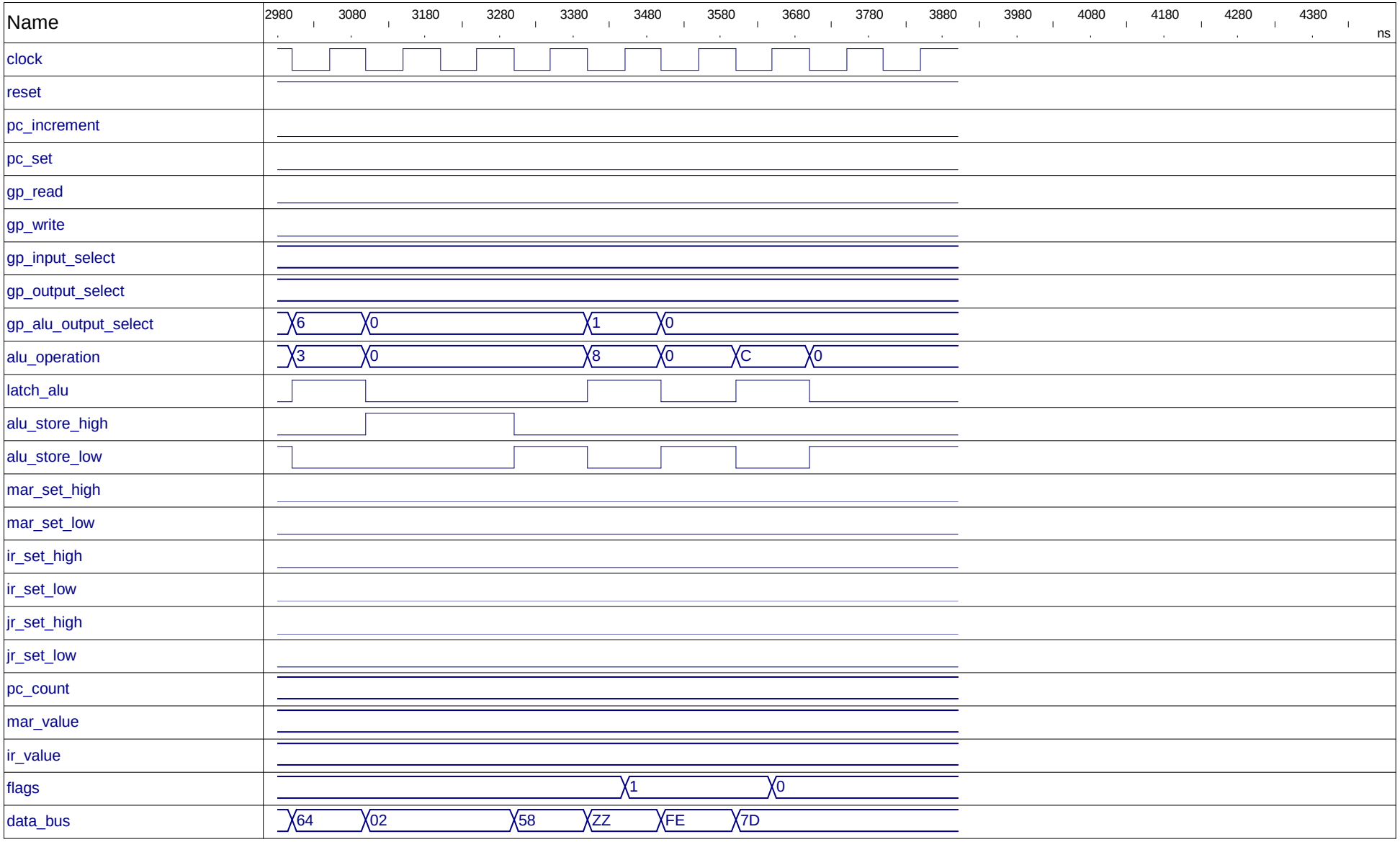
Datapath


Name
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
ns
clock
reset
pc_increment
pc_set
gp_read
gp_write
gp_input_select
X
0
1
2
3
4
5
6
gp_output_select
X
0
gp_alu_output_select
X
0
alu_operation
X
0
latch_alu
alu_store_high
alu_store_low
mar_set_high
mar_set_low
ir_set_high
ir_set_low
jr_set_high
jr_set_low
pc_count
XXXX
0000
FACE
FACF
mar_value
XXXX
0000
ir_value
XXXX
0000
00EF
BEEF
flags
X
data_bus
XX
ZZ
EF
BE
CE
FA
ZZ
00
01
02
03
04
05
06

Datapath


Name
1490
1590
1690
1790
1890
1990
2090
2190
2290
2390
2490
2590
2690
2790
2890
ns
clock
reset
pc_increment
pc_set
gp_read
gp_write
gp_input_select
gp_output_select
gp_alu_output_select
alu_operation
latch_alu
alu_store_high
alu_store_low
mar_set_high
mar_set_low
ir_set_high
ir_set_low
jr_set_high
jr_set_low
pc_count
mar_value
ir_value
flags
data_bus
7
0
1
2
3
4
5
6
7
0
4
5
0
6
0
1
0
0
00AD
DEAD
00AD
0004
0
07
00
01
02
03
04
05
06
07
AD
DE
00
04
05
0B

Datapath


Name
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3180
3280
3380
3480
3580
3680
3780
3880
3980
4080
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4280
4380
ns
clock
reset
pc_increment
pc_set
gp_read
gp_write
gp_input_select
gp_output_select
gp_alu_output_select
6
0
1
0
alu_operation
3
0
8
0
C
0
latch_alu
alu_store_high
alu_store_low
mar_set_high
mar_set_low
ir_set_high
ir_set_low
jr_set_high
jr_set_low
pc_count
mar_value
ir_value
flags
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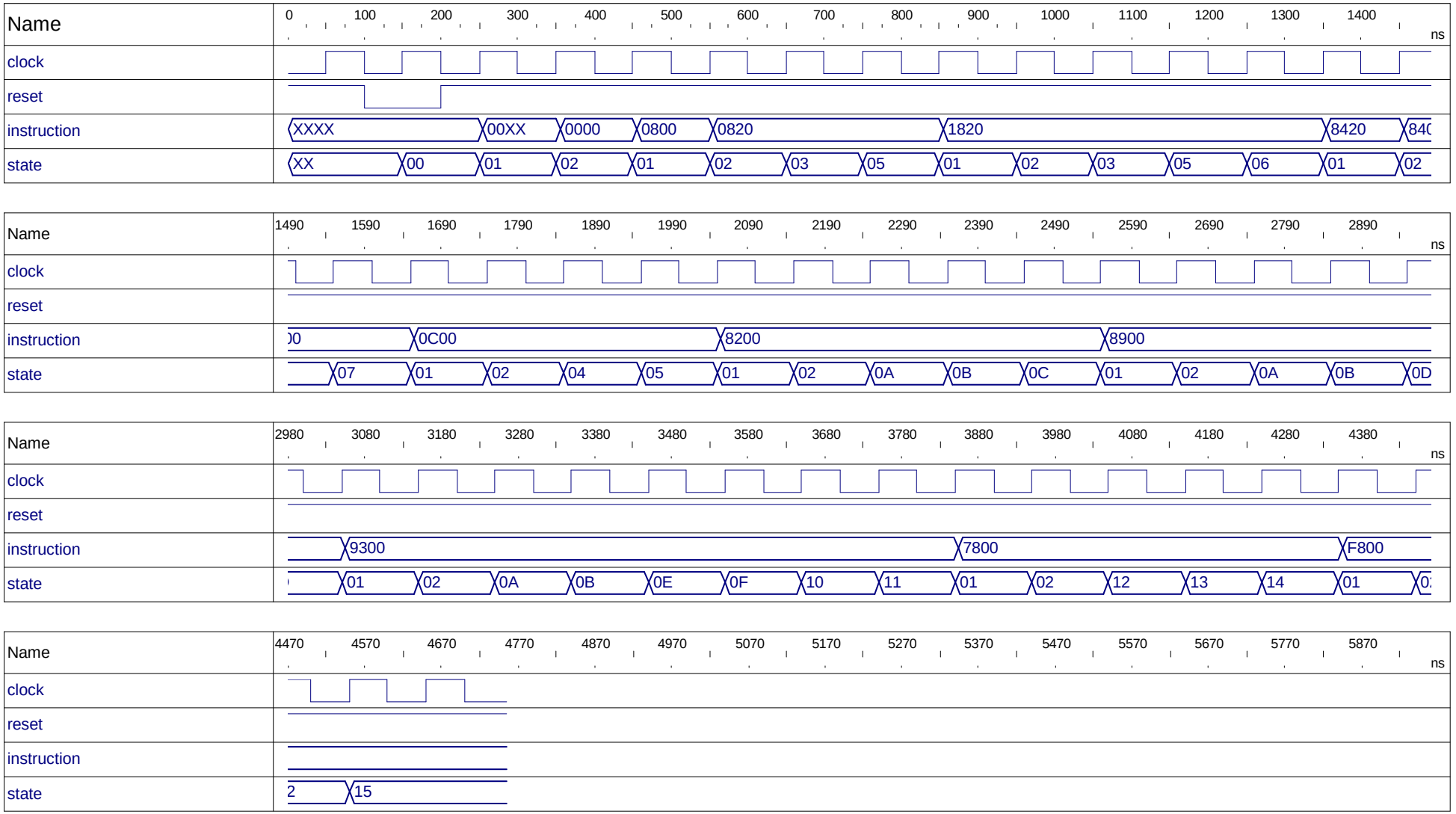
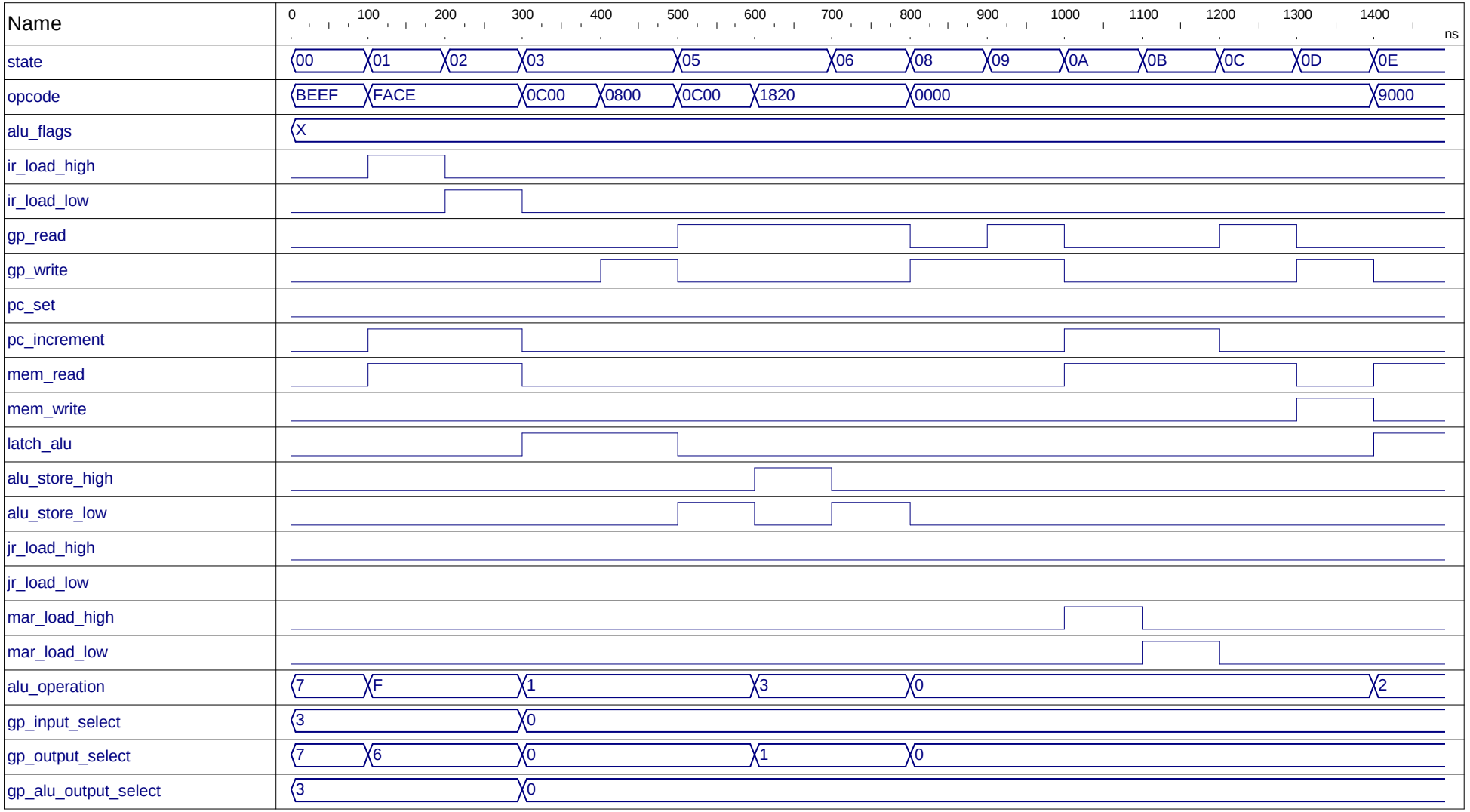
0
data_bus
64
02
58
ZZ
FE
7D

