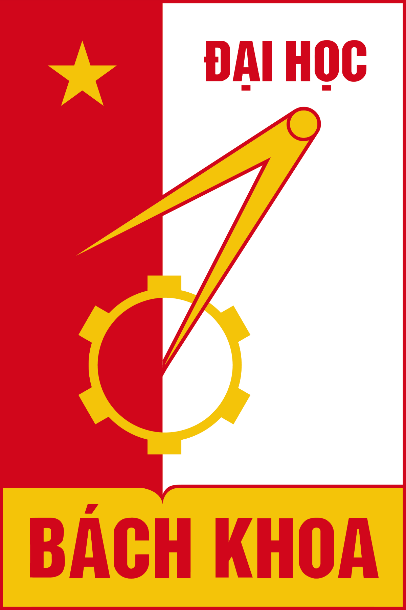
HANOI UNIVERSITY OF SCIENCE AND TECHNOLOGY

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING



Design a RISC Stored-Program Machine

A report on Digital Design Using VHDL Project

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hust

Group 2

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# Introduction and Overview

R

educed instruction-set computers (RISC) are designed to have a **small set of instructions**, which mean a **large number of instructions** per programthat execute in **short clock cycles** per instruction. RISC machines are optimized to achieve efficient pipelining of their instruction streams. The machine also serves as a starting point for developing architectural variants and a more robust instruction set.

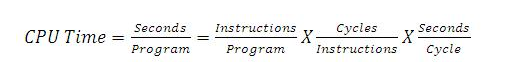


Figure Execution time

As opposite to RISC is the CISC ( Complex Instruction Set Computer ) architecture which have a **large set of instructions**, which will **minimize number of instructions** per program but at the cost of an **increase in the number of cycles** per instruction. The designers have to make the tradeoffs to selecting an architecture that serves an application. Table 1 below is all the differences of two architecture. Once an architecture has been selected, a circuit that has sufficient performance (speed) must be synthesized. Hardware description languages (HDLs) play a key role in this process by modeling the system and serving as a descriptive medium that can be used by a synthesis tool.

|  |  |
| --- | --- |
| RISC | CISC |
| Focus on software | Focus on hardware |
| Uses only Hardwired control unit | Uses both hardwired and microprogrammed control unit |
| Transistors are used for more registers | Transistors are used for storing complex  Instructions |
| Fixed sized instructions | Variable sized instructions |
| Can perform only Register to Register Arithmetic operations | Can perform REG to REG or REG to MEM or MEM to MEM |
| Requires more number of registers | Requires less number of registers |
| Code size is large | Code size is small |
| An instruction executed in a single clock cycle | Instruction takes more than one clock cycle |
| An instruction fit in one word | Instructions are larger than the size of one word |

Table RISC vs. CISC

Our design is a modified version from the reference book that can be found at the end of this text. Though the book explained pretty clear about this topic, I’m still going to discuss as manything as posible in my word. The book even contains a full verilog implementation code already, but as we “copy” and try to run it, a few bugs still found. So we have spent quite a lot of time to fix and optimize the code.

Check out this github link for the source code : <https://github.com/canh25xp/RISC-SPM>

# Work distribution

|  |  |  |  |
| --- | --- | --- | --- |
|  | Cảnh | Khuê | Dũng |
| Leader | X |  |  |
| Researching | X | X | X |
| Code Writer and simulation | X |  |  |
| Testing and Fixing |  | X | X |
| Report |  |  | X |
| Presentation | X | X | X |

# Design Hierarchy

We using the Top-Down methodology to design the system. Which mean the top-level block ( module ) is define first, all the sub-blocks ( instances ) necessary to build the top-level is define later. The hierarchy tree is shown in the *figure 2*

Diagram

Description automatically generated

Figure Hierarchy Table

As you can see in the diagram. The top-block is the module RISC-SPM, it called out three sub-block instances, which is the Control Unit, Processing Unit and Memory\_Unit. The Processing Unit is then call out 7 Register Unit, a D-FlipFlop, a Program Counter, 2 Multiplexer and a Arithmetic Logic Unit.

# Hardware composition

RISC-SPM or Reduced Instruction Set Computer Store Program Machine consists of three functional units :

* 1.Processing Unit ( Processor )
* 2.Controll Unit ( Controller )
* 3.Memory Unit ( RAM )

The Overall Architecture of the RISC-SPM is shown in *figure 3*.

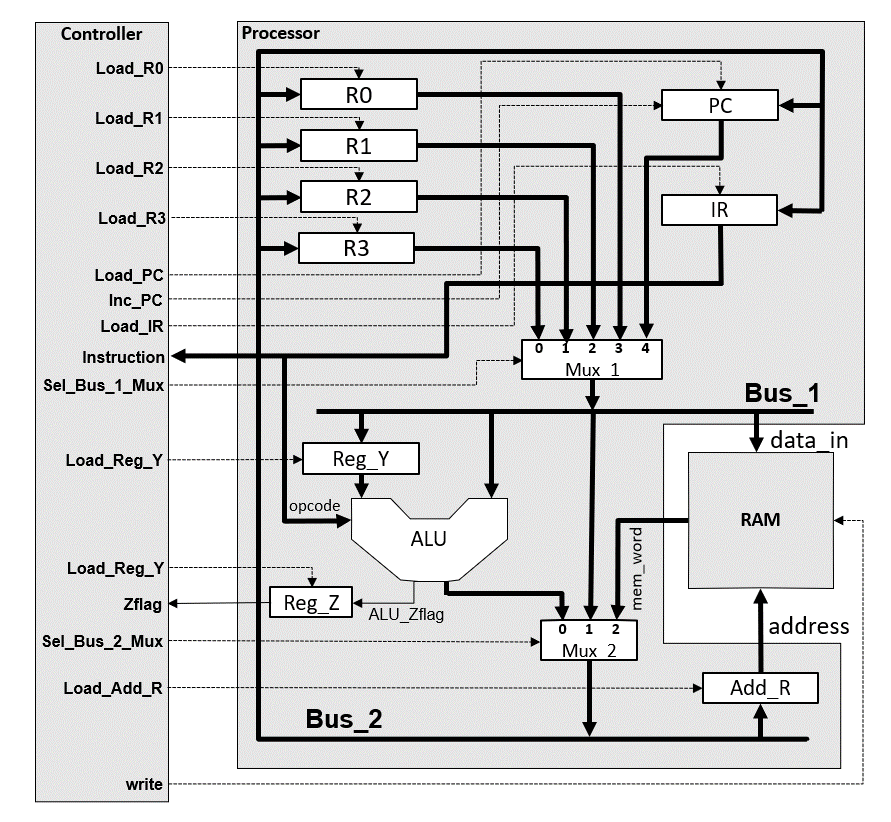


Figure Architecture of RISC-SPM

Program instructions and data are stored in memory

Instructions are fetched from memory synchronously, decoded and executed to :

* Operate on data with ALU
* Change the contents of storage registers
* Change the content of the program counter (PC), instruction register (IR) and the address register (ADD\_R)
* Change the content of memory
* Retrieve data and instructions from memory
* Control the movement of data on the system busses

The Program Counter (PC) contains the address of the next instruction to be executed

The Instruction Register (IR) contains the instruction that currently being executed

The address register (Add\_R) contains the address of the memory location that will be addressed next by a read or write operation.

## Processing Unit

The processor includes registers, buses, control lines, and an ALU capable of performing arithmetic and logic operations on its operands depends on the opcode held in the instruction register. Its take control from the Control\_Unit, manipulate the Registers and read/write data to Memory\_Unit.

