Computer-Aided VLSI System Design

Homework 2: Simple MIPS CPU

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Goal

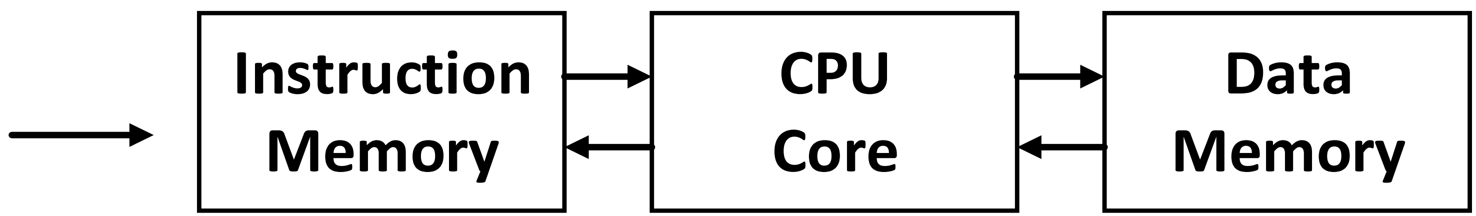
- In this homework, you will learn
  - How to write testbench
  - How to design FSM
  - How to use IP
  - Generate patterns for testing

Introduction

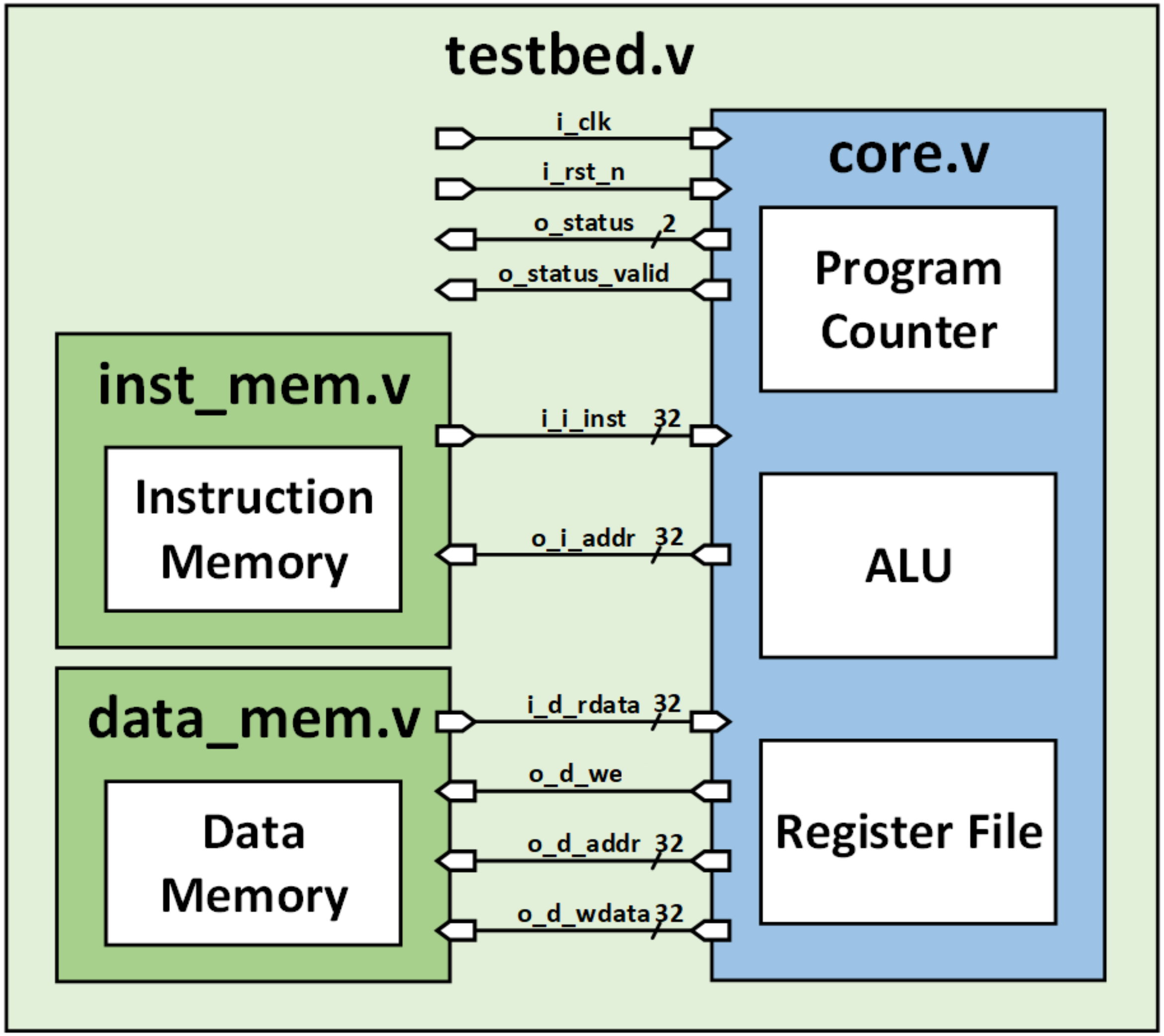
- Central Processing Unit (CPU) is the important core in the computer system. In this homework, you are asked to design a simple MIPS CPU, which contains the basic module of program counter, ALU and register files. The instruction set of the simple CPU is similar to MIPS structure.