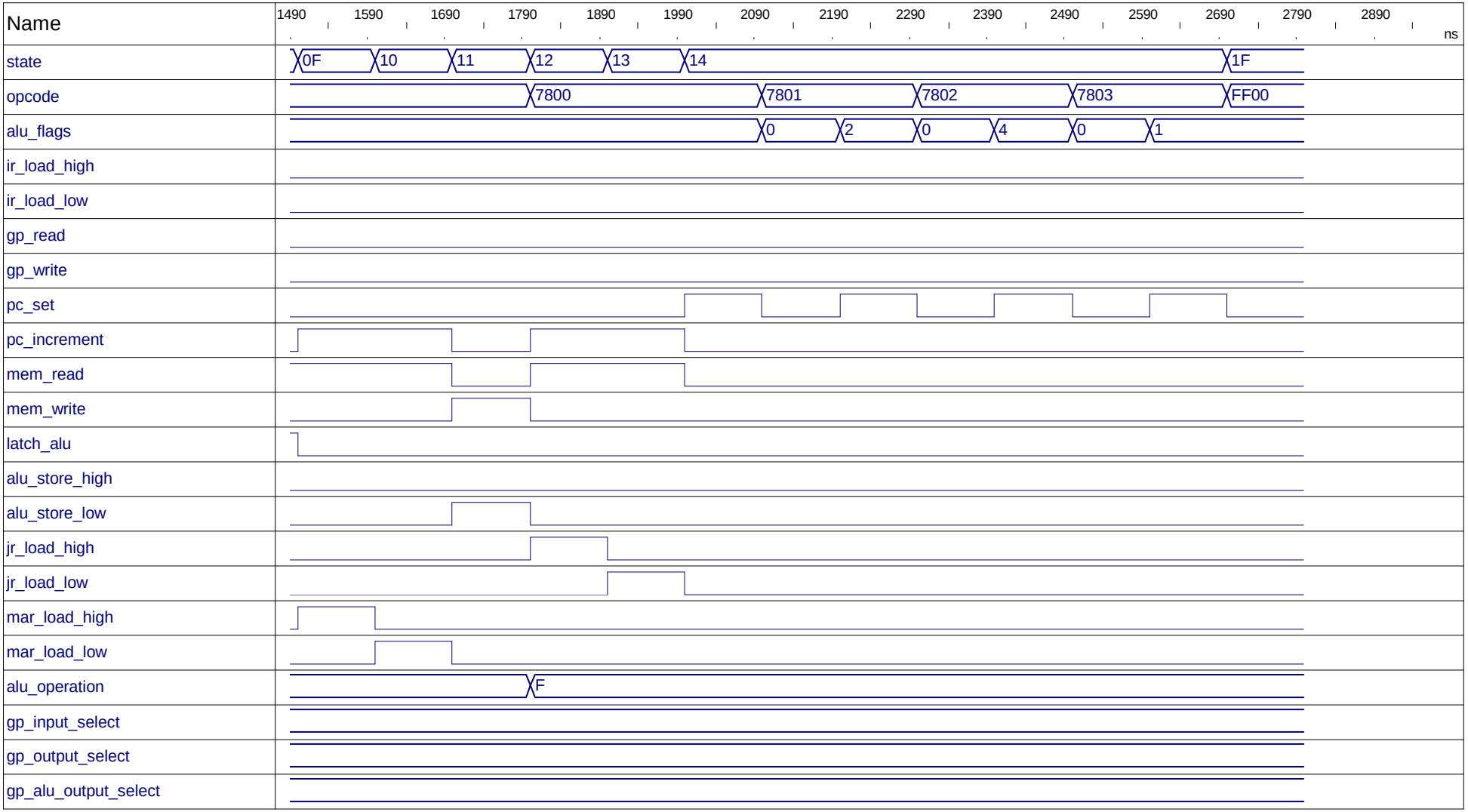
Control state machine



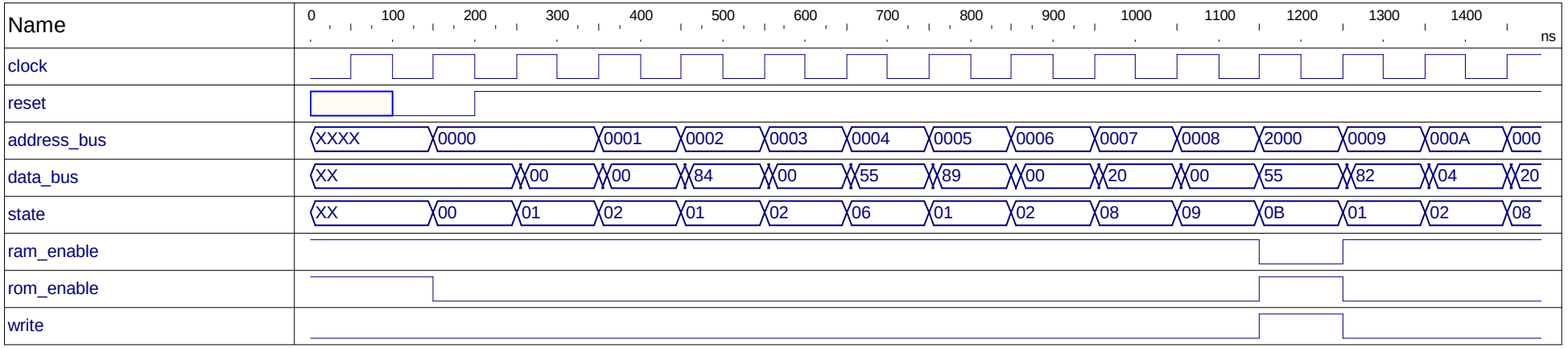
Control signal translator

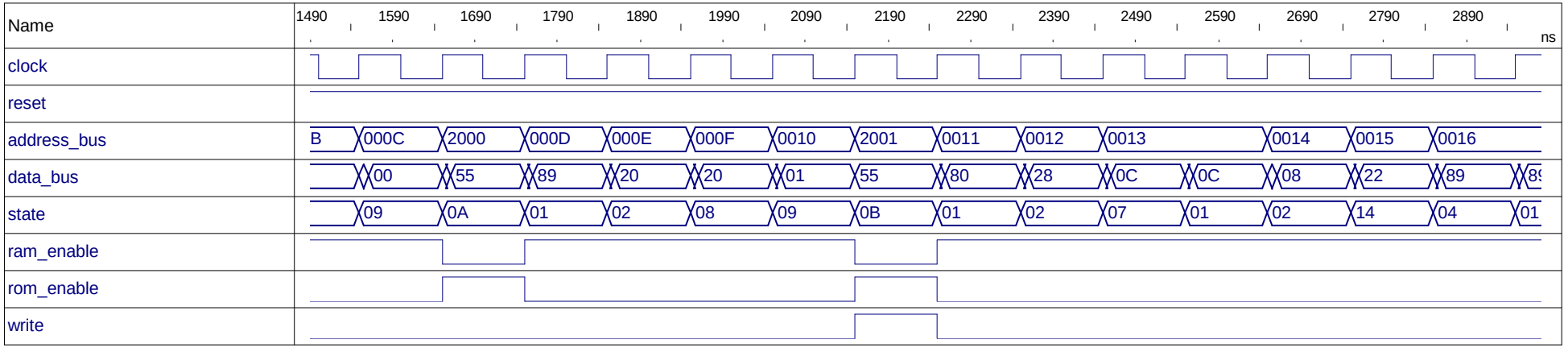


Control signal translator

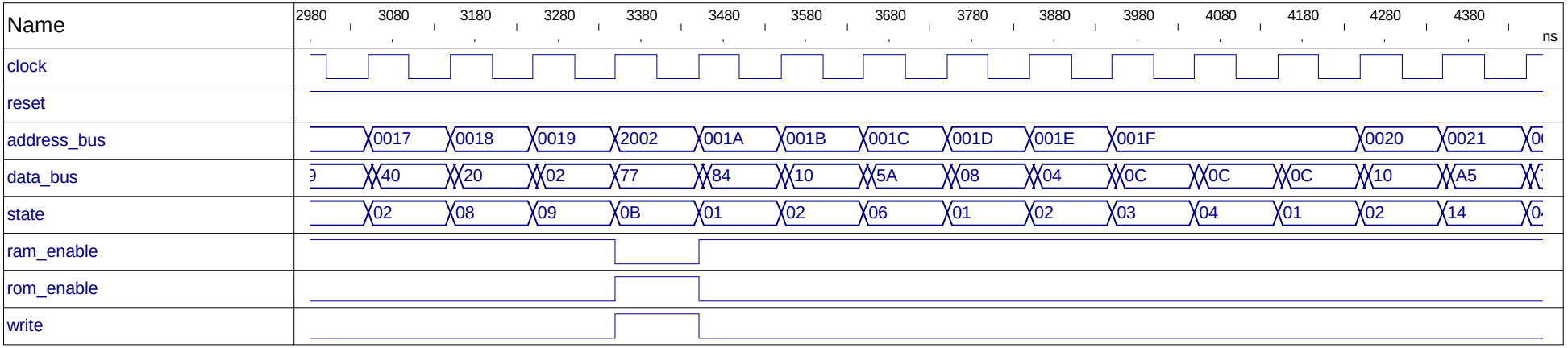


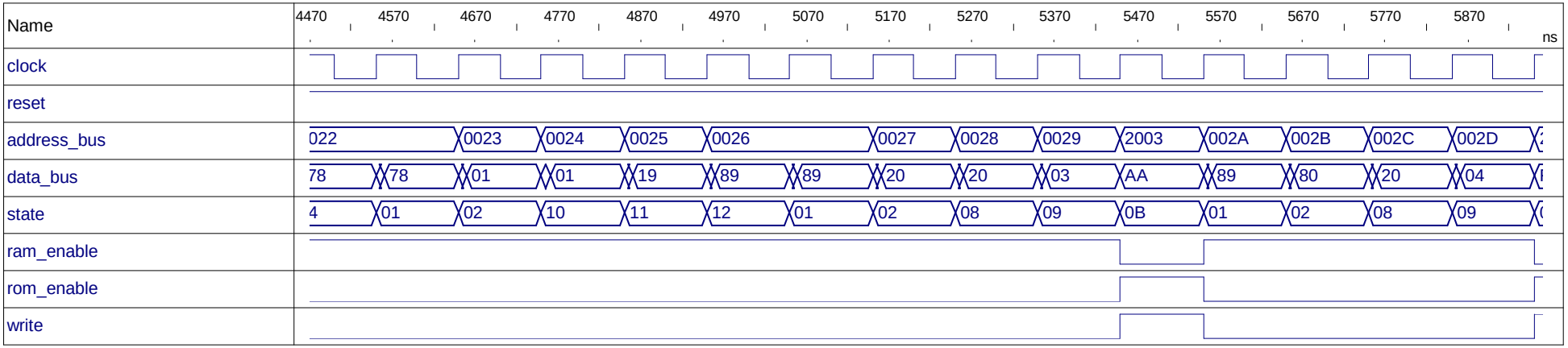
CPU test program, part A



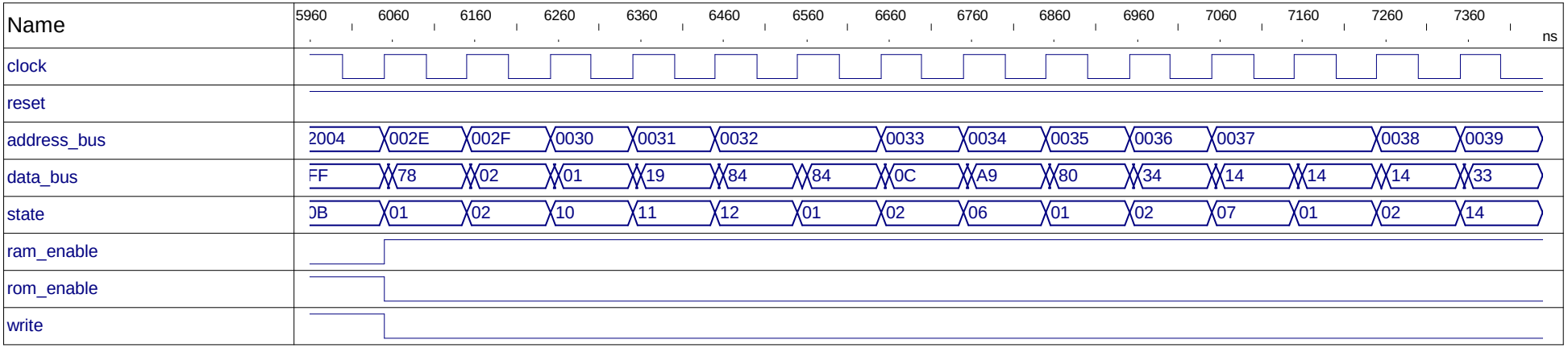


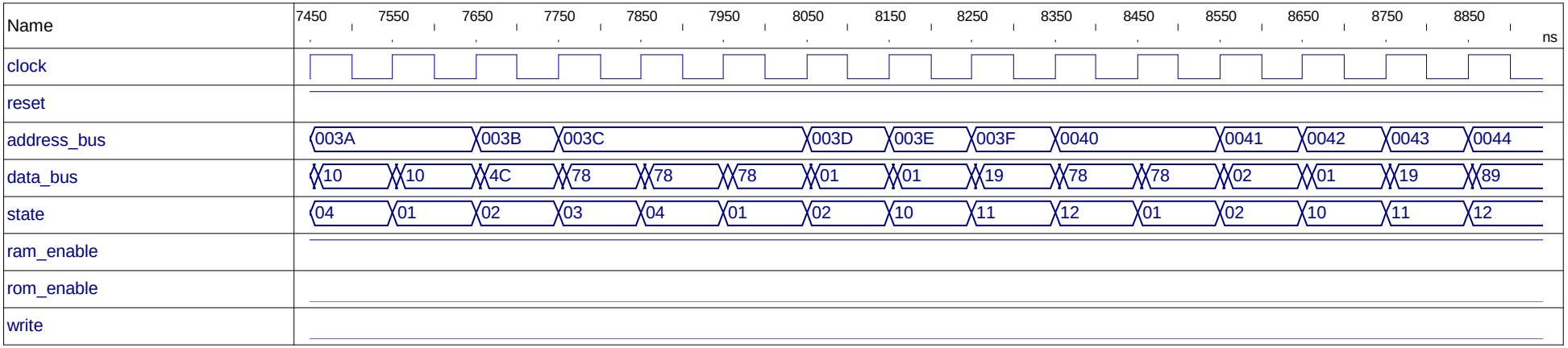
CPU test program, part A



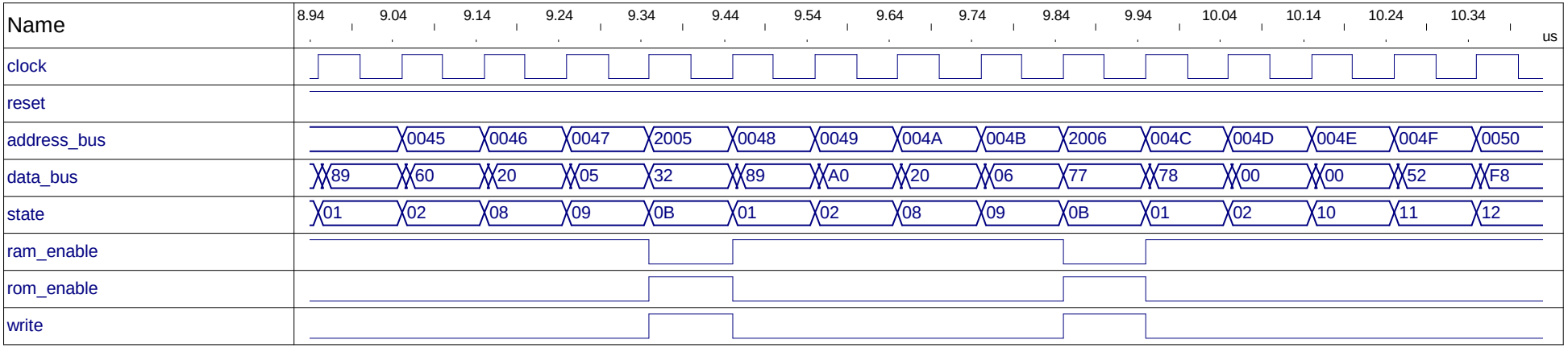


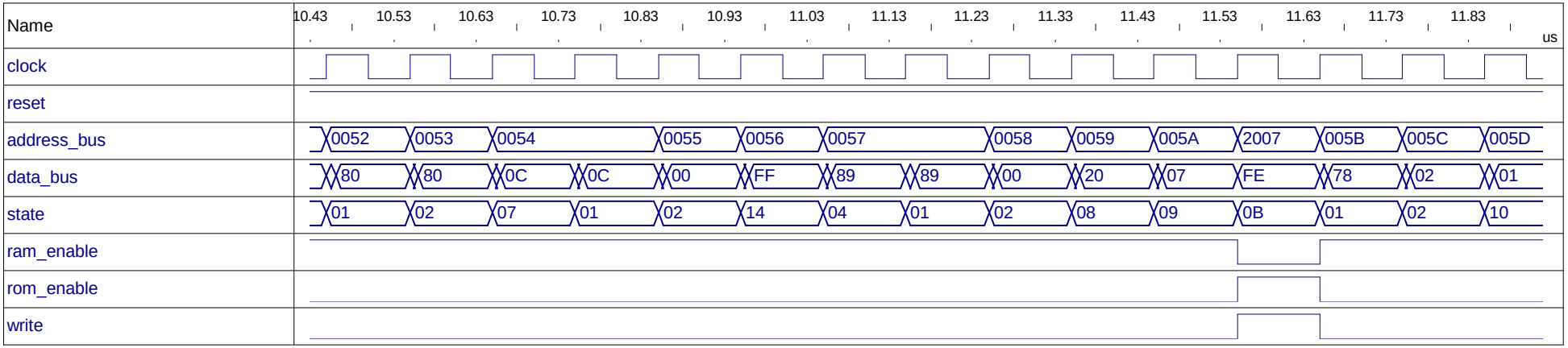
CPU test program, part A



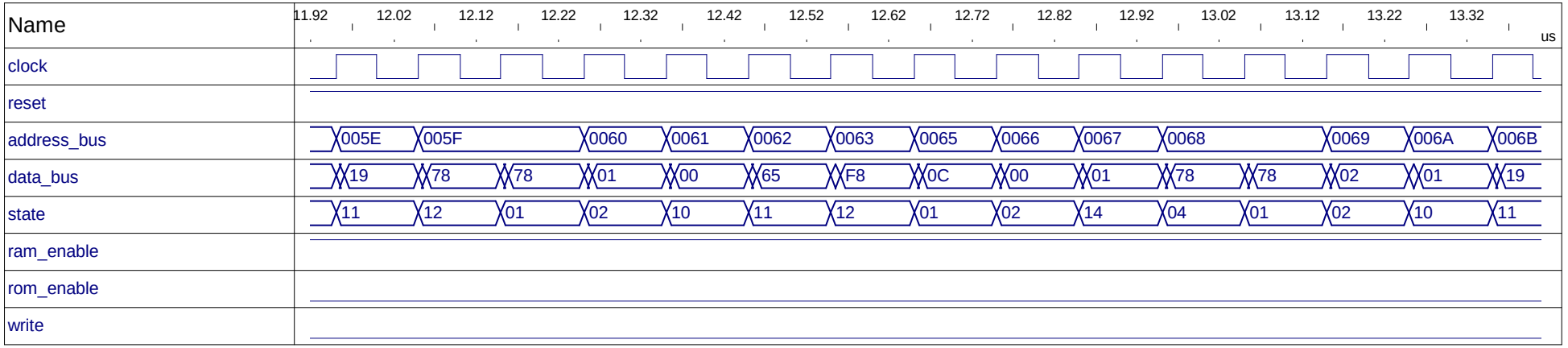


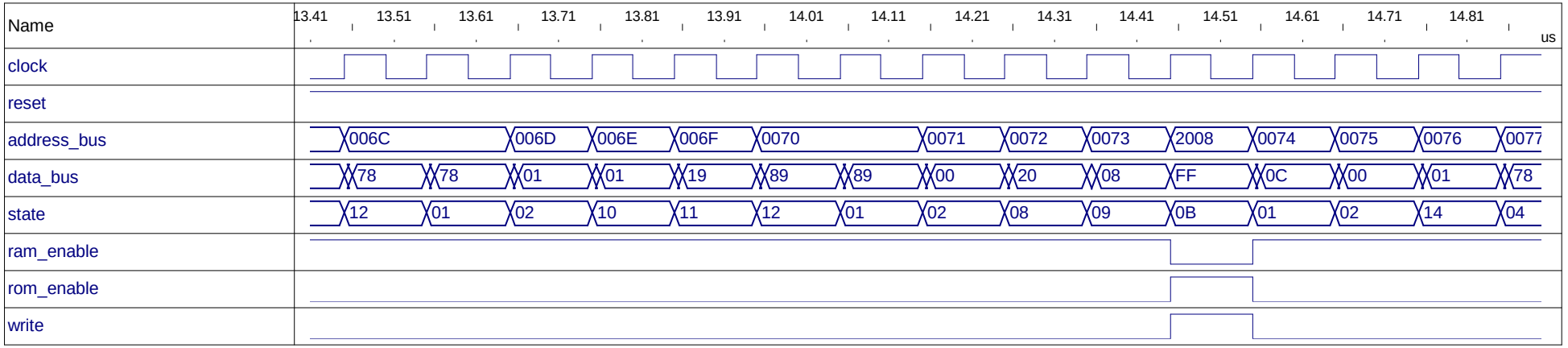
CPU test program, part A



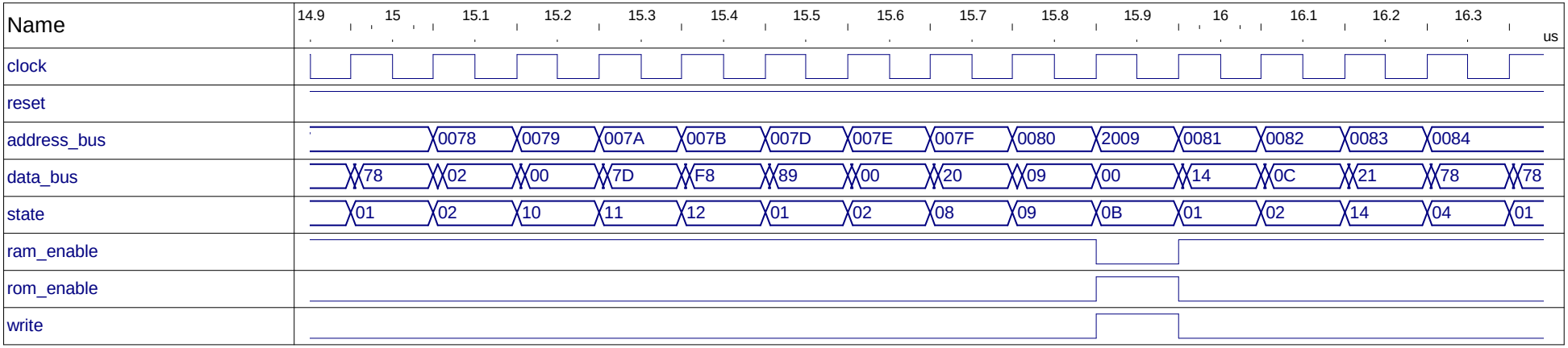


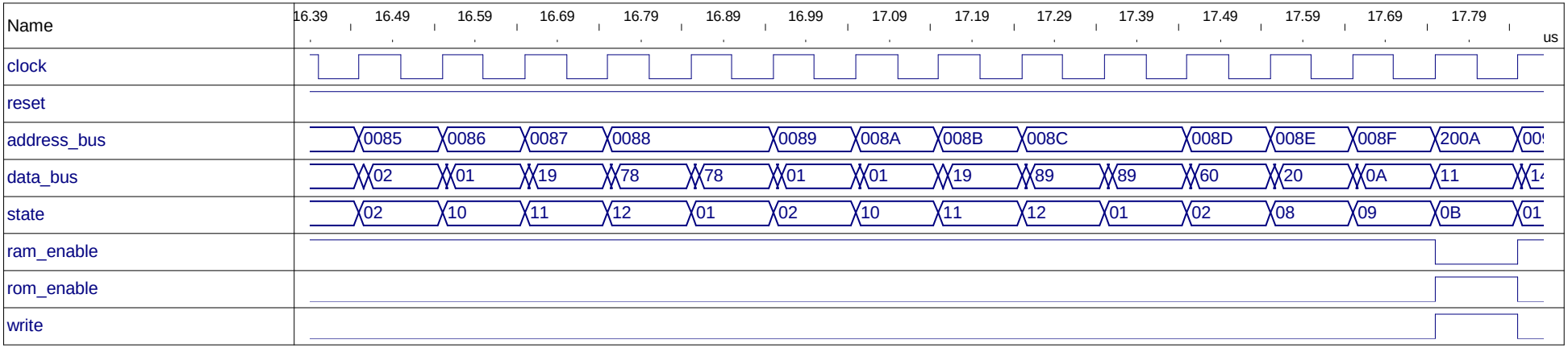
CPU test program, part A



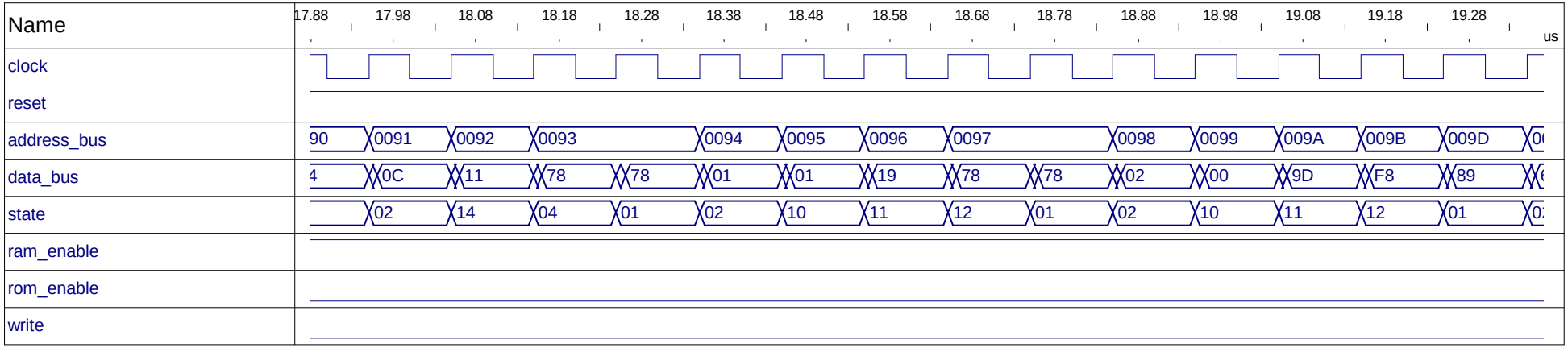


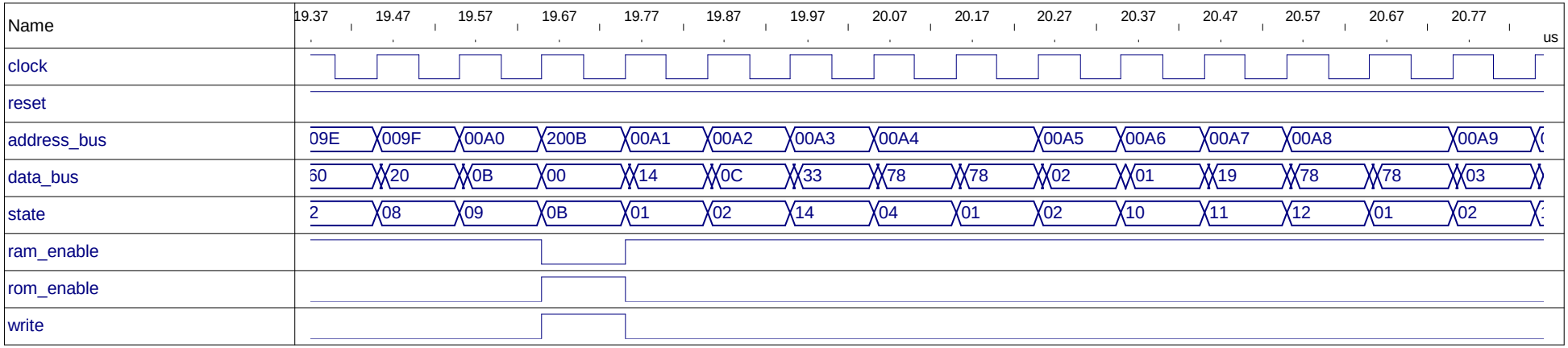
CPU test program, part A





CPU test program, part A

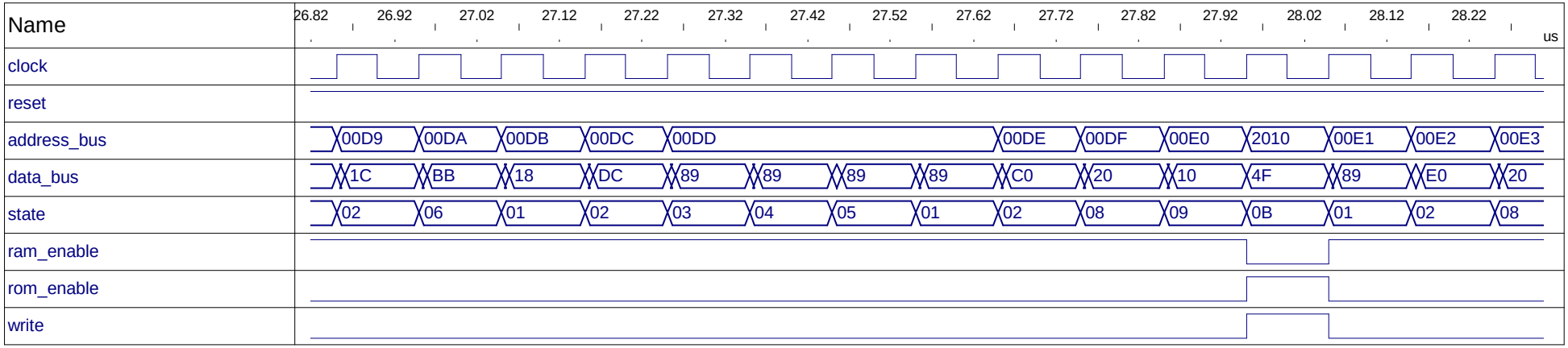


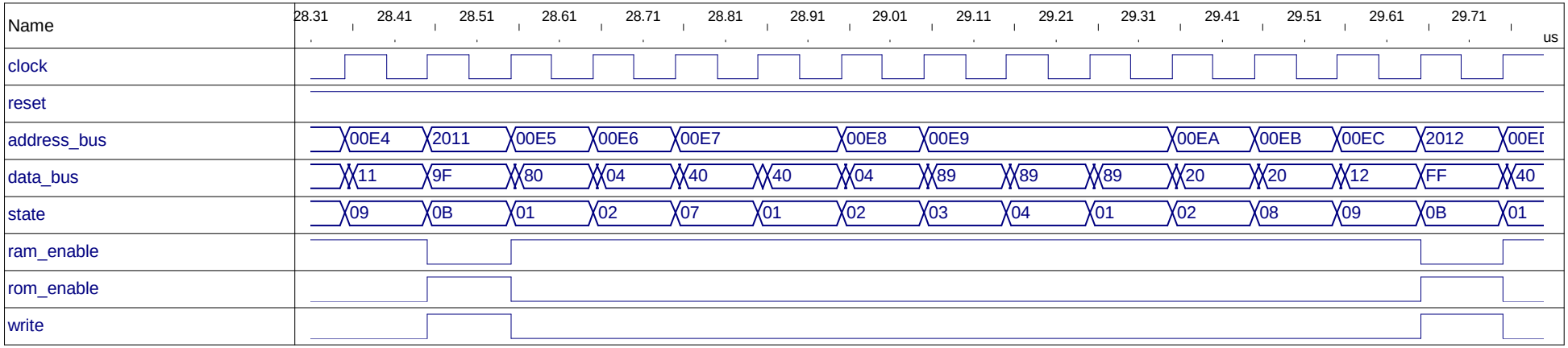


CPU test program, part A

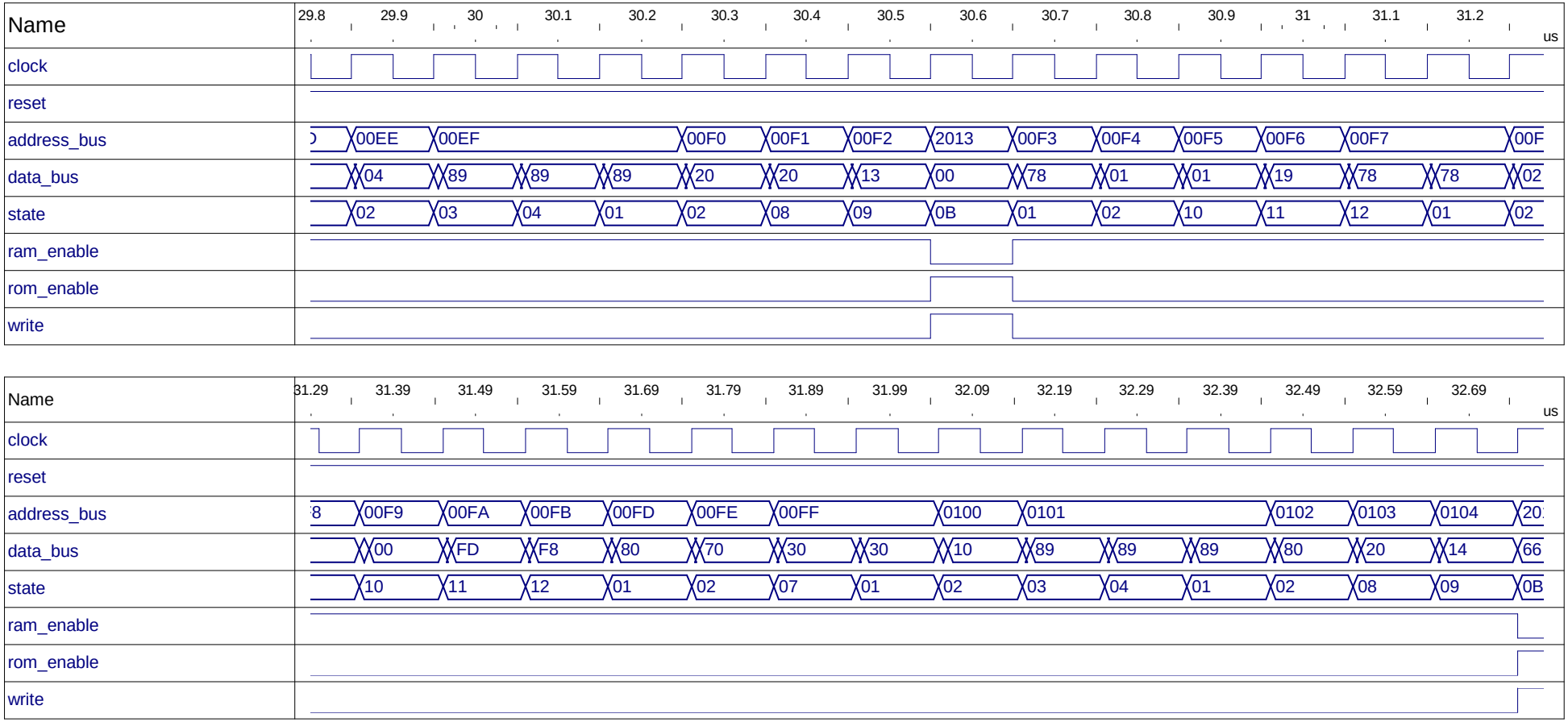
CPU test program, part A

CPU test program, part A



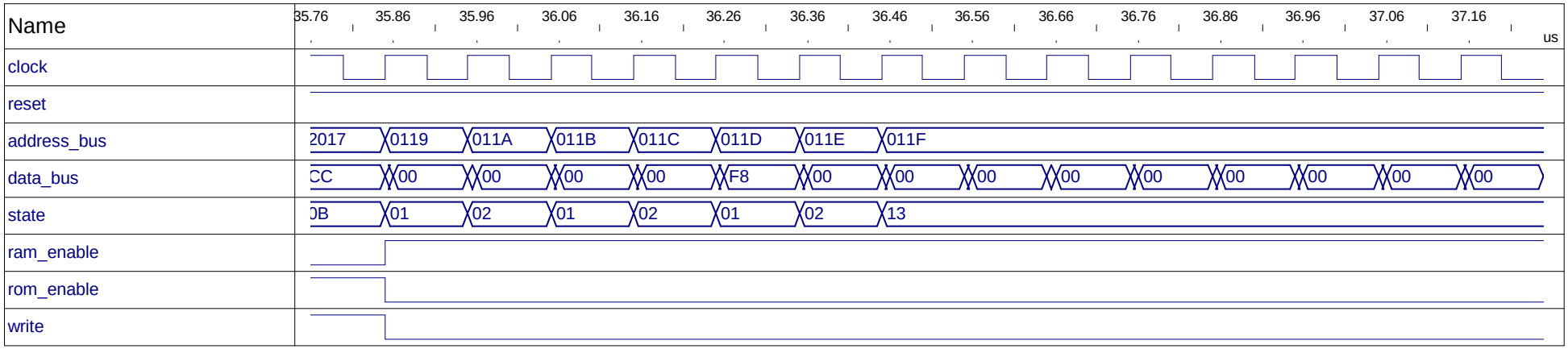


CPU test program, part A

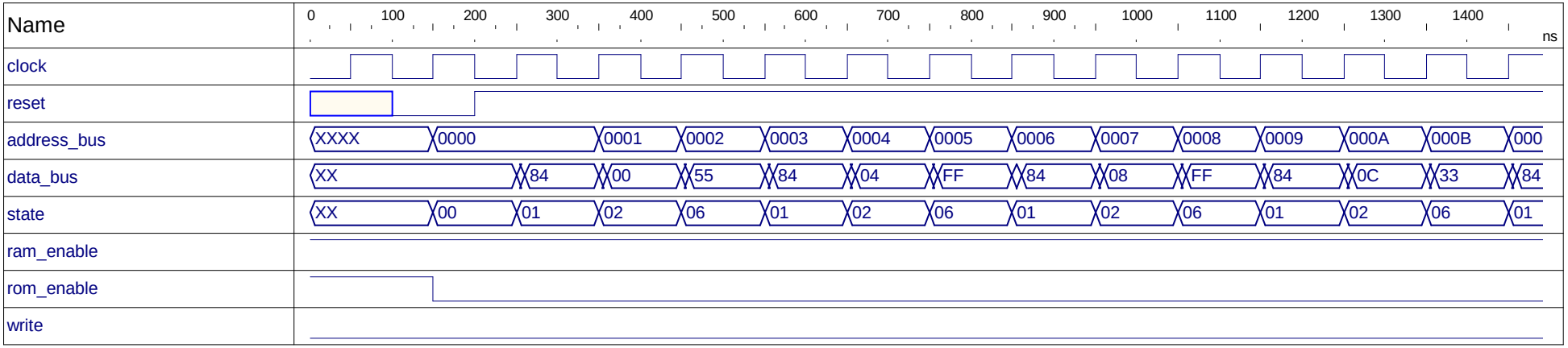


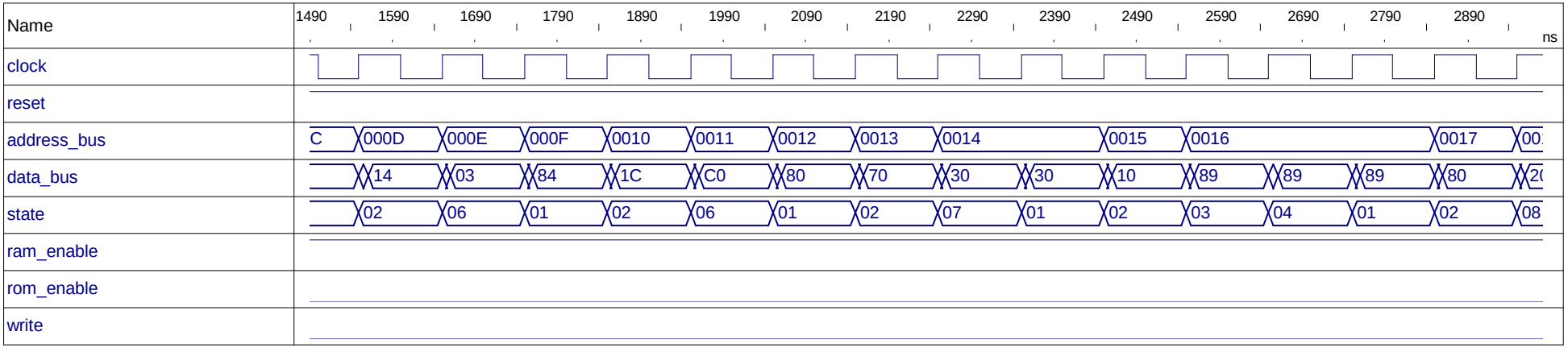
CPU test program, part A

CPU test program, part A

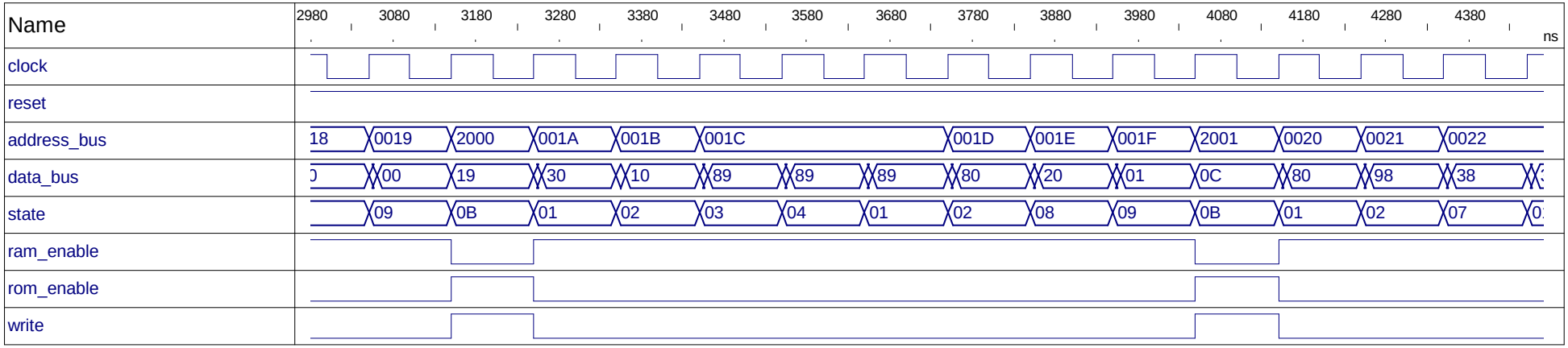


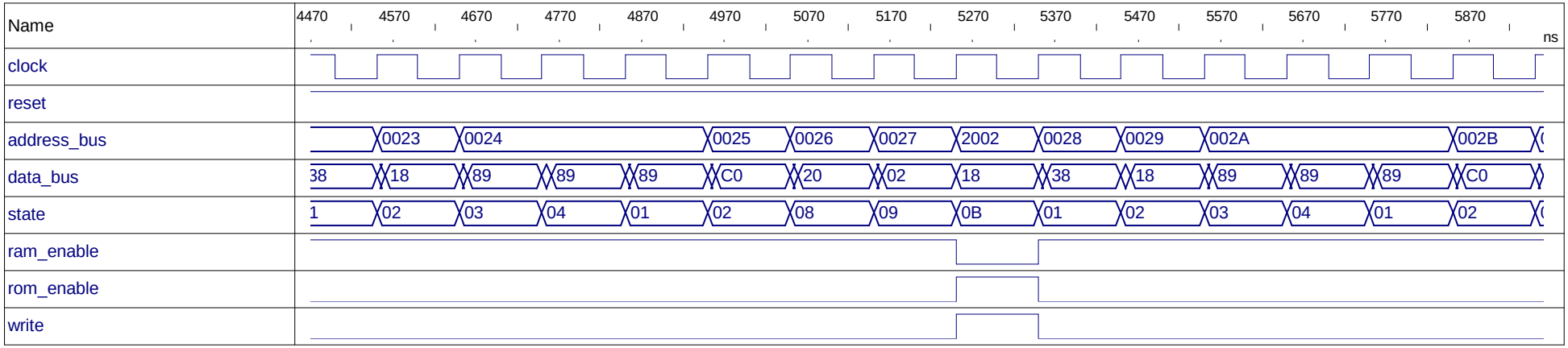
CPU test program B



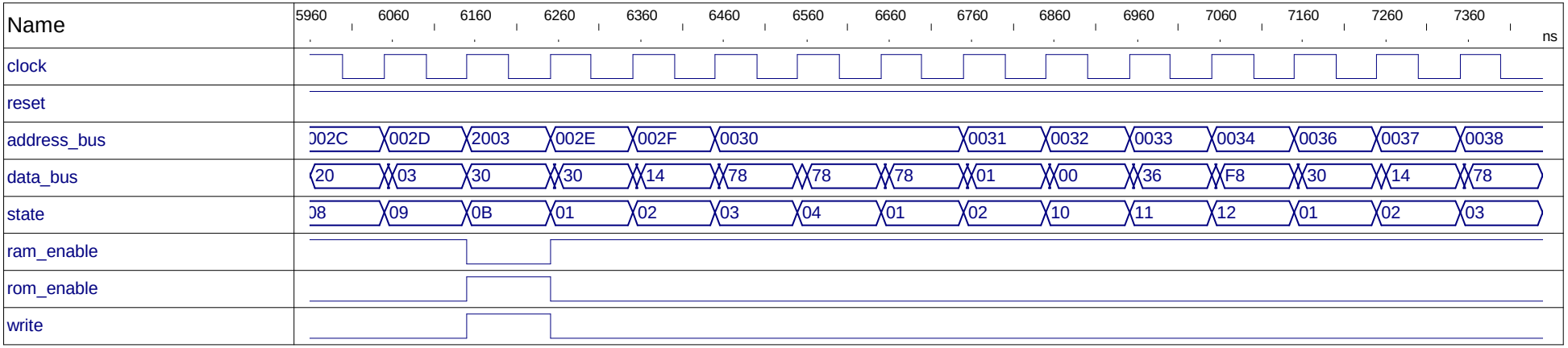


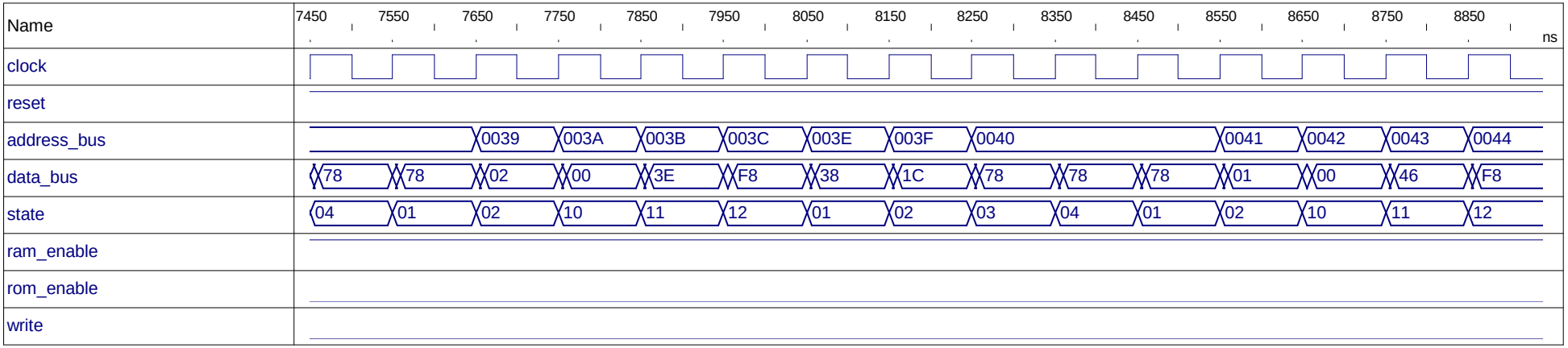
CPU test program B



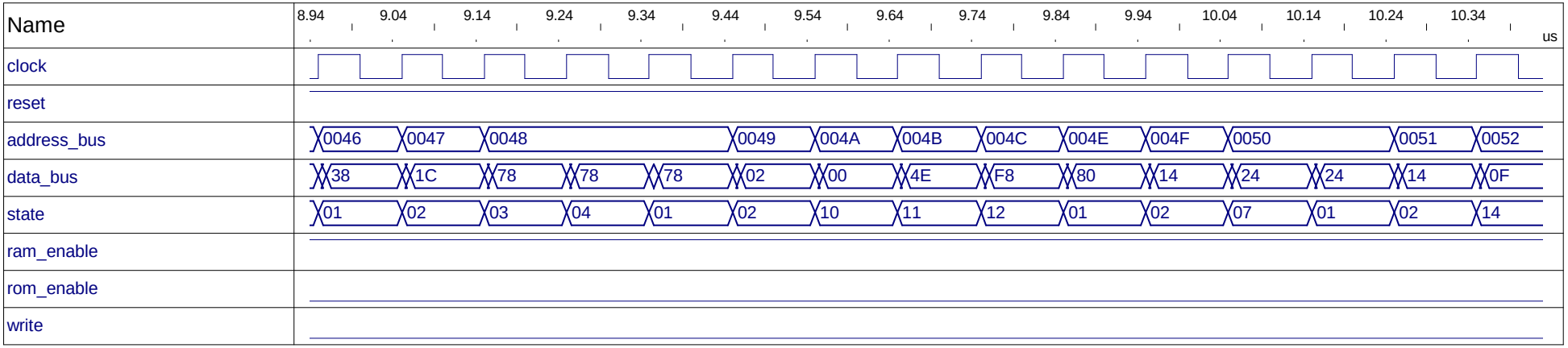


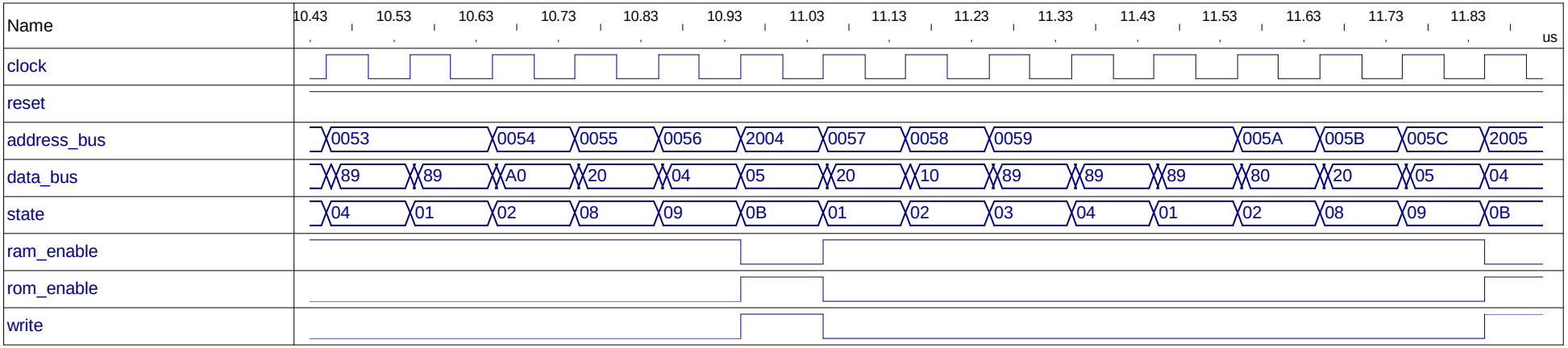
CPU test program B



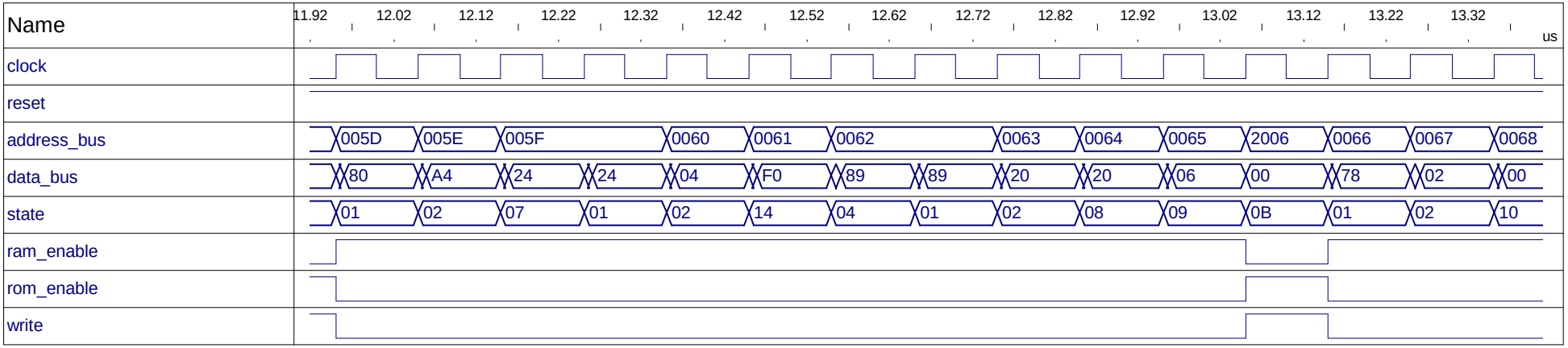


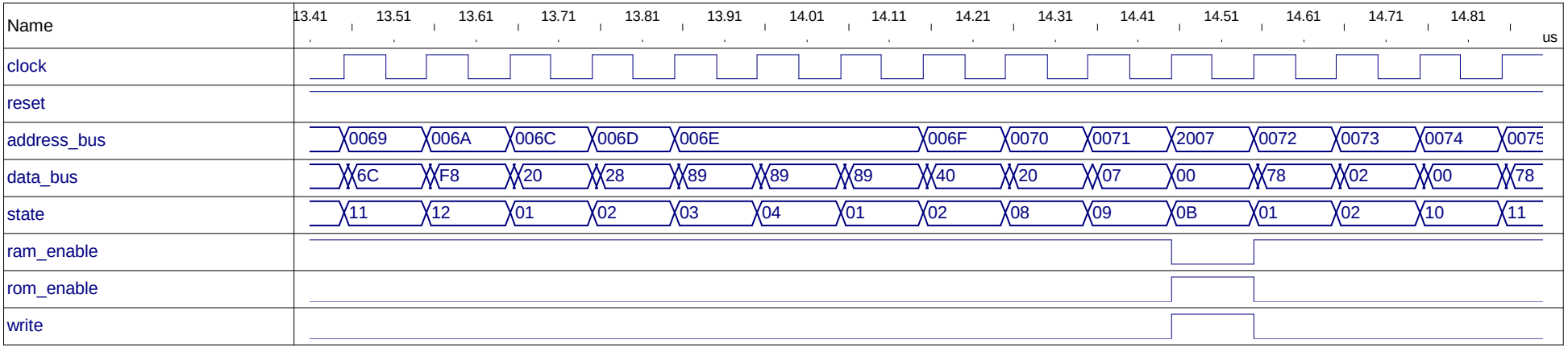
CPU test program B



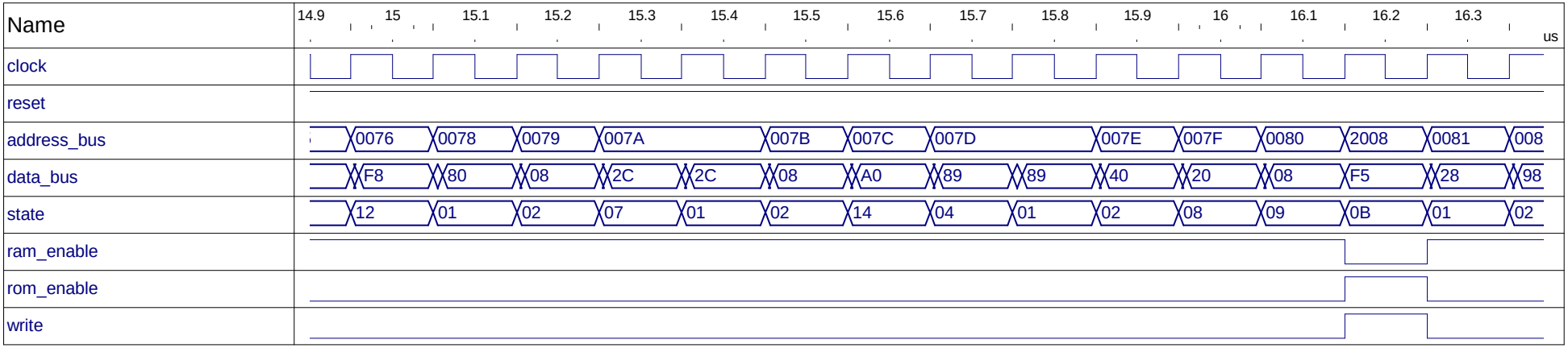


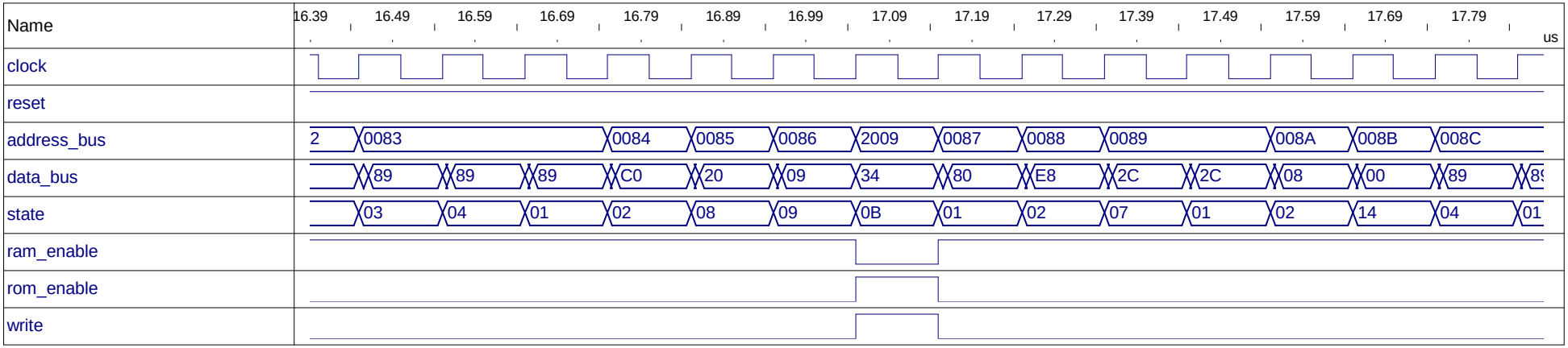
CPU test program B





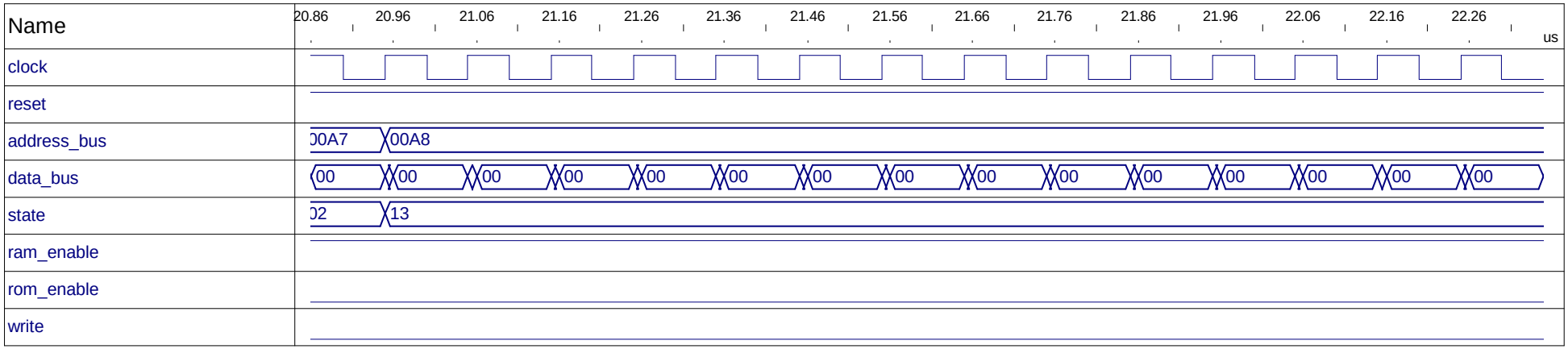
CPU test program B





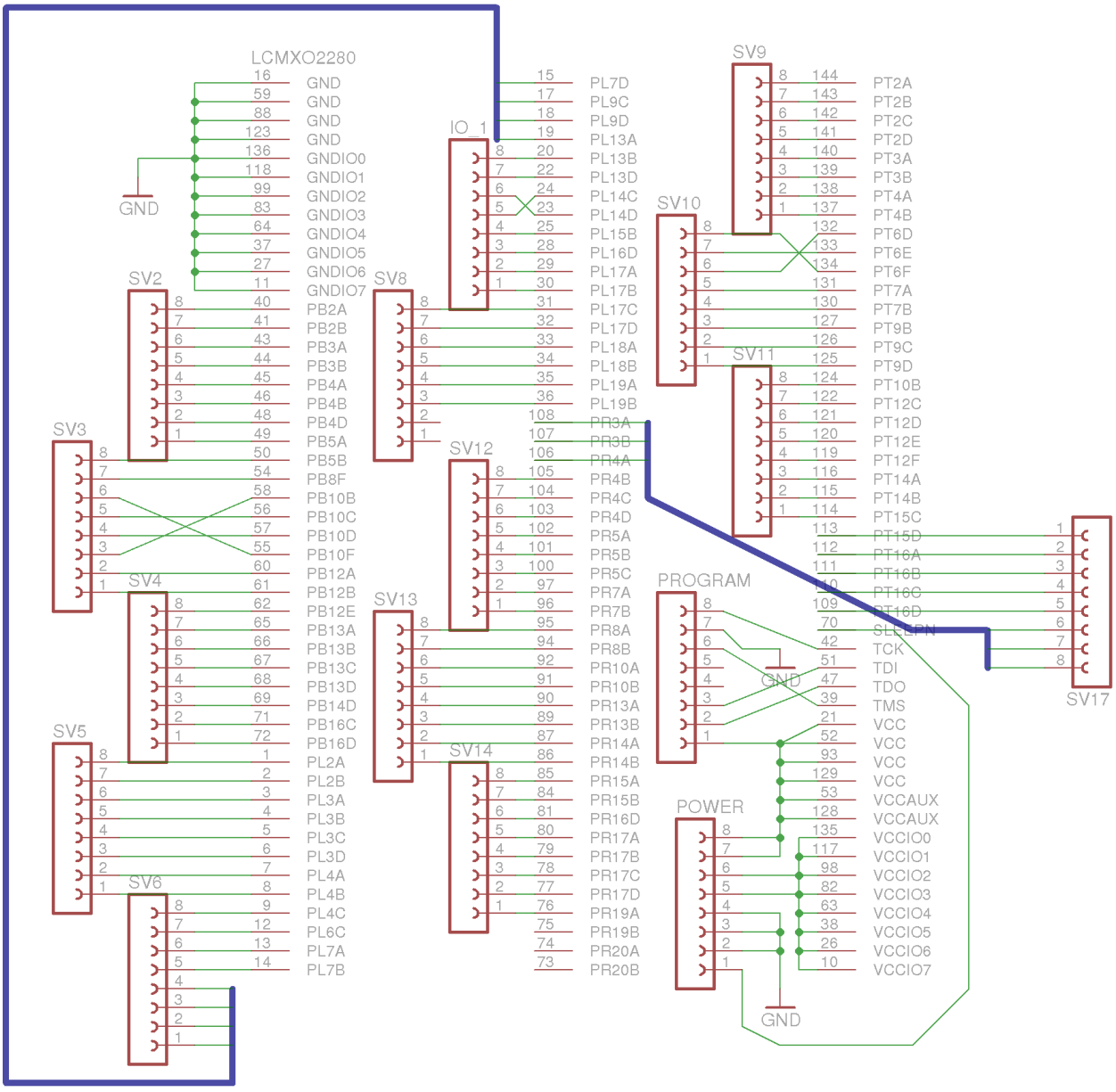
CPU test program B

CPU test program B

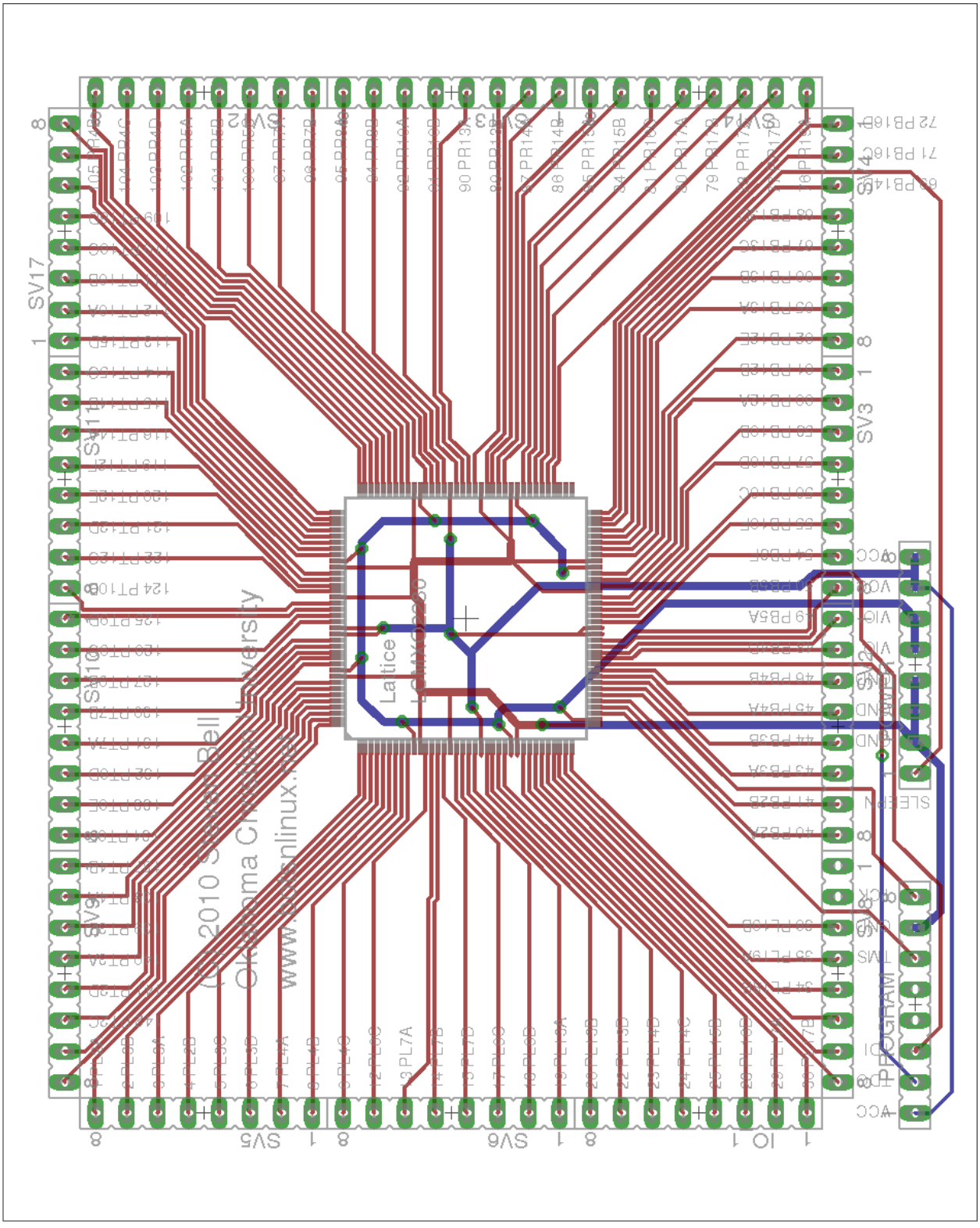


D PCB diagrams

D.1 Eagle schematic



D.2 Eagle layout



E Assembler code

```
1  /**
2   * \file main.cpp
3   * Main code file for Steven's (purposeful|powerful|pimpin'|pernicious)
        assembler (SPASM)
4   * \author Steven Bell <steven.bell@student.oc.edu>
5   * \date 4 November 2010
6   * $LastChangedDate: 2010-12-14 23:24:10 -0600 (Tue, 14 Dec 2010) $
7   */
8
9  /*
10  * Command-line arguments
11  * Usage:
12  *  spasm [args] inputfile
13  *
14  * -o             Output file
15  * -v, --verbose  Verbose mode, print out lots of information about what's
        going on
16  * -d, --dump     Do a hex dump of the program after it is assembled
17  * -h, --help     Print this help message
18  */
19
20 #include <QCoreApplication>
21 #include <QStringList>
22 #include <QFile>
23 #include "cstdio"
24 #include "console.h"
25 #include "parser.h"
26
27 int main(int argc, char* argv[])
28 {
29   // Read the input arguments
30   // We don't really need QCoreApplication for anything except the arguments,
        so maybe there's
31   // a better way to do this?
32   QCoreApplication app(argc, argv);
33   QStringList argList = app.arguments();
34
35   // If the help flag was specified, then just print the help message and quit
36   if(argList.contains("-h") || argList.contains("--help")){
37     printf("SPASM - Steven's special-purpose assembler\n");
38     printf("Copyright (c) 2010 Steven Bell <steven.bell@student.oc.edu>\n\n");
39     printf("Usage:\n");
40     printf("  spasm [args] inputfile\n\n");
41     printf(" -o, --output     Output file\n");
42     printf(" -v, --verbose    Verbose mode, print out lots of information
          about what's going on\n");
43     printf(" -s, --simulator  Do a hex dump of the program for the Verilog
          testbench\n");
44     printf(" -l, --listing    Print a command listing useful for debugging\n")
          ;
45     printf(" -h, --help       Print this help message\n");
```

```
46      printf(" Note that the -s, -l, and -v arguments are mutually exclusive.\n\
            n");
47      return(0);
48    }
49
50    // Get the input file name
51    QString inputFilePath(argList.last()); // Assume input file name is the last
          argument
52
53    // Determine the output file name
54    // If the -o flag was specified, use that name regardless of extension
55    QString outputFilePath;
56    if(argList.contains("-o")){
57      outputFilePath = argList.at(argList.indexOf("-o") + 1);
58    }
59    else if(argList.contains("--output")){
60      outputFilePath = argList.at(argList.indexOf("--output") + 1);
61    }
62    else{
63      // If no output file was specified, then use the input file name with the
            .S19 file extension
64      outputFilePath = inputFilePath + ".s19"; // Do something to strip off the
            extension
65    }
66
67    // Determine what kind of output to send to the terminal
68    bool verbose = false;
69    bool simDump = false;
70    bool listing = false;
71
72    if(argList.contains("-v") || argList.contains("--verbose")){
73      verbose = true;
74    }
75    else if(argList.contains("-s") || argList.contains("--simulator")){
76      simDump = true;
77    }
78    else if(argList.contains("-l") || argList.contains("--listing")){
79      listing = true;
80    }
81    Console::instance().setVerbose(verbose);
82
83    // Open the input file
84    QFile inputFile(inputFilePath);
85    if(!inputFile.open(QIODevice::ReadOnly | QIODevice::Text)){
86      printf("Failed to open file %s\n", inputFilePath.toAscii().constData());
87      return(1);
88    }
89
90    Parser p;
91    QByteArray programBytes;
92
93    // Run the first pass of the parser
94    // When undefined labels are encountered, the parser inserts 0x0000
95    // If undefined aliases are encountered, the parser throws an error
```

```
96    while(!inputFile.atEnd())
97    {
98      QString command(inputFile.readLine()); // Get the command string to parse
99      VERBOSE(p.linesRead(), command.trimmed().toAscii().constData()); // Print
          the command
100
101     // TODO: for each line, store the starting address so we can create a
          listing-style output
102     QByteArray commandBytes = p.parseLine(command);
103     programBytes.append(commandBytes);
104   }
105
106   // Fill in the labels which were undefined in the first pass
107   p.assignUnknownLabels(programBytes);
108
109   if(simDump){
110     for(int i = 0; i < programBytes.length(); i++){
111       printf("%02x\n", (unsigned char)(programBytes[i]));
112     }
113   }
114
115 /* Create the output file (Motorola SREC format)
116    All values are are hexadecimal, but are written in pairs of ASCII
         characters.
117    The format follows this pattern:
118    | "S1" | Byte Count | Start address | Data Data Data Data | Checksum |
119    |      |   1 byte   |    2 bytes    |    Up to 32 bytes   |  1 byte  |
120
121 */
122
123   // Open the file
124   QFile outputFile(outputFilePath);
125   outputFile.open(QIODevice::WriteOnly | QIODevice::Text);
126
127   int i = 0;
128   while(i < programBytes.length())
129   {
130     unsigned char checksum; // The checksum is the ones' complement of the sum
          of the byte count, address, and data
131
132     // Create the line header
133     int lineByteCount = programBytes.length() - i; // Number of bytes
          remaining
134     lineByteCount = (lineByteCount < 32) ? lineByteCount : 32; // If there are
          more than 32 bytes remaining, only print 32 of them
135     QString lineString = QString("S1%1%2").arg(lineByteCount + 3, 2, 16, QChar
          ('0')).arg(i, 4, 16, QChar('0'));
136     checksum += lineByteCount; // Add the data byte count to the checksum
137     checksum += i; // Add the starting address to the checksum
138
139     for(int j = 0; j < lineByteCount; j++)
140     {
