Computer Architecture
Final project: CPU

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Due 23:59, 2023/12/25 (Mon.)

Outline

- Announcement & Data Preparation
- Goal & Specifications
- Test Pattern
- Simulation
- Synthesizable Coding Style Check
- Report
- Submission
- Grading Policy
- Appendix

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Announcement

- 1 ~ 2 people / group
- Please find a representative to fill out the google form before 11:59, 11/20(Mon.)
  - 分組表單
  - TA will help you find group members if you can not find any partner
  - Select “徵隊友” in the form
- The final member list will be announced before 23:59, 11/22 (Wed.)
  - Those who do not response will be regarded as one people in one group

Data Preparation

- Decompress CA_Final.zip
- Directory hierarchy:
  - 00_TB/
    - tb.v ➔ testbench file
    - Memory.v ➔ memory file
    - Pattern/ ➔ test pattern directory
  - 01_RTL/
    - 00_license.sh ➔ EDA tool license source command
    - 01_run.sh ➔ vcs/ncverilog command
    - 99_clean_up.sh ➔ Command to clean temporary data
    - CHIP.v ➔ Your design
  - 02_Assembly/ ➔ Assembly files directory
  - 03_Python/ ➔ Pattern generator files directory

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Goal

- Implement a CPU
- Add multiplication/division unit (mulDiv) to CPU (HW2)
- Handle multi-cycle operations
- Get more familiar with assembly and Verilog

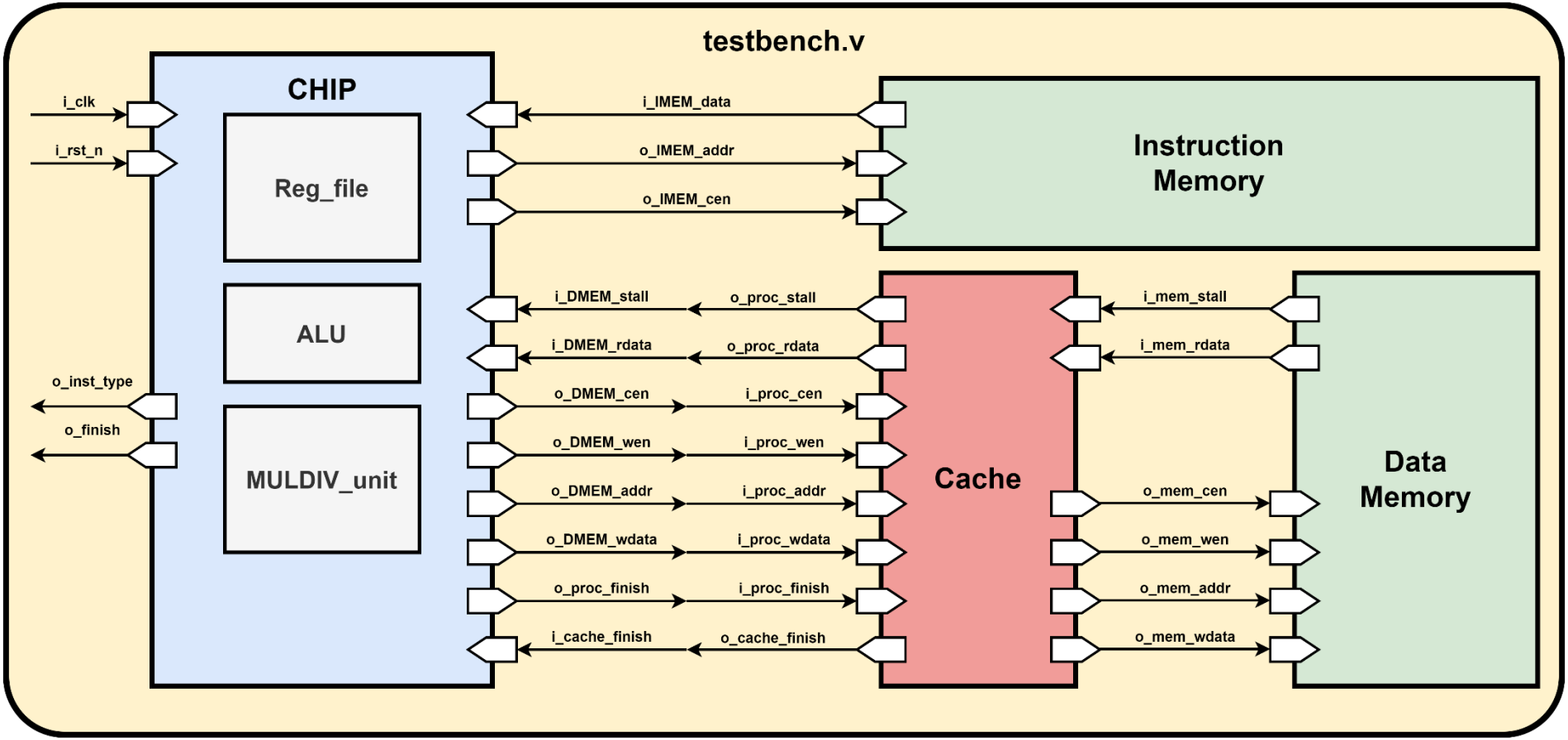
- BONUS:
  - Implement L1 cache
  - What benefit cache brings from

Supporting Instructions

- Your design must **at least** support
  - `auipc, jal, jalr`
  - `add, sub, and, xor`
  - `addi, slli, slti, srai`
  - `lw, sw`
  - `mul`
  - `beq, bge, blt, bne`
  - `ecall (the end of program)`

- See “Instruction_Set_Listings.pdf” for more information of machine code

Block Diagram



Specification – CHIP I/O

Signal Name	I/O	Width	Description
i_clk	I	1	Clock signal
i_rst_n	I	1	Active **low** asynchronous reset
i_IMEM_data	I	32	Instruction binary code
o_IMEM_addr	O	32	PC address
o_IMEM_cen	O	1	Set **high** to load instruction
i_DMEM_stall	I	1	Active **high** control signal that asks processor to wait
i_DMEM_rdata	I	32	64-bit output data
o_DMEM_cen	O	1	Set **high** to enable memory functions
o_DMEM_wen	O	1	Set **high** for write, **low** for read
o_DMEM_addr	O	32	Data memory address
o_DMEM_wdata	O	32	Data for writing to data memory
o_finish	O	1	Set **high** for finishing the procedure

Specification – CHIP I/O

Signal Name	I/O	Width	Description
i_cache_finish	I	1	Finish signal from cache
o_proc_finish	O	1	Finish signal to cache

Specification – CHIP I/O

- Do not modify the I/O interface!!