Instruction set

```
addi $7 $3 4
sub  $7 $7 $5
sw   $7 $4 8
bne  $3 $5 12
lw   $6 $0 8
add  $7 $6 $2
sw   $7 $4 8
eof
```



Block Diagram



Input/Output

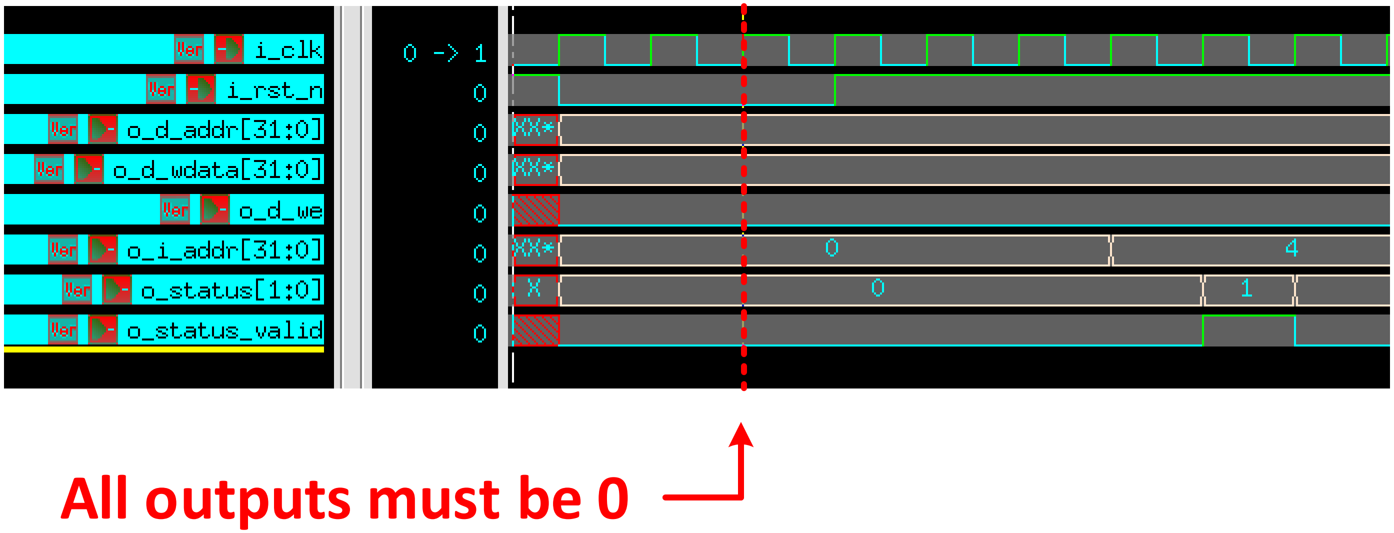
Signal Name	I/O	Width	Simple Description
i_clk	I	1	Clock signal in the system.
i_rst_n	I	1	Active low asynchronous reset.
o_i_addr	O	32	Address from program counter (PC)
i_i_inst	I	32	Instruction from instruction memory
o_d_we	O	1	Write enable of data memory Set low for reading mode, and high for writing mode
o_d_addr	O	32	Address for data memory
o_d_wdata	O	32	Unsigned data input to data memory
i_d_rdata	I	32	Unsigned data output from data memory
o_status	O	2	Status of core processing to each instruction
o_status_valid	O	1	Set high if ready to output status

Specification

- All outputs should be synchronized at clock **rising** edge.
- Instruction memory and data memory are provided. All values in memory are reset to be zero.
- You should create **32 unsigned 32-bit registers** in register file.
- Less than **1024** instructions are provided for each pattern.
- The whole processing time can't exceed **120000** cycles.