### Arithmetic Logic Unit

For the purposes of this example, the ALU has two operand datapaths, data\_1 and data\_2, and its instruction set is limited to only 4 instructions, that is :

|  |  |
| --- | --- |
| Opcode | Action |
| ADD | Adds the datapaths to form data\_1 + data\_2 |
| SUB | Subtracts the datapaths to form data\_1 - data\_2 |
| AND | Takes the bitwise and of the datapaths data\_1 & data\_2 |
| NOT | Takes the bitwise Boolean complement of data\_1 |

The ALU take the output of Reg\_y is input for data\_in and Bus\_1 as input for data\_2.

The Output result of the ALU is go to the Mux\_2 and the zero flag bit is go to input of the Reg\_Z. Note that the zero flag bit is set ( bit 1 ) when the ALU result is equals to 0.

### Register Unit

There are 9 registers in our design :

* 5 general-purpose registers R0, R1, R2, R3, Reg\_y ( 8-bit )
* 3 special purpose register PC, IR, Add\_R ( 8-bit )
* 1 flag register Reg\_Z ( 1-bit )

All registers have a load signal to store data, a clock signal (clk) to synchronize and a reset signal (rst) to erase data (all bits are set to 0). Note that the **reset signal is active low**, which mean it’ll reset when signal is low (0)

The zero flag register Reg\_Z is a 1-bit register, so basically it is a D flip flop.

The Program Counter Register (PC) has an additional signal Inc\_PC to increase PC by 1 unit.

### Multiplexer

There are 2 multiplexers in the Processing Unit :

* Mux\_1 : it's a 5-1 multiplexer
  + Output : Bus\_1
  + Input : R0, R1, R2, R3, PC
  + Control input : Sel\_Bus\_Mux\_1 ( 3 bits )
* Mux\_2 : it's a 3-1 multiplexer
  + Output : Bus\_2
  + Input : ALU's output, Bus\_1
  + Control input : Sel\_Bus\_Mux\_1 ( 2 bits )

An instruction can be fetched from memory, placed on Bus\_2, and loaded into the instruction register. A word of data can be fetched from memory, and steered to a general-purpose register or to the operand register (Reg\_Y) prior to an operation of the ALU. The result of an ALU operation can be placed on Bus\_2, loaded into a register, and subsequently transferred to memory. A dedicated register (Reg\_Z) holds a flag indicating that the result of an ALU operation is 0.

## Control Unit

The Control Unit is a FSM ( Finite State Machine ), or more specifically, a Mealy Machine. Because the output (The control signals, which will be discuss later) of it depends on the state and external input ( instruction, Zflag, rst )

### Function of the control unit

* Determine when and which registers to be load
* Select the path of data through the multiplexers
* Determine when data should be written to memory
* Control the three-state busses in the architecture.

### Control Signals

There are 13 output signals of the controller, 1 instruction input, 1 zero flag input and a reset signal input. The Action of each control signal is describe as below.

|  |  |
| --- | --- |
| Control Signal | Action |
| Load\_Add\_R | Loads the Address Register |
| Load\_PC | Loads Bus\_2 to the Program Counter |
| Load\_IR | Loads Bus\_2 to the Instruction Register |
| Inc\_PC | Increments the Program Counter |
| Sel\_Bus\_1\_Mux | Selects among the Program Counter, R0, R1, R2, and R3 to drive Bus\_1 |
| Sel\_Bus\_2\_Mux | Selects among ALU\_out, Bus\_1, and memory to drive Bus\_2 |
| Load\_R0 | Loads general purpose register R0 |
| Load\_R1 | Loads general purpose register R1 |
| Load\_R2 | Loads general purpose register R2 |
| Load\_R3 | Loads general purpose register R3 |
| Load\_Reg\_Y | Loads Bus\_2 to the register Reg\_Y |
| Load\_Reg\_Z | Stores the zero Flag of ALU in register Reg\_Z |
| write | Loads Bus\_1 into the memory |

### Instruction Set

A machine language program consists of a stored sequence of 8-bit words (bytes). The format of an instruction of RISC\_SPM can be long or short, depending on the operation :

* Short instructions : requires 1 byte of memory to specifies 4-bit opcode, 2-bit source register address, a 2-bit destination register address.
* Long instruction : requires 2 bytes of memory. The first word of a long instruction contains a 4-bit opcode. The remaining 4 bits of the word can be used to specify addresses of a pair of source and destination registers, depending on the instruction. The second word contains the address of the memory word that holds an operand required by the instruction.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Opcode | | | | Dst | | Src | |
| 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 |

Table Short instruction format

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Opcode | | | | Dst | | Src | | Address | | | | | | | |
| 0 | 1 | 1 | 0 | x | x | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |

Table Long instruction format

The instruction mnemonics and their actions are listed below.

|  |  |
| --- | --- |
|  | Action |
| Short instruction | |
| NOP | No operation is performed; all registers retain their values. The addresses of the source and destination register are don't-cares, they have no effect. |
| ADD | Adds the contents of the source and destination registers and stores the result into the destination register. |
| SUB | Subtracts the content of the source register from the destination register and stores the result into the destination register. |
| AND | Forms the bitwise and of the contents of the source and destination registers and stores the result into the destination register. |
| NOT | Forms the bitwise complement of the content of the source register and stores the result into the destination register. |
| HALT | Halts execution until reset |
| Long instruction | |
| RD | Reads a word from the location specified by the second byte and loads the result into the destination register. The source register bits are don't-cares. |
| WR | Writes the contents of the source register to the word in memory specified by the address held in the second byte. The destination register bits are don't-cares. |
| BR | Branches the activity flow by loading the program counter with the word at the address specified by the second byte of the instruction. The source and destination bits are don't-cares. |
| BRZ | Branches if the zero flag register is asserted. |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Ins | Opcode | Dst | Src | Action |
| NOP | 0000 | xx | xx | none |
| ADD | 0001 | dst | src | dst <= src + dst |
| SUB | 0010 | dst | src | dst <= dst - src |
| AND | 0011 | dst | src | dst <= src && dst |
| NOT | 0100 | dst | src | dst <= ~ src |
| RD | 0101 | dst | xx | dst <= memory [Add\_R] |
| WR | 0110 | xx | src | memory[Add\_R] < = src |
| BR | 0111 | xx | xx | PC <= memory[Add\_R] |
| BRZ | 1000 | xx | xx | PC <= memory[Add\_R] |
| HALT | 1111 | xx | xx | Halts execution until reset (Finish programm) |

The RISC\_SPM instruction set is summarized below.

### Controller States

Each instruction has three phases : fetch, decode, and execute.

* Fetching : Retrieves an instruction from memory . Its takes **2 clock cycles**, one to load  
  the address register and one to retrieve the addressed word from memory.
* Decoding : Decodes the instruction, manipulates datapaths ,and loads registers. Its takes **1 clock cycle**
* Execution : Generates the results of the instruction. Its might take 0, 1 or 2 clock cycles, depends on the instruction :
  + NOP : 0 clock
  + ADD, SUB, AND, NOT : 1 clock
  + RD, WR, BR, BRZ : 2 clocks ( the BRZ instruction might take 0 instruction if the zero flag not set )

Below is the table of 11 states and the description of each state

|  |  |
| --- | --- |
| State | Action |
| idle | State entered after reset is asserted. No action. |
| fet1 | Load the Add\_R with the contents of the PC. (Note: PC is initialized to the starting address 00H by the reset action.) The state is entered at the first active clock after reset is de-asserted, and is revisited after a NOP instruction is decoded. |
| fet2 | Load the IR with the word addressed by the Add\_R, and increment the PC to point to the next location in memory, in anticipation of the next instruction or data fetch. |
| dec | Decode the IR and assert signals to control datapaths and register transfers. |
| exe | Execute the ALU operation for a single-byte instruction, conditionally assert the zero flag, and load the destination register. |
| rd1 | Load the Add\_R with the second byte of a RD instruction, and increment the PC. |
| rd2 | Load the destination register with the memory word addressed by the byte loaded in rd1. |
| wr1 | Load the Add\_R with the second byte of a WR instruction, and increment the PC. |
| wr2 | Load the source register with the memory word addressed by the byte loaded in wr1. |
| br1 | Load the Add\_R with the second byte of a BR instruction, and increment the PC. |
| br2 | Load the PC with the memory word addressed by the byte loaded in br1. |
| halt | Default state to trap failure to decode a valid instruction. |

### 

### State transition diagram

Figure State transition diagram

*Figure 4* is a “State transition diagram”, do not misunderstanding it with “State diagram”, though it might looks like it, it is not. It mearly show how many states are there in the fsm and the transition between them. The ASM chart will give us a full detail about the fsm.