141       // Add the bytes
```

```
      lineString.append(QString("%1").arg((unsigned char)(programBytes[i]), 2,
          16, QChar('0')));
      checksum += programBytes[i];
      i++;
    }
    // Write the checksum
    checksum = ~checksum;
    lineString.append(QString("%1").arg(checksum, 2, 16, QChar('0')));
    outputFile.write(lineString.toAscii().constData());
    outputFile.write("\n"); // Write a newline
  }


return(0);
}
```

```
/** parser.cpp
 * Class declaration for the parser class, which parses sets of instructions
    passed to it.
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 24 November 2010
 * $LastChangedDate: 2010-12-14 23:24:10 -0600 (Tue, 14 Dec 2010) $
 */

#ifndef PARSER_H
#define PARSER_H

#include <QString>
#include <QHash>
#include <QByteArray>

class Parser
{

public:
  typedef enum
  {
    NOP = 0x00,
    ADD = 0x01,
    SUB = 0x02,
    MUL = 0x03,
    AND = 0x04,
    OR = 0x05,
    LSR = 0x06,
    LSL = 0x07,
    COMP = 0x08,
    ASR = 0x09,
    ASL = 0x0a,
    NEG = 0x0b, // Two's complement
    // PASSTHROUGH (0x0c) is for internal use only
    JUMP = 0x0f,
    LOAD = 0x10,
    STORE = 0x11,
    MOVE = 0x12,
```

```
38      LSTACK = 0x13,
39      JSR = 0x14,
40      RSUB = 0x15,
41      RINT = 0x16,
42      HALT = 0x1F,
43      INVALID = 0xFF
44    } Opcode;
45
46    typedef enum
47    {
48      A = 0,
49      B = 1,
50      C = 2,
51      D = 3,
52      E = 4,
53      F = 5,
54      G = 6,
55      H = 7
56    } RegisterCode;
57
58    typedef enum
59    {
60      NONE = 0,
61      REGISTER = 2,
62      IMMEDIATE = 4,
63      ADDRESS = 8
64    } TokenType;
65
66    Parser();
67    QByteArray parseLine(QString line);
68    void assignUnknownLabels(QByteArray& code);
69    int linesRead(void) {return(mLineCount);}
70
71  private:
72    bool parseRegisterDest(QStringList* tokens, unsigned short* opcodeBytes);
73    Opcode stringToOpcode(QString str);
74    TokenType parseParameterToken(QString token, int allowable, unsigned short &
          value);
75
76    int mLineCount; ///< Counts how many lines have been parsed
77
78    /// Address where the next instruction will be stored in memory, used for
          labels
79    unsigned int mByteLocation;
80
81    /// Map of addresses to unknown labels
82    QHash<unsigned short, QString> mUnknownLabels;
83
84    /// Map of defines and labels to addresses
85    QHash<QString, QString> mDefineTable;
86
87  };
88
89  #endif // PARSER_H
```

```
/** parser.cpp
 * Code to parse instructions given one at a time. Labels are held
    persistently and handled appropriately.
 * Author: Steven Bell <steven.bell@student.oc.edu>
 * Date: 24 November 2010
 * $LastChangedDate: 2010-12-14 23:24:10 -0600 (Tue, 14 Dec 2010) $
 */

#include <cstdio>
#include <QStringList>
#include "console.h"
#include "parser.h"


/** Constructor
 */
Parser::Parser()
{
  mByteLocation = 0;
  mLineCount = 1; // Line numbers start at 1, not 0!
}

/** Parses a single line of code, which is assumed to contain a single
   instruction at most.
 * \param line Text string to parse.
 */
QByteArray Parser::parseLine(QString command)
{
  // Strip off any comment
  int commentPos = command.indexOf('*');
  if(commentPos != -1){ // If a comment delimeter was found,
    command = command.left(commentPos);
  }

  QStringList tokens = command.split(QRegExp(",|\\s"), QString::SkipEmptyParts
     );

  // TODO: should use a regex here to make sure that we don't end up with
  // funky characters in the labels.
  while(!tokens.isEmpty() && tokens.first().contains(QRegExp("^[a-zA-Z]\\w+:$"
     )))
  {
    // Parse the label(s) from the front, if there are any
    QString label = tokens.first();
    label = label.remove(QChar(':')); // Take the colon off the end
    VERBOSE(mLineCount, "Label␣found␣at␣0x%04x:␣\"%s\"", mByteLocation, label.
       toAscii().constData());

    // Create a string with the memory address so we can use it like any other
        define
    mDefineTable[label] = QString("0x%1").arg(mByteLocation, 4, 16, QChar('0')
       );
    tokens.removeFirst();
  }
```

```
48
49  if(tokens.isEmpty()){ // If there's nothing, or only labels,
50    VERBOSE(mLineCount, "Empty line!"); // Then move on
51    mLineCount++;
52    return(QByteArray());
53  }
54
55  QByteArray commandBytes; // Complete set of bytes, including immediates and
        addresses
56  unsigned short opcodeBytes = 0; // Pair of bytes used to assemble the opcode
57  unsigned short parsedBytes; // Values returned from each token parsing
58  Parser::TokenType parseResult; // Return type of token that was parsed
59
60  QString codeString = tokens.first(); // Save this in a separate variable so
        we can use it to differentiate the jumps
61  Parser::Opcode code = stringToOpcode(codeString);
62  tokens.removeFirst();
63  opcodeBytes = code << 11; // Move the code into the 5 highest bytes
64  mByteLocation += 2;
65
66  switch(code){
67    case Parser::NOP:
68    case Parser::HALT:
69    case Parser::RSUB:
70    case Parser::RINT:
71      VERBOSE(mLineCount, "No args required");
72      break;
73    case Parser::ADD:
74    case Parser::SUB:
75    case Parser::MUL:
76    case Parser::AND:
77    case Parser::OR:
78      VERBOSE(mLineCount, "Two args required, register and register/immediate"
            );
79
80      parseRegisterDest(&tokens, &opcodeBytes);
81
82      parseResult = parseParameterToken(tokens.first(), Parser::REGISTER |
            Parser::IMMEDIATE, parsedBytes);
83      tokens.removeFirst();
84      if(parseResult == REGISTER){
85        opcodeBytes = opcodeBytes | (parsedBytes << 5); // Put the source
              register into bytes 7-5
86        // Don't have to set the source type, since it's already 00
87      }
88      else if(parseResult == IMMEDIATE){
89        // Append the immediate to the extra bytes
90        commandBytes.append((char)parsedBytes);
91        mByteLocation += 1;
92        opcodeBytes = opcodeBytes | (0x0400); // Set the source type bits to
              immediate
93      }
94      else{
```

```
95          ERROR(mLineCount, "Expected␣register␣or␣immediate␣as␣second␣argument")
                ;
96        }
97        break;
98      case Parser::LSR:
99      case Parser::LSL:
100     case Parser::ASR:
101     case Parser::ASL:
102     case Parser::COMP:
103     case Parser::NEG:
104       VERBOSE(mLineCount, "One␣register␣argument␣required");
105       parseRegisterDest(&tokens, &opcodeBytes); // The first argument must
              always be a the destination register
106       break;
107     case Parser::JUMP:
108       if(codeString.toUpper() == "JCAR"){
109         opcodeBytes = opcodeBytes | (0x0001); // Carry code is binary 01
110       }
111       else if(codeString.toUpper() == "JZERO"){
112         opcodeBytes = opcodeBytes | (0x0002); // Zero code is binary 10
113       }
114       else if(codeString.toUpper() == "JNEG"){
115         opcodeBytes = opcodeBytes | (0x0003); // Negative code is binary 11
116       }
117       // Jump always code is binary 00, so we don't have to do anything
118       // Fall through the case so that we can get the memory argument
119     case Parser::LSTACK:
120     case Parser::JSR:
121       VERBOSE(mLineCount, "One␣memory␣argument␣required");
122       parseResult = parseParameterToken(tokens.first(), Parser::ADDRESS,
              parsedBytes);
123       tokens.removeFirst();
124       if(parseResult == ADDRESS){
125         commandBytes.append((char)(parsedBytes >> 8));
126         commandBytes.append((char)parsedBytes);
127         mByteLocation += 2;
128       }
129       else{
130         ERROR(mLineCount, "Expected␣address␣or␣label␣as␣first␣argument");
131       }
132
133       break;
134     case Parser::LOAD:
135       VERBOSE(mLineCount, "Two␣args␣required,␣register␣and␣register/immediate/
              memory");
