

# Lecture 13: Pipelining

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601.229 Computer Systems Fundamentals



# MIPS overview



- ▶ Developed by MIPS Technologies in 1984, first product in 1986
- ▶ Used in
  - ▶ Silicon Graphics (SGI) Unix workstations
  - ▶ Digital Equipment Corporation (DEC) Unix workstation
  - ▶ Nintendo 64
  - ▶ Sony PlayStation
- ▶ Inspiration for ARM (esp. v8)

# Overview

- ▶ 32 bit architecture (registers, memory addresses)
- ▶ 32 registers
- ▶ Multiply and divide instructions
- ▶ Floating point numbers

## Example: Addition

- ▶ Mathematical view of addition

$$a = b + c$$

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- ▶ MIPS instruction

add a,b,c

a, b, c are registers

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  - 4-7 \$a0-\$a3 arguments for a function call

# 32 Registers

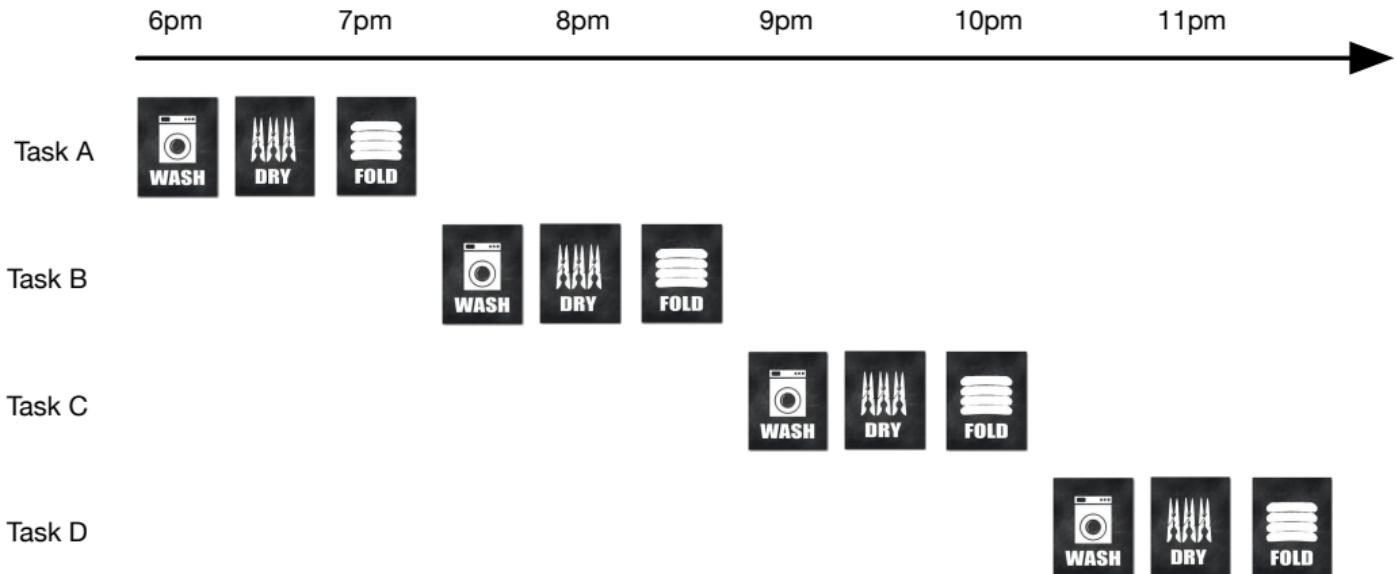
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  - 16-23 \$s0-\$s7 saved, have to be preserved by function

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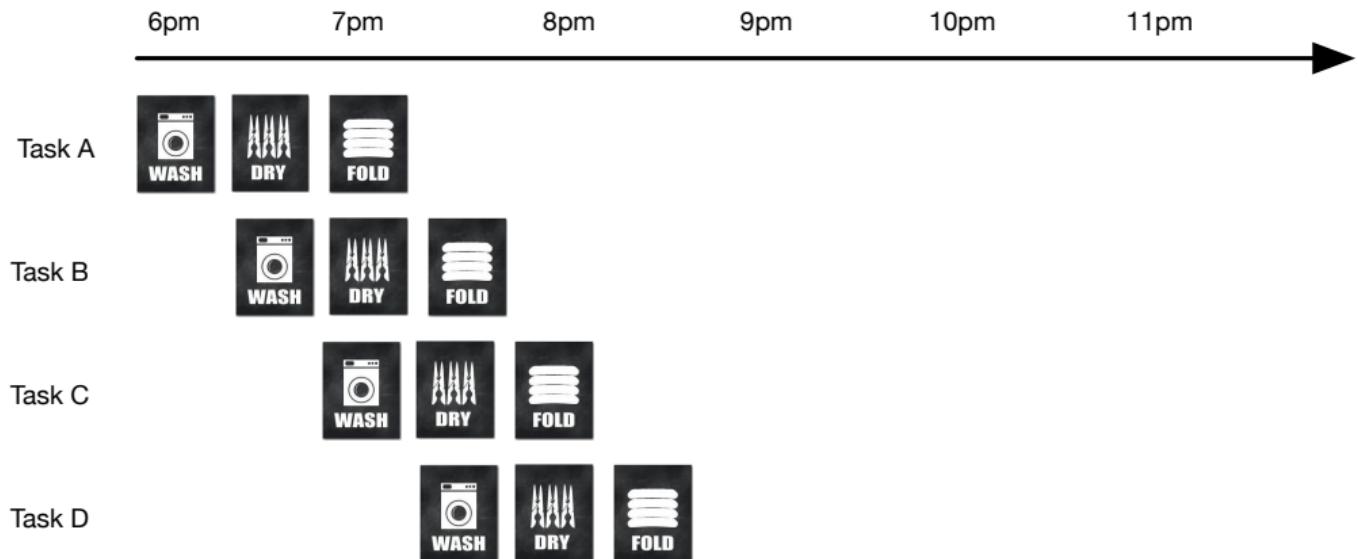
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  - 16-23 \$s0-\$s7 saved, have to be preserved by function
  - 26-27 \$k0-\$k1 reserved for kernel
  - 28 \$gp global area pointer
  - 29 \$sp stack pointer
  - 30 \$fp frame pointer

# Pipelining

# Laundry Analogy



# Laundry Pipelined



# Speed-up

- ▶ Theoretical speed-up: 3 times
- ▶ Actual speed-up in example: 2 times
  - ▶ sequential:  $1:30 + 1:30 + 1:30 + 1:30 = 6 \text{ hours}$
  - ▶ pipelined:  $1:30 + 0:30 + 0:30 + 0:30 = 3 \text{ hours}$
- ▶ Many tasks → speed-up approaches theoretical limit

# MIPS instruction pipeline

# MIPS Pipeline

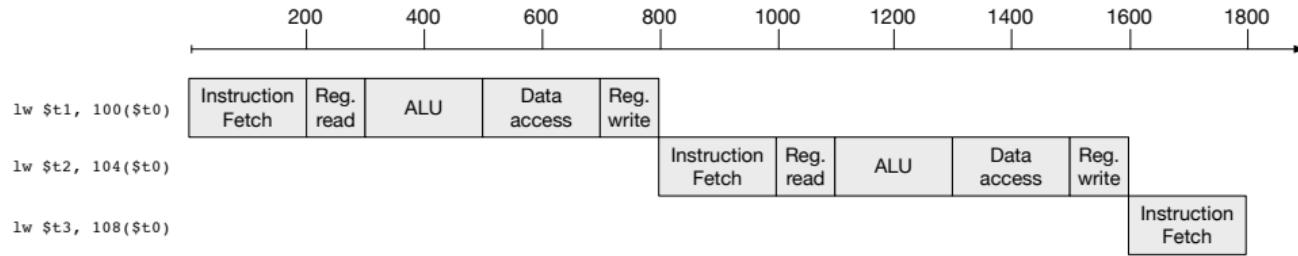
- ▶ Fetch instruction from memory
- ▶ Read registers and decode instruction (note: registers are always encoded in same place in instruction)
- ▶ Execute operation OR calculate an address
- ▶ Access an operand in memory
- ▶ Write result into a register

# Time for Instructions

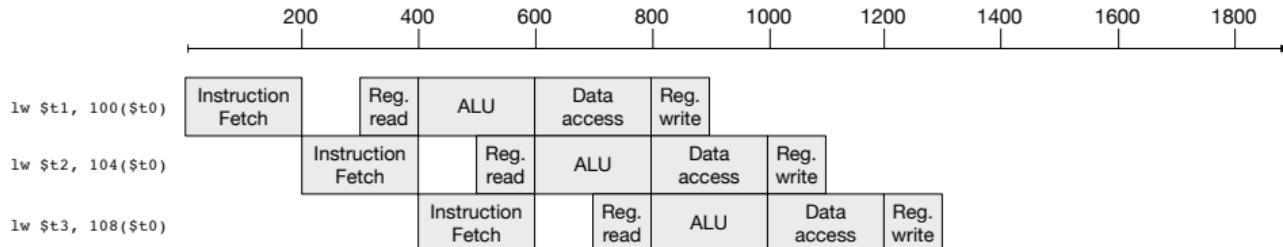
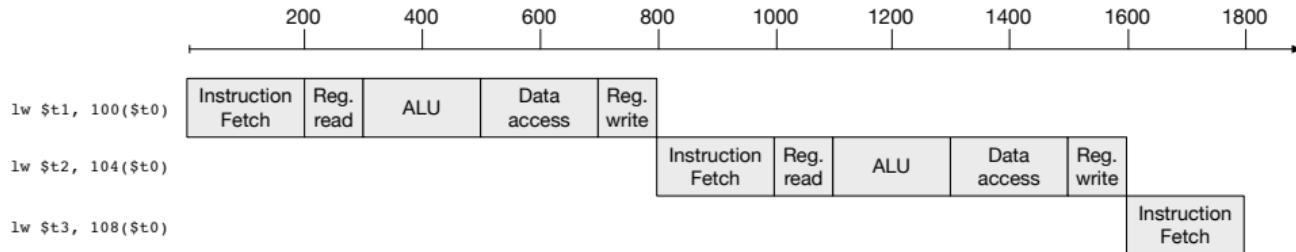
Breakdown for each type of instruction