### ASM chart

A full ASM chart is shown in *figure 5*. Later on, I with break down each part of it. Some thing to note here, is that the controller has too many output signals to put on the diagram, so I will only mention about the set (1) signal, other signals is remain as reset (0).

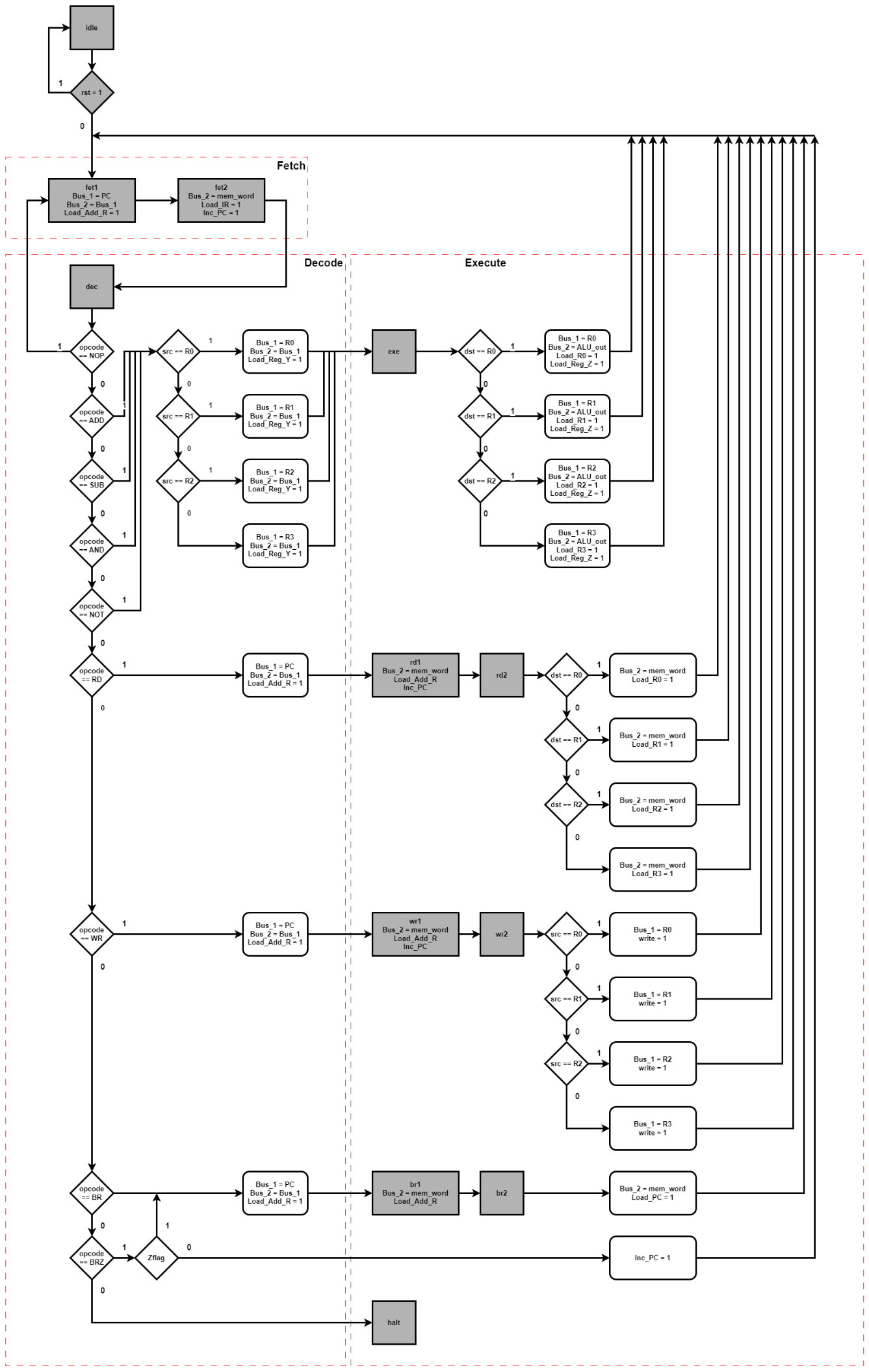
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Figure ASM chart

**Diagram, schematic

Description automatically generated**

Figure NOP, ADD, SUB, AND, NOT

*Figure 6* is the ASM diagram for implementing all the arithmetic operation : ADD, SUB, AND, NOT.