136       parseRegisterDest(&tokens, &opcodeBytes); // The first argument must
              always be a the destination register
137       parseResult = parseParameterToken(tokens.first(), Parser::REGISTER |
              Parser::IMMEDIATE | Parser::ADDRESS, parsedBytes);
138       tokens.removeFirst();
139       if(parseResult == REGISTER){ // COPY
140         opcodeBytes = opcodeBytes | (parsedBytes << 5); // Put the source
              register as
141         // Don't have to set the source type, since it's already 00
```

```
142       }
143       else if(parseResult == IMMEDIATE){
144         commandBytes.append((char)parsedBytes);
145         mByteLocation += 1;
146         opcodeBytes = opcodeBytes | (0x0400); // Set the source type bits to
              immediate
147       }
148       else if(parseResult == ADDRESS){
149         commandBytes.append((char)(parsedBytes >> 8));
150         commandBytes.append((char)parsedBytes);
151         mByteLocation += 2;
152         opcodeBytes = opcodeBytes | (0x0200); // Set the source type bits to
              memory
153       }
154
155       break;
156     case Parser::STORE:
157       VERBOSE(mLineCount, "Two␣args␣required,␣register␣and␣memory");
158
159       parseResult = parseParameterToken(tokens.first(), Parser::REGISTER,
            parsedBytes);
160       tokens.removeFirst();
161       if(parseResult == REGISTER){
162         opcodeBytes = opcodeBytes | (parsedBytes << 5);
163       }
164       else{
165         ERROR(mLineCount, "Expected␣register␣as␣first␣argument");
166       }
167
168       parseResult = parseParameterToken(tokens.first(), Parser::ADDRESS,
            parsedBytes);
169       tokens.removeFirst();
170       if(parseResult == ADDRESS){
171         commandBytes.append((char)(parsedBytes >> 8));
172         commandBytes.append((char)parsedBytes);
173         mByteLocation += 2;
174         opcodeBytes = opcodeBytes | (0x0100); // Set the destination type bits
              to memory
175       }
176       else{
177         ERROR(mLineCount, "Expected␣address␣as␣second␣argument");
178       }
179
180       break;
181     case Parser::MOVE:
182       // This code is repeated several times essentially verbatim.  Time for a
            function?
183       VERBOSE(mLineCount, "Two␣addresses␣required\n");
184       parseResult = parseParameterToken(tokens.first(), Parser::ADDRESS,
            parsedBytes);
185       tokens.removeFirst();
186       if(parseResult == ADDRESS){
187         commandBytes.append((char)(parsedBytes >> 8));
188         commandBytes.append((char)parsedBytes);
```

```
189         mByteLocation += 2;
190       }
191       else{
192         ERROR(mLineCount, "Expected address as first argument");
193       }
194       parseResult = parseParameterToken(tokens.first(), Parser::ADDRESS,
              parsedBytes);
195       tokens.removeFirst();
196       if(parseResult == ADDRESS){
197         commandBytes.append((char)(parsedBytes >> 8));
198         commandBytes.append((char)parsedBytes);
199         mByteLocation += 2;
200       }
201       else{
202         ERROR(mLineCount, "Expected address as second argument");
203       }
204
205
206      break;
207     default:
208         ERROR(mLineCount, "Unrecognized opcode");
209       break;
210   }
211
212   // Make sure that we've used up all of the arguments.  If not, print a
        warning
213   if(!tokens.isEmpty()){
214     WARNING(mLineCount, "Unused arguments");
215   }
216
217   commandBytes.push_front((char)(opcodeBytes & 0x00ff));
218   commandBytes.push_front((char)(opcodeBytes >> 8));
219
220   mLineCount++;
221   // Byte location was already handled in-line
222
223   return(commandBytes);
224 }
225
226 /** This function goes through all of the locations in the unknown labels list
        and
227   * replaces the placeholder address with the correct value.  If the label is
        not
228   * found, then it prints an error.
229   */
230 void Parser::assignUnknownLabels(QByteArray& code)
231 {
232   QHash<unsigned short, QString>::iterator i;
233   for(i = mUnknownLabels.begin(); i != mUnknownLabels.end(); i++)
234   {
235     if(mDefineTable.contains(i.value())){
236       QString replacementString = mDefineTable[i.value()];
237       bool conversionOk; // Assume that it works; since we created the value!
```

```
238       unsigned int replacementValue = replacementString.mid(3).toUShort(&
              conversionOk, 16);
239
240       // TODO: This will fail badly if the code has multiple segments or doesn
              't start at 0.
241       code[i.key()] = (replacementValue >> 8);
242       code[i.key() + 1] = (replacementValue & 0x00FF);
243
244
245       VERBOSE(mLineCount, "Replacing␣label␣\"%s\"␣with␣0x%04x", i.value().
              toAscii().constData(), replacementValue);
246     }
247     else{
248       ERROR(mLineCount, "Unknown␣label␣\"%s\"", i.value().toAscii().constData
              ());
249     }
250   }
251 }
252
253
254 /* This function removes one of the tokens from the list
255  */
256 bool Parser::parseRegisterDest(QStringList* tokens, unsigned short*
        opcodeBytes)
257 {
258   unsigned short parsedBytes;
259   Parser::TokenType parseResult = parseParameterToken(tokens->first(), Parser
          ::REGISTER, parsedBytes);
260   tokens->removeFirst();
261   if(parseResult == REGISTER){
262     *opcodeBytes = *opcodeBytes | (parsedBytes << 2); // Put the destination
            register into bytes 4-2
263     return(true);
264   }
265   else{
266     ERROR(mLineCount, "Expected␣register␣as␣first␣argument");
267     return(false);
268   }
269 }
270
271
272 /** Converts a string token (e.g, ADD or HALT) into an enum constant
        representing
273  * the opcode.
274  */
275 Parser::Opcode Parser::stringToOpcode(QString str)
276 {
277   str = str.toUpper(); // Force everything to uppercase
278
279   if(str == "NOP"){
280     return(NOP);
281   }
282   else if(str == "ADD"){
283     return(ADD);
```

```
284   }
285   else if(str == "SUB"){
286     return(SUB);
287   }
288   else if(str == "MUL"){
289     return(MUL);
290   }
291   else if(str == "AND"){
292     return(AND);
293   }
294   else if(str == "OR"){
295     return(OR);
296   }
297   else if(str == "LSR"){
298     return(LSR);
299   }
300   else if(str == "LSL"){
301     return(LSL);
302   }
303   else if(str == "COMP"){
304     return(COMP);
305   }
306   else if(str == "ASR"){
307     return(ASR);
308   }
309   else if(str == "ASL"){
310     return(ASL);
311   }
312   else if(str == "NEG"){
313     return(NEG);
314   }
315   else if(str == "JMP" || str == "JCAR" || str == "JZERO" || str == "JNEG"){
316     return(JUMP);
317   }
318   else if(str == "LOAD" || str == "COPY"){
319     return(LOAD);
320   }
321   else if(str == "STORE"){
322     return(STORE);
323   }
324   else if(str == "MOVE"){
325     return(MOVE);
326   }
327   else if(str == "LSTACK"){
328     return(LSTACK);
329   }
330   else if(str == "JSR"){
331     return(JSR);
332   }
333   else if(str == "RSUB"){
334     return(RSUB);
335   }
336   else if(str == "RINT"){
337     return(RINT);
```

```
338   }
339   else if(str == "HALT"){
340     return(HALT);
341   }
342   else{
343     return(INVALID);
344   }
345 }
346
347
348 /** Takes a single token, determines what type of token it is, and parses its
      value.
349  * If the token is a label or macro, it looks it up in the appropriate table
       and
350  * substitutes that value.
351  * \param token The token to parse.
352  * \param allowable Acceptable types of tokens.  Multiple types can be
       selected using bitwise OR. If
353  * a token of the selected type is not found, this function will return
       failure.
354  * \param value 2-byte variable which will hold the parsed value.
355  * \return The type of token that was parsed.  This could be a 3-bit register
       (registerCode),