Instruction class	Instr. fetch	Register read	ALU oper.	Data access	Register write	Total time
Load word (lw)	200ps	100ps	200ps	200ps	100ps	800ps
Store word (sw)	200ps	100ps	200ps	200ps		700ps
R-format (add)	200ps	100ps	200ps		100ps	600ps
Branch (beq)	200ps	100ps	200ps			500ps

# Pipeline Execution



# Pipeline Execution



# Speed-up

- ▶ Theoretical speed-up: 4 times
- ▶ Actual speed-up in example: 1.71 times
  - ▶ sequential:  $800\text{ps} + 800\text{ps} + 800\text{ps} = 2400\text{ps}$
  - ▶ pipelined:  $1000\text{ps} + 200\text{ps} + 200\text{ps} = 1400\text{ps}$
- ▶ Many tasks → speed-up approaches theoretical limit

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- ▶ All instructions are 4 bytes
  - easy to fetch next instruction
- ▶ Few instruction formats
  - parallel op decode and register read
- ▶ Memory access limited to load and store instructions
  - stage 3 used for memory access, otherwise operation execution
- ▶ Words aligned in memory
  - able to read in one instruction
  - (aligned = memory address multiple of 4)

# Hazards

# Hazards

- ▶ Hazard = next instruction cannot be executed in next clock cycle
- ▶ Types
  - ▶ structural hazard
  - ▶ data hazard
  - ▶ control hazard

# Structural Hazard

- ▶ Definition: instructions overlap in resource use in same stage
- ▶ For instance: memory access conflict

	1	2	3	4	5	6	7
i1	FETCH	DECODE	MEMORY	MEMORY	ALU	REGISTER	
i2		FETCH	DECODE	MEMORY conflict	MEMORY	ALU	REGISTER

- ▶ MIPS designed to avoid structural hazards

# Data Hazard

- ▶ Definition: instruction waits on result from prior instruction
- ▶ Example

```
add $s0, $t0, $t1
```

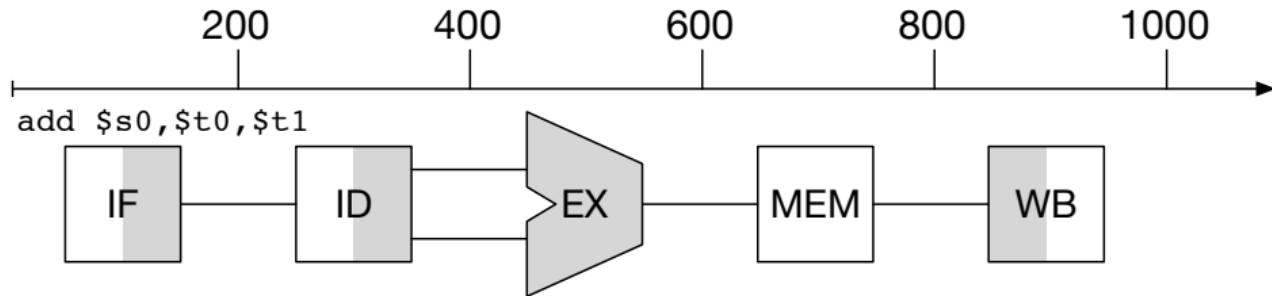
```
sub $t0, $s0, $t3
```

- ▶ add instruction writes result to register \$s0 in stage 5
- ▶ sub instruction reads \$s0 in stage 2

⇒ Stage 2 of sub has to be delayed

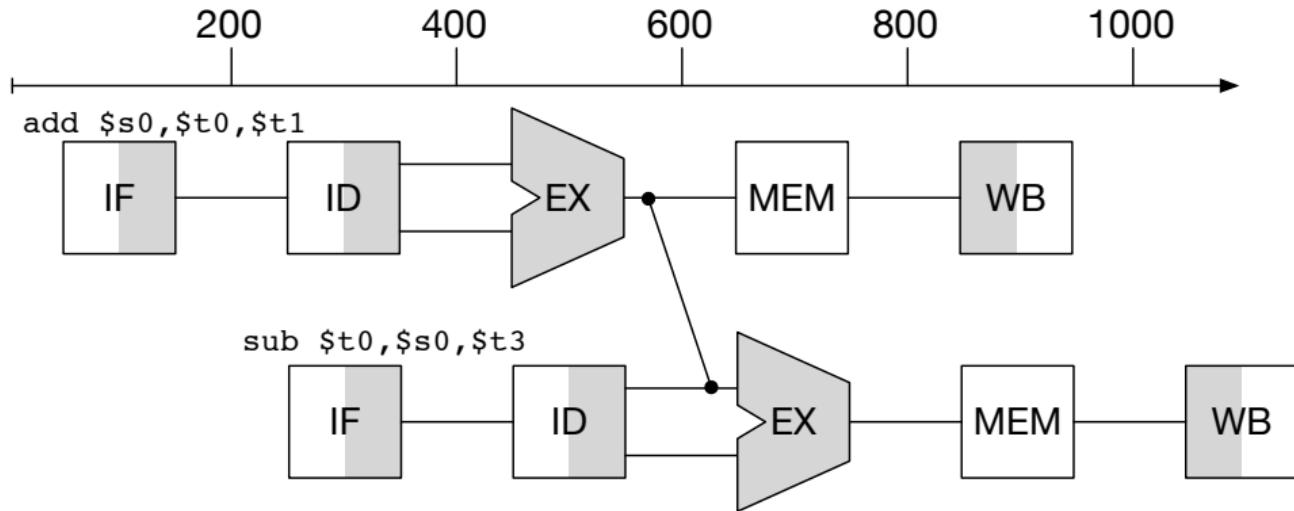
- ▶ We overcome this in hardware

# Graphical Representation



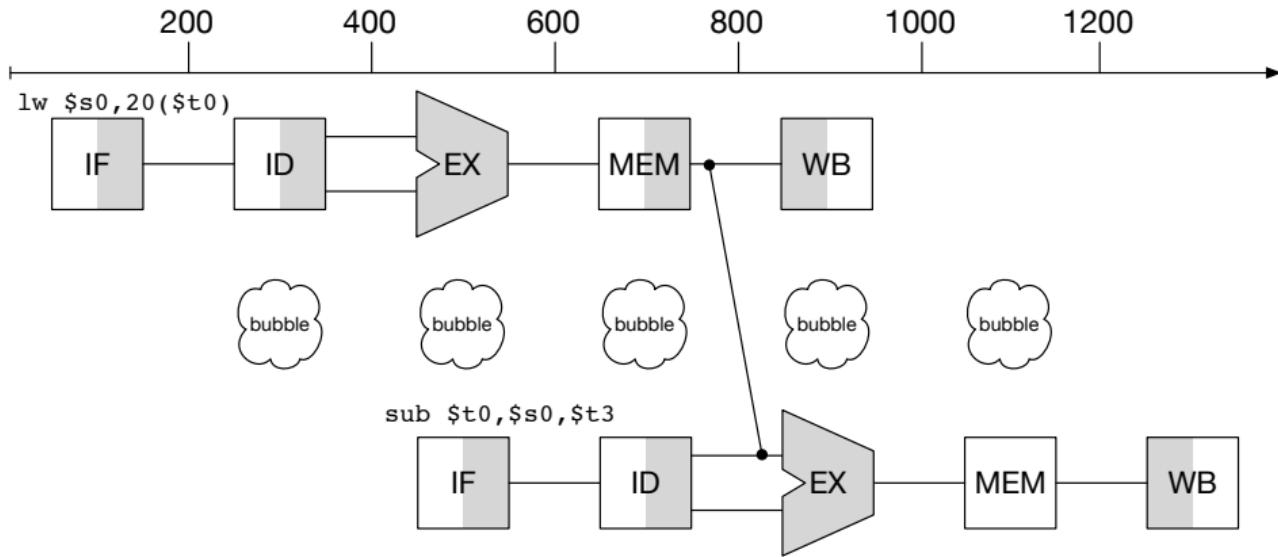
- ▶ IF: instruction fetch
- ▶ ID: instruction decode
- ▶ EX: execution
- ▶ MEM: memory access
- ▶ WB: write-back

# Add and Subtract



- ▶ Add wiring to circuit to directly connect output of ALU for next instruction

# Load and Subtract



- ▶ Add wiring from memory lookup to ALU
- ▶ Still 1 cycle unused: "pipeline stall" or "bubble"

# Reorder Code

## Code with data hazard

```
lw $t1, 0($t0)
lw $t2, 4($t0)
add $t3, $t1, $t2
sw $t3, 12($t0)
lw $t4, 8($t0)
add $t5, $t1, $t4
sw $t5, 16($t0)
```

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```

Load instruction now completed in time

# Clicker quiz!

Clicker quiz omitted from public slides

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Clicker quiz omitted from public slides

# Control Hazard

- ▶ Also called branch hazard
- ▶ Selection of next instruction depends on outcome of previous
- ▶ Example

```
add $s0, $t0, $t1
beq $s0, $s1, ff40
sub $t0, $s0, $t3
```