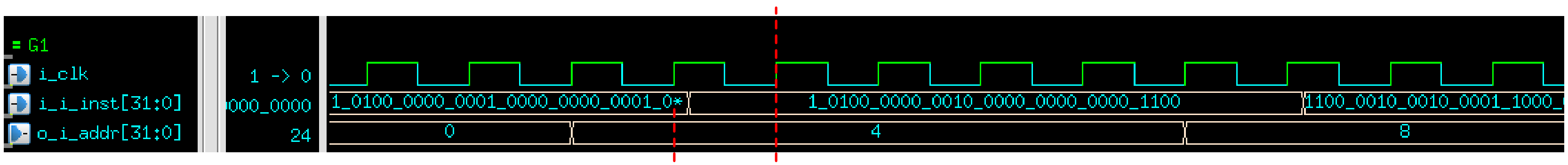
Specification

- You should set all your outputs and register file to be zero when i_rst_n is **low**. Active low asynchronous reset is used.



Specification

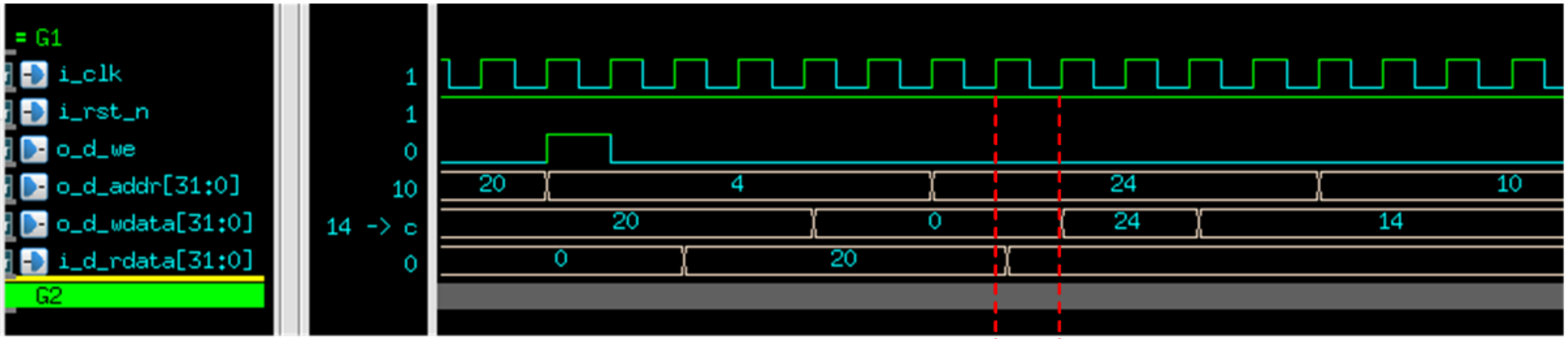
- After outputting o_i_addr to instruction memory, the core can receive the corresponding i_i_inst at the next rising edge of the clock.



Output o_i_addr for relative instruction **Get i_i_inst at the next rising edge of clock**

Specification

- To load data from the data memory, set o_d_we to **0** and o_d_addr to relative address value. i_d_rdata can be received at the next rising edge of the clock.