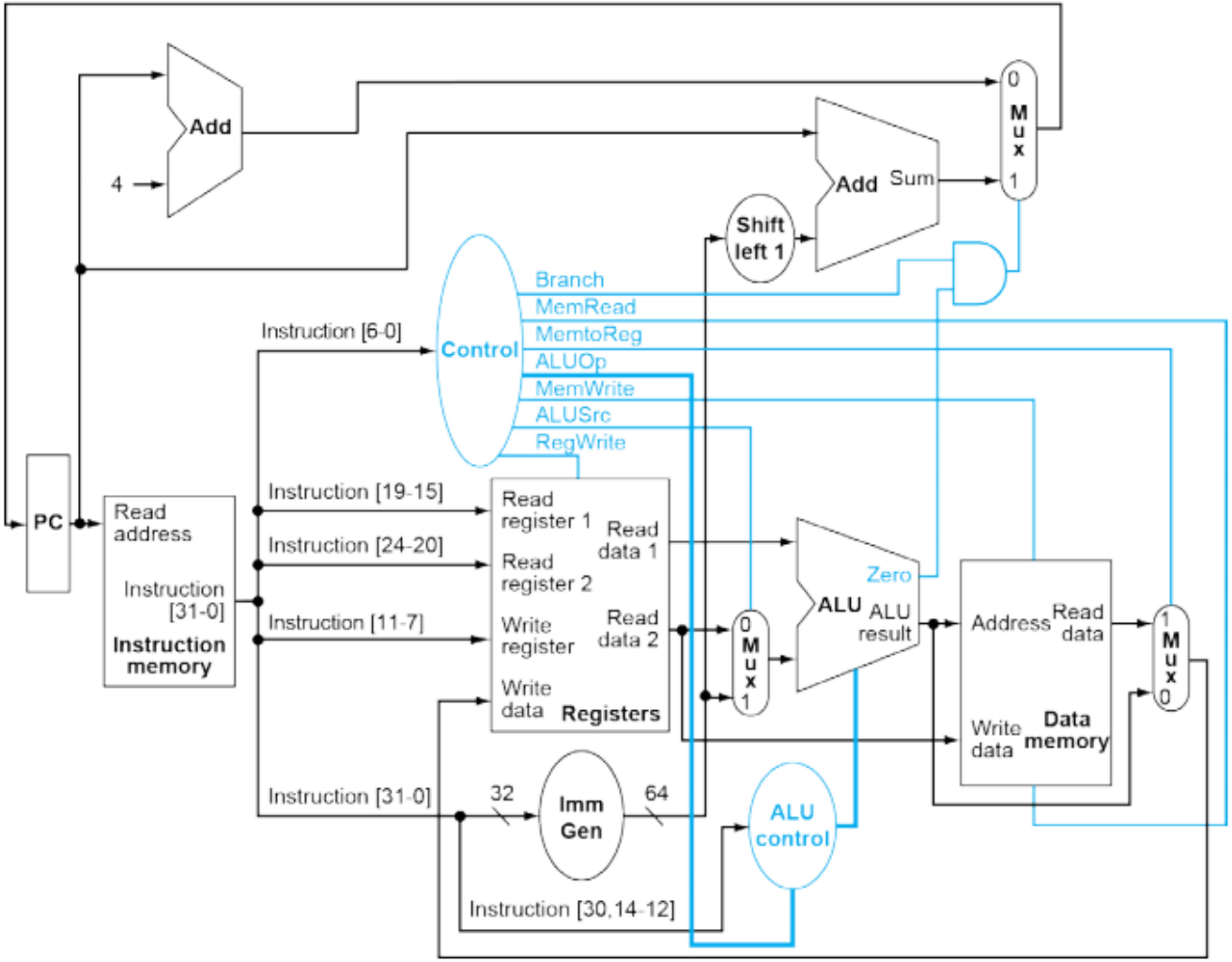
```
//---------------------------- DO NOT MODIFY THE I/O INTERFACE!! ----------------------------//
module CHIP #(                                                                               //
    parameter BIT_W = 32                                                                     //
)(                                                                                           //
    // clock                                                                                 //
        input               i_clk,                                                       //
        input               i_rst_n,                                                     //
    // instruction memory                                                                    //
        input  [BIT_W-1:0]  i_IMEM_data,                                                 //
        output [BIT_W-1:0]  o_IMEM_addr,                                                 //
        output              o_IMEM_cen,                                                  //
    // data memory                                                                           //
        input               i_DMEM_stall,                                                //
        input  [BIT_W-1:0]  i_DMEM_rdata,                                                //
        output              o_DMEM_cen,                                                  //
        output              o_DMEM_wen,                                                  //
        output [BIT_W-1:0]  o_DMEM_addr,                                                 //
        output [BIT_W-1:0]  o_DMEM_wdata,                                                //
    // finnish procedure                                                                     //
        output              o_finish                                                     //
    // cache                                                                                 //
        input               i_cache_finish                                               //
        output              o_proc_finish                                                //
);                                                                                           //
//---------------------------- DO NOT MODIFY THE I/O INTERFACE!! ----------------------------//
```

Specification – Other Description

- All inputs are synchronized with the negative edge clock.
- All outputs should be synchronized at clock rising edge.
- You should reset all your outputs when i_rst_n is **low**. Active low asynchronous reset is used and only once.
- The runtime of the design should be within 10000 cycles
- **The operators “ * ” and “ / “ are forbidden except for index**

Quick Review – Architecture

- Not complete (does not include jal, jalr, …)



TODO

- Parameters declaration
  - Instructions
  - Opcode
  - …

```
// ---------------------------------
// Parameters
// ---------------------------------

    // TODO: any declaration
```

- Wires & Registers declaration
  - PC
  - …

```
// ---------------------------------
// Wires and Registers
// ---------------------------------

    // TODO: any declaration
        reg [BIT_W-1:0] PC, next_PC;
```

TODO

- Continuous Assignment
  - …
- Submodules
  - Register file
  - ALU
  - …

```
// ---------------------------------------
// Continuous Assignment
// ---------------------------------------

    // TODO: any wire assignment

// ---------------------------------------
// Submoddules
// ---------------------------------------

    // TODO: Reg_file wire connection
    Reg_file reg0(
        .i_clk  (i_clk),
        .i_rst_n(i_rst_n),
        .wen    (),
        .rs1    (),
        .rs2    (),
        .rd     (),
        .wdata  (),
        .rdata1 (),
        .rdata2 ()
    );
```

Register File

- Do not modify this part !!!
- Initial values
  - X0 stores constant 0
  - X2 stores stack pointer
  - X3 stores global pointer
  - Others are 0

```
module Reg_file(i_clk, i_rst_n, wen, rs1, rs2, rd, wdata, rdata1, rdata2);

    parameter BITS = 32;
    parameter word_depth = 32;
    parameter addr_width = 5; // 2^addr_width >= word_depth

    input i_clk, i_rst_n, wen; // wen: 0:read | 1:write
    input [BITS-1:0] wdata;
    input [addr_width-1:0] rs1, rs2, rd;

    output [BITS-1:0] rdata1, rdata2;

    reg [BITS-1:0] mem [0:word_depth-1];
    reg [BITS-1:0] mem_nxt [0:word_depth-1];

    integer i;

    assign rdata1 = mem[rs1];
    assign rdata2 = mem[rs2];

    always @(*) begin
        for (i=0; i<word_depth; i=i+1)
            mem_nxt[i] = (wen && (rd == i)) ? wdata : mem[i];
    end

    always @(posedge i_clk or negedge i_rst_n) begin
        if (!i_rst_n) begin
            mem[0] <= 0;
            for (i=1; i<word_depth; i=i+1) begin
                case(i)
                    32'd2: mem[i] <= 32'hbffffff0;
                    32'd3: mem[i] <= 32'h10008000;
                    default: mem[i] <= 32'h0;
                endcase
            end
        end
        else begin
            mem[0] <= 0;
            for (i=1; i<word_depth; i=i+1)
                mem[i] <= mem_nxt[i];
        end
    end
endmodule
```

TODO: Always blocks

- Combinational circuits
- Sequential circuits
- …

```
// ---------------------------------------------------------------------
// Always Blocks
// ---------------------------------------------------------------------

    // Todo: any combinational/sequential circuit

    always @(posedge i_clk or negedge i_rst_n) begin
        if (!i_rst_n) begin
            PC <= 32'h00010000; // Do not modify this value!!!
        end
        else begin
            PC <= next_PC;
        end
    end
endmodule
```