356  * a one byte immediate value, a two byte immediate address, or a failure.
357   */
358 Parser::TokenType Parser::parseParameterToken(QString token, int allowable,
      unsigned short &value)
359 {
360   bool conversionOk;
361
362   // Use a set of regular expressions to sort the tokens
363   // If the token is a single letter, A-H (a-h) then it is a register
364   if(((allowable & REGISTER) != 0) && token.contains(QRegExp("^[a-hA-H]$"))){
365     VERBOSE(mLineCount, "Token␣is␣register");
366     char regChar = token.at(0).toLower().toAscii();
367     value = regChar - 97; // 97 is ascii for 'a'
368     return(REGISTER);
369   }
370
371   // If the token begins with 0x, then it is a hexadecimal address
372   else if(((allowable & ADDRESS) != 0) && token.contains(QRegExp("^0x[0-9a-fA-
        F_]+$"))){
373     VERBOSE(mLineCount, "Token␣is␣hex␣address");
374     value = token.toUShort(&conversionOk, 16); // Qt doesn't mind the leading
          0x
375     if(conversionOk){
376       return(ADDRESS);
377     }
378     else{
379       return(NONE);
380     }
381   }
382   // If the token begins with 0b, then it is a binary address
```

```
383   else if(((allowable & ADDRESS) != 0) && token.contains(QRegExp("^0b[01_]+$")
          )){
384     VERBOSE(mLineCount, "Token␣is␣binary␣address");
385     value = token.mid(2).toUShort(&conversionOk, 2); // Drop the "0b" and
            convert
386     if(conversionOk){
387       return(ADDRESS);
388     }
389     else{
390       return(NONE);
391     }
392   }
393   // If the token begins with any digit, then it is a decimal address
394   else if(((allowable & ADDRESS) != 0) && token.contains(QRegExp("^[-+]?\\d+$"
          ))){
395     VERBOSE(mLineCount, "Token␣is␣decimal␣address");
396     value = token.toUShort(&conversionOk, 10); // Qt automatically handles
            negative values
397     if(conversionOk){
398       return(ADDRESS);
399     }
400     else{
401       return(NONE);
402     }
403   }
404
405   // If the token begins with #0x, then it is a hexadecimal immediate
406   else if(((allowable & IMMEDIATE) != 0) && token.contains(QRegExp("^#0x[0-9a-
          fA-F_]+$"))){
407     VERBOSE(mLineCount, "Token␣is␣hex␣immediate");
408     value = token.mid(3).toUShort(&conversionOk, 16); // Drop the #0x
409     if(conversionOk){
410       return(IMMEDIATE);
411     }
412     else{
413       return(NONE);
414     }
415   }
416   // If the token begins with #0b, then it is a binary address
417   else if(((allowable & IMMEDIATE) != 0) && token.contains(QRegExp("^#0b[01_]+
          $"))){
418     VERBOSE(mLineCount, "Token␣is␣binary␣immediate");
419     value = token.mid(3).toUShort(&conversionOk, 2); // Drop the "#0b" and
            convert
420     if(conversionOk){
421       return(IMMEDIATE);
422     }
423     else{
424       return(NONE);
425     }
426   }
427   // If the token begins with '#' and then any digit, then it is a decimal
          address
```

```
  else if(((allowable & IMMEDIATE) != 0) && token.contains(QRegExp("^#[-+]?\\d
      +$"))){
    VERBOSE(mLineCount, "Token␣is␣decimal␣immediate");
    value = token.mid(1).toUShort(&conversionOk, 10); // Drop the "#"
    if(conversionOk){
      return(IMMEDIATE);
    }
    else{
      return(NONE);
    }
  }
  else if(token.contains(QRegExp("^[a-zA-Z]\\w+$"))){
    // If the token starts with a letter, contains only alphanumeric
       characters and
    // underscores, and is at least 2 characters long, then see if it's a
       label or macro

    if(mDefineTable.contains(token)){
      // Replace the macro or label with the appropriate token
      // Call this function recursively on the replaced token
      return(parseParameterToken(mDefineTable[token], allowable, value));
    }
    else{
      // If the table doesn't contain what we're looking for, just substitute
         a placeholder
      // address and put this location into the unknown labels table.
      if(allowable & ADDRESS){
        VERBOSE(mLineCount, "Encountered␣unknown␣label␣%s␣at␣0x%04x", token.
           toAscii().constData(), mByteLocation);
        mUnknownLabels[mByteLocation] = token;
        value = 0;
        return(ADDRESS);
      }
      else{
        // If an address isn't allowed here, then it's an error
        ERROR(mLineCount, "Unexpected␣token␣\"%s\"", token.toAscii().constData
           ());
        return(NONE);
      }
    }
  }
  else{
    ERROR(mLineCount, "Unexpected␣token␣\"%s\"", token.toAscii().constData());
    return(NONE);
  }
}
```

```
/** \file console.h
 * Singleton class which handles printing of messages, errors and warnings
 * to the console.  It contains flags which can be used to turn messages on
 * and off, and keeps track of the total number of errors/warnings.
 * \author Steven Bell <steven.bell@student.oc.edu>
 * \date 12 December 2010
 */
```

```
8
9  class Console
10 {
11 public:
12   static Console& instance();
13   void setVerbose(bool verbose);
14   void printError(int lineNum, const char* format, ...);
15   void printWarning(int lineNum, const char* format, ...);
16   void printMessage(int lineNum, const char* format, ...);
17   void printVerbose(int lineNum, const char* format, ...);
18   void printSummary(void);
19   bool errorOccured(void) {return(mErrorCount > 0);}
20
21 private:
22   Console(); ///< Private singleton constructor
23   static Console mInstance;
24   int mErrorCount; ///< Number of times the error message function has been
        called
25   int mWarningCount; ///< Number of times the warning function has been called
26   bool mVerbose; ///< Whether or not to print verbose stuff.
27
28 };
29
30 // Convenience macros
31 #define ERROR(line, ...) Console::instance().printError(line, __VA_ARGS__)
32 #define WARNING(line, ...) Console::instance().printWarning(line, __VA_ARGS__)
33 #define MESSAGE(line, ...) Console::instance().printMessage(line, __VA_ARGS__)
34 #define VERBOSE(line, ...) Console::instance().printVerbose(line, __VA_ARGS__)
```

```
1  /** \file console.cpp
2   * \author Steven Bell <steven.bell@student.oc.edu>
3   * \date 12 December 2010
4   */
5
6  #include <cstdio>
7  #include <cstdarg>
8  #include "console.h"
9
10 // Single instance instantiation
11 Console Console::mInstance;
12
13 Console::Console()
14 {
15   mErrorCount = 0;
16   mWarningCount = 0;
17 }
18
19 Console& Console::instance(void)
20 {
21   return(mInstance);
22 }
23
24 void Console::printError(int lineNum, const char*format, ...)
25 {
```

```
26    mErrorCount++;
27
28    va_list argptr;
29    va_start(argptr, format);
30    printf("%d␣Error:␣", lineNum);
31    vprintf(format, argptr);
32    printf("\n");
33    va_end(argptr);
34  }
35
36  void Console::printWarning(int lineNum, const char*format, ...)
37  {
38    mWarningCount++;
39
40    va_list argptr;
41    va_start(argptr, format);
42    printf("%d␣Warning:␣", lineNum);
43    vprintf(format, argptr);
44    printf("\n");
45    va_end(argptr);
46  }
47
48  void Console::printMessage(int lineNum, const char*format, ...)
49  {
50    va_list argptr;
51    va_start(argptr, format);
52    printf("%d␣:␣", lineNum);
53    vprintf(format, argptr);
54    printf("\n");
55    va_end(argptr);
56  }
57
58  void Console::printVerbose(int lineNum, const char*format, ...)
59  {
60    if(mVerbose){
61      va_list argptr;
62      va_start(argptr, format);
63      printf("%d␣:␣", lineNum);
64      vprintf(format, argptr);
65      printf("\n");
66      va_end(argptr);
67    }
68  }
69
70  void Console::printSummary(void)
71  {
72    printf("\n");
73    printf("%d␣errors,␣%d␣warnings\n", mErrorCount, mWarningCount);
74  }
75
76
77  void Console::setVerbose(bool verbose)
78  {
79    mVerbose = verbose;
```

```
80 }
```

F Final test program

The code on the following pages is based on the test code provided on Blackboard and modified for my assembler. The code was syntax-highlighted with Vim.