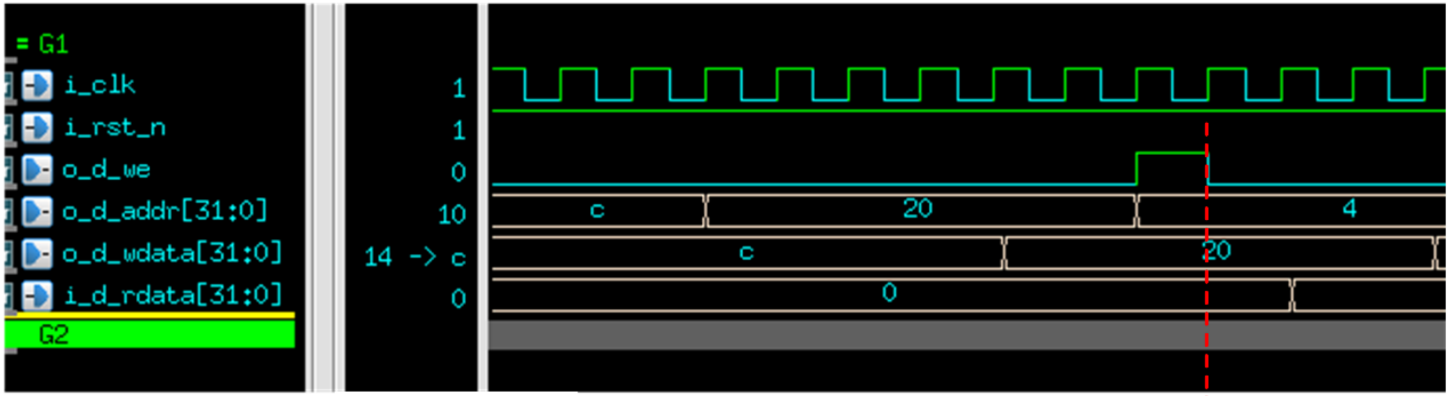


o_d_we = 0, load data from data memory at o_d_addr = 24

Receive i_d_rdata at next rising edge of clock

Specification

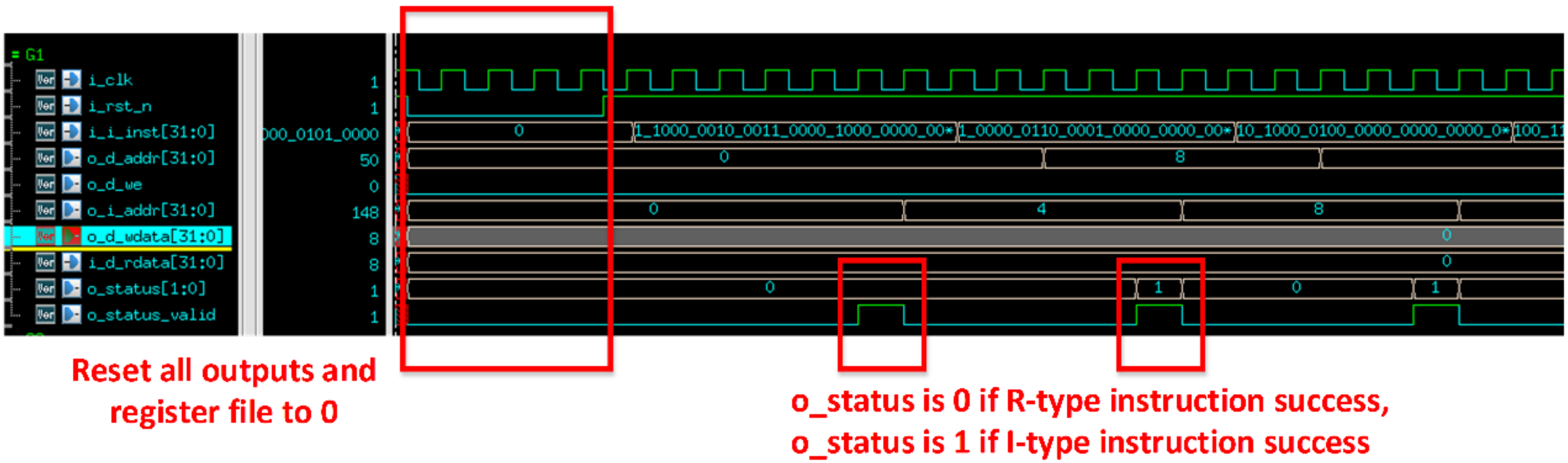
- To save data to the data memory, set o_d_we to **1**, o_d_addr to relative address value, and o_d_wdata to the written data.



o_d_we = 1, store o_d_wdata
to data memory at o_d_addr = 4

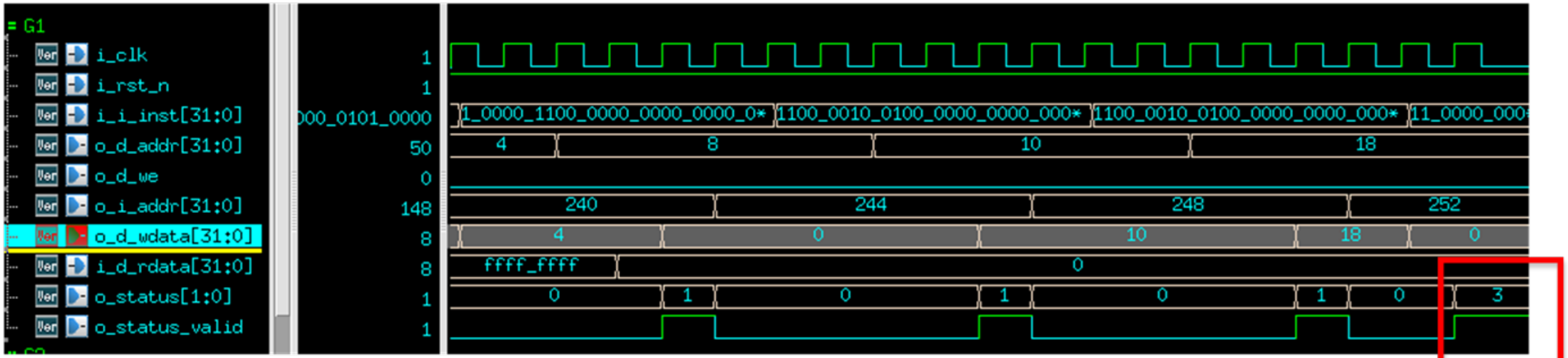
Specification

- Your o_status_valid should be turned to **high** for only **one cycle** for every o_status.
- The testbench will get your output at negative clock edge to check the o_status if your o_status_valid is **high**.