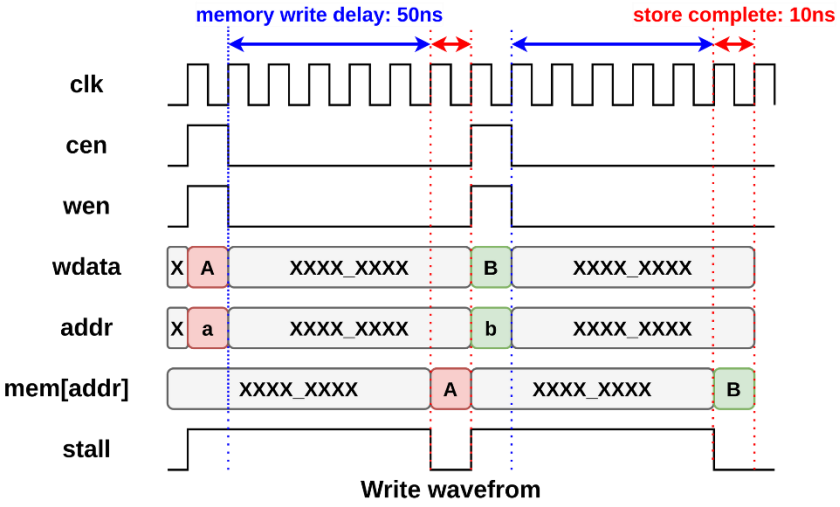
TODO: MUL

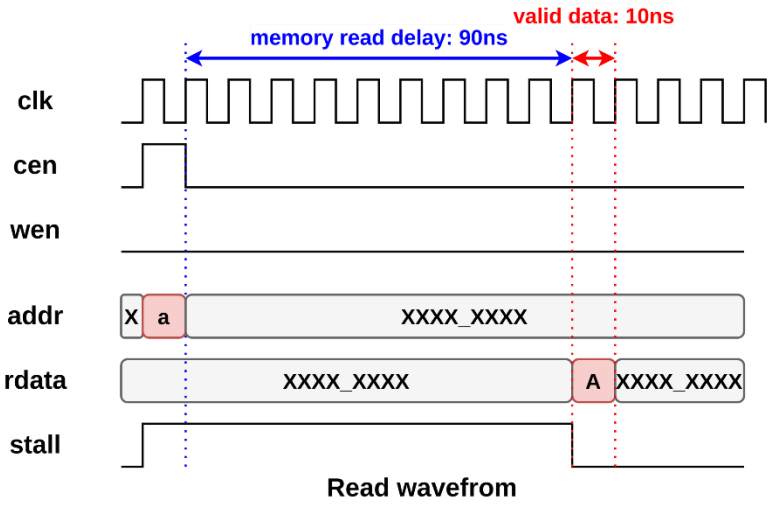
- Your HW2

```
module MULDIV_unit(
    // TODO: port declaration
    );
    // Todo: HW2
endmodule
```

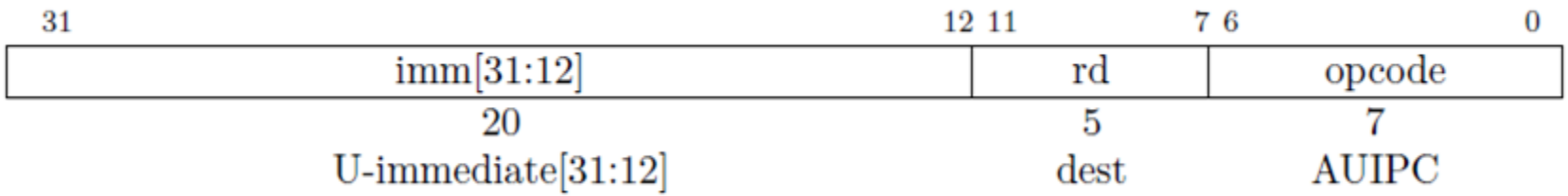
Supplement: Memory control signals

Function	cen	wen
Hold	0	X
Read	1	0
Write	1	1



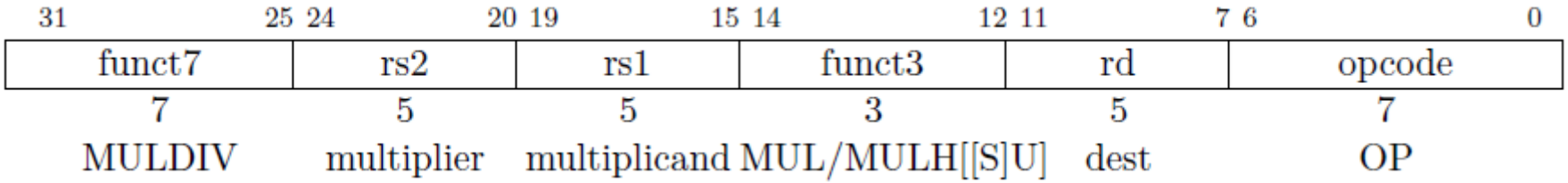


Supplement: Instruction "auipc"



- Add upper immediate to PC, and store the result to rd
  - `auipc` rd, U-immediate
- Example: `auipc` x5, 1 (PC = 0x0001001c)
  - 0x0001001c + 0x00001000 = 0x0001101c
  - Store 0x0001101c in x5

Supplement: Instruction "mul"



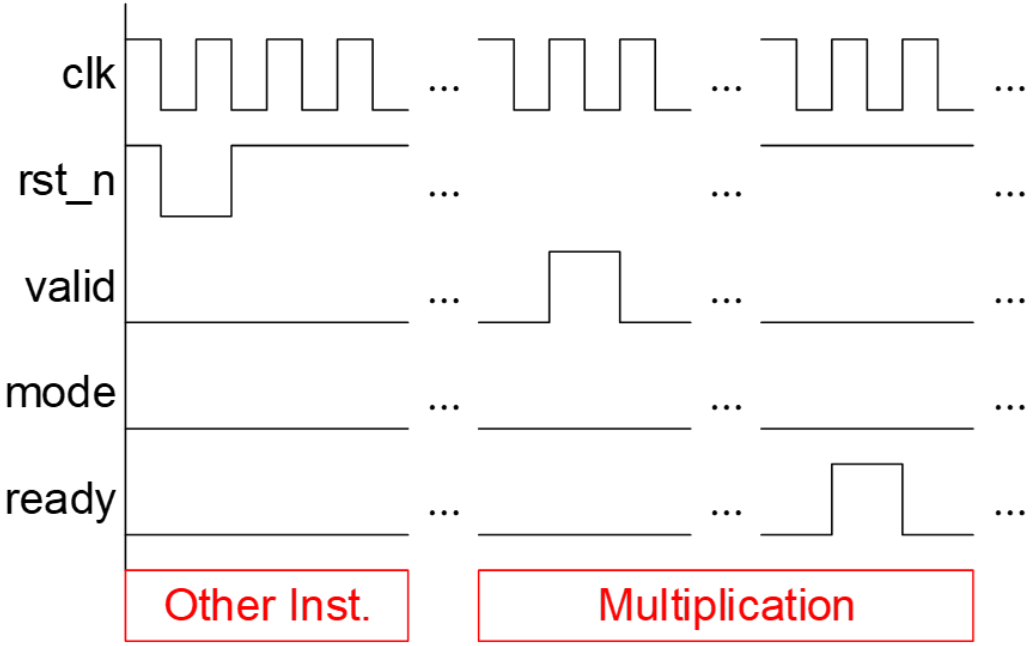
- Not included in RV32I
- Store the lower 32-b result (rs1 × rs2) to rd

- Example: `mul` x10, x10, x6
  - x10 = 0x00000001, x6 = 0x00000002
  - 0x00000001 × 0x00000002 = 0x00000002
  - Store 0x00000002 in x10

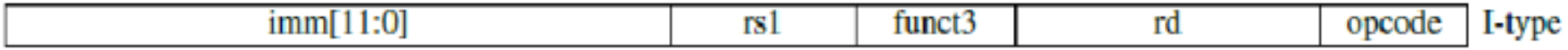
- **Your mulDiv can support this instruction!**

Supplement: Multi-Cycle Operation

- Once CPU decodes `mul` operation, issue valid to your mulDiv
- Once CPU receives ready, store the lower 32-b result to rd
- You might have to design FSM in your CPU



Supplement: Instruction "ecall"