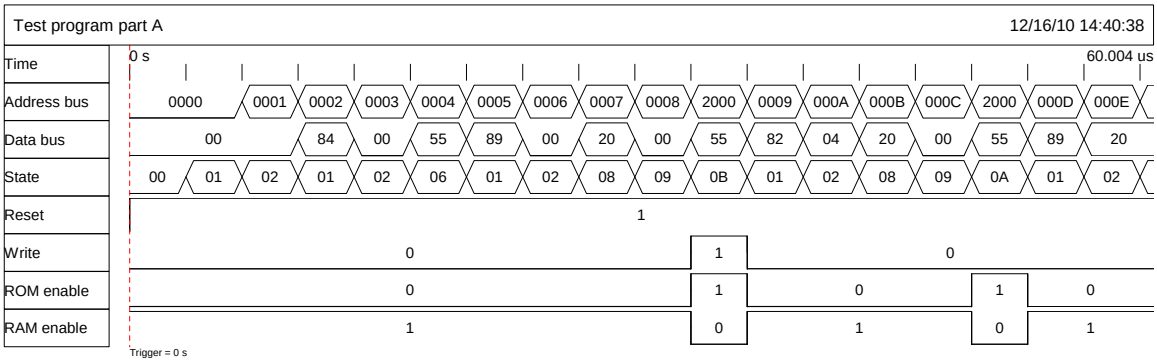
```
* Final test program for IC design, Part A
* Steven Bell
* 13 December 2010
*
* Several changes were made from the code given on Blackboard to this code:
*  - The assembler takes two opcodes at most, so adding an immediate to a register
*    puts the value back into that same register.  A COPY is done first to achieve
*    the effect of adding an immediate and putting the result in another register.
*  - The registers are labeled a through h.
*  - RAM is located at 0x2000 through 0x3999.

* Test NOP
NOP

* Test LOAD and STORE with RAM
LOAD a, #0x55 * Load immediate
STORE a, 0x2000 * Store to RAM, 0x55 expected
LOAD b, 0x2000 * Load back from RAM into another register
STORE b, 0x2001 * Store back to RAM, 0x55 expected

* Test ADD
COPY c, b * Copy from b into c
ADD c, #0x22 * Add an immediate to c
STORE c, 0x2002 * Expect 0x77

* Test flags from ADD
LOAD e, #0x5A
ADD b, a  * Should give 0xAA in b
ADD e, #0xA5  * Should give 0xFF in e
JCAR end * Should not jump
STORE b, 0x2003  * Should be 0xAA
STORE e, 0x2004  * Should be 0xFF
JZERO end * Should not jump

* Test SUBtract and flags
LOAD d, #0xA9
COPY f, b * Copy b to f (should be 0xAA)
SUB f, #0x33  * Subtract 0x33, f should be 0x77
SUB d, c  * Subtract c from d, d should be 0x32
JCAR end  * Should not jump
JZERO end  * Should not jump
STORE d, 0x2005  * Should be 0x32
STORE f, 0x2006  * Should be 0x77
JMP pass1
HALT

pass1:
COPY a, e  * Copy 0xFF into a
ADD a, #0xFF  * Add 0xFF, should give 0xFE with carry
STORE a, 0x2007  * Should be 0xFE
JZERO end  * Should not jump
JCAR pass2  * Should jump
HALT

pass2:
ADD a, #0x01  * Should give 0xFF, no carry
JZERO end  * Should not jump
JCAR end  * Should not jump
STORE a, 0x2008  * Should give 0xFF
ADD a, #0x01  * Should give 0x00 with a carry
JZERO pass3  * Should jump
HALT

pass3:
STORE a, 0x2009  * Should give 0x00
SUB d, #0x21  * Should give 0x11 in d
JZERO end  * Should not jump
JCAR end  * Should not jump
STORE d, 0x200A  * Should give 0x11
SUB d, #0x11  * Should give 0x00 in d
JCAR end  * Should not jump
JZERO pass4  * Should jump
HALT

pass4:
```

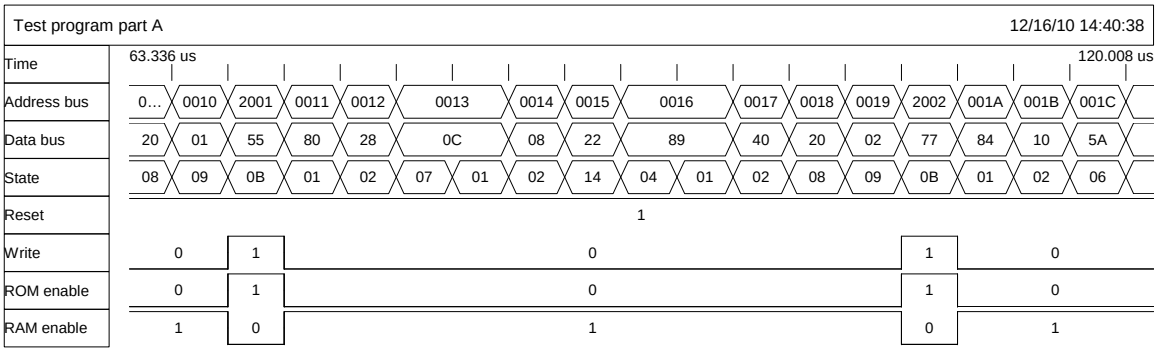
```
STORE d, 0x200B  * Should give 0x00
SUB d, #0x33  * Should give -0x33 = 0xCD in d
JZERO end  * Should not jump
JNEG pass5  * Should jump
HALT

pass5:
STORE d, 0x200C  * Should give -0x33 = 0xCD
ADD f, #0x00  * f should contain 0x77, and it shouldn't change!
JCAR end  * Should not branch
SUB f, e  * e should contain 0xFF, giving 0x78 with a borrow
JZERO end  * Should not jump
JNEG end  * Should not jump (the resulting value is positive)
JCAR pass6  * Should jump (a borrow occured)

* Test multiply
pass6:
STORE f, 0x200D  * Should give 0x78
COPY g, b  * Should give 0xAA in g
MUL g, #0xA5  * Multiply giving 6D92
STORE g, 0x200E  * Store the top half of the multiply (0x6D)
STORE h, 0x200F  * Store the bottom half of the multiply (0x92)
LOAD h, #0xBB  * Load 0xBB into h
MUL h, g  * Multiply the top and bottom half of gh together, result should be 0x4F9F
STORE g, 0x2010  * Write the result out (0x4F)
STORE h, 0x2011  * (0x9F)

* Test unary ALU operations
COPY b, a  * b should contain 0x00
COMP b  * b should be 0xFF
STORE b, 0x2012
COMP b  * Complement again, should give 0x00
STORE b, 0x2013
JCAR end  * Shouldn't jump
JZERO pass7  * Should jump
HALT

pass7:
COPY e, d  * e should now contain 0xCD = 0b 1100 1101
LSR e  * Logical shift right
STORE e, 0x2014  * Should be 0b 0110 0110 = 0x66
LSR e * Logical shift right again
STORE e, 0x2015 * Should be 0x 0011 0011 = 0x33
COPY g, e  * g should now be 0x33
LSL g  * Logical shift left
STORE g, 0x2016 * Should be 0x 0110 0110 = 0x66
LSL g
STORE g, 0x2017  * Should be 0x 1100 1100 = 0xCC

end:
NOP
NOP
HALT
```

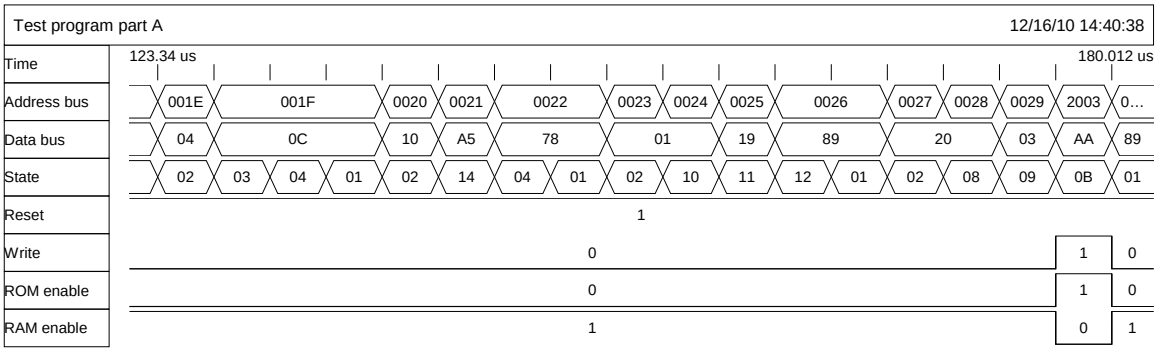
```
* Final test program for IC design, Part B
* Steven Bell
* 14 December 2010
*
* Several changes were made from the code given on Blackboard to this code:
*  - The assembler takes two opcodes at most, so adding an immediate to a register
*    puts the value back into that same register.  A COPY is done first to achieve
*    the effect of adding an immediate and putting the result in another register.
*  - The registers are labeled a through h.
*  - RAM is located at 0x2000 through 0x3999.

* Begin by loading registers with their nominal values from part A

LOAD a, #0x55
LOAD b, #0xFF
LOAD c, #0xFF
LOAD d, #0x33
* e will be assigned later
LOAD f, #0x03
* g will be assigned later
LOAD h, #0xC0

* Continue testing shifts
COPY e, d  * Copy 0x33 = 0b 0011 0011 into e
LSR e  * Shift e right (shift in a 0, giving 0b 0001 1001 = 0x19)
STORE e, 0x2000  * Should give 0x19
LSR e * 0b 0000 1100 = 0x0C
STORE e, 0x2001  * Should give 0x0C
COPY g, e
LSL g * 0b 0001 1000 = 0x18
STORE g, 0x2002  * Should give 0x18
LSL g * 0b 0011 0000 = 0x30
STORE g, 0x2003  * Should give 0x30

* Test shifts with jumps
LSR f  * Shift 0b 0000 0011 to get 0b 0000 0001 with a carry
JCAR shift1  * Should jump
HALT

shift1:
LSR f  * f should now be 0x00
JZERO shift2  * Should jump
HALT

shift2:
LSL h  * h was 0xC0 = 0b 1100 0000, should now be 0b 1000 0000 with a carry
JCAR shift3  * Should jump
HALT

shift3:
LSL h  * h will now be 0x00
JZERO pass8  * Should jump
HALT

* Test AND
pass8:
COPY f, a  * Copy 0x55 into f
AND f, #0x0F  * Mask the top four bits
STORE f, 0x2004  * Should be 0x05
AND e, a  * e = 0b 0000 1100, a = 0b 0101 0101
STORE e, 0x2005  * Should be 0x04
COPY b, f  * Copy 0x00 into b
AND b, #0xF0
STORE b, 0x2006  * Should be 0x00
JZERO pass9
HALT

* Test AND of 0x00 and 0xFF, and jump on zero
pass9:
AND c, b  * c = 0xFF, b = 0x00
STORE c, 0x2007  * Should be 0x00
JZERO pass10  * Should jump
HALT

* Test OR
```

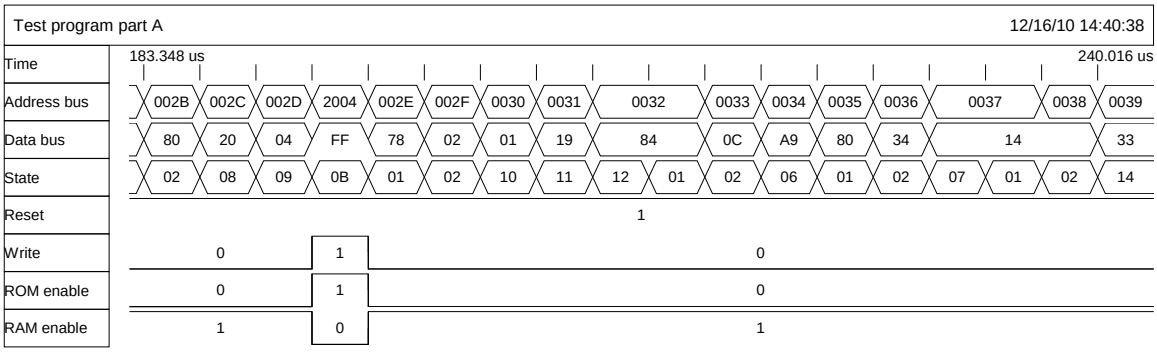
```
pass10:
COPY c, a  * Copy 0x55 into c
OR c, #0xA0  * 0b 0101 0101  OR 0b 1010 0000 gives 0xF5
STORE c, 0x2008  * Should be 0xF5
OR g, e  * g = 0x30 OR e = 0x04
STORE g, 0x2009  * Should be 0x34
COPY c, h  * Copy 0x00 into c
OR c, #0x00
STORE c, 0x200A  * Should be 0x00
JZERO pass11  * Should jump
HALT

pass11:
OR h, b  * 0x00 OR 0x00
STORE h, 0x200B  * Should be 0x00
JZERO end  * Should jump
HALT

end:
STORE a, 0x200C  * Should be 0x55
MOVE 0x200C, 0x200D  * Put 0x55 into 0x200C
LOAD b, 0x200D
HALT
```

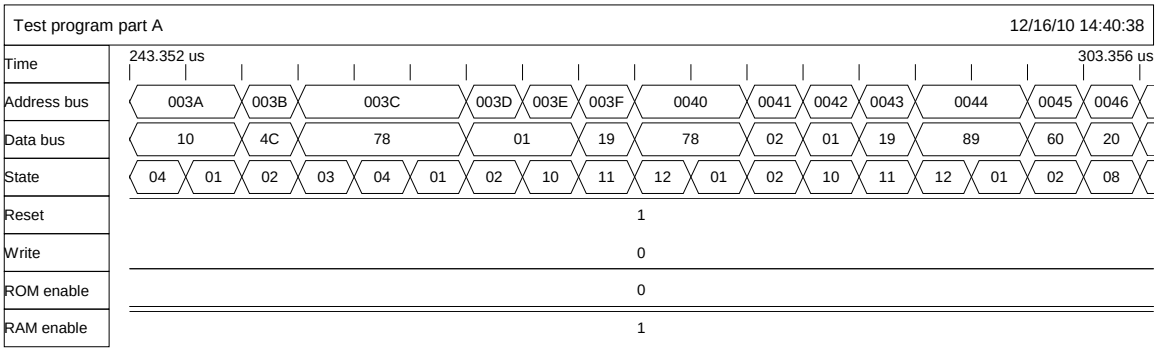
G Logic analyzer captures

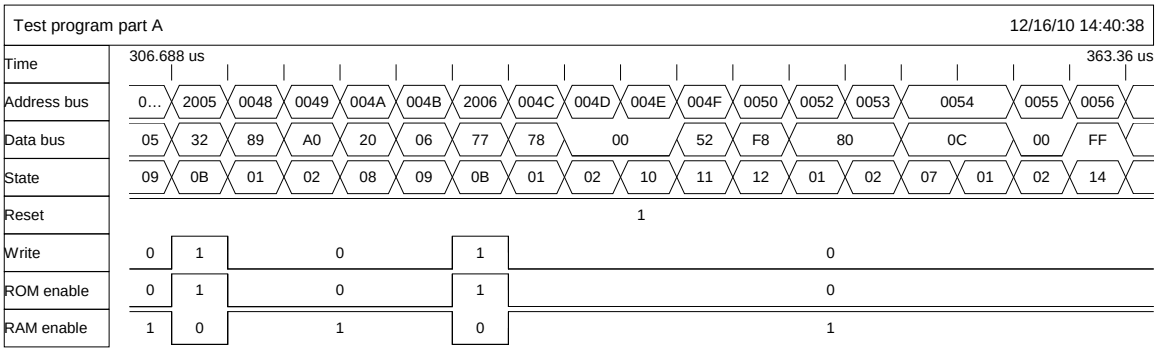

Test program part A
12/16/10 14:40:38
Time
0 s
60.004 us
Address bus
0000 0001 0002 0003 0004 0005 0006 0007 0008 2000 0009 000A 000B 000C 2000 000D 000E
Data bus
00 84 00 55 89 00 20 00 55 82 04 20 00 55 89 20
State
00 01 02 01 02 06 01 02 08 09 0B 01 02 08 09 0A 01 02
Reset
1
Write
0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1
Trigger = 0 s

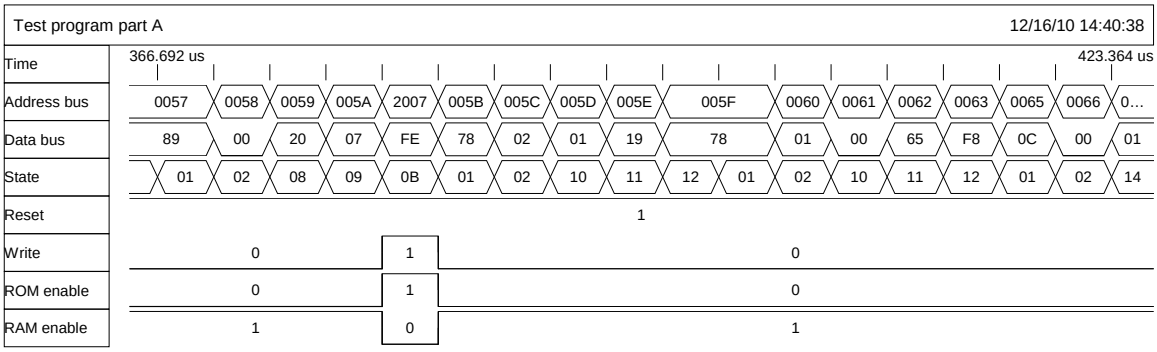

Test program part A
12/16/10 14:40:38
Time
63.336 us
120.008 us
Address bus
0… 0010 2001 0011 0012 0013 0014 0015 0016 0017 0018 0019 2002 001A 001B 001C
Data bus
20 01 55 80 28 0C 08 22 89 40 20 02 77 84 10 5A
State
08 09 0B 01 02 07 01 02 14 04 01 02 08 09 0B 01 02 06
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1

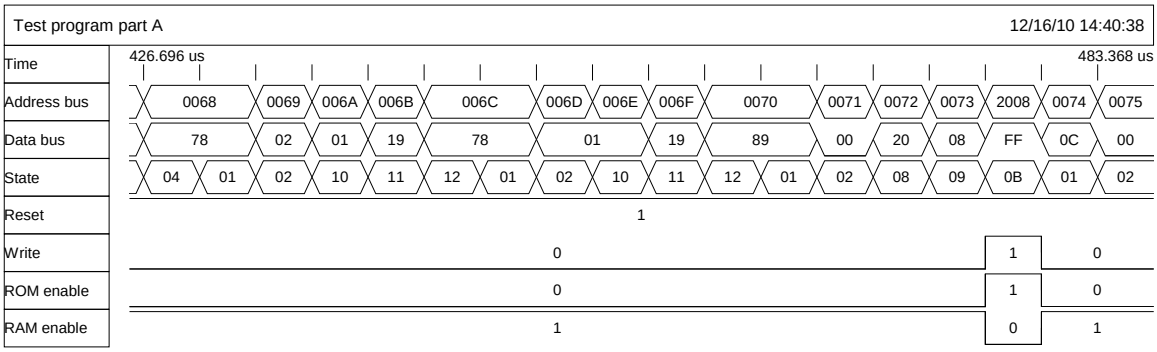

Test program part A
12/16/10 14:40:38
Time
123.34 us
180.012 us
Address bus
001E
001F
0020
0021
0022
0023
0024
0025
0026
0027
0028
0029
2003
0…
Data bus
04
0C
10
A5
78
01
19
89
20
03
AA
89
State
02
03
04
01
02
14
04
01
02
10
11
12
01
02
08
09
0B
01
Reset
1
Write
0
1
0
ROM enable
0
1
0
RAM enable
1
0
1