Specification

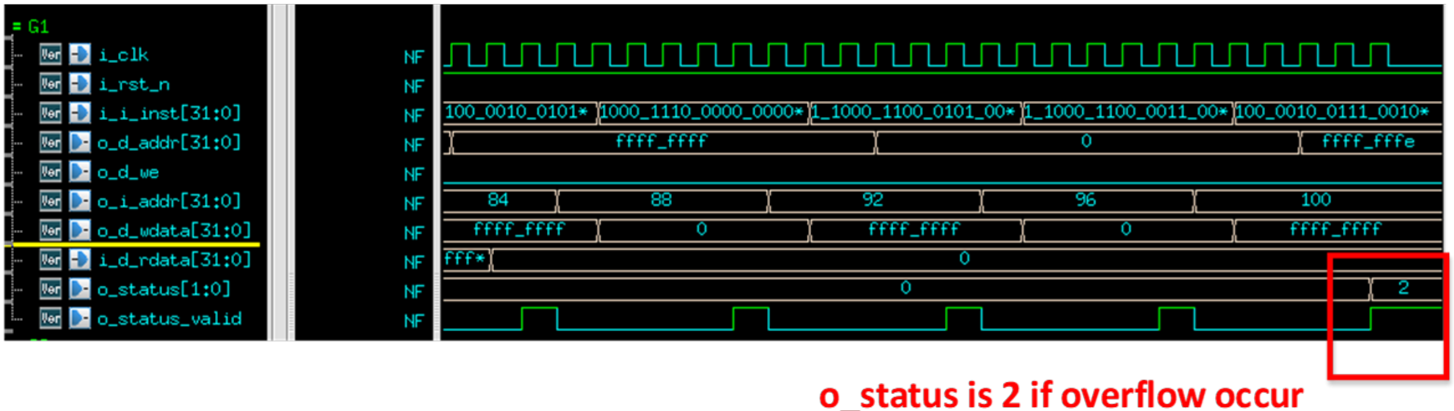
- When you set o_status_valid to **high** and o_status to **3**, stop processing. The testbench will check your data memory value with golden data.



o_status is 3 if instruction is EOF

Specification

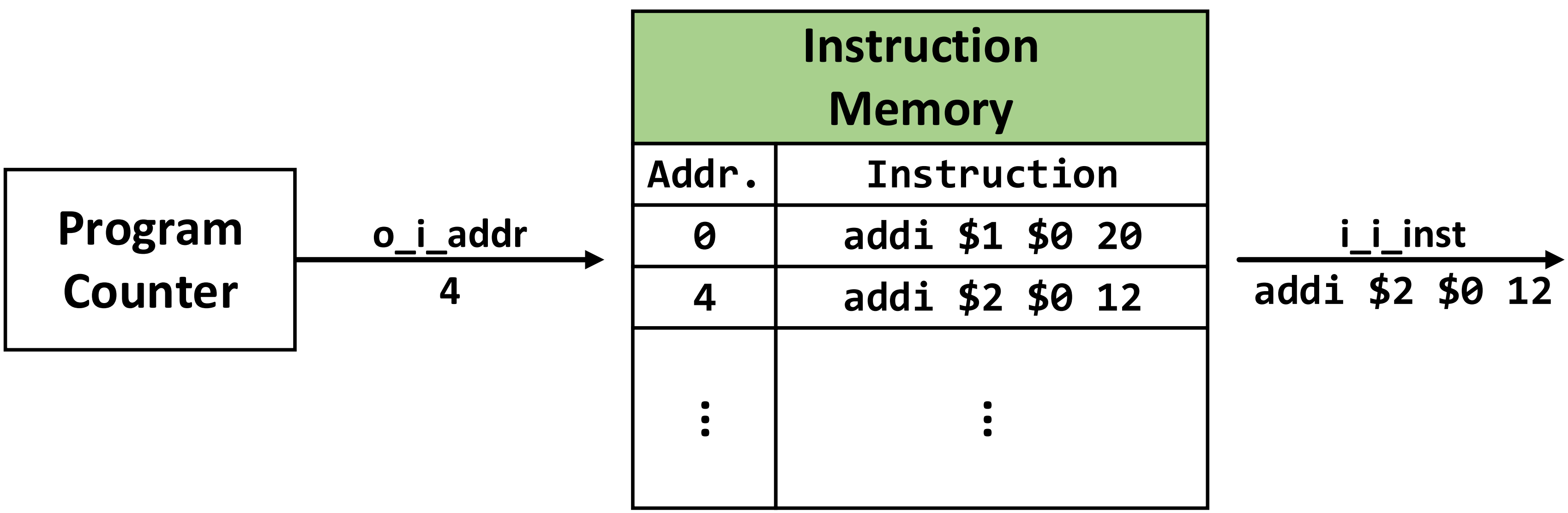
- If overflow happened, stop processing and raise o_status_valid to **high** and set o_status to **2**. The testbench will check your data memory value with golden data.