- Environment call: represent the end of procedure here
- Example:
  - `addi a0, x0, 10` ➔ `00a00513`
  - `ecall` ➔ `00000073 (machine code)`

- **Pull up** the signal **o_finish** when all tasks are done inside the processor and cache if implemented
- The testbench will check the answer and golden after **o_finish** is pull up

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Test Pattern I0: Leaf Example

- Modified from lecture slides
- The procedure loads a,b,c,d from 0x00010064 0x00010070, and stores the result to 0x00010074
- Simulation:

```
vcs ../00_TB/tb.v CHIP.v -full64 -R -\
debug_access+all +v2k +notimingcheck +define+I0
```

```
def leaf(a,b,c,d):
    f = (a+b) - (c+d)
    return f
```

```
.data
    a: .word 5
    b: .word 6
    c: .word 8
    d: .word 0
.text
.globl __start
```

0x00010074	00	00	00	03
0x00010070	00	00	00	00
0x0001006c	00	00	00	08
0x00010068	00	00	00	06
0x00010064	00	00	00	05

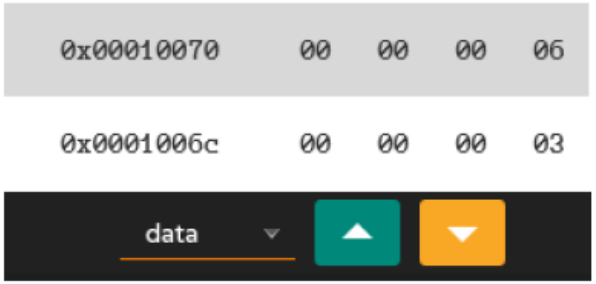
Test Pattern I1: Fact

- Modified from lecture slides
- The procedure loads n from 0x0001006c, and stores the result to 0x00010070
- Simulation:

```
vcs ../00_TB/tb.v CHIP.v -full64 -R -\
debug_access+all +v2k +notimingcheck +define+I1
```

```
def fact(n):
    if n < 1:
        return 1
    else:
        return n*fact(n-1)
```

```
.data
n: .word 3
```



Test Pattern I2: HW1

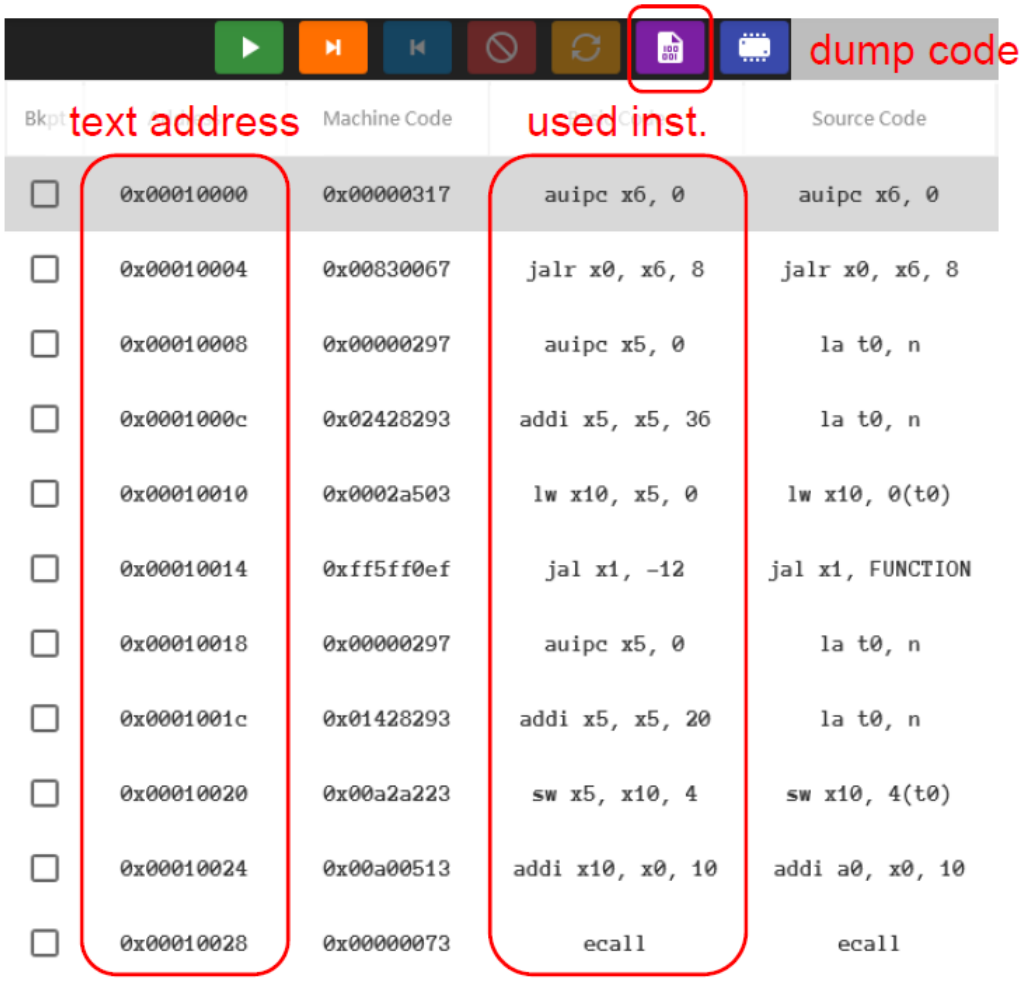
- Design your assembly first (hw1.s)
  - $T(n) = \begin{cases} 5T\left(\left\lfloor \frac{n}{2} \right\rfloor\right) + 6n + 4, & if\ n \geq 2 \\ 2, & n = 1 \end{cases}$
  - E.g., T(8) = 842, T(13) = 1082
  - **Implement with recursive function only**
- The instructions should be generated by yourself to test this pattern, TA will run this part by TA's golden one.

```
FUNCTION:
    # Todo: Define your own function in HW1
    # You should store the output into x10


# Do NOT modify this part!!!
17 references
__start:
    la   t0, n
    lw   x10, 0(t0)
    jal  x1,FUNCTION
    la   t0, n
    sw   x10, 4(t0)
    addi a0,x0,10
    ecall
```

Test Pattern I2: HW1

- Go to simulator
- Dump code → binary file



Bkpt	Machine Code	Source Code
0x00010000	0x00000317	auipc x6, 0
0x00010004	0x00830067	jalr x0, x6, 8
0x00010008	0x00000297	auipc x5, 0
0x0001000c	0x02428293	addi x5, x5, 36
0x00010010	0x0002a503	lw x10, x5, 0
0x00010014	0xff5ff0ef	jal x1, -12
0x00010018	0x00000297	auipc x5, 0
0x0001001c	0x01428293	addi x5, x5, 20
0x00010020	0x00a2a223	sw x5, x10, 4
0x00010024	0x00a00513	addi x10, x0, 10
0x00010028	0x00000073	ecall

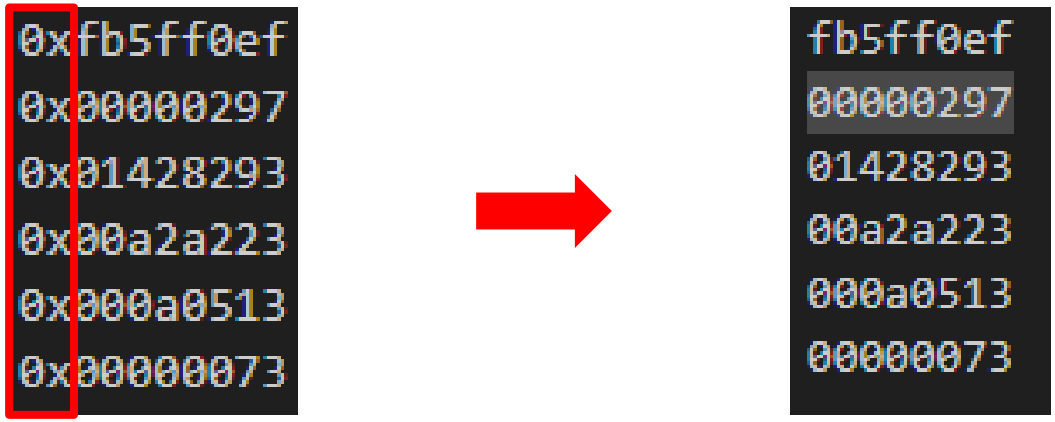
```
1  0x00000317
2  0x00830067
3  0x00000297
4  0x02428293
5  0x0002a503
6  0xff5ff0ef
7  0x00000297
8  0x01428293
9  0x00a2a223
10 0x00a00513
11 0x00000073
```