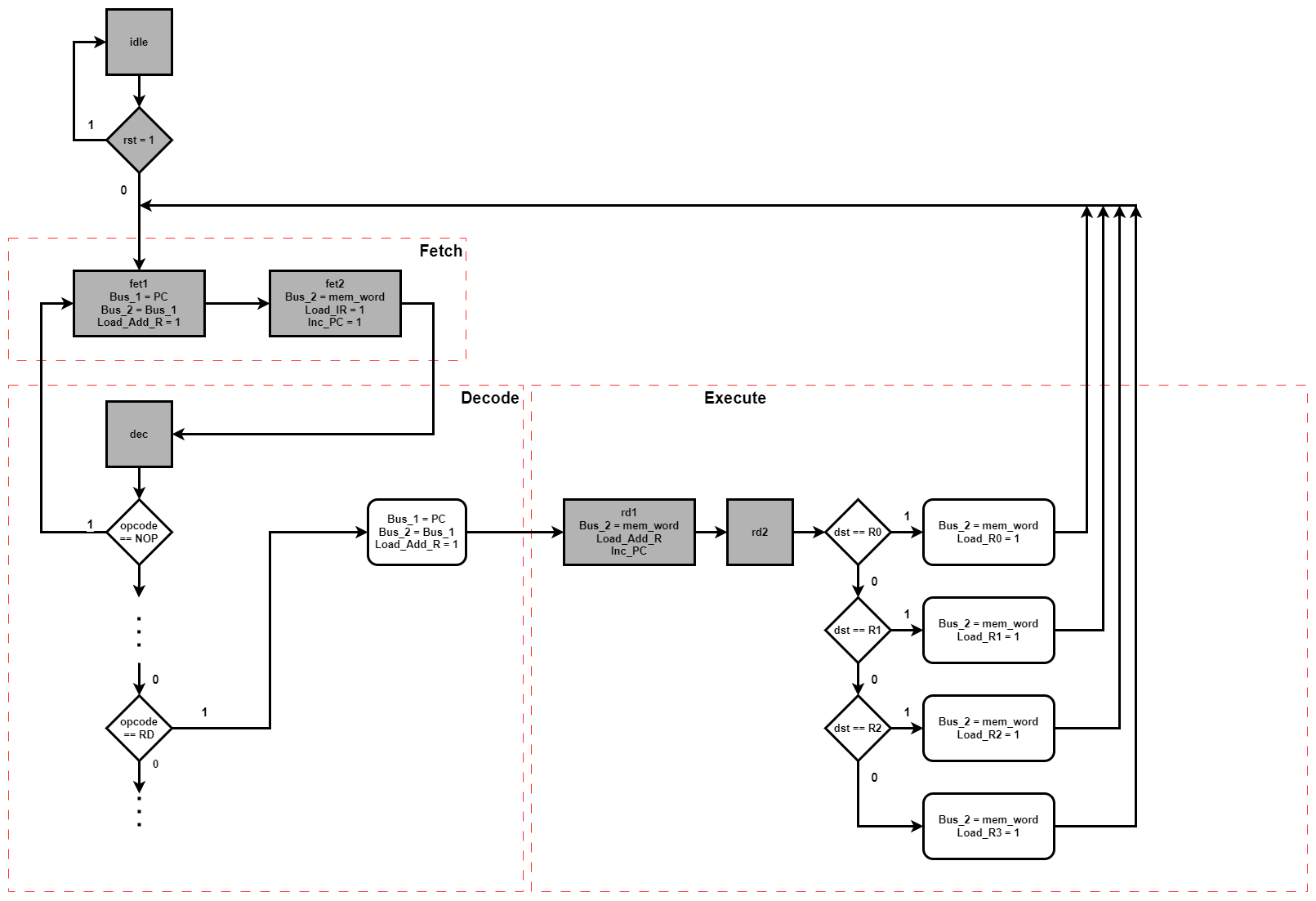


Figure RD

*Figure 7* is the ASM diagram for the read instruction.

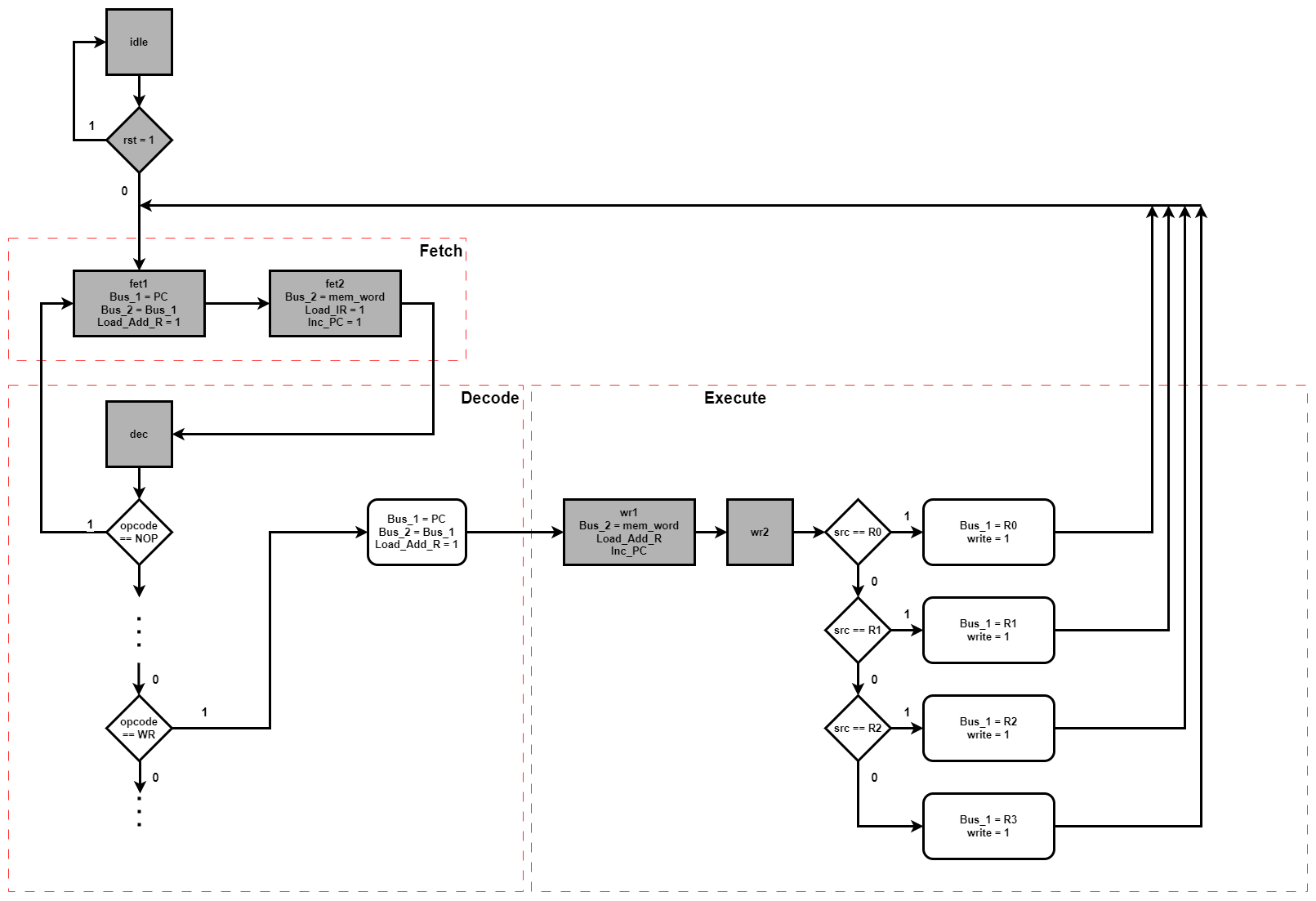


Figure WR

*Figure 8* is the ASM diagram for the Write instruction.