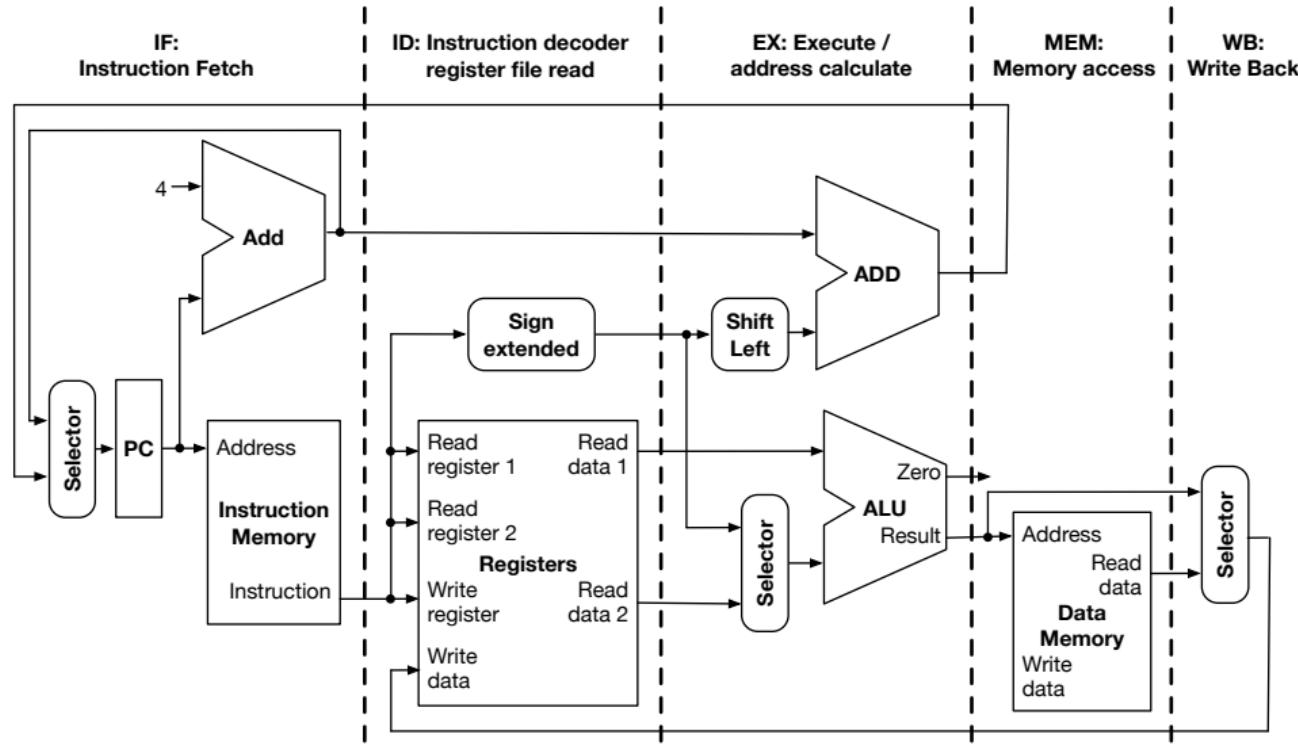
- ▶ sub instruction only executed if branch condition fails  
→ cannot start until branch condition result known

# Branch Prediction

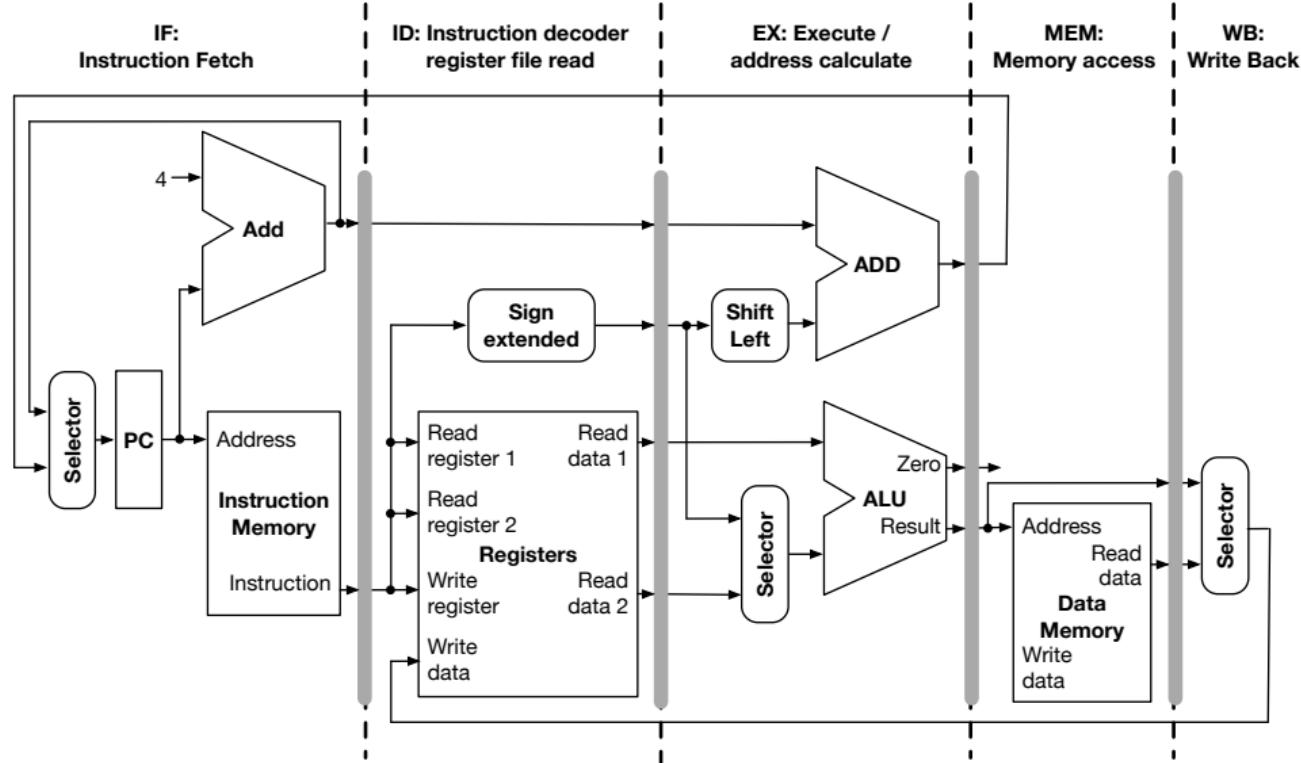
- ▶ Assume that branches are never taken  
→ full speed if correct
- ▶ More sophisticated
  - ▶ keep record of branch taken or not
  - ▶ make prediction based on history