Test Pattern I2: HW1

- Modify and save to the pattern directory as:

  00_TB/Pattern/I2/mem_I.dat

Delete



- Simulation

```
vcs ../00_TB/tb.v CHIP.v -full64 -R -\
debug_access+all +v2k +notimingcheck +define+I2
```

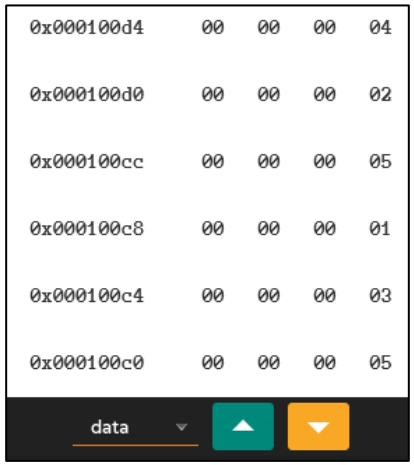
Test Pattern I3: Sorting

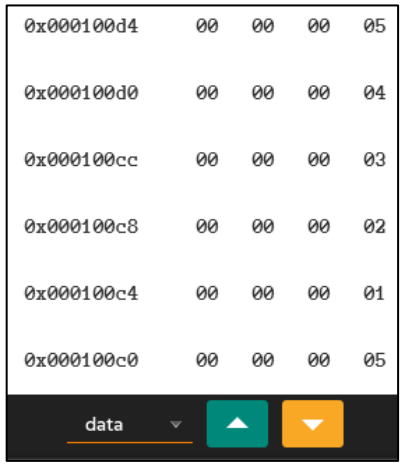
- This procedure sorts N numbers and stores them in order back to memory
- The procedure loads N from 0x000100c0, and sorts numbers in memory banks start at 0x000100c4
- Simulation:

```
vcs ../00_TB/tb.v CHIP.v -full64 -R -\
debug_access+all +v2k +notimingcheck +define+I3
```

```
def sort(v, n):
    for i in range(n):
        for j in range(i-1,-1,-1):
            if v[j] > v[j+1]:
                v[j], v[j+1] = v[j+1], v[j]
    return v
```

```
.data
    n: .word 5
    a: .word 3
    b: .word 1
    c: .word 5
    d: .word 2
    e: .word 4
```





Pattern Generation

- Three python codes provided:
  - I0_leaf_gen.py
  - I1_fact_gen.py
  - I2_hw1_gen.py
  - I3_sort_gen.py
- TA will change the variables in *_gen.py to generate new test patterns when testing your CPU design

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Simulation

- There are two files in folder named “code”
  - CHIP.v (your project)
  - tb.v (testbench)
  - memory.v (memory file)
- To run simulation, you should run source command in advance
  - `$ source 00_license.sh` (use given file)

Simulation (cont.)

- Verilog simulation
  - `$ source 01_run.sh [I0/I1/I2/I3]`
  - TA will run your code with following format of command in 01_run.sh :

```
vcs ../00_TB/tb.v CHIP.v -full64 -R -\
debug_access+all +define+$1 +v2k +notimingcheck
```

  - The word in the block "$1" is the instruction set of test pattern. Ex: `$ source 01_run.sh I0`
  - Make sure to pass every given sets without any error messages.

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Synthesizable Coding Style Check

Register Name	Type	Width	Bus	MB	AR	AS	SR	SS	ST
alu_in_reg	Flip-flop	32	Y	N	Y	N	N	N	N
counter_reg	Flip-flop	5	Y	N	Y	N	N	N	N
shreg_reg	Flip-flop	64	Y	N	Y	N	N	N	N
state_reg	Flip-flop	2	Y	N	Y	N	N	N	N

- All sequential elements must be flip-flops
- **Make sure there is no latches in your design**
- Check by Design Compiler
- Command:
  - `$ dv -no_gui`
  - `design_vision> read_verilog HW2.v`
- Exit:
  - `design_vision> exit`

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Report

- Record the execution cycle number of each instruction set
  - Ex:

```
Success!
The test result is .....PASS :)
Total execution cycle :                    131
```

Instruction Set	Execution cycle
I0	131
I1	…
I2	…
I3	…

- Snapshot the “Register table” in Design Compiler

Report

- Work description
  - Draw the block diagram of your CPU architecture
  - Describe how you design the data path of instructions not referred in the lecture slides (jal, jalr, auipc, …)
  - Describe how you handle multi-cycle instructions (mul, div …)
  - Describe your observation
- [BONUS] Cache design
  - Briefly describe your cache architecture
  - Describe how your cache improves time performance
    - Ex:

Instruction Set	Without Cache	With Cache	Speedup
I0	75	75	1
I1	680	658	1.03
I2	202	180	1.12
I3	525	338	1.55

- List a work distribution table

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Submission

- **Deadline: 23:59, 2023/12/25 (Mon.)**
  - Late submission: 50% reduction per day
- Upload Final_group_<group_id>_vk.zip to NTUCOOL
  - (k is the number of version, k =1,2,…)
  - Final_group_<group_id>_vk.zip
    - Final_group_<group_id>/
      - CHIP.v
      - report.pdf
  - TA will only check the last version of your homework.

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Grading Policy

- **Synthesizable design check before grading**
- **(60%)** Test pattern
  - Each instruction set: 12%
    - Default: 8%
    - Change test pattern: 4 %
  - Hidden pattern: 12%
- **(20%)** Execution time performance
  - This would be graded after getting full credit from test pattern
- **(20% + 5% bonus)** Report
  - 20% CHIP, 5% cache
- **(15% bonus)** cache implementation
- Other rules:
  - Lose **10-point** for any wrong format rule. Don't compress all homework folder.