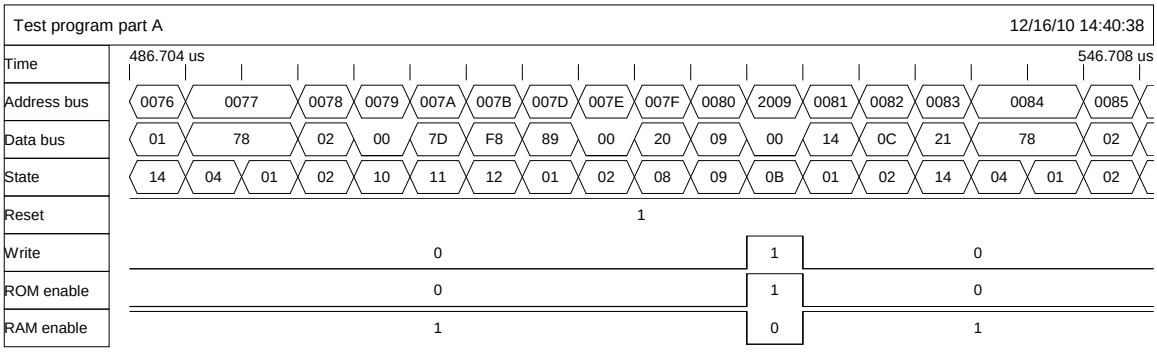

Test program part A
12/16/10 14:40:38
Time
183.348 us
240.016 us
Address bus
002B
002C
002D
2004
002E
002F
0030
0031
0032
0033
0034
0035
0036
0037
0038
0039
Data bus
80
20
04
FF
78
02
01
19
84
0C
A9
80
34
14
33
State
02
08
09
0B
01
02
10
11
12
01
02
06
01
02
07
01
02
14
Reset
1
Write
0
1
0
ROM enable
0
1
0
RAM enable
1
0
1

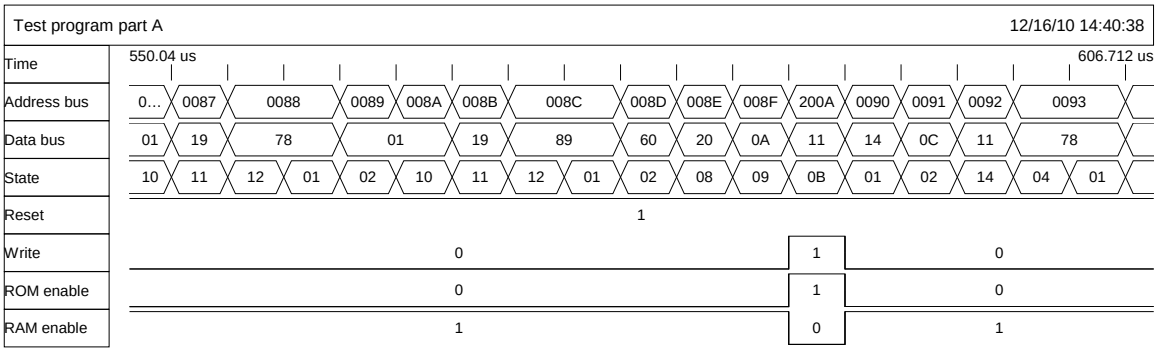

Test program part A
12/16/10 14:40:38
Time
243.352 us
303.356 us
Address bus
003A 003B 003C 003D 003E 003F 0040 0041 0042 0043 0044 0045 0046
Data bus
10 4C 78 01 19 78 02 01 19 89 60 20
State
04 01 02 03 04 01 02 10 11 12 01 02 10 11 12 01 02 08
Reset
1
Write
0
ROM enable
0
RAM enable
1

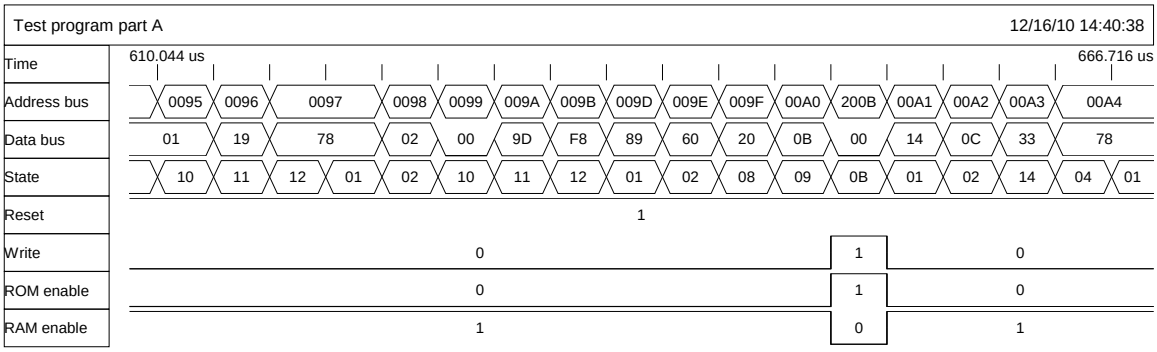

Test program part A
12/16/10 14:40:38
Time
306.688 us
363.36 us
Address bus
0… 2005 0048 0049 004A 004B 2006 004C 004D 004E 004F 0050 0052 0053 0054 0055 0056
Data bus
05 32 89 A0 20 06 77 78 00 52 F8 80 0C 00 FF
State
09 0B 01 02 08 09 0B 01 02 10 11 12 01 02 07 01 02 14
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1

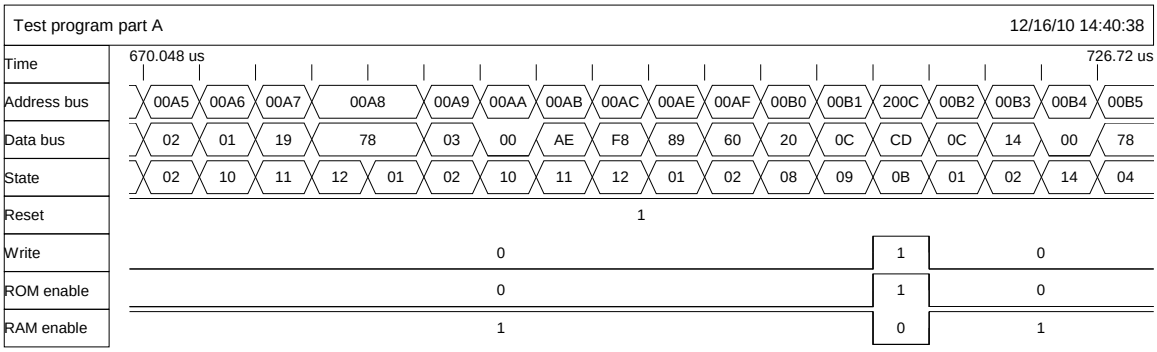

Test program part A
12/16/10 14:40:38
Time
366.692 us
423.364 us
Address bus
0057 0058 0059 005A 2007 005B 005C 005D 005E 005F 0060 0061 0062 0063 0065 0066 0…
Data bus
89 00 20 07 FE 78 02 01 19 78 01 00 65 F8 0C 00 01
State
01 02 08 09 0B 01 02 10 11 12 01 02 10 11 12 01 02 14
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

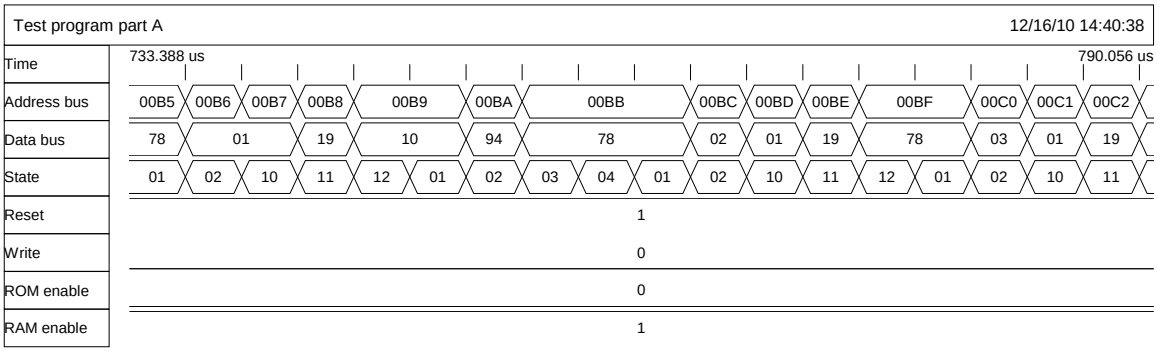

Test program part A
12/16/10 14:40:38
Time
426.696 us
483.368 us
Address bus
0068 0069 006A 006B 006C 006D 006E 006F 0070 0071 0072 0073 2008 0074 0075
Data bus
78 02 01 19 78 01 19 89 00 20 08 FF 0C 00
State
04 01 02 10 11 12 01 02 10 11 12 01 02 08 09 0B 01 02
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

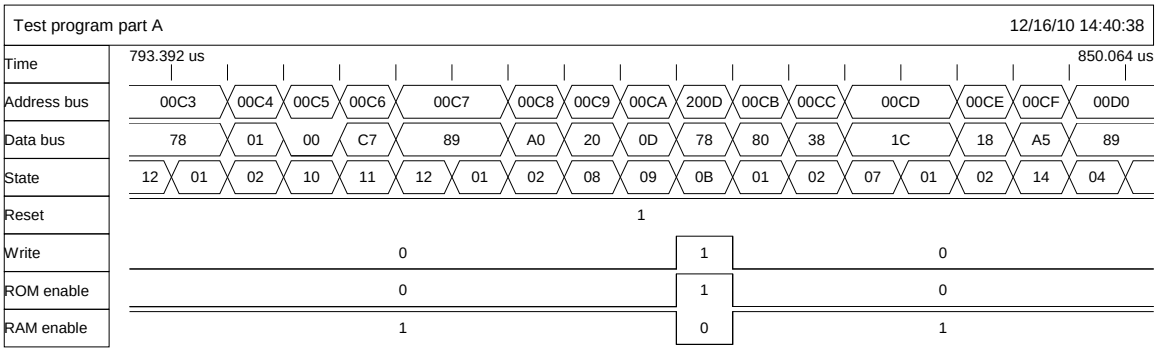

Test program part A
12/16/10 14:40:38
Time
486.704 us
546.708 us
Address bus
0076 0077 0078 0079 007A 007B 007D 007E 007F 0080 2009 0081 0082 0083 0084 0085
Data bus
01 78 02 00 7D F8 89 00 20 09 00 14 0C 21 78 02
State
14 04 01 02 10 11 12 01 02 08 09 0B 01 02 14 04 01 02
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

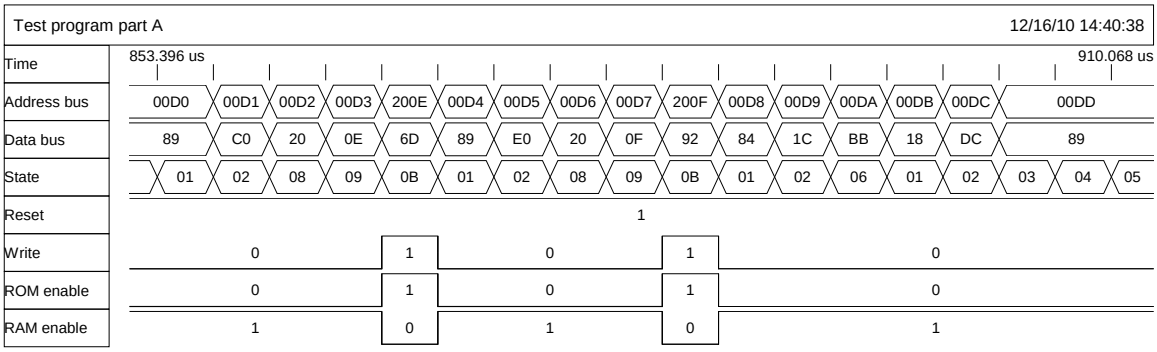

Test program part A
12/16/10 14:40:38
Time
550.04 us
606.712 us
Address bus
0… 0087 0088 0089 008A 008B 008C 008D 008E 008F 200A 0090 0091 0092 0093
Data bus
01 19 78 01 19 89 60 20 0A 11 14 0C 11 78
State
10 11 12 01 02 10 11 12 01 02 08 09 0B 01 02 14 04 01
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

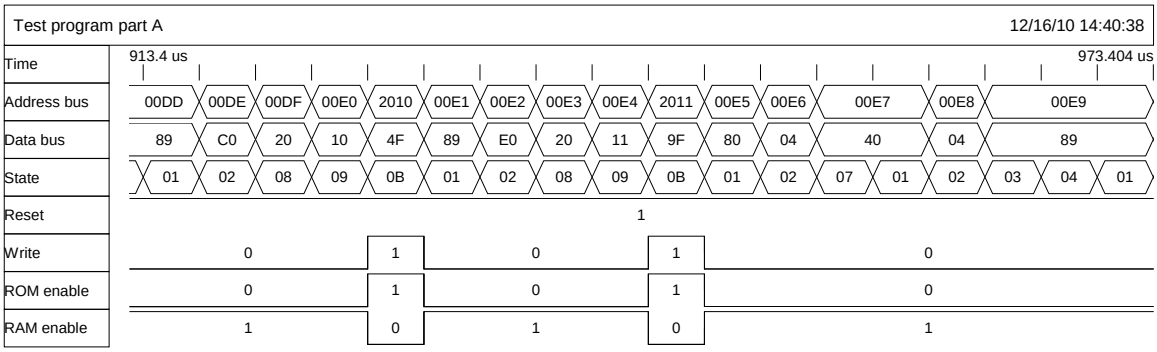

Test program part A
12/16/10 14:40:38
Time
610.044 us
666.716 us
Address bus
0095 0096 0097 0098 0099 009A 009B 009D 009E 009F 00A0 200B 00A1 00A2 00A3 00A4
Data bus
01 19 78 02 00 9D F8 89 60 20 0B 00 14 0C 33 78
State
10 11 12 01 02 10 11 12 01 02 08 09 0B 01 02 14 04 01
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

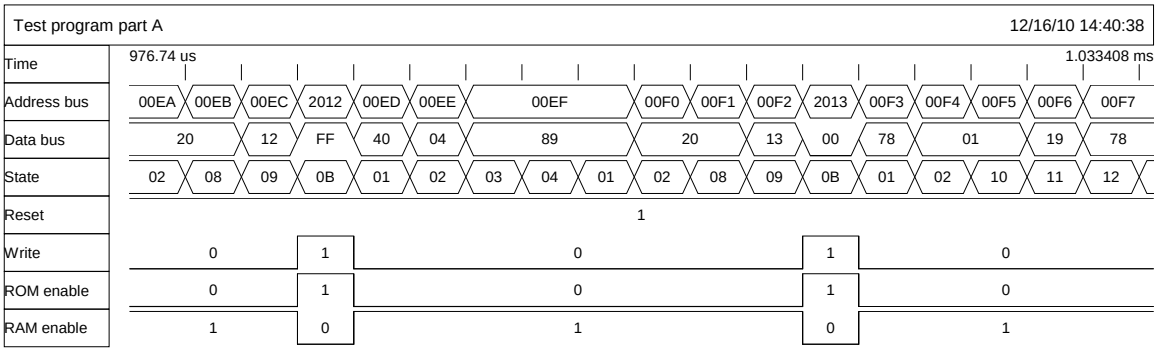

Test program part A
12/16/10 14:40:38
Time
670.048 us
726.72 us
Address bus
00A5 00A6 00A7 00A8 00A9 00AA 00AB 00AC 00AE 00AF 00B0 00B1 200C 00B2 00B3 00B4 00B5
Data bus
02 01 19 78 03 00 AE F8 89 60 20 0C CD 0C 14 00 78
State
02 10 11 12 01 02 10 11 12 01 02 08 09 0B 01 02 14 04
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

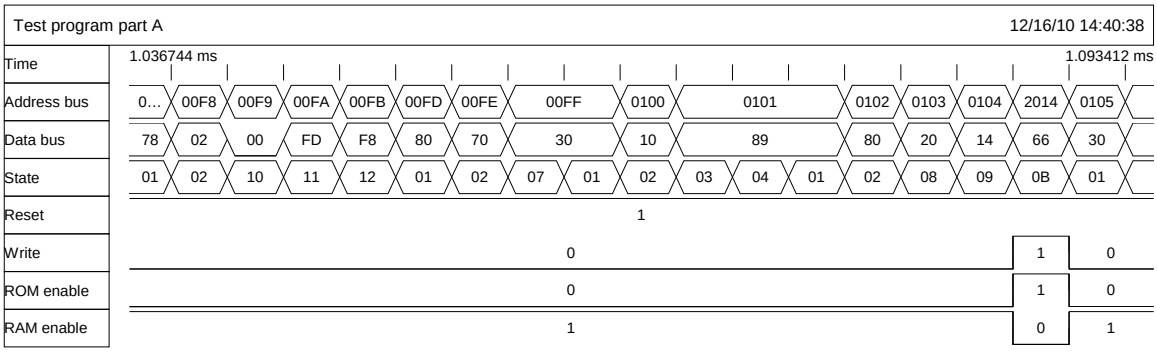

Test program part A
12/16/10 14:40:38
Time
733.388 us
790.056 us
Address bus
00B5 00B6 00B7 00B8 00B9 00BA 00BB 00BC 00BD 00BE 00BF 00C0 00C1 00C2
Data bus
78 01 19 10 94 78 02 01 19 78 03 01 19
State
01 02 10 11 12 01 02 03 04 01 02 10 11 12 01 02 10 11
Reset
1
Write
0
ROM enable
0
RAM enable
1

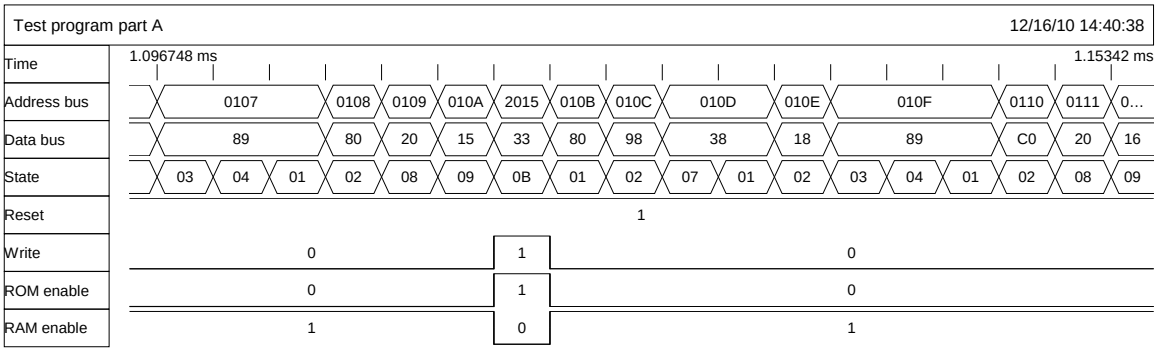

Test program part A
12/16/10 14:40:38
Time
793.392 us
850.064 us
Address bus
00C3 00C4 00C5 00C6 00C7 00C8 00C9 00CA 200D 00CB 00CC 00CD 00CE 00CF 00D0
Data bus
78 01 00 C7 89 A0 20 0D 78 80 38 1C 18 A5 89
State
12 01 02 10 11 12 01 02 08 09 0B 01 02 07 01 02 14 04
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

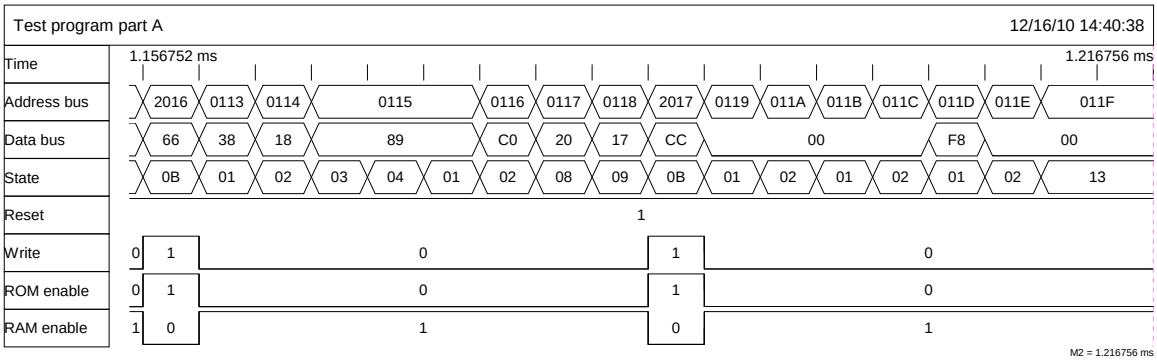

Test program part A
12/16/10 14:40:38
Time
853.396 us
910.068 us
Address bus
00D0 00D1 00D2 00D3 200E 00D4 00D5 00D6 00D7 200F 00D8 00D9 00DA 00DB 00DC 00DD
Data bus
89 C0 20 0E 6D 89 E0 20 0F 92 84 1C BB 18 DC 89
State
01 02 08 09 0B 01 02 08 09 0B 01 02 06 01 02 03 04 05
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1