# Pipelined data path

# Datapath

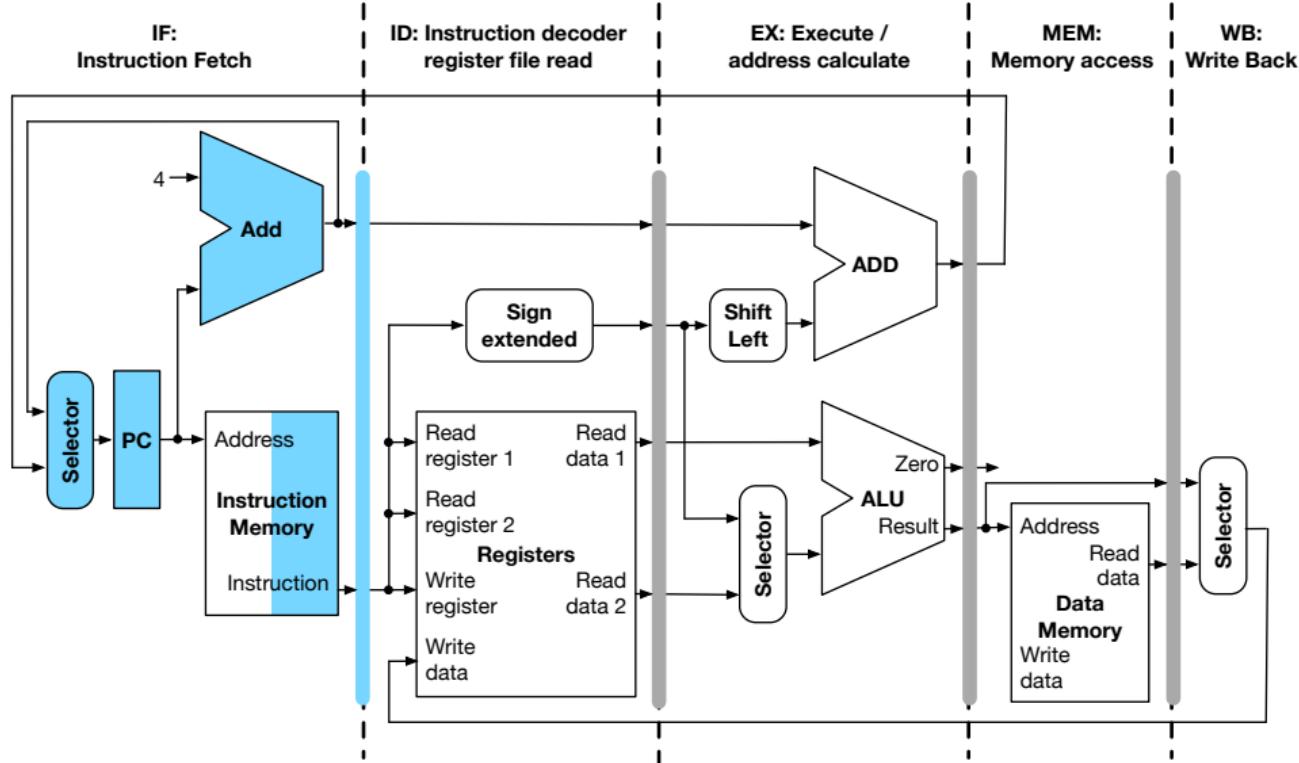


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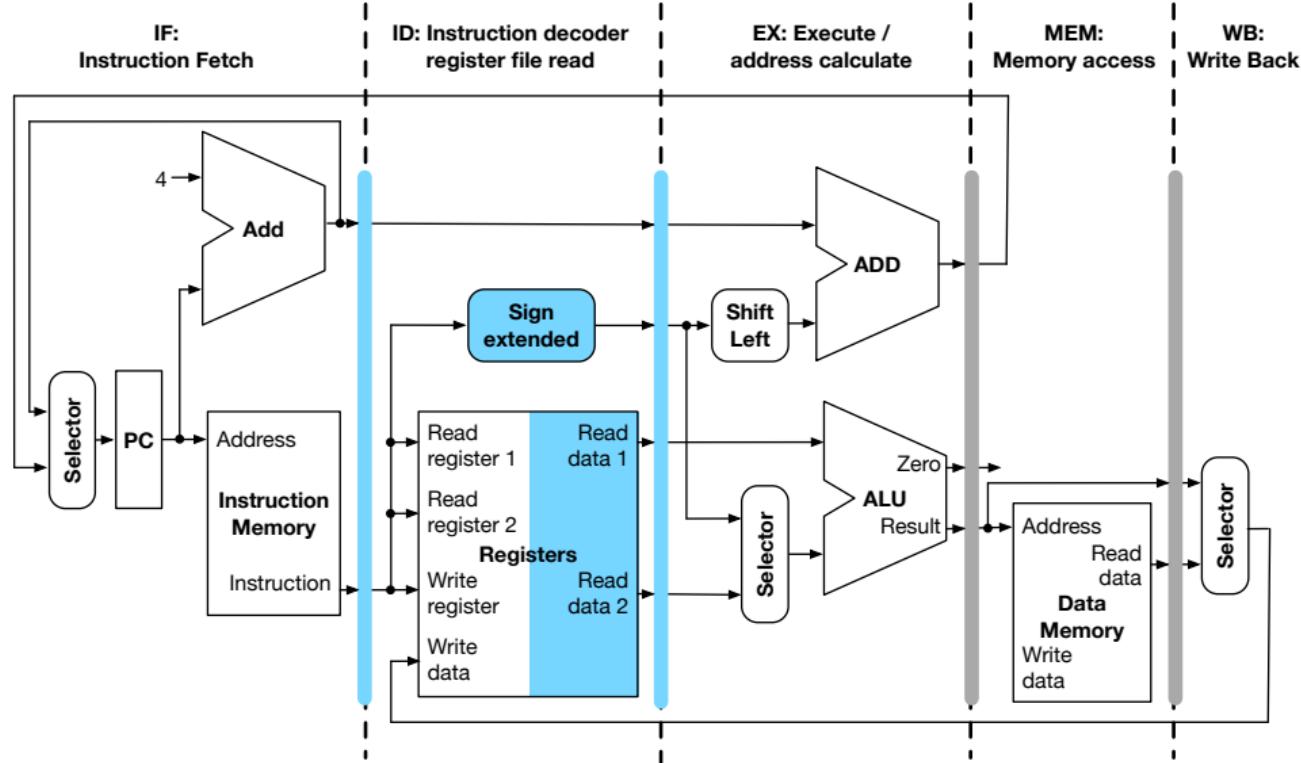