Total 20% bonus for cache

DOs and DONTs for the TAs

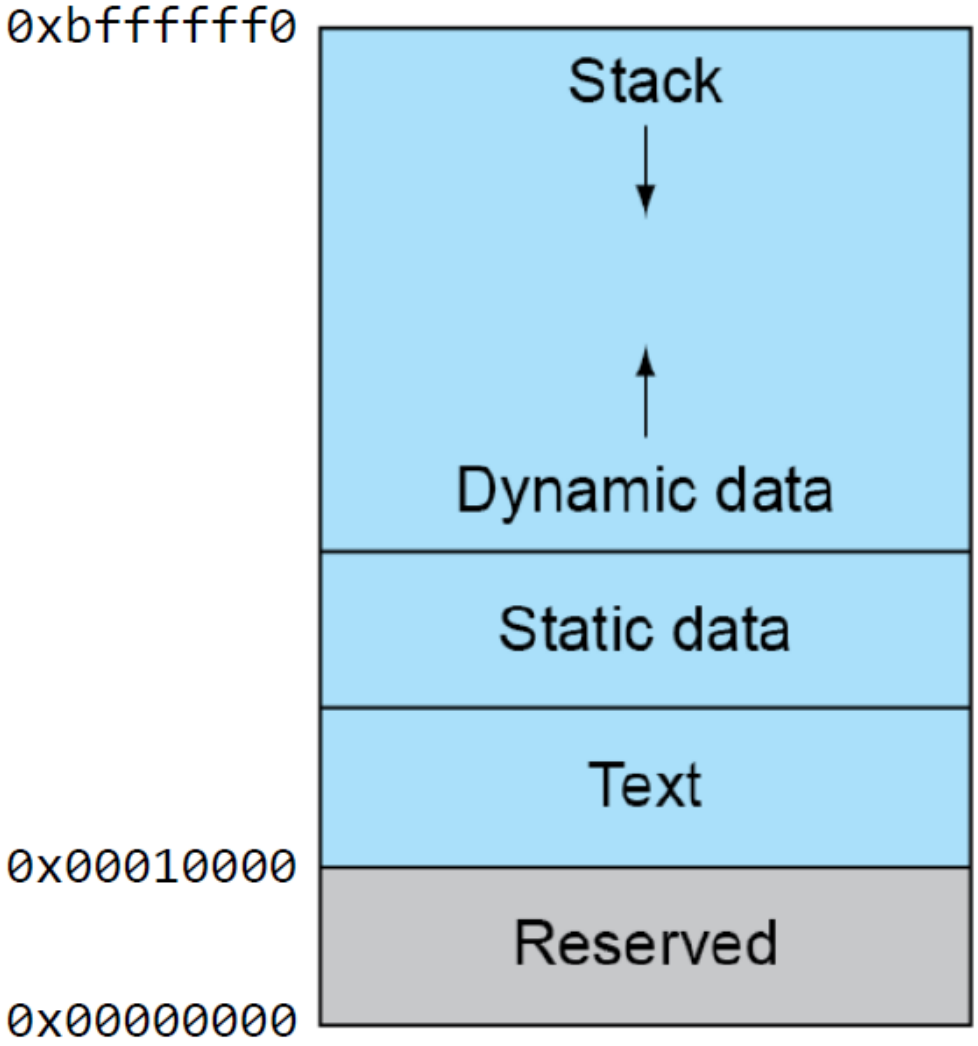
- TAs are happy to help, but they will NOT debug for you.
- TAs do NOT answer questions not related to the course.
- If you want to discuss with TAs face-to-face, please email the TAs to schedule an appointment instead of stopping by the lab directly.

Cache Implementation & Memory Layout

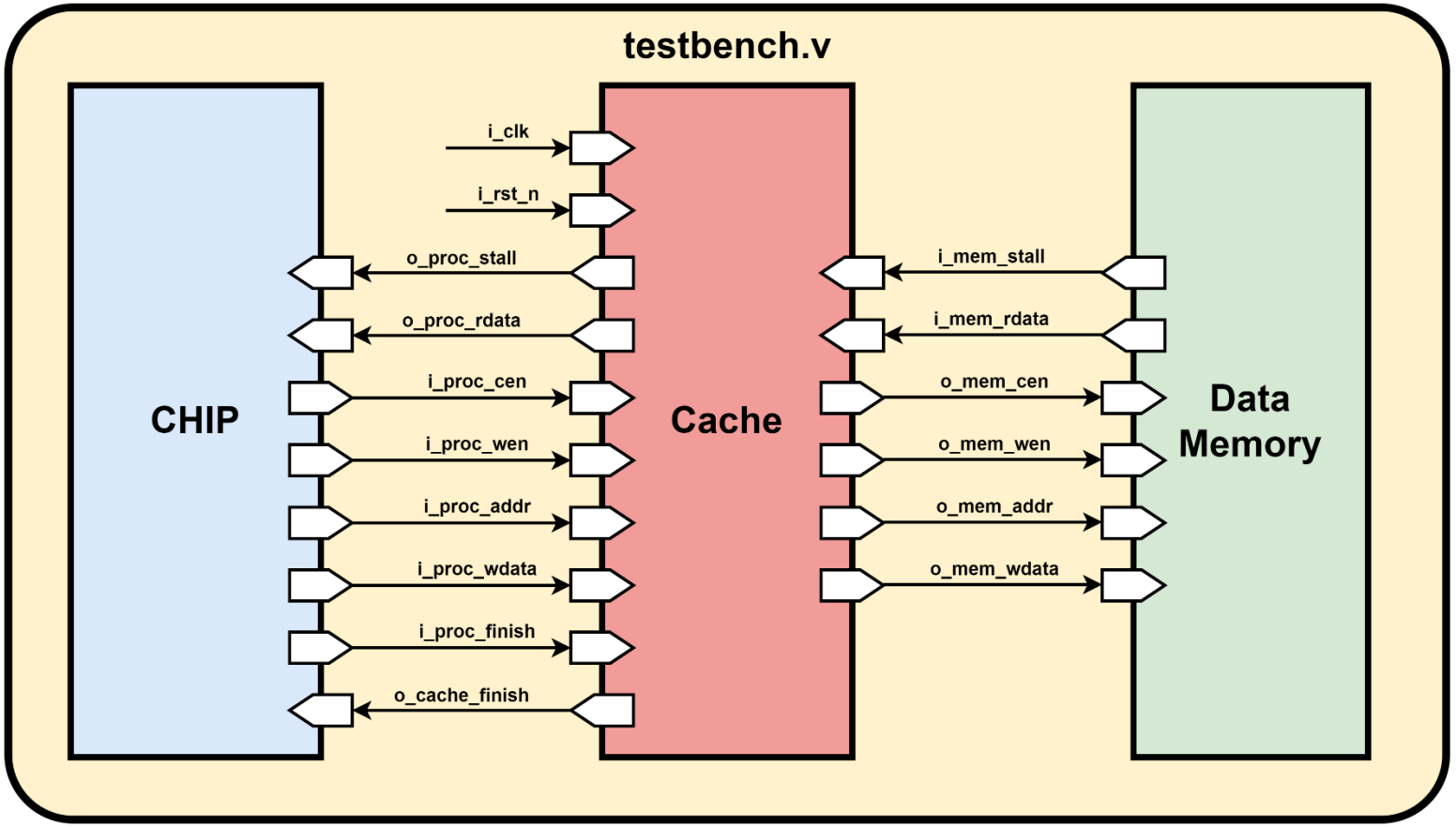
APPENDIX

Memory Layout

- In Jupiter simulator
- Text
  - Program code
- Data
  - Variables, arrays, etc.
- Stack
  - Automatic storage



Specification – Cache I/O



Signal Name	I/O	Width	Description
i_clk	I	1	Clock signal
i_rst_n	I	1	Active **low** asynchronous reset