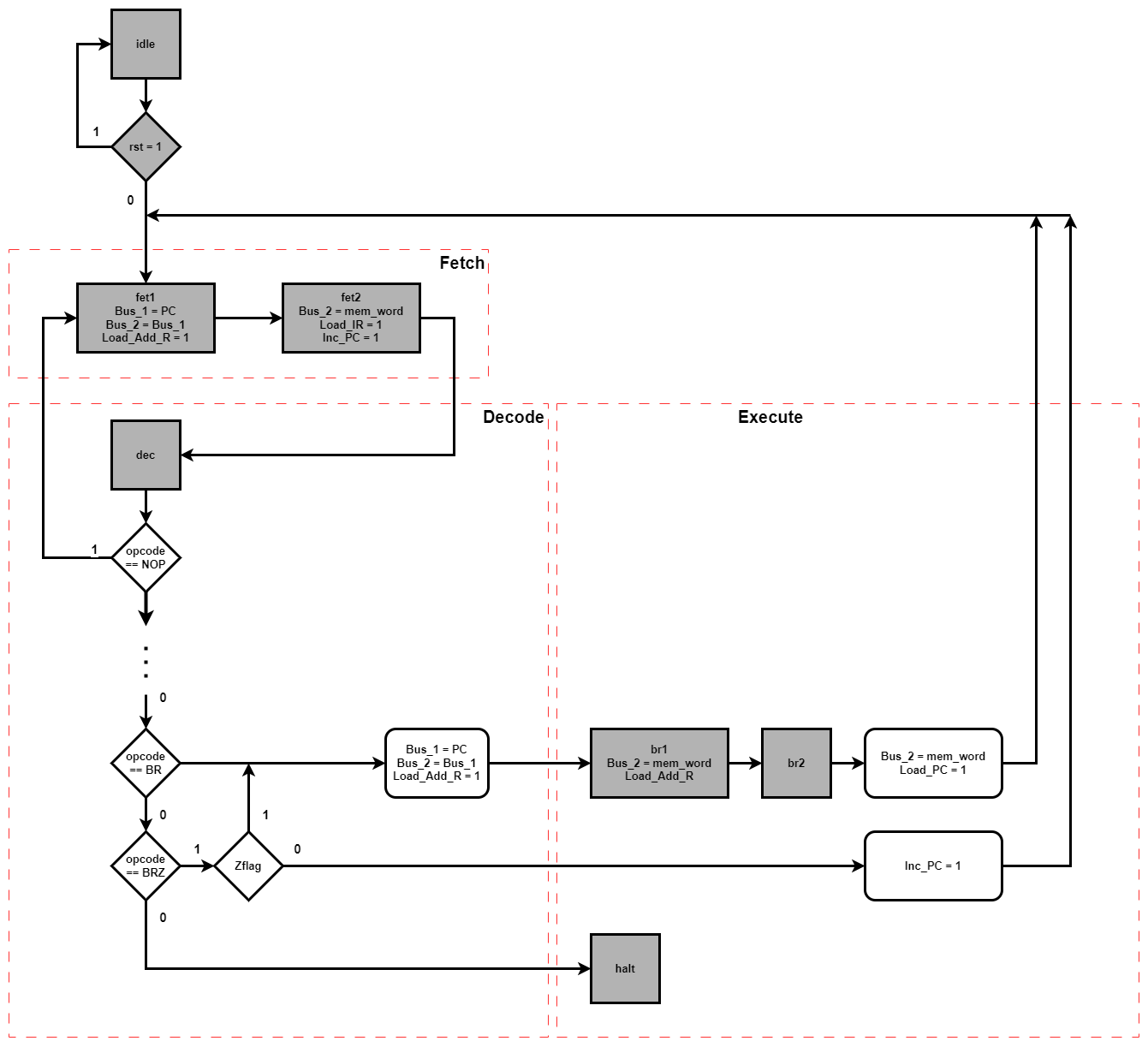


Figure BR, BRZ

*Figure 9* is the ASM diagram for the BR and BRZ instruction.

## Memory Unit

For simplicity, the memory unit of the machine is modeled as an array of D flip-flops that form a **256 bytes** RAM.

This RAM ( Random Access Memory ) receiving an 8-bit address and output the data stored in the corresponding address. It also have an 8-bit input data. When the rising edge of the write signal is triggered, the input data is written to the corresponding position of the address.

There are no ROM ( Read-Only Memory ) in this design.

# Verilog implementation

All the verilog source codes is located in the source code folder or in my github website : <https://github.com/canh25xp/RISC-SPM>

# Design Verification

To ensure the working of the machine, each module has it own testbench : Memory Unit, Control Unit, Register Unit, Arithmetic Logic Unit.

## Register Unit testbench

module Register\_Unit\_tb;

    reg clk,rst, load;

    reg [7:0] data\_in = 8'b00110011;

    wire [7:0] data\_out;

    Register\_Unit Test\_Register(data\_out, data\_in, load, clk, rst);

    initial clk=1'b0;

    always #5 clk=~clk;

    initial begin

            rst=1'b1; load=0'b0;

        #17 load=1'b1;

        #21 load=0'b0;

        #15 data\_in = 8'b11001100;

        #3  load=1'b1;

        #5  load=0'b0;

        #10 rst=0'b0;

        #10 $stop;

    end

endmodule

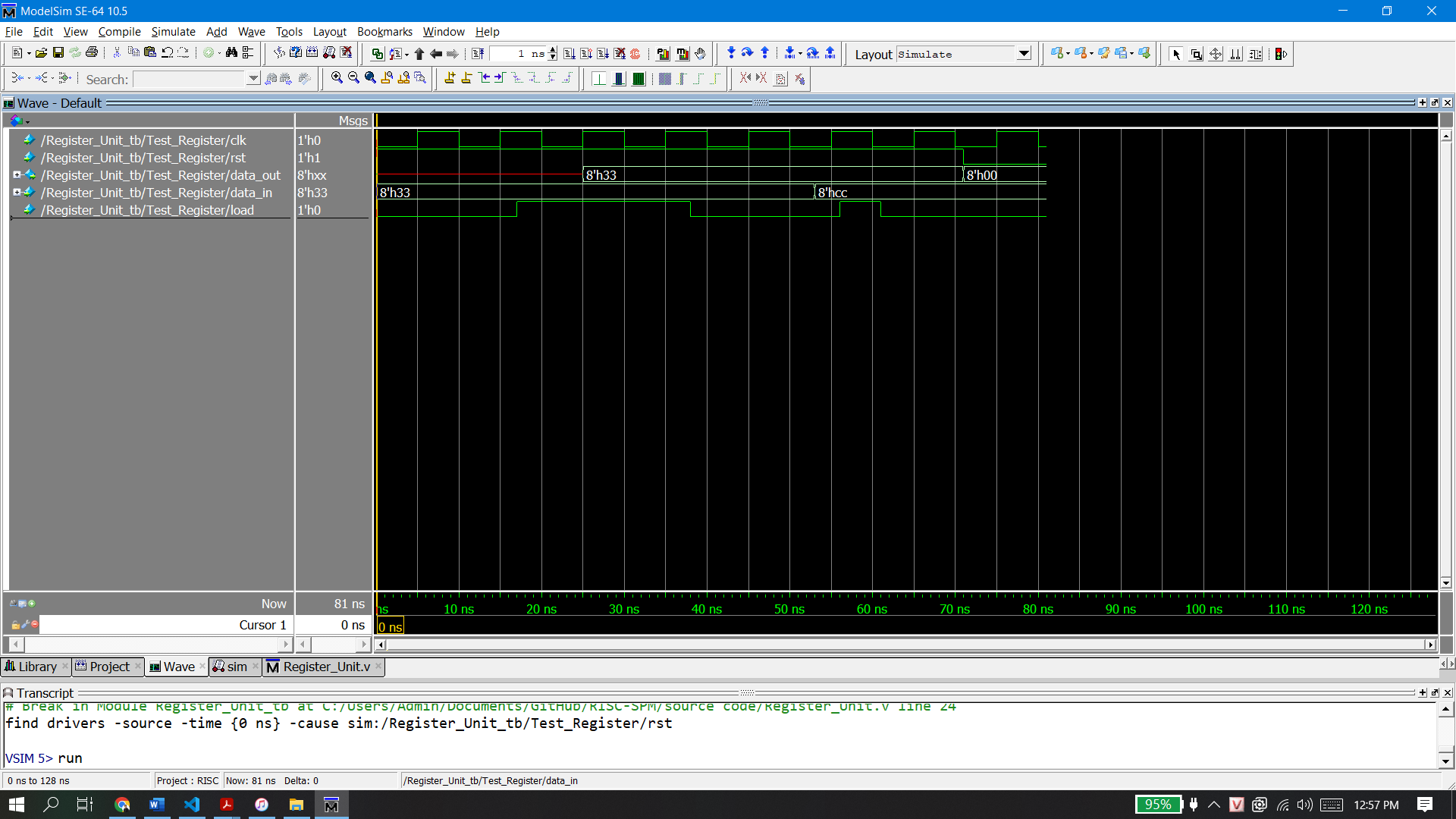


Figure Register testbench waveform

## Program Counter testbench

module Program\_Counter\_tb;

    reg clk,rst, Load\_PC, Inc\_PC;

    reg [7:0] data\_in;

    wire[7:0] count;

    Program\_Counter Test\_Counter(count, data\_in, Load\_PC, Inc\_PC, clk, rst);

    initial clk=1'b0;

    always #5 clk=~clk;

    initial begin

                rst=1;Load\_PC=0;

        #5      data\_in=8'b00000001;

        #5      Load\_PC=1;

        #10     Load\_PC=0;

        #20     Inc\_PC=1;

        #100    Inc\_PC=0;

        #5      rst=0;

        #5      rst=1;

        #5      data\_in=8'b10000000;