# Load

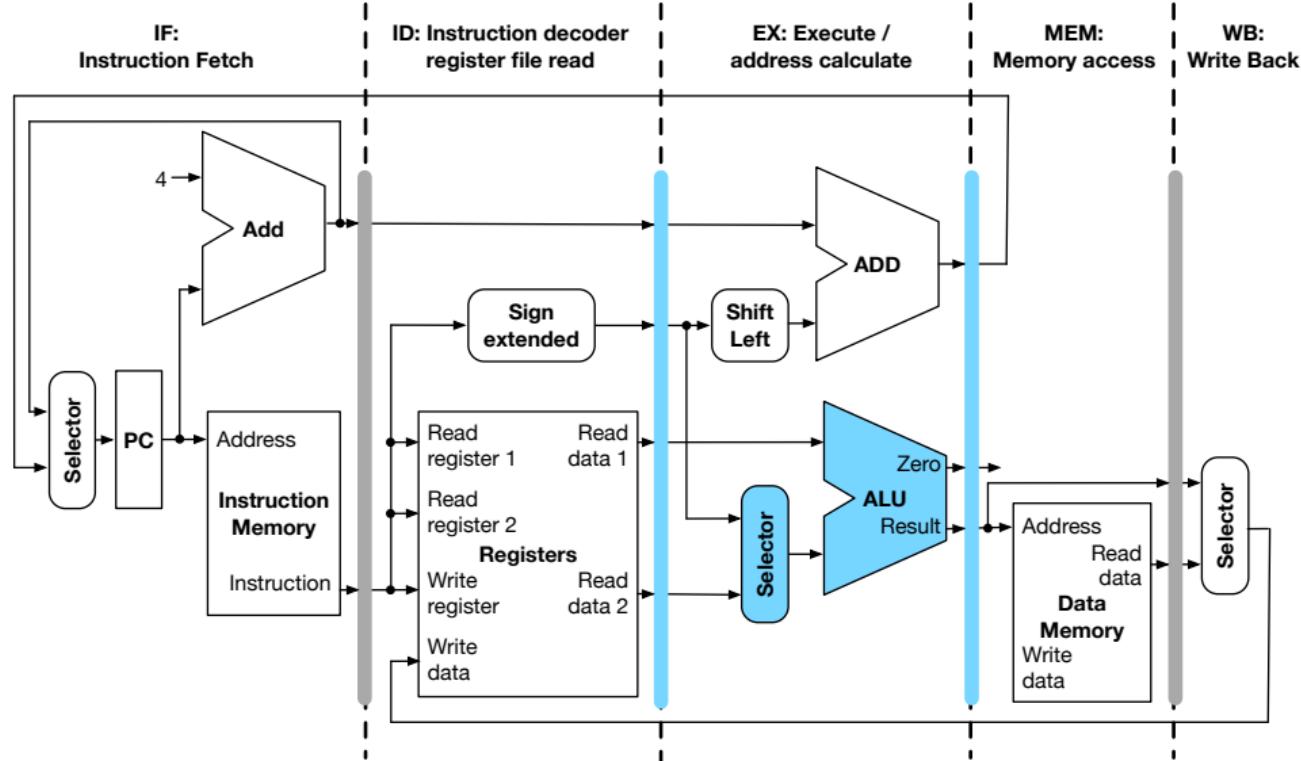
# Load: Stage 1



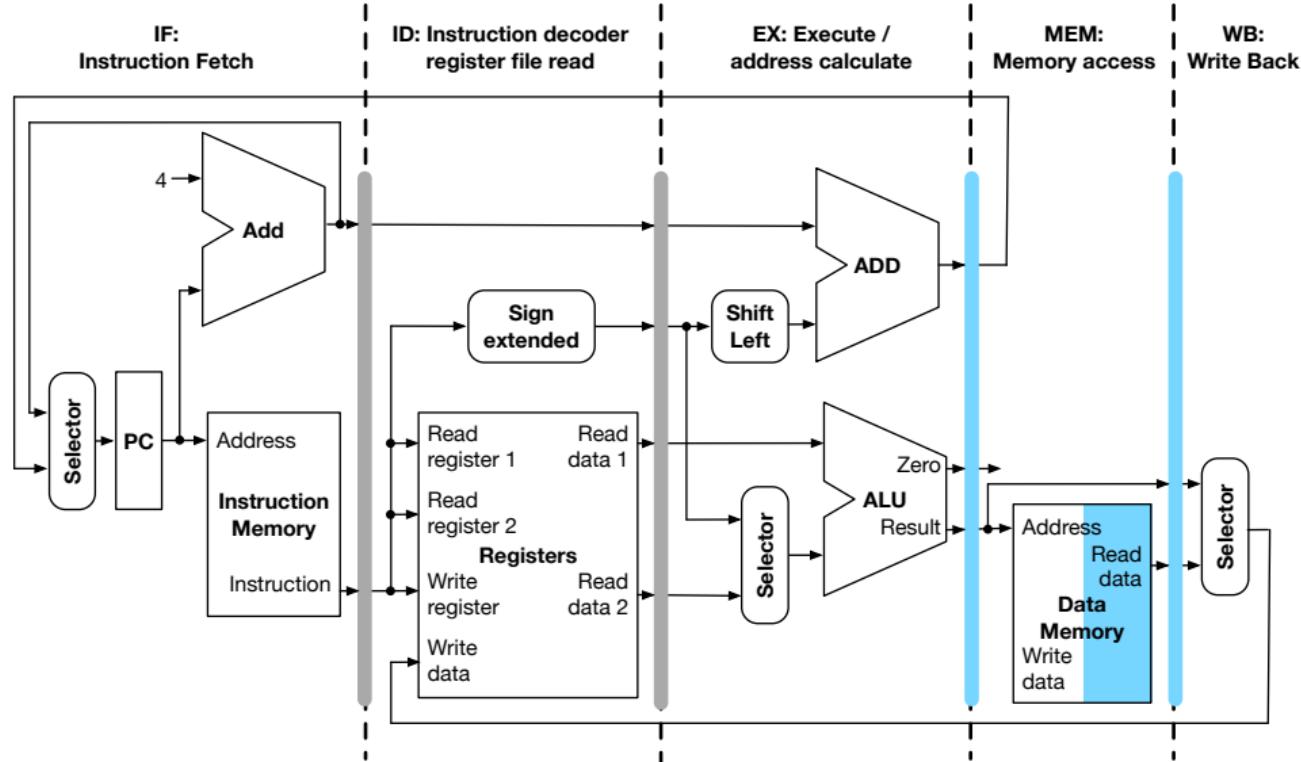
# Load: Stage 2



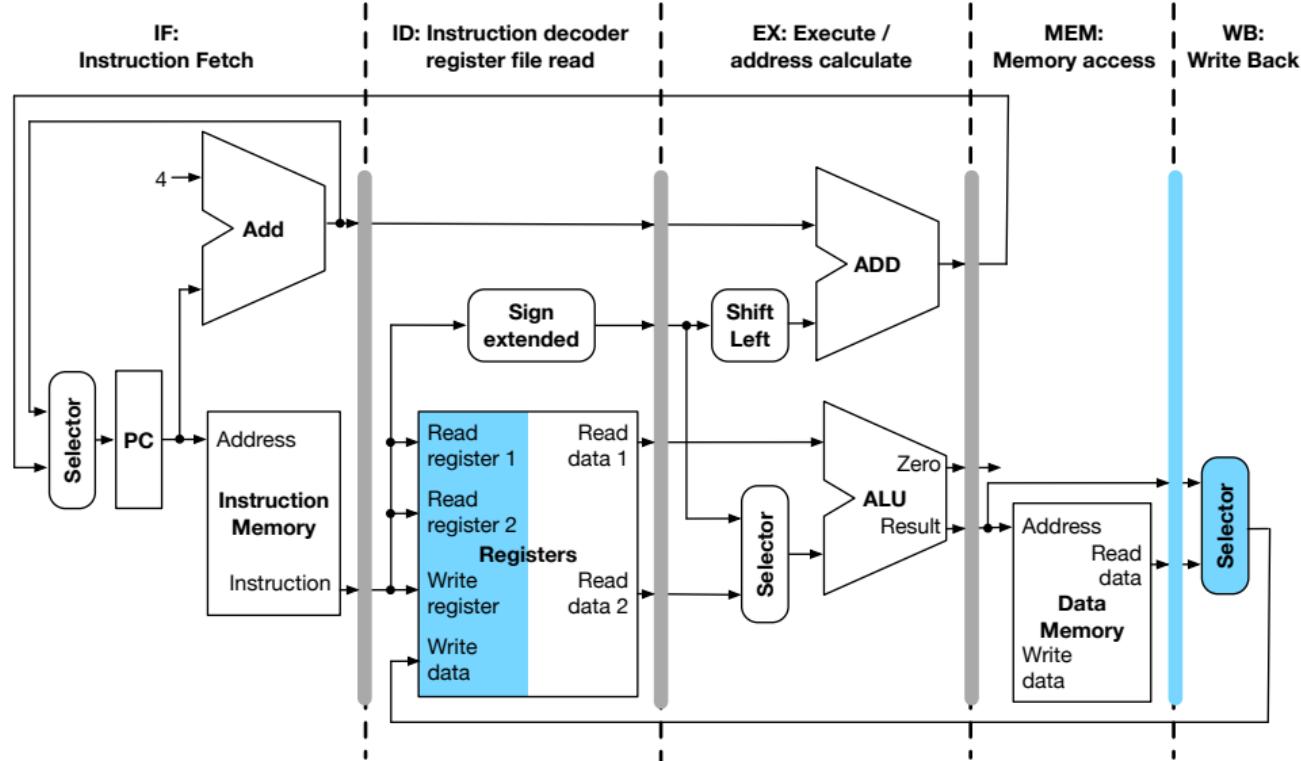
# Load: Stage 3



# Load: Stage 4

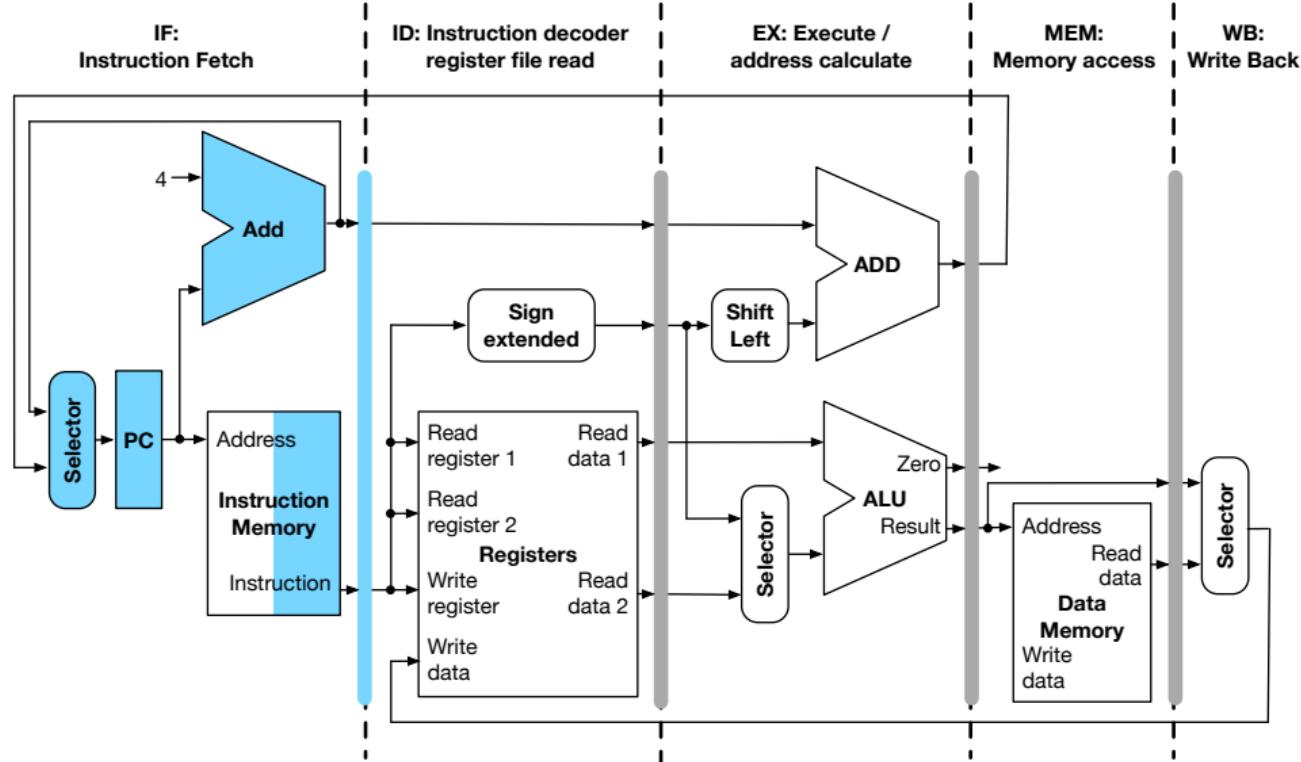


# Load: Stage 5

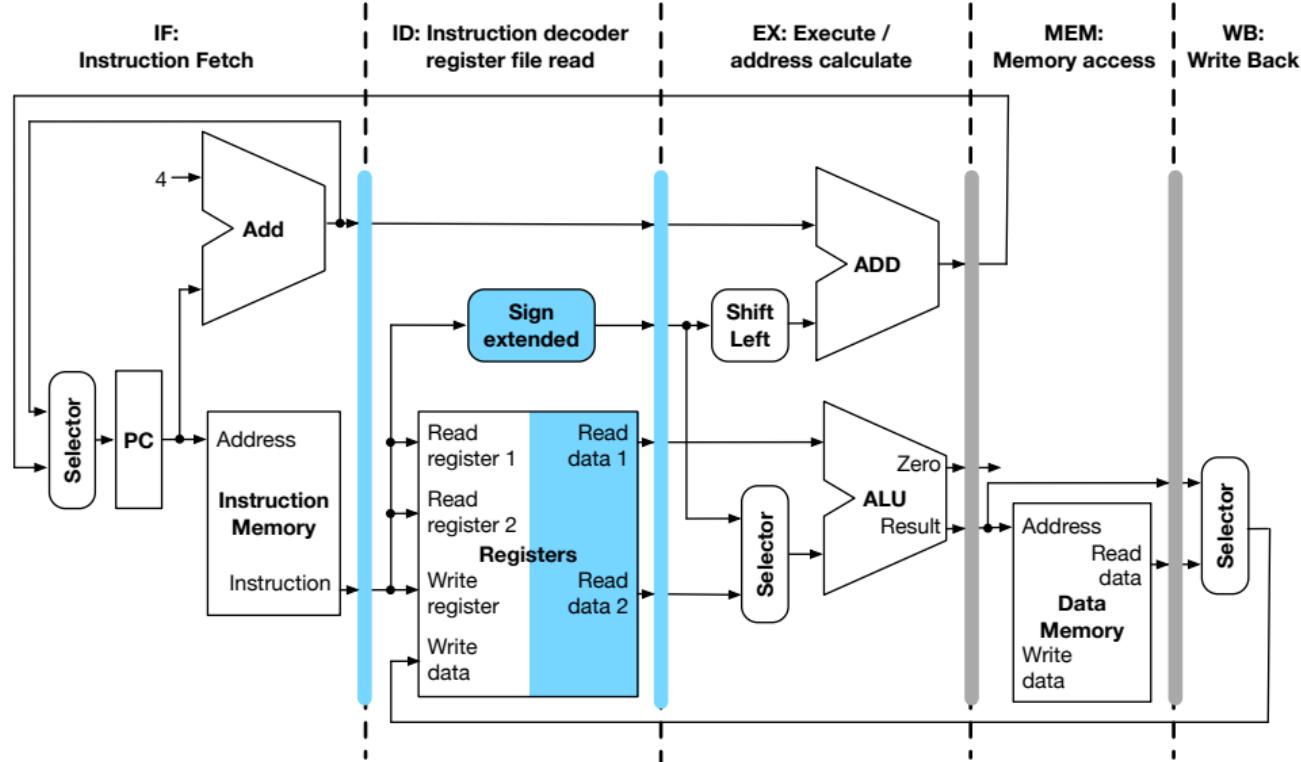