Specification – Cache I/O

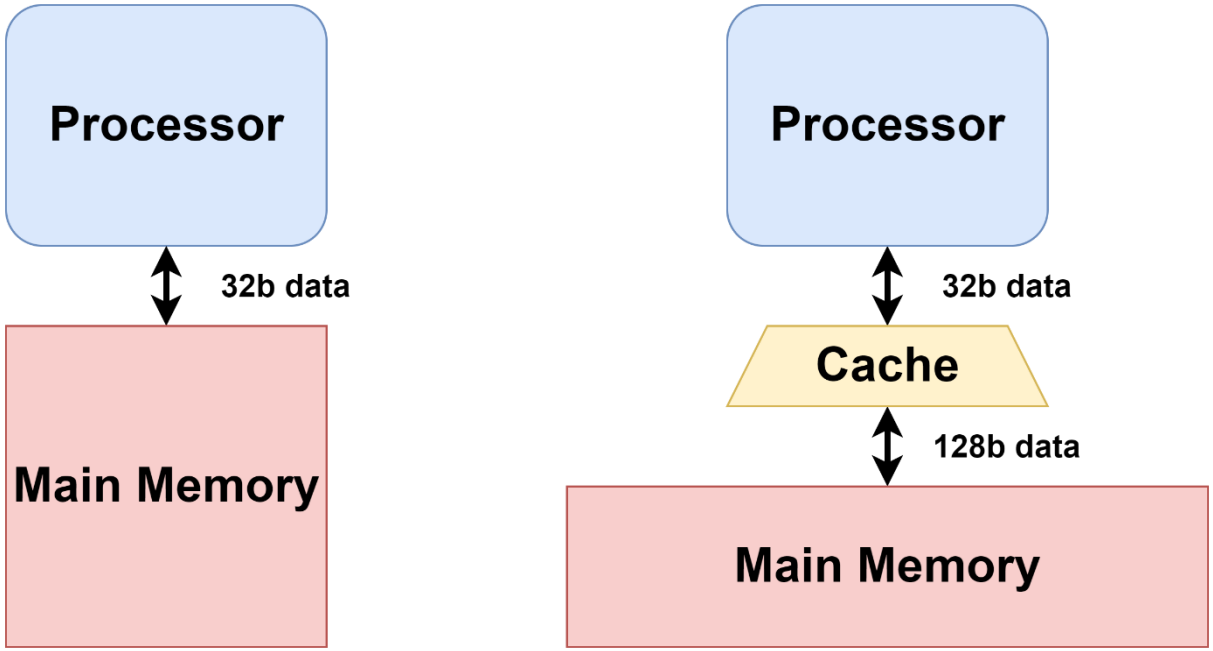
Signal Name	I/O	Width	Description
i_proc_cen	I	1	Active **high** enable signal for read and write
i_proc_wen	I	1	Active **high** enable signal for write
i_proc_addr	I	32	Data memory address
i_proc_wdata	I	32	Data bus for writing to memory
o_proc_rdata	O	32	Data that processor to access from cache
o_proc_stall	O	1	Active **high** control signal that asks processor to wait
o_mem_cen	O	1	Set **high** to enable memory functions
o_mem_wen	O	1	Set **high** for write, **low** for read
o_mem_addr	O	32	Data memory address
o_mem_wdata	O	128	Data bus for writing to memory
i_mem_rdata	I	128	Data that cache to access from memory
i_mem_stall	I	1	Active **high** control signal that asks cache to wait
o_cache_available	O	1	set this value to **1** if the cache is implemented

Specification – Cache I/O

Signal Name	I/O	Width	Description
i_proc_finish	I	1	Finish signal from processor (To tell the cache to store all data back to the main memory)
o_cache_finish	O	1	Finish signal to cache (To tell the processor all data is stored back to the main memory)

Memory Data Transportation

- Two transportation approaches for main memory



A. Set o_cache_available to 0: **32-bit** data transport directly to processor

B. Set o_cache_available to 1: **128-bit** data transport to cache

Specification – Cache I/O

- Do not modify the I/O interface!!

```
module Cache#(
        parameter BIT_W = 32,
        parameter ADDR_W = 32
    )(
        input i_clk,
        input i_rst_n,
        // processor interface
            input i_proc_cen,
            input i_proc_wen,
            input [ADDR_W-1:0] i_proc_addr,
            input [BIT_W-1:0]  i_proc_wdata,
            output [BIT_W-1:0] o_proc_rdata,
            output o_proc_stall,
            input i_proc_finish,
            output o_cache_finish,
        // memory interface
            output o_mem_cen,
            output o_mem_wen,
            output [ADDR_W-1:0] o_mem_addr,
            output [BIT_W*4-1:0]  o_mem_wdata,
            input [BIT_W*4-1:0] i_mem_rdata,
            input i_mem_stall,
            output o_cache_available
    );
```

Specification – Capacity Constraint

- The capacity of cache should be limited under 2Kb
  - Considering the tolerance, **the total register number used to implement the cache must less than 3000**
  - Check the number through design-compiler
    - Ex:

```
Inferred memory devices in process
        in routine Cache line 647 in file
                '/home/r11943138/111_2_CA/final/Final_group_20/CHIP.v'.
=================================================================================
|    Register Name    |   Type    | Width | Bus | MB | AR | AS | SR | SS | ST |
=================================================================================
|    cache_reg_reg    | Flip-flop |  976  |  Y  | N  | Y  | N  | N  | N  | N  |
|      state_reg      | Flip-flop |   1   |  N  | N  | Y  | N  | N  | N  | N  |
=================================================================================
```

➔ $976 + 1 = 977 \leq 3000$

```
Inferred memory devices in process
        in routine Cache line 1032 in file
                '/home/r11943138/111_2_CA/final/Final_group_16/CHIP.v'.
=================================================================================
|    Register Name    |   Type    | Width | Bus | MB | AR | AS | SR | SS | ST |
=================================================================================
| data_from_mem_s_reg | Flip-flop |   32  |  Y  | N  | Y  | N  | N  | N  | N  |
|   cache_mem_s_reg   | Flip-flop | 54272 |  Y  | N  | Y  | N  | N  | N  | N  |
|     state_s_reg     | Flip-flop |   3   |  Y  | N  | Y  | N  | N  | N  | N  |
|     mode_s_reg      | Flip-flop |   1   |  N  | N  | Y  | N  | N  | N  | N  |
=================================================================================
```