Program Counter

- Program counter is used to control the address of instruction memory.

`$pc = $pc + 4` for every instruction (except **`beq, bne`**)



Instruction mapping

- **R-type**

[31:26]	[25:21]	[20:16]	[15:11]	[10:0]
opcode	$s2	$s3	$s1	Not used

31 … 0

- **I-type**

[31:26]	[25:21]	[20:16]	[15:0]
opcode	$s2	$s1	im

31 … 0

- **EOF**

[31:26]	[25:0]
opcode	Not used

31 … 0

Instruction

Operation	Assemble	Opcode	Type	Meaning	Note
Add (integer)	add	6’d1	R	\$s1 = \$s2 + \$s3	Signed Operation
Subtract (integer)	sub	6’d2	R	\$s1 = \$s2 - \$s3	Signed Operation
Multiply (integer)	mul	6’d3	R	\$s1 = \$s2 * \$s3	Signed Operation
Add (floating point)	fp_add	6’d13	R	\$s1 = \$s2 + \$s3	Floating Point Operation
Subtract (floating point)	fp_sub	6’d14	R	\$s1 = \$s2 - \$s3	Floating Point Operation
Multiply (floating point)	fp_mul	6’d15	R	\$s1 = \$s2 * \$s3	Floating Point Operation
Add immediate	addi	6’d4	I	\$s1 = \$s2 + im	Signed Operation
Load word	lw	6’d5	I	\$s1 = Mem[\$s2 + im]	Signed Operation
Store word	sw	6’d6	I	Mem[\$s2 + im] = \$s1	Signed Operation

Instruction (cont'd)

Operation	Assemble	Opcode	Type	Meaning	Note
AND	and	6'd7	R	$s1 = $s2 & $s3	Bit-wise
OR	or	6'd8	R	$s1 = $s2 | $s3	Bit-wise
NOR	nor	6'd9	R	$s1 = ~($s2 | $s3)	Bit-wise
Branch on equal	beq	6'd10	I	if($s1==$s2), $pc = $pc + im; else, $pc = $pc + 4	PC-relative Unsigned Operation
Branch on not equal	bne	6'd11	I	if($s1!=$s2), $pc = $pc + im; else, $pc = $pc + 4	PC-relative Unsigned Operation
Set on less than	slt	6'd12	R	if($s2<$s3), $s1 = 1; else, $s1 = 0	Signed Operation
Shift left logical	sll	6'd16	R	$s1 = $s2 << $s3	Unsigned Operation
Shift right logical	srl	6'd17	R	$s1 = $s2 >> $s3	Unsigned Operation
End of File	eof	6'd18	EOF	Stop processing	Last instruction in the pattern

Note: The notation of **`im`** in I-type instruction is **2's complement.**
Note: Signed operations indicates that the data in register file are expressed in **2's complement**.

Floating Point

- For instructions **`fp_add, fp_sub, fp_mul`**, you will have to implement operations with **floating point** format
- Only normal numbers will be provided in test patterns
  - You do not need to consider infinity, denormalized numbers, and NaN
- IEEE 754 single precision format [1]
  - Round to nearest even [2]

[31]	[30:23]	[22:0]
sign	**exponent**	**mantissa**

31 **0**

Floating Point

Rounding

1.BBGRXXX

Guard bit: LSB of result

Round bit: 1st bit removed

Sticky bit: OR of remaining bits

- **Round up conditions**
  - Round = 1, Sticky = 1 → > 0.5
  - Guard = 1, Round = 1, Sticky = 0 → Round to even

Value	*Fraction*	*GRS*	*Incr?*	*Rounded*
128	1.0000000	000	N	1.000
15	1.1010000	100	N	1.101
17	1.0001000	010	N	1.000
19	1.0011000	110	Y	1.010
138	1.0001010	011	Y	1.001
63	1.1111100	111	Y	10.000