# Store

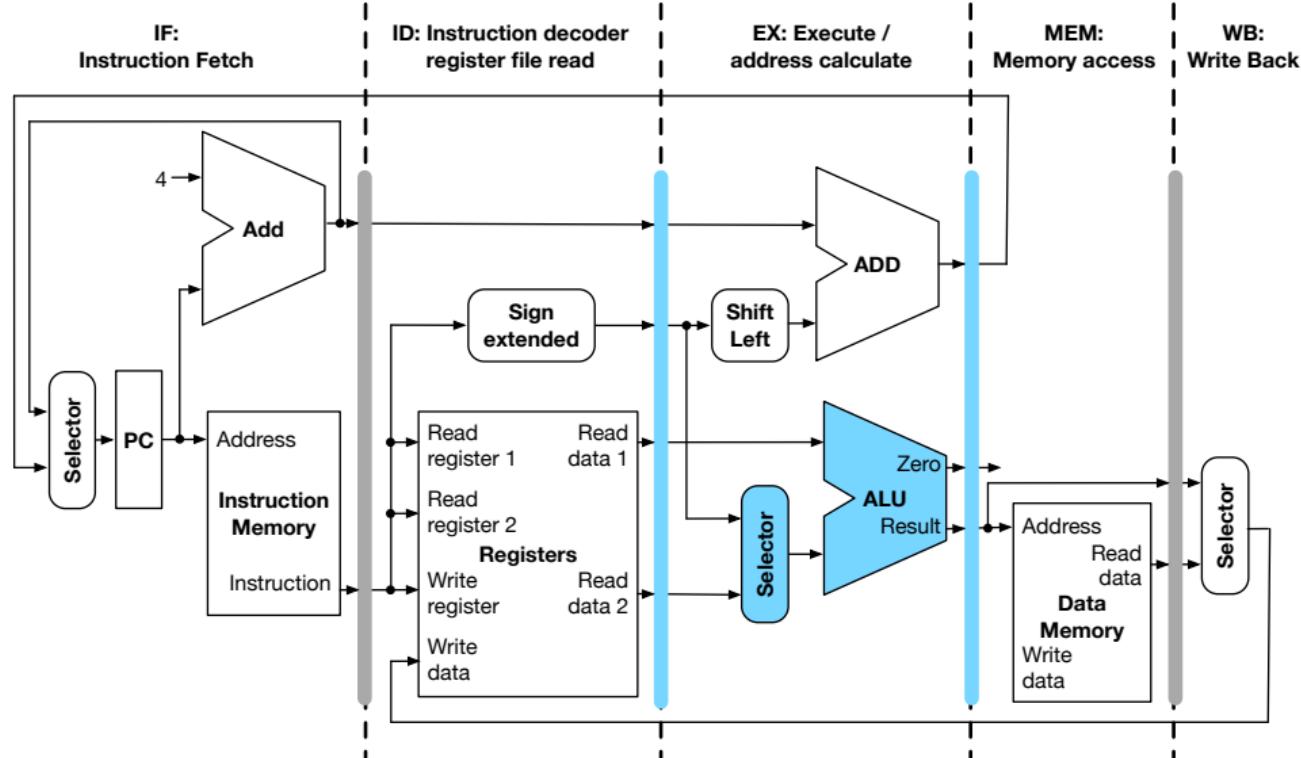
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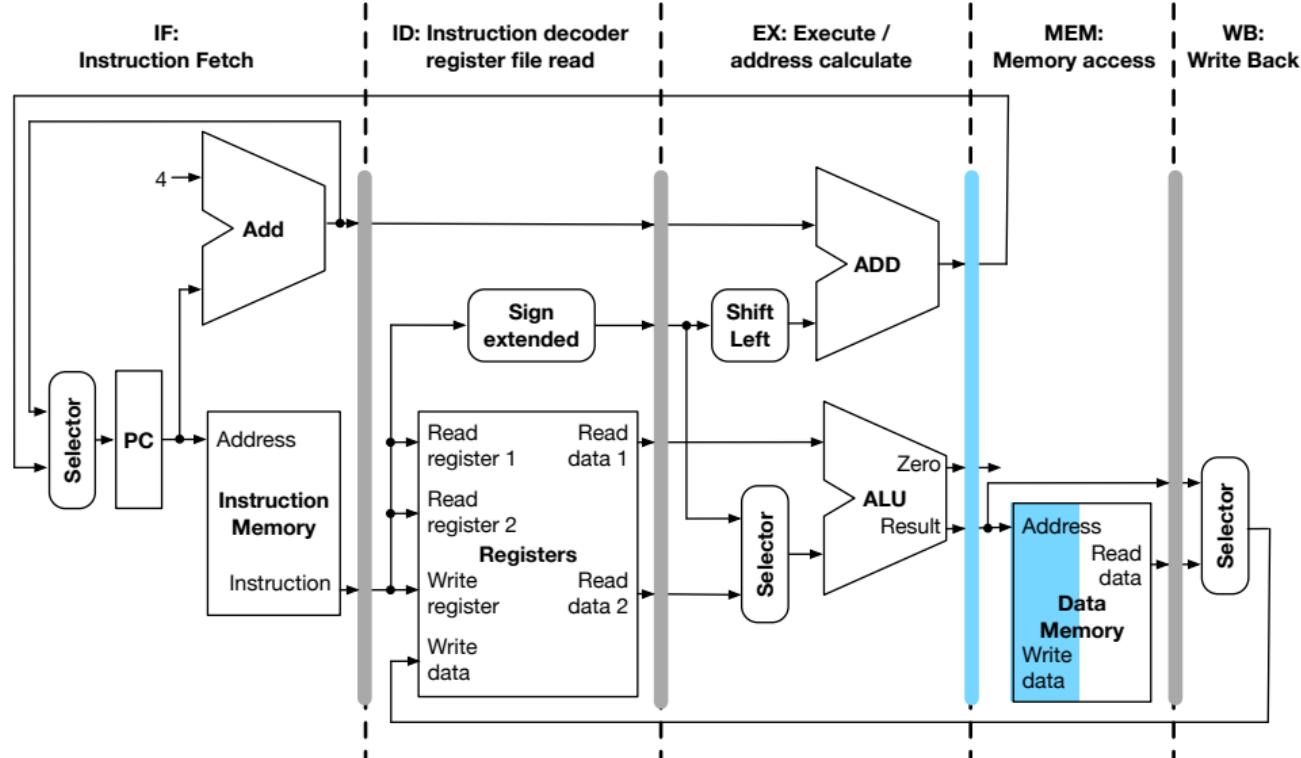
# Store: Stage 2



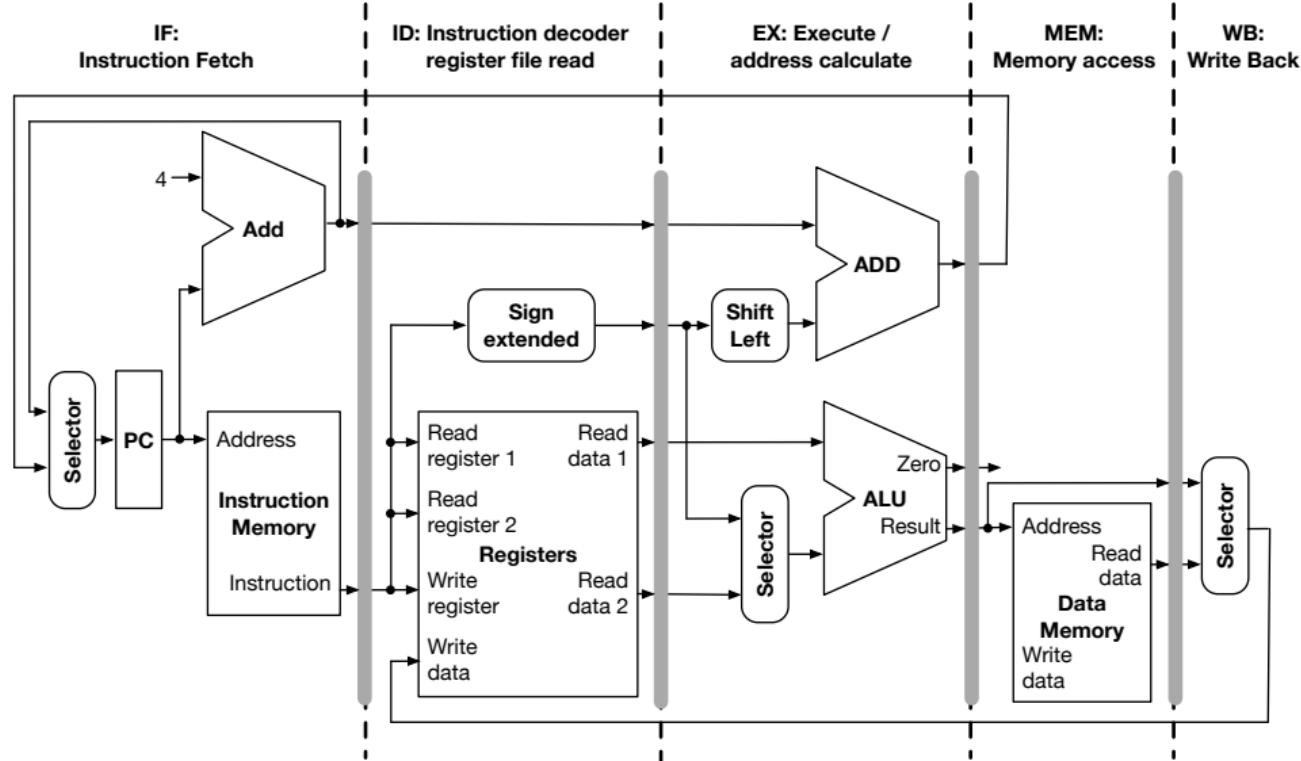
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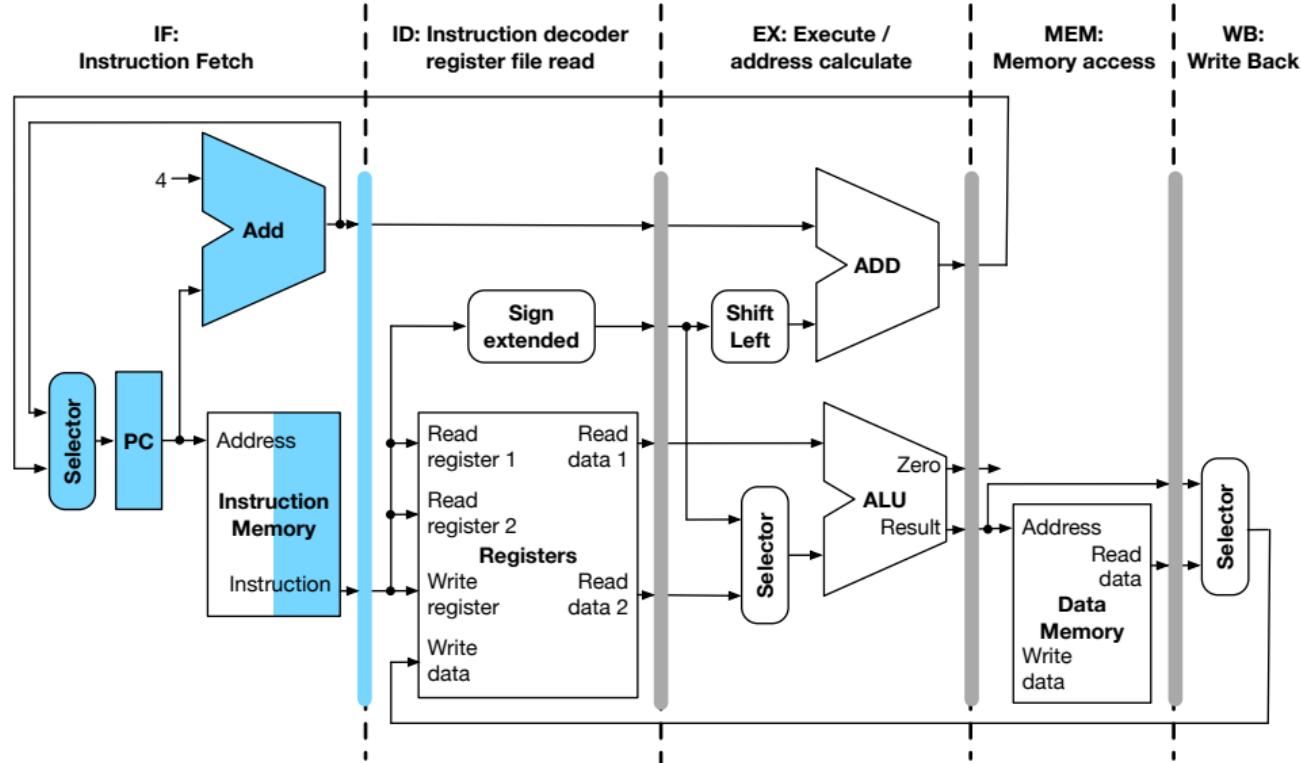