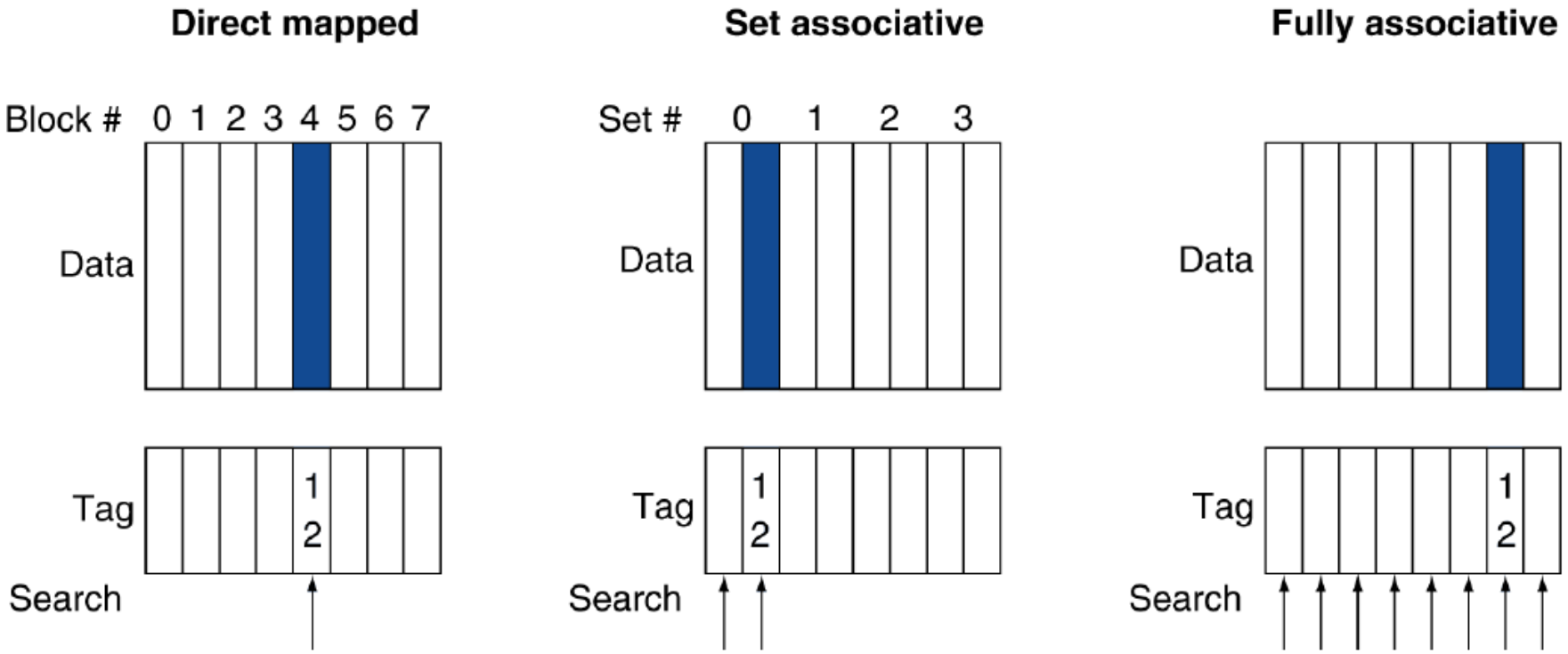
➔ $32 + 54272 + 3 + 1 > 3000$

Default connection

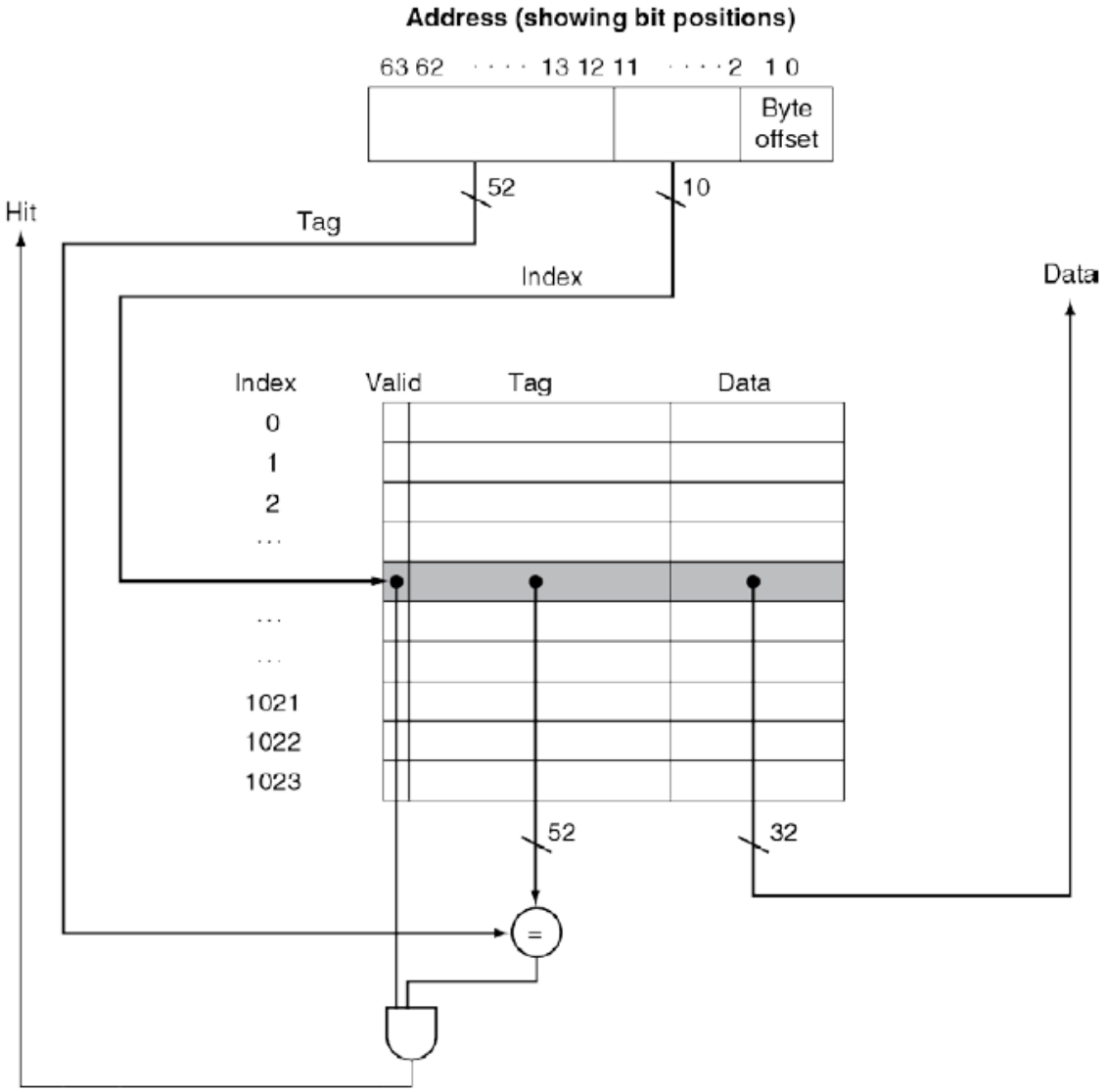
- Connect the memory and processor directly
- Remember to annotate this part if you want to design it by yourself

```
//--------------------------------------------//
//          default connection                //
assign o_mem_cen = i_proc_cen;                //
assign o_mem_wen = i_proc_wen;                //
assign o_mem_addr = i_proc_addr;              //
assign o_mem_wdata = i_proc_wdata;            //
assign o_proc_rdata = i_mem_rdata[0+:BIT_W];//
assign o_proc_stall = i_mem_stall;            //
//--------------------------------------------//
```

Review – Implement Method

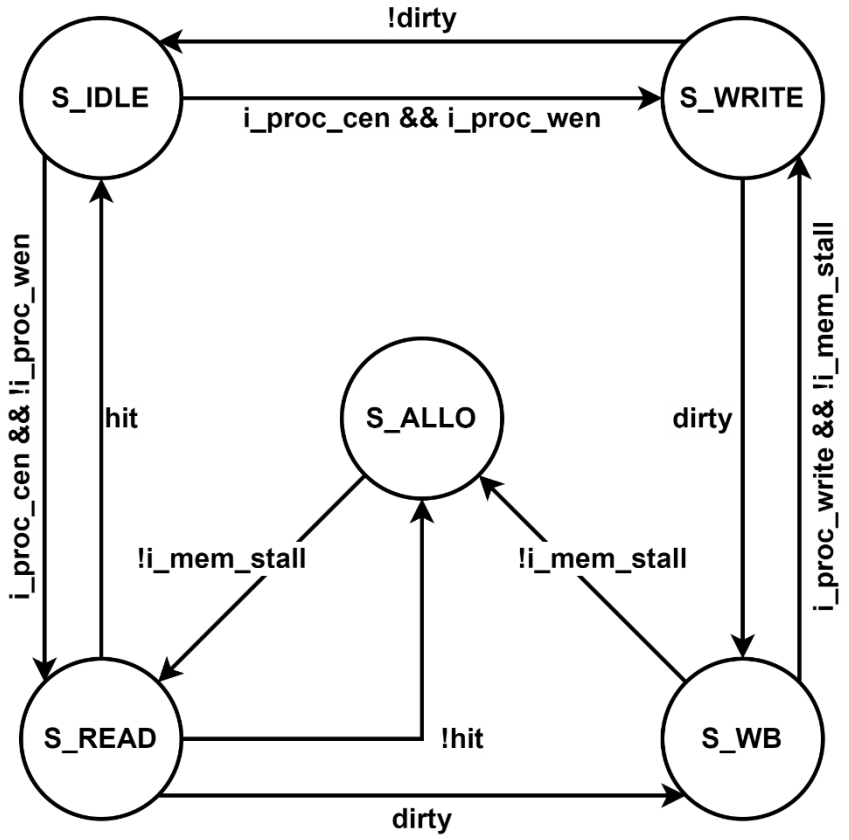


Review – Example Architecture



Example FSM

- You can design it by yourself



Stall

- When the cache needs to access data from the memory and then wait for several cycles, the i_proc_stall signal should be set high to stall the processor.
- A stall is necessary
  - **Read miss** in write back caches

Write through or write back

- Write through
  - Also update memory
  - Easy to implement
  - Longer write latency
- Write back
  - Keep tracking
  - More complex
  - More efficiently
- Write back policy
  - Least Recently Used (LRU)
  - Least Frequently Used (LFU)