        #5      Load\_PC=1;

        #10     Load\_PC=0;

    end

endmodule

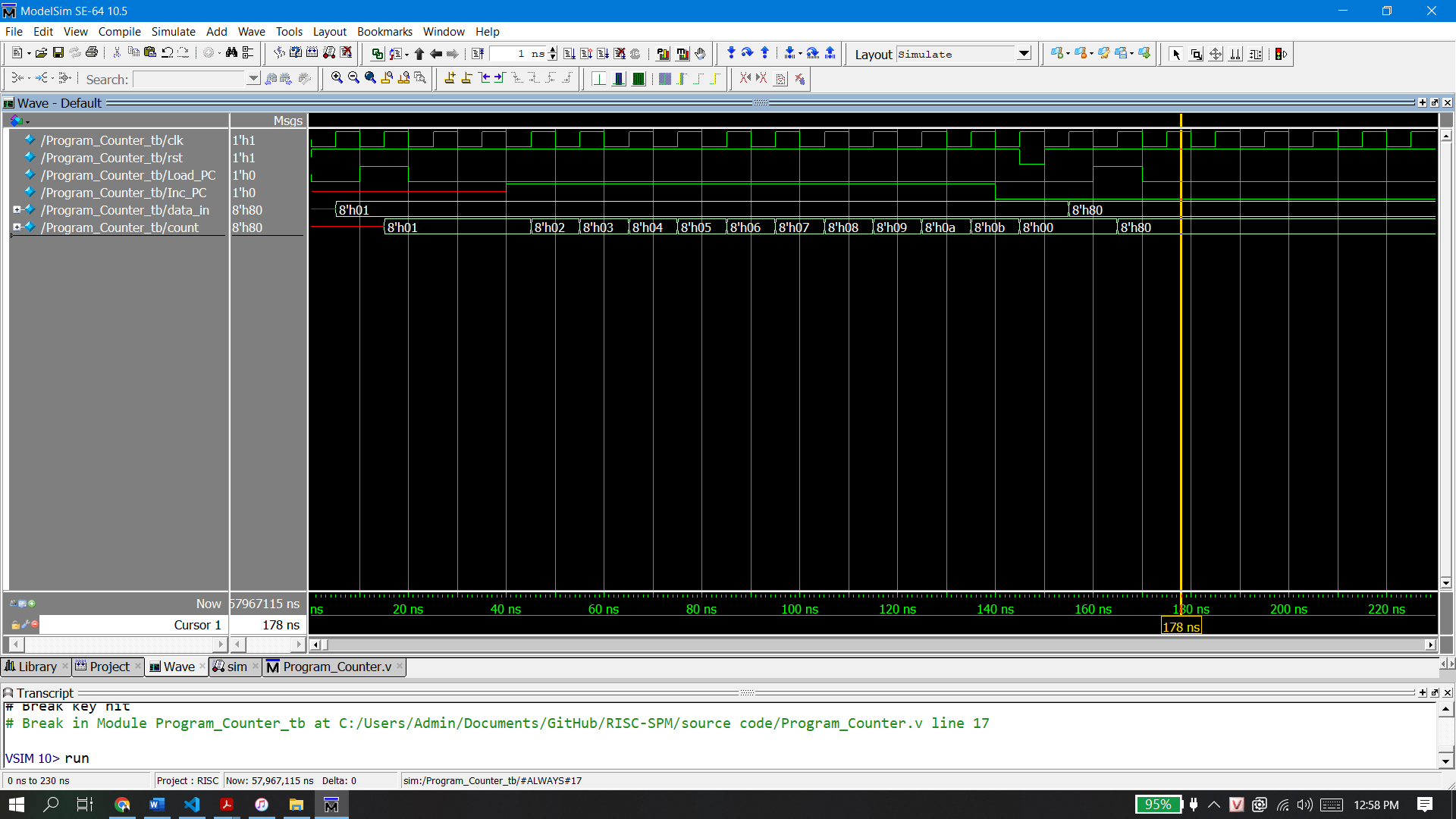


Figure Program Counter testbench waveform

## Arithmetic Logic Unit testbench

module Arithmetic\_Logic\_Unit\_tb;

    reg [7:0] data\_1, data\_2;

    reg [3:0] opcode;

    wire[7:0] out;

    wire      Zflag;

    Arithmetic\_Logic\_Unit ALU(out, Zflag, data\_1, data\_2, opcode);

    initial begin

        #0 data\_1 = 64; data\_2 = 128; opcode = `NOP;

        // 64 =  01000000

        // 128 = 10000000

        #5 opcode = `ADD; //result should be 192

        #5 opcode = `SUB; //result should be 64

        #5 opcode = `AND; //result should be 0

        #5 opcode = `NOT; //result should be 127

    end

endmodule

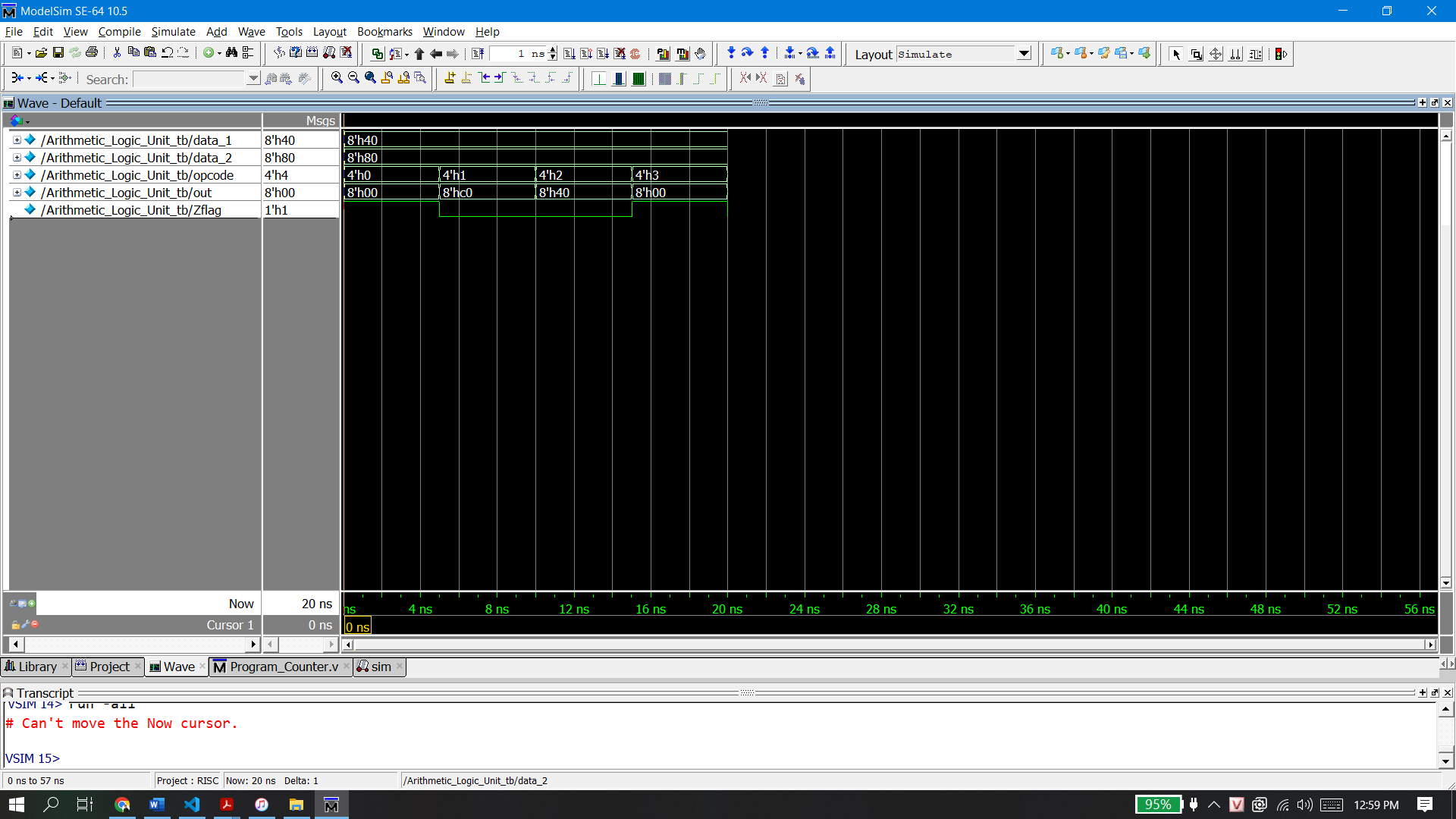


Figure ALU testbench waveform

## Multiplexer testbench

module Mux\_3\_1\_tb;

    reg [7:0] in0, in1, in2;

    reg [1:0] sel;

    wire [7:0] out;

    Mux\_3\_1 Test\_Mux (out, in0, in1, in2, sel);

    initial begin

        in0 = 0; in1 = 128; in2 = 255;

        #5 sel = 2'b00;

        #5 sel = 2'b01;

        #5 sel = 2'b10;

        #5 sel = 2'b11;

    end

endmodule

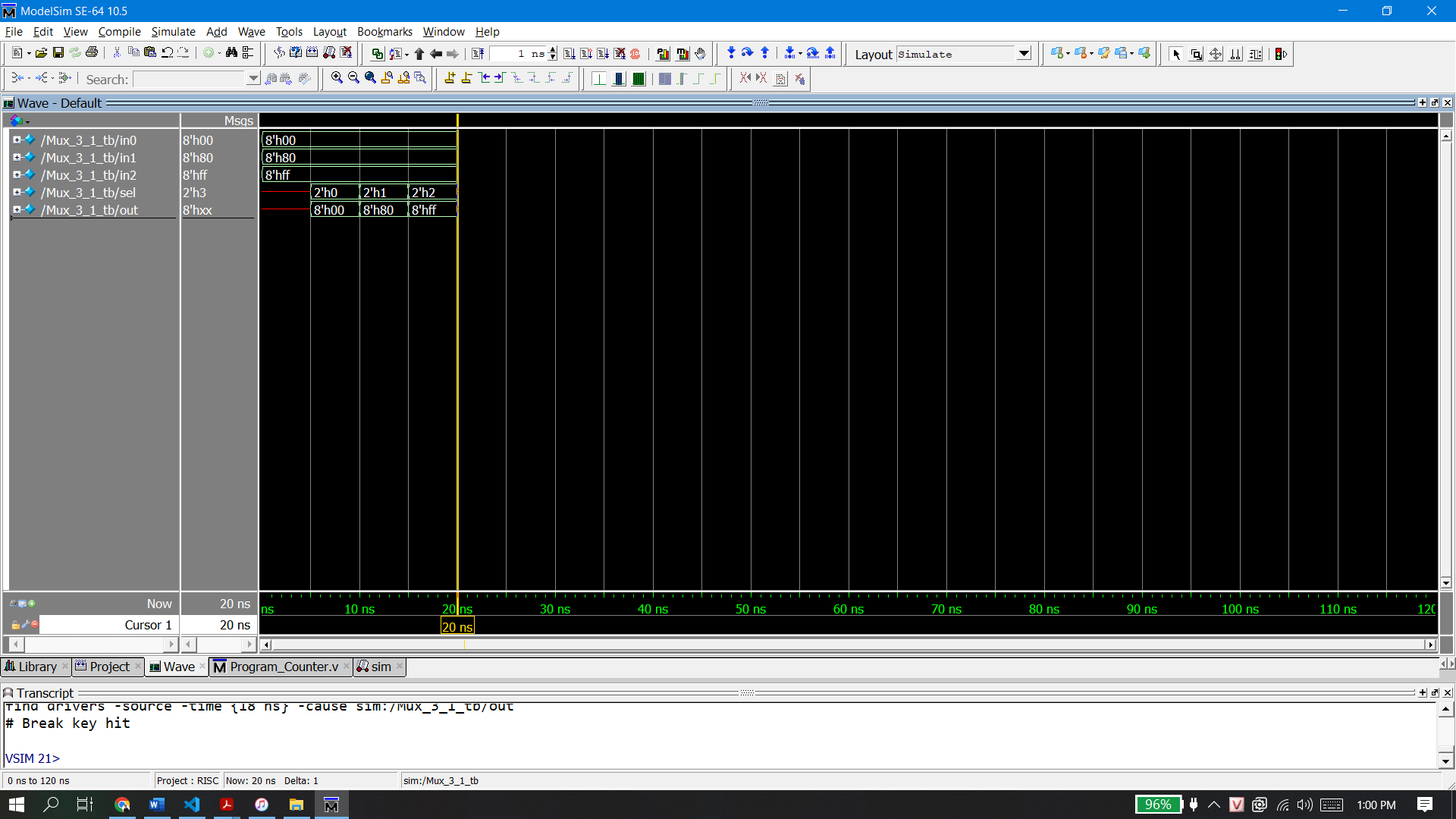


Figure Mux\_3\_1\_tb waveform

## Full Module Testbench

module RISC\_SPM\_tb;

    reg rst, clk;

    reg[8:0]i;

    RISC\_SPM MCU (clk,rst);

    initial begin

        clk = 0;

        forever #5 clk = ~clk;

    end

    initial begin

        #0 rst=0;

            for(i=0;i<=255;i=i+1)

                MCU.Ram.memory[i]=0;

        #10 rst=1;

    end

    initial begin

        #5

        MCU.Ram.memory[0]= 8'b0000\_00\_00;  //NOP

        MCU.Ram.memory[1]= 8'b0101\_01\_00;  //R1 = memory[128] = 6

        MCU.Ram.memory[2]= 128;

        MCU.Ram.memory[3]= 8'b0101\_00\_00;  //R0 = memory[129] = 1

        MCU.Ram.memory[4]= 129;

        MCU.Ram.memory[5]= 8'b0010\_01\_00;   //R1 = R1 - R0

        MCU.Ram.memory[6]=8'b1000\_00\_00;   //BRZ to memory[130] = 10 ( HALT )

        MCU.Ram.memory[7]=130;

        MCU.Ram.memory[8]= 8'b0111\_00\_11;  //BR to memory[131] = 5

        MCU.Ram.memory[9]= 131;

        MCU.Ram.memory[10]=8'b1111\_00\_00;  //HALT

        //Load data

        MCU.Ram.memory[128]=6;

        MCU.Ram.memory[129]=1;

        MCU.Ram.memory[130]=10;