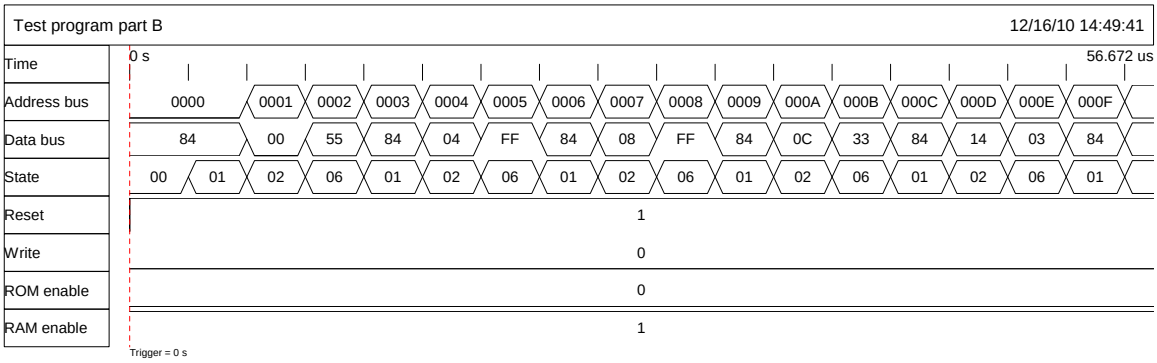

Test program part A
12/16/10 14:40:38
Time
913.4 us
973.404 us
Address bus
00DD 00DE 00DF 00E0 2010 00E1 00E2 00E3 00E4 2011 00E5 00E6 00E7 00E8 00E9
Data bus
89 C0 20 10 4F 89 E0 20 11 9F 80 04 40 04 89
State
01 02 08 09 0B 01 02 08 09 0B 01 02 07 01 02 03 04 01
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1

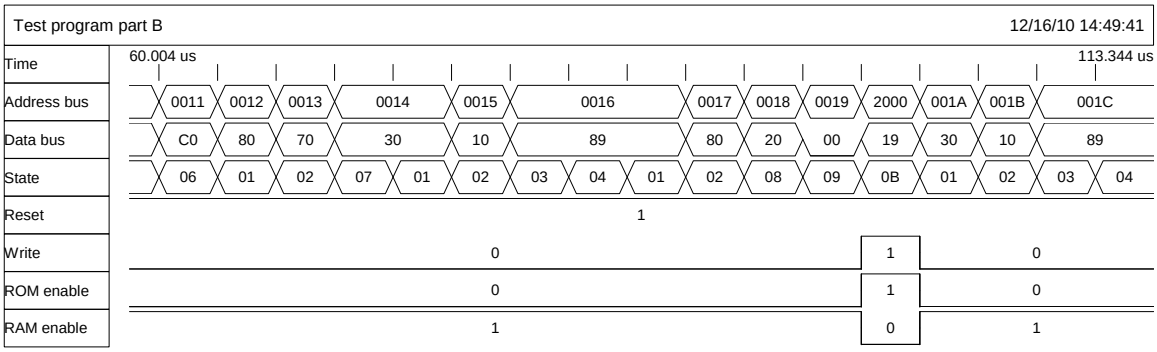

Test program part A
12/16/10 14:40:38
Time
976.74 us
1.033408 ms
Address bus
00EA 00EB 00EC 2012 00ED 00EE 00EF 00F0 00F1 00F2 2013 00F3 00F4 00F5 00F6 00F7
Data bus
20 12 FF 40 04 89 20 13 00 78 01 19 78
State
02 08 09 0B 01 02 03 04 01 02 08 09 0B 01 02 10 11 12
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1

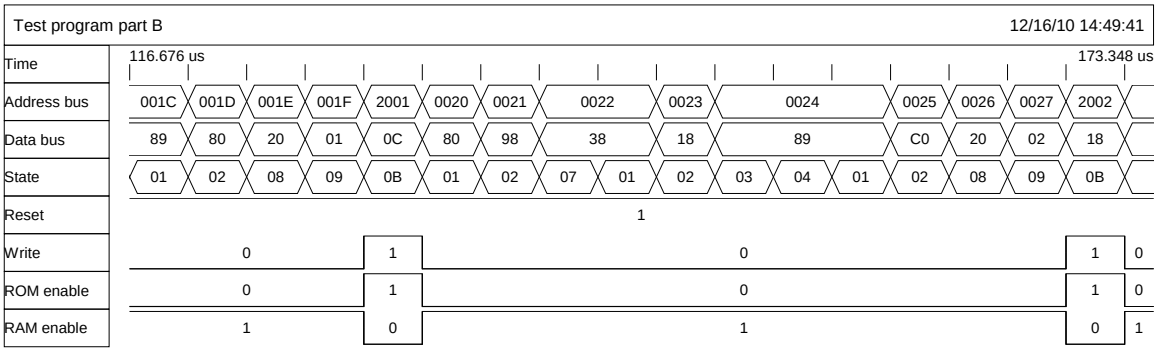

Test program part A
12/16/10 14:40:38
Time
1.036744 ms
1.093412 ms
Address bus
0… 00F8 00F9 00FA 00FB 00FD 00FE 00FF 0100 0101 0102 0103 0104 2014 0105
Data bus
78 02 00 FD F8 80 70 30 10 89 80 20 14 66 30
State
01 02 10 11 12 01 02 07 01 02 03 04 01 02 08 09 0B 01
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1


Test program part A
12/16/10 14:40:38
Time
1.096748 ms
1.15342 ms
Address bus
0107 0108 0109 010A 2015 010B 010C 010D 010E 010F 0110 0111 0…
Data bus
89 80 20 15 33 80 98 38 18 89 C0 20 16
State
03 04 01 02 08 09 0B 01 02 07 01 02 03 04 01 02 08 09
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1

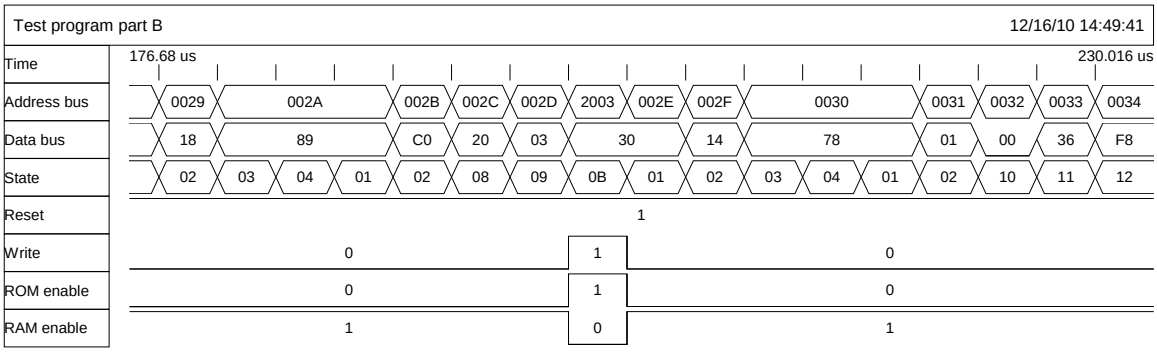

Test program part A
12/16/10 14:40:38
Time
1.156752 ms
1.216756 ms
Address bus
2016 0113 0114 0115 0116 0117 0118 2017 0119 011A 011B 011C 011D 011E 011F
Data bus
66 38 18 89 C0 20 17 CC 00 F8 00
State
0B 01 02 03 04 01 02 08 09 0B 01 02 01 02 01 02 13
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1
M2 = 1.216756 ms


Test program part B
12/16/10 14:49:41
Time
0 s
56.672 us
Address bus
0000 0001 0002 0003 0004 0005 0006 0007 0008 0009 000A 000B 000C 000D 000E 000F
Data bus
84 00 55 84 04 FF 84 08 FF 84 0C 33 84 14 03 84
State
00 01 02 06 01 02 06 01 02 06 01 02 06 01 02 06 01
Reset
1
Write
0
ROM enable
0
RAM enable
1
Trigger = 0 s

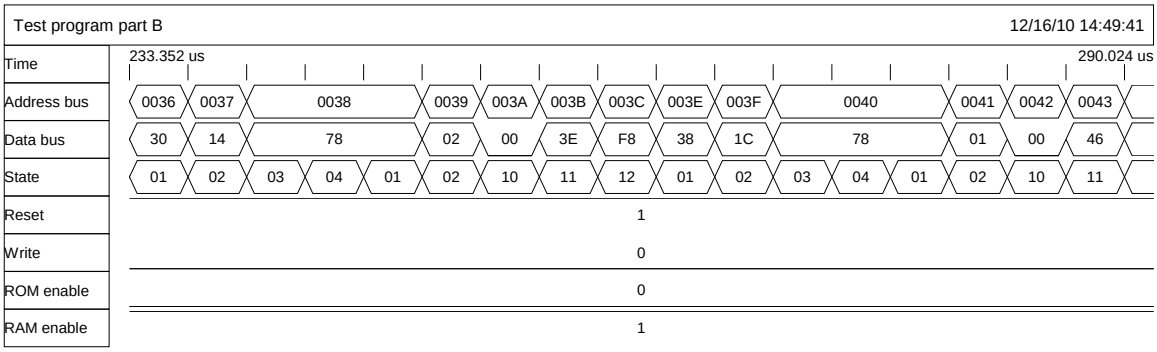

Test program part B
12/16/10 14:49:41
Time
60.004 us
113.344 us
Address bus
0011 0012 0013 0014 0015 0016 0017 0018 0019 2000 001A 001B 001C
Data bus
C0 80 70 30 10 89 80 20 00 19 30 10 89
State
06 01 02 07 01 02 03 04 01 02 08 09 0B 01 02 03 04
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1



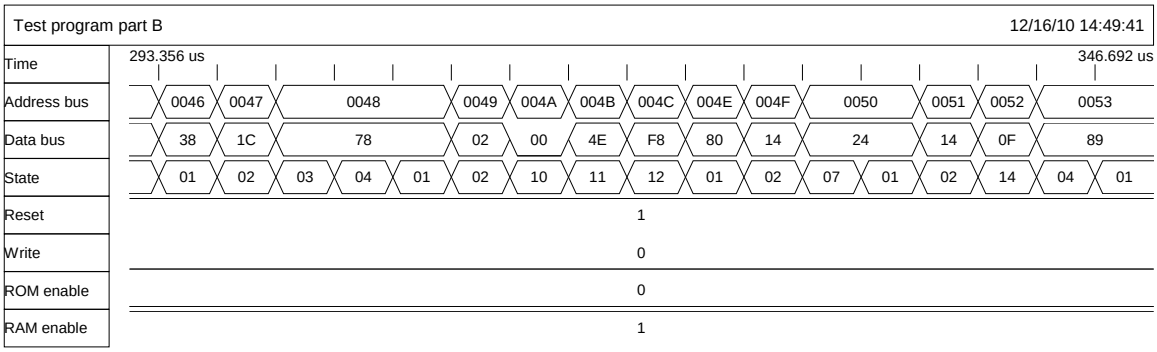
Time 116.66001759 us to 174.990026385 us Page 3



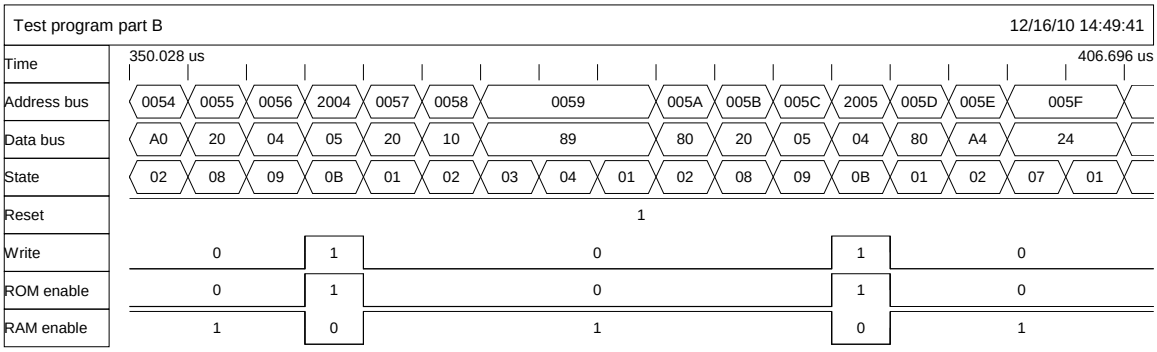
Time 175.001513192 us to 233.331521987 us Page 4

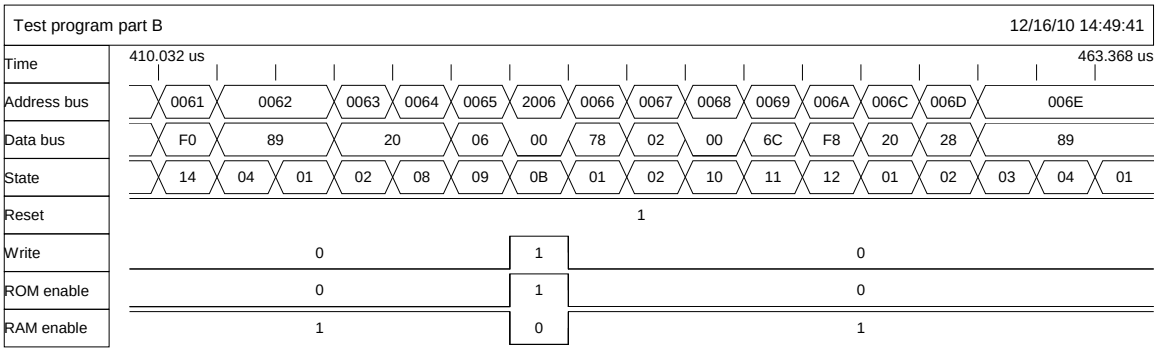


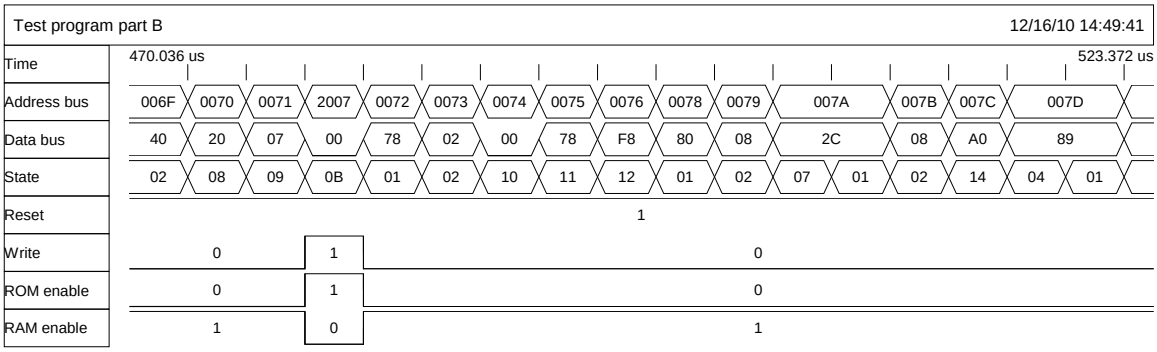
Time 233.343008795 us to 291.67301759 us Page 5

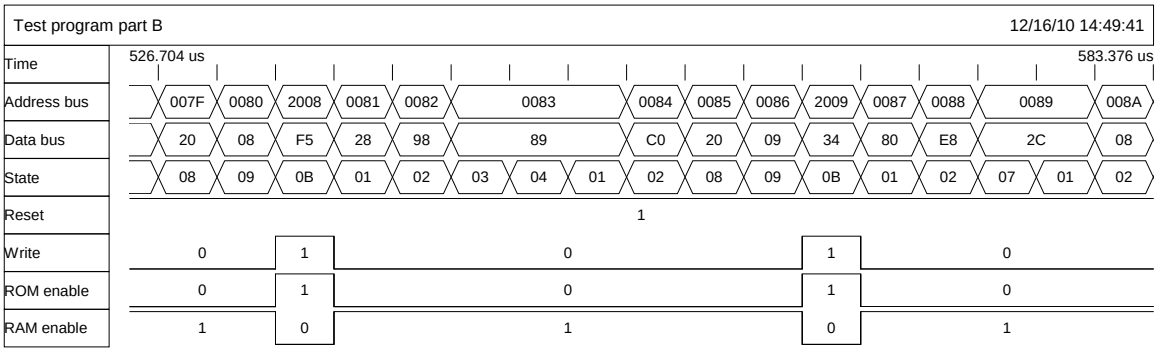


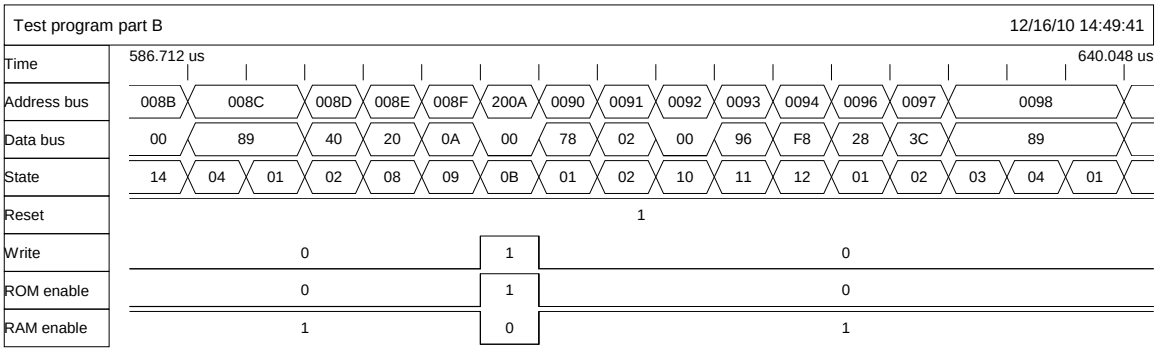
Time 291.684504397 us to 350.014513192 us Page 6

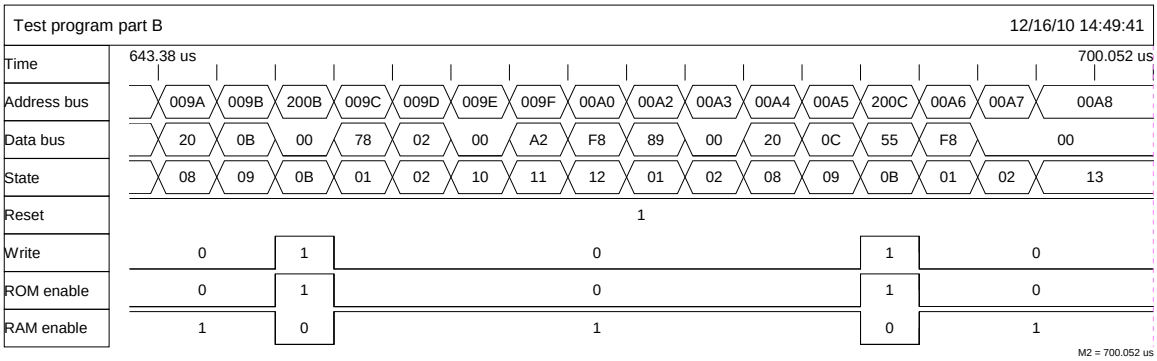

Test program part B
12/16/10 14:49:41
Time
350.028 us
406.696 us
Address bus
0054 0055 0056 2004 0057 0058 0059 005A 005B 005C 2005 005D 005E 005F
Data bus
A0 20 04 05 20 10 89 80 20 05 04 80 A4 24
State
02 08 09 0B 01 02 03 04 01 02 08 09 0B 01 02 07 01
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1


Test program part B
12/16/10 14:49:41
Time
410.032 us
463.368 us
Address bus
0061 0062 0063 0064 0065 2006 0066 0067 0068 0069 006A 006C 006D 006E
Data bus
F0 89 20 06 00 78 02 00 6C F8 20 28 89
State
14 04 01 02 08 09 0B 01 02 10 11 12 01 02 03 04 01
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1


Test program part B
12/16/10 14:49:41
Time
470.036 us
523.372 us
Address bus
006F 0070 0071 2007 0072 0073 0074 0075 0076 0078 0079 007A 007B 007C 007D
Data bus
40 20 07 00 78 02 00 78 F8 80 08 2C 08 A0 89
State
02 08 09 0B 01 02 10 11 12 01 02 07 01 02 14 04 01
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1


Test program part B
12/16/10 14:49:41
Time
526.704 us
583.376 us
Address bus
007F 0080 2008 0081 0082 0083 0084 0085 0086 2009 0087 0088 0089 008A
Data bus
20 08 F5 28 98 89 C0 20 09 34 80 E8 2C 08
State
08 09 0B 01 02 03 04 01 02 08 09 0B 01 02 07 01 02
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1


Test program part B
12/16/10 14:49:41
Time
586.712 us
640.048 us
Address bus
008B 008C 008D 008E 008F 200A 0090 0091 0092 0093 0094 0096 0097 0098
Data bus
00 89 40 20 0A 00 78 02 00 96 F8 28 3C 89
State
14 04 01 02 08 09 0B 01 02 10 11 12 01 02 03 04 01
Reset
1
Write
0 1 0
ROM enable
0 1 0
RAM enable
1 0 1


Test program part B
12/16/10 14:49:41
Time
643.38 us
700.052 us
Address bus
009A 009B 200B 009C 009D 009E 009F 00A0 00A2 00A3 00A4 00A5 200C 00A6 00A7 00A8
Data bus
20 0B 00 78 02 00 A2 F8 89 00 20 0C 55 F8 00
State
08 09 0B 01 02 10 11 12 01 02 08 09 0B 01 02 13
Reset
1
Write
0 1 0 1 0
ROM enable
0 1 0 1 0
RAM enable
1 0 1 0 1
M2 = 700.052 us