Memory IP

- Instruction memory
  - Size: 1024 × 32 bit
  - i_addr[11:2] for address mapping in instruction memory
- Data memory
  - Size: 64 × 32 bit
  - i_addr[7:2] for address mapping in data memory

```
module inst_mem (
    input                i_clk,     // 1-bit
    input                i_rst_n,   // 1-bit
    input  [ 31 : 0 ]    i_addr,    // 32-bit
    output [ 31 : 0 ]    o_inst     // 32-bit
);
```

```
module data_mem (
    input                i_clk,
    input                i_rst_n,
    input                i_we,
    input  [ 31 : 0 ] i_addr,
    input  [ 31 : 0 ] i_wdata,
    output [ 31 : 0 ] o_rdata
);
```

Status

- 4 statuses of o_status

o_status[1:0]	Definition
2’d0	R_TYPE_SUCCESS
2’d1	I_TYPE_SUCCESS
2’d2	MIPS_OVERFLOW
2’d3	MIPS_END

Overflow

- Overflow may be happened.
  - **Situation1**: Overflow happened at arithmetic instructions (add, sub, mul, addi)
  - **Situation2**: If output address are mapped to unknown address in data/instruction memory. (Do not consider the case if instruction address is beyond eof, but the address mapping is in the size of instruction memory)

rtl.f

- Filelist

```
// ----------------------------------------------------------------------------
// Simulation: HW2 simple mips CPU
// ----------------------------------------------------------------------------

// define files
// ----------------------------------------------------------------------------
../00_TESTBED/define.v

// testbench
// ----------------------------------------------------------------------------
../00_TESTBED/testbed.v
../00_TESTBED/inst_mem.vp
../00_TESTBED/data_mem.vp

// design files
// ----------------------------------------------------------------------------
./core.v
```

core.v

- **Do not modify interface**

```
module core #( // DO NOT MODIFY!!!
    parameter ADDR_WIDTH = 32,
    parameter INST_WIDTH = 32,
    parameter DATA_WIDTH = 32
) (
    input                       i_clk,
    input                       i_rst_n,
    output  [ADDR_WIDTH-1:0]   o_i_addr,
    input   [ADDR_WIDTH-1:0]   i_i_inst,
    output                      o_d_we,
    output  [ADDR_WIDTH-1:0]   o_d_addr,
    output  [DATA_WIDTH-1:0]   o_d_wdata,
    input   [DATA_WIDTH-1:0]   i_d_rdata,
    output  [            1:0]   o_status,
    output                      o_status_valid
);

endmodule
```

define.v

```
// opcode definition
`define OP_ADD       1
`define OP_SUB       2
`define OP_MUL       3
`define OP_ADDI      4
`define OP_LW        5
`define OP_SW        6
`define OP_AND       7
`define OP_OR        8
`define OP_NOR       9
`define OP_BEQ       10
`define OP_BNE       11
`define OP_SLT       12
`define OP_FP_ADD    13
`define OP_FP_SUB    14
`define OP_FP_MUL    15
`define OP_SLL       16
`define OP_SRL       17
`define OP_EOF       18

// MIPS status definition
`define R_TYPE_SUCCESS 0
`define I_TYPE_SUCCESS 1
`define MIPS_OVERFLOW 2
`define MIPS_END 3
```

testbed_temp.v

- Things to add in your testbench
  - Clock
  - Reset
  - Waveform file
  - Function test
  - …

```
module testbed;

    reg clk = 0;
    reg rst_n = 1;
    wire [ 31 : 0 ] imem_addr;
    wire [ 31 : 0 ] imem_inst;
    wire            dmem_we;
    wire [ 31 : 0 ] dmem_addr;
    wire [ 31 : 0 ] dmem_wdata;
    wire [ 31 : 0 ] dmem_rdata;
    wire [  1 : 0 ] mips_status;
    wire            mips_status_valid;
```

```
core u_core (
        .i_clk(),
        .i_rst_n(),
        .o_i_addr(),
        .i_i_inst(),
        .o_d_we(),
        .o_d_addr(),
        .o_d_wdata(),
        .i_d_rdata(),
        .o_status(),
        .o_status_valid()
);

inst_mem  u_inst_mem (
        .i_clk(),
        .i_rst_n(),
        .i_addr(),
        .o_inst()
);

data_mem  u_data_mem (
        .i_clk(),
        .i_rst_n(),
        .i_we(),
        .i_addr(),
        .i_wdata(),
        .o_rdata()
);
```