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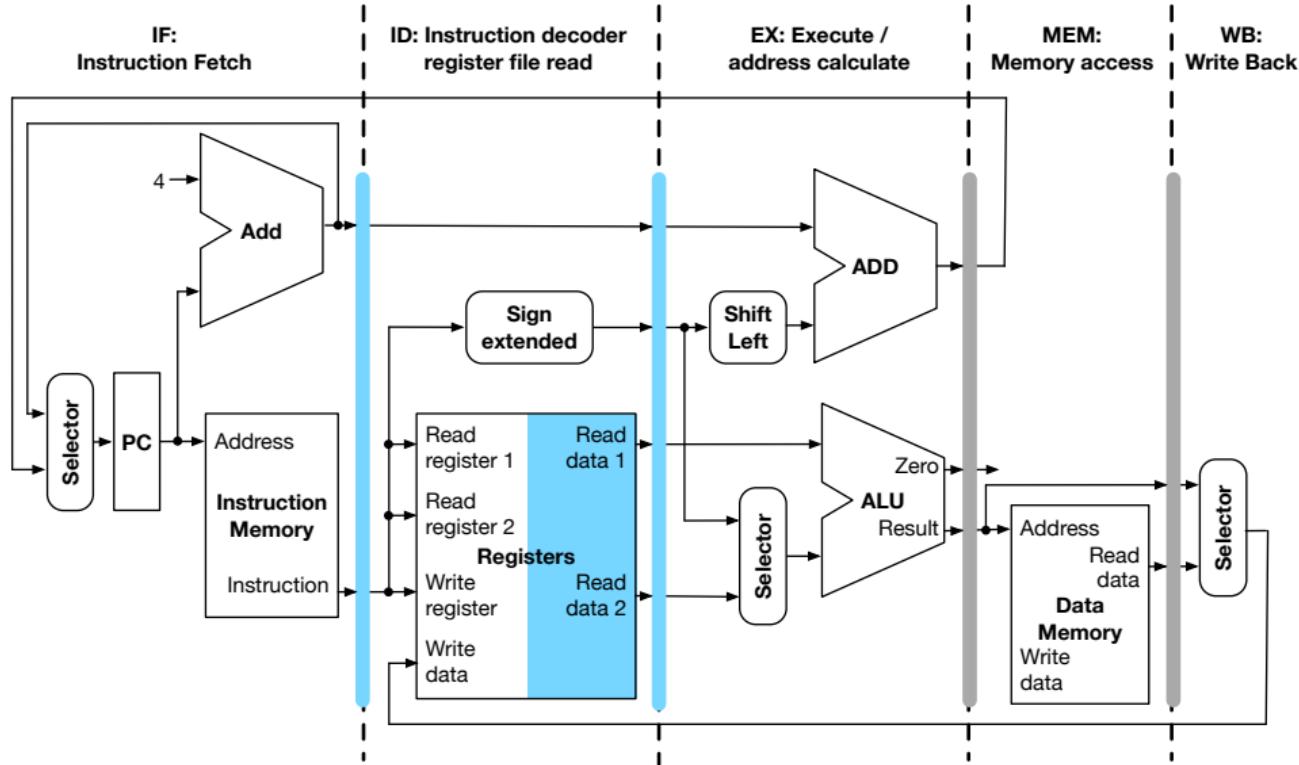


# Add

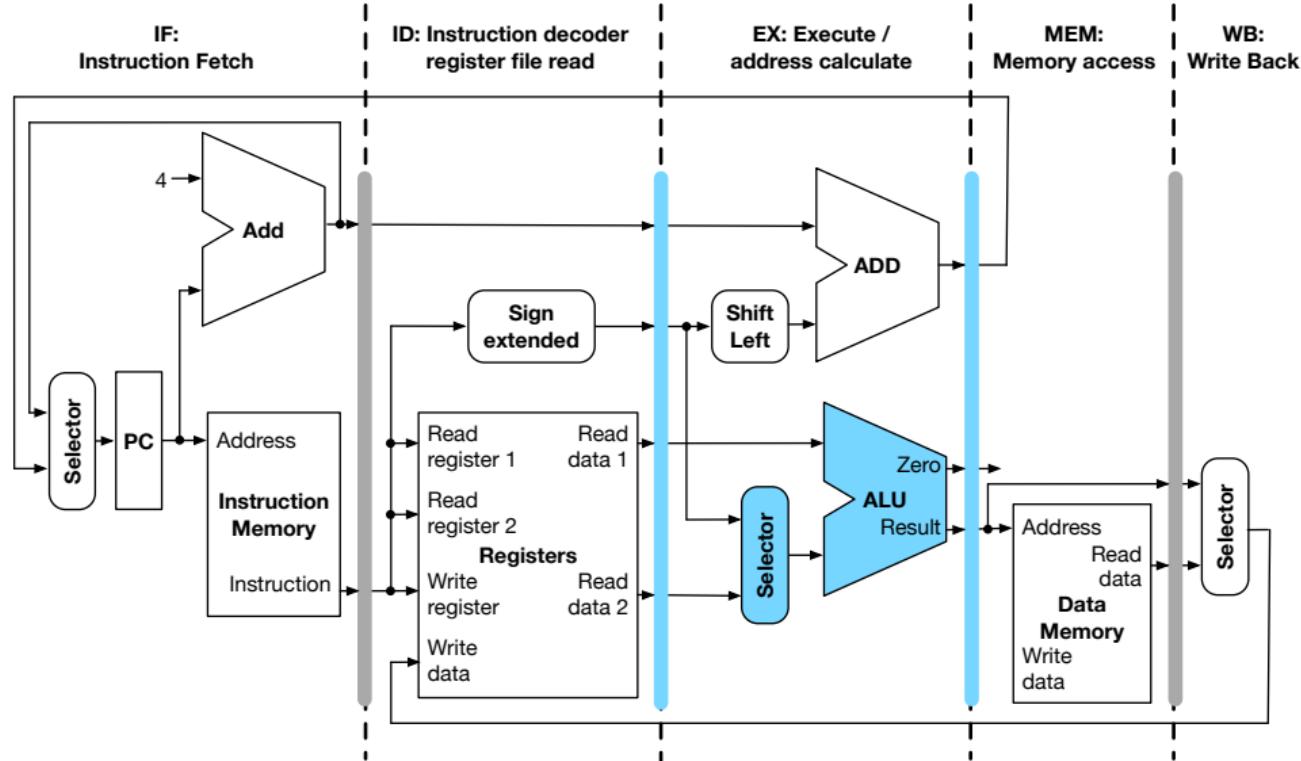
# Add: Stage 1



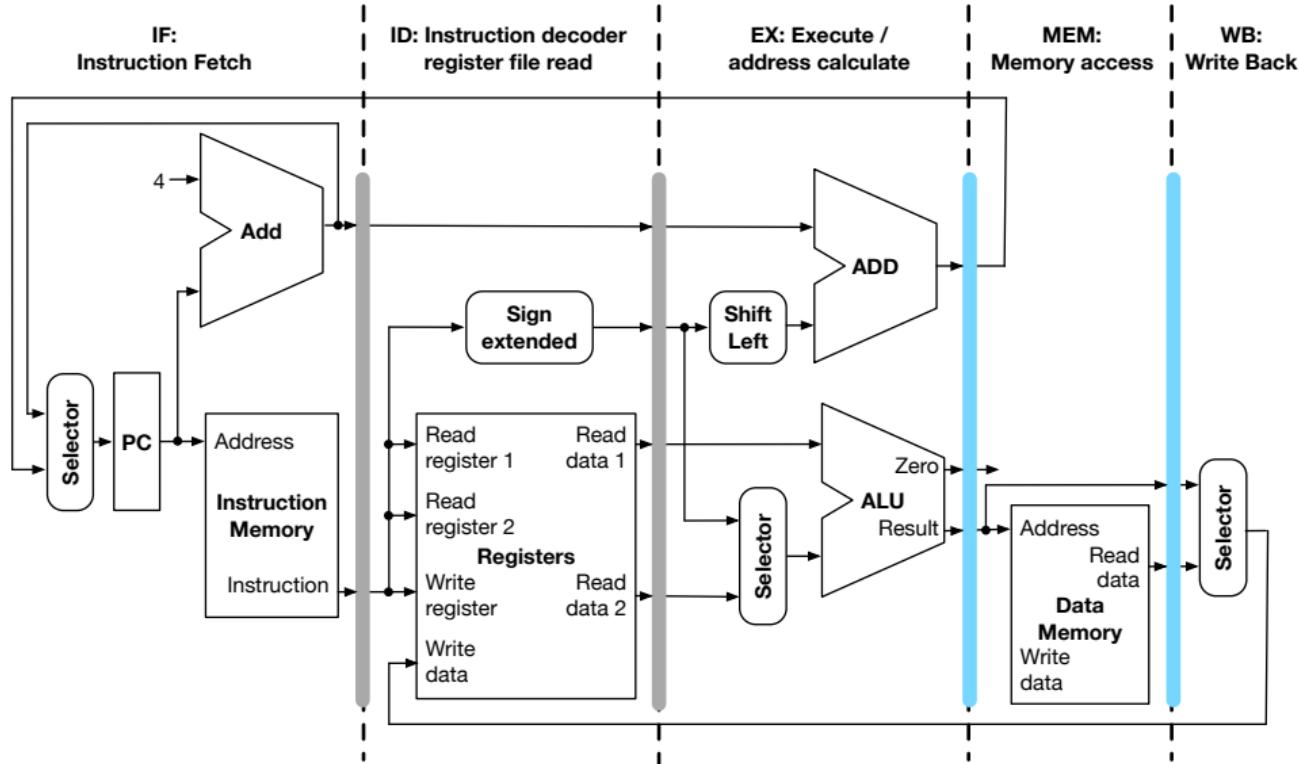
## Add: Stage 2



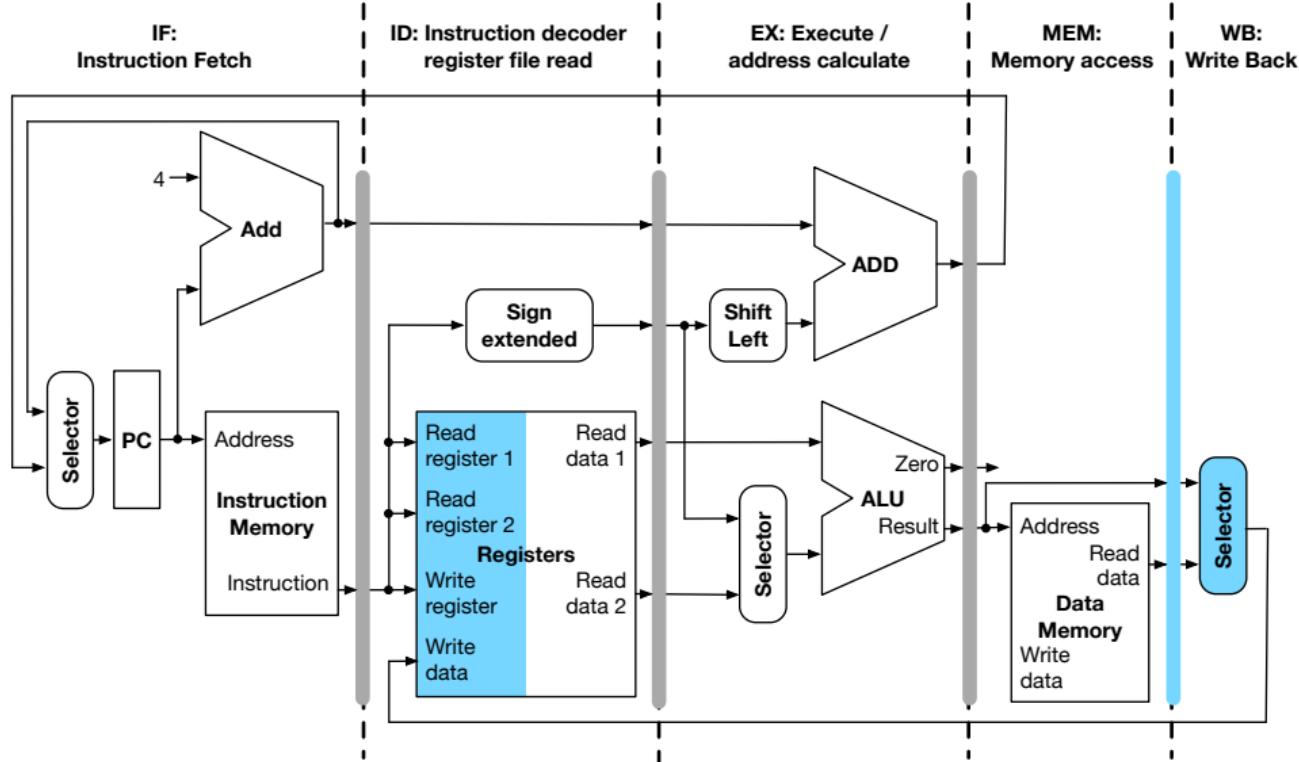
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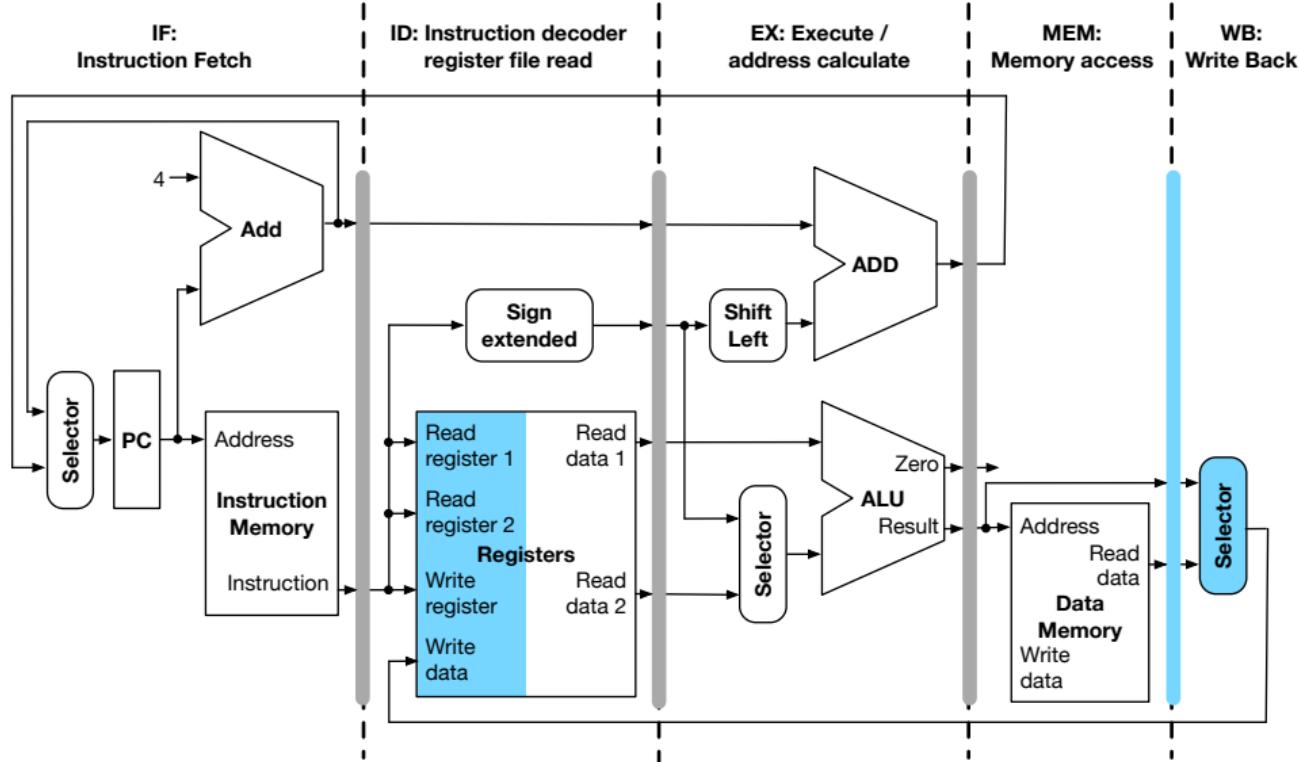


# Add: Stage 5



# Write to register

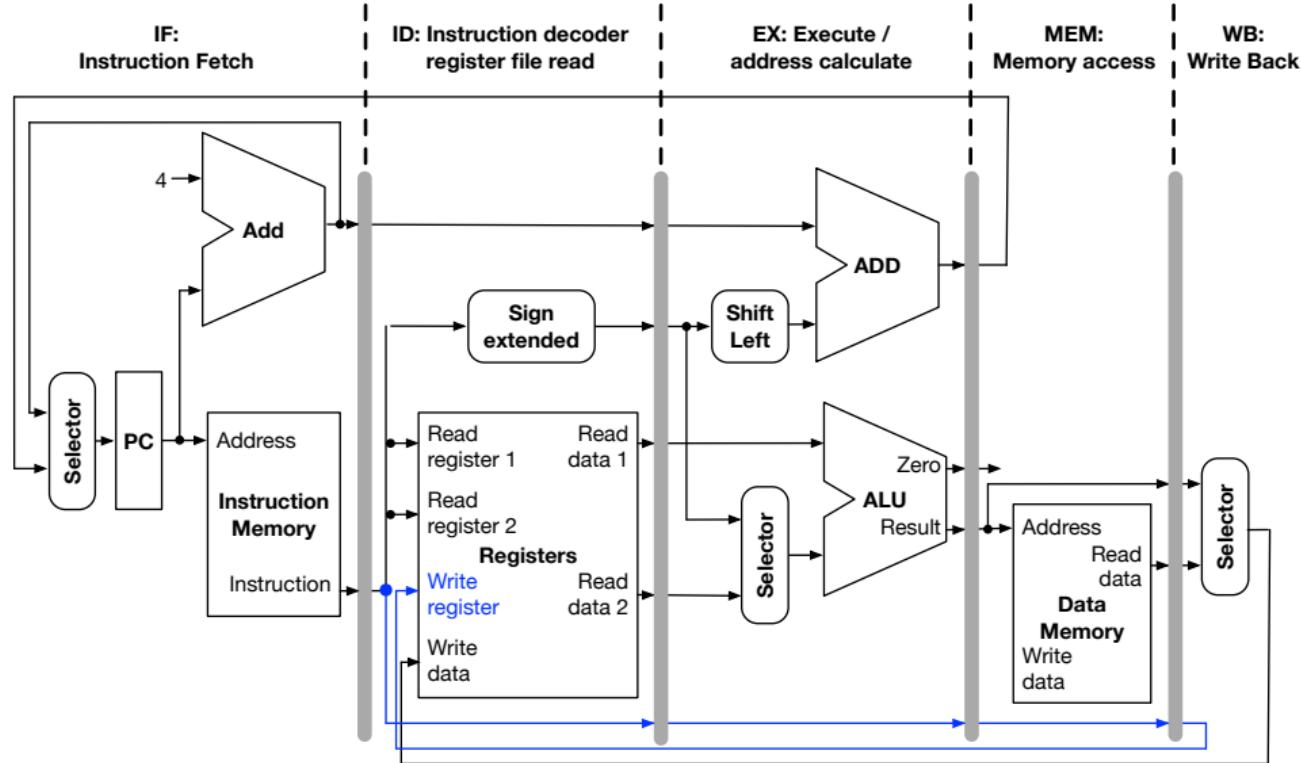
# Which Register?



# Problem

- ▶ Write register
  - ▶ decoded in stage 2
  - ▶ used in stage 5
- ▶ Identity of register has to be passed along

# Data Path for Write Register