        MCU.Ram.memory[131]=5;

    end

    initial #2800 $stop;

endmodule

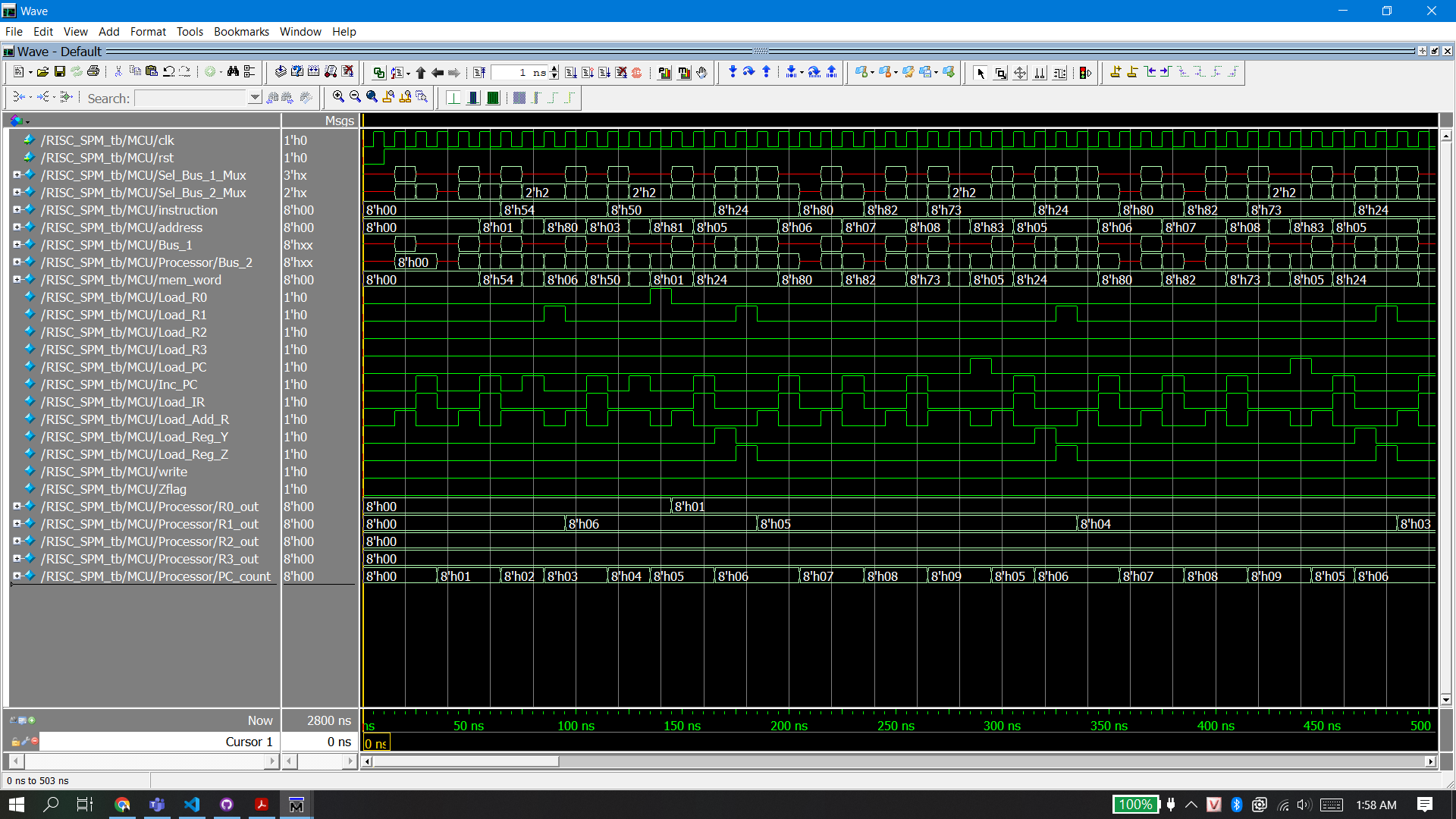


Figure Full Module waveform 1

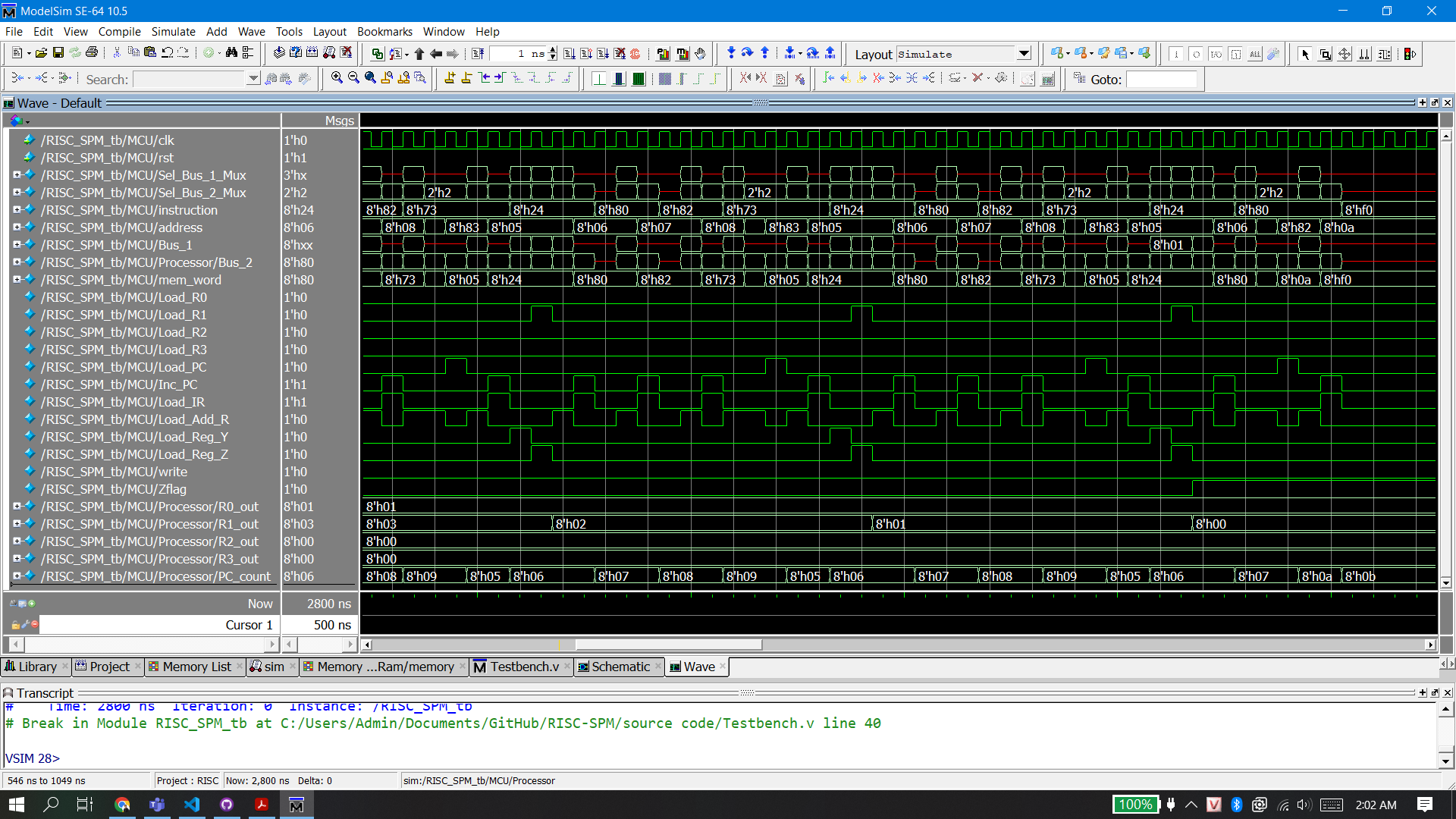
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Figure Full Module waveform 2

# Conclusion

This article builds an 8-bit RISC CPU, introduces the design process and experimental test in detail, including: hardware composition, instruction set system, etc. The focus is on the design of the controller. Based on the finite state machine, the correspondence and transfer between instructions and states has been realized, and a detailed simulation experiment has been carried out. The results prove that the CPU functions normally and meets expectations.

# Reference

[1] Michael D. Ciletti’s Advanced Digital Design with the Verilog HDL, 2005

[2] Samir Palnitkar’s Verilog HDL: A Guide to Digital Design and Synthesis, Second Edition, 2003