Protected Files

- The following files are protected
  - inst_mem.vp
  - data_mem.vp

```
module inst_mem (
    input                i_clk,
    input                i_rst_n,
    input   [ 31 : 0 ] i_addr,
    output  [ 31 : 0 ] o_inst
);
`protected
Ndi5kSQH5DT^<D9i:i7T7ceFn3@o:C2]Ke:L;dfq^QGQOG?3K:ogIe8]1ge<gcg3
lCH3E]ekmLN<RVkKa1o39E7E21a;`hJRSFMUb2pAgL?TeZdH>]^RK;KWYU@>G2G6
H[IMYG;D<[Z>[;0`?NbPoEAQM<_ZfDbp1HN@HmqSO`Q<5[53C:9UD4^:Y44]9a^e
PDH[cdHb;HPi\R4k7mAlPdY8ZpI=4?nNZgQ2I>QUg[agM4j@cTl]hnMoC<i1F9DR
[kf;]ULlecpF`H;9L2DeZa>@LdfLgfB8l4bWgT:_P3?ENhifQW@_Ne;gMZE9@f0A
OERY:F4d68KqAIn]N1dj4LN7_8:Uigk?9UJ9JYQM4l=Lq\TEXDQO1>Zo^SJq=Cge
?kp68am:9p81Q1[<jSXm?;GhoPHHYKp\Q][2epXn_18k8LA5g=N7=D?=VOX<Ham8
[A:Qc;RlpO38>d9_Qk9cfk?:5hXP>LT3n=DP08A_]WPa6nA3cYZjGl32qB9]I4kp
>=:4m9P`dCB8@?ip`@VR7AahIggjNR:M1:_\KXElBFOm<Bb@ZS[^W7EheJ18mX8;
?7F`Pg\CCA8igfFUoWY@k>Yq=U3_4>E5O_nJ\`aUGcfWD_89dab]cUQfF<?2P?OG
qWglWC[\iqnjC<OipHHnb<T4Sg<:UORVSVocI_g?<a@o__<PQ493cZIE;7^Sp1AQ
G<cl7[]R\>VT]]LA\7?Uk=]\bG19MT9N;K<Y92[iKOged92EIkQZliW>qlG]QI?5
ST06RFN<KJl@VM1EWKSmB1B5U:BaX`E7of7mqOJBgO`9k$
`endprotected

endmodule
```

Command

- 01_run
  - Usage: ./01_run p0

```
vcs -f rtl.f -full64 -R -debug_access+all
+define+$1 +v2k
```

- 99_clean_up

```
rm -rf *.history *.key *.log
rm -rf novas.rc novas.fsdb novas.conf
rm -rf INCA_libs nWaveLog BSSLib.lib++
```

PATTERN

- Files in PATTERN are for your references

inst_assemble.dat

```
----------------------
R-type  $s2  $s3  $s1
I-type  $s2  $s1  im
----------------------
and     $1   $3   $1
lw      $3   $1    8
bne     $2   $0    8
add     $7   $1   $4
slt     $6   $5   $4
slt     $4   $1   $1
lw      $1   $3   12
lw      $7   $7    4
bne     $6   $7    8
lw      $6   $5    8
lw      $5   $2    8
```

Grading Policy

- TA will run your code with following command

```
vcs -f rtl.f -full64 -R -debug_access+all +define+p0 +v2k
```

- Pass the patterns to get full score
  - Provided pattern: **70%**
    - **30%** for each test (data from data memory: **15%**, status check: **15%**)
    - **10%** for spyglass check
  - Hidden pattern: **30%** (20 patterns in total)
    - **1.5%** for each test (data & status both correct)
- **No delay submission is allowed**
- Lose **5 point** for any wrong naming rule or format for submission

Submission

- Create a folder named **studentID_hw2**, and put all below files into the folder

```
r11943133_hw2
│    └── 01_RTL
│         │   ├── rtl.f (your file list)
│         │   ├── core.v
│         │   ├── flist.v (your file list for lint check)
│         │   └── all other design files (optional)
```

- Compress the folder **studentID_hw2** in a tar file named **studentID_hw2_v*k*.tar** (*k* is the number of version, *k* =1,2,…)
  - Use lower case for student ID. (Ex. r11943133_hw2_v1.tar)

- Submit to NTU Cool

Hint

- Design your FSM with following states
  1. Idle
  2. Instruction Fetching
  3. Instruction decoding
  4. ALU computing/ Load data
  5. Data write-back
  6. Next PC generation
  7. Process end

Reference

- [1] IEEE 754 Single Precision Format
  - https://zh.wikipedia.org/zh-tw/IEEE_754
- [2] Round to Nearest Even
  - https://www.cs.cmu.edu/afs/cs/academic/class/15213-s16/www/lectures/04-float.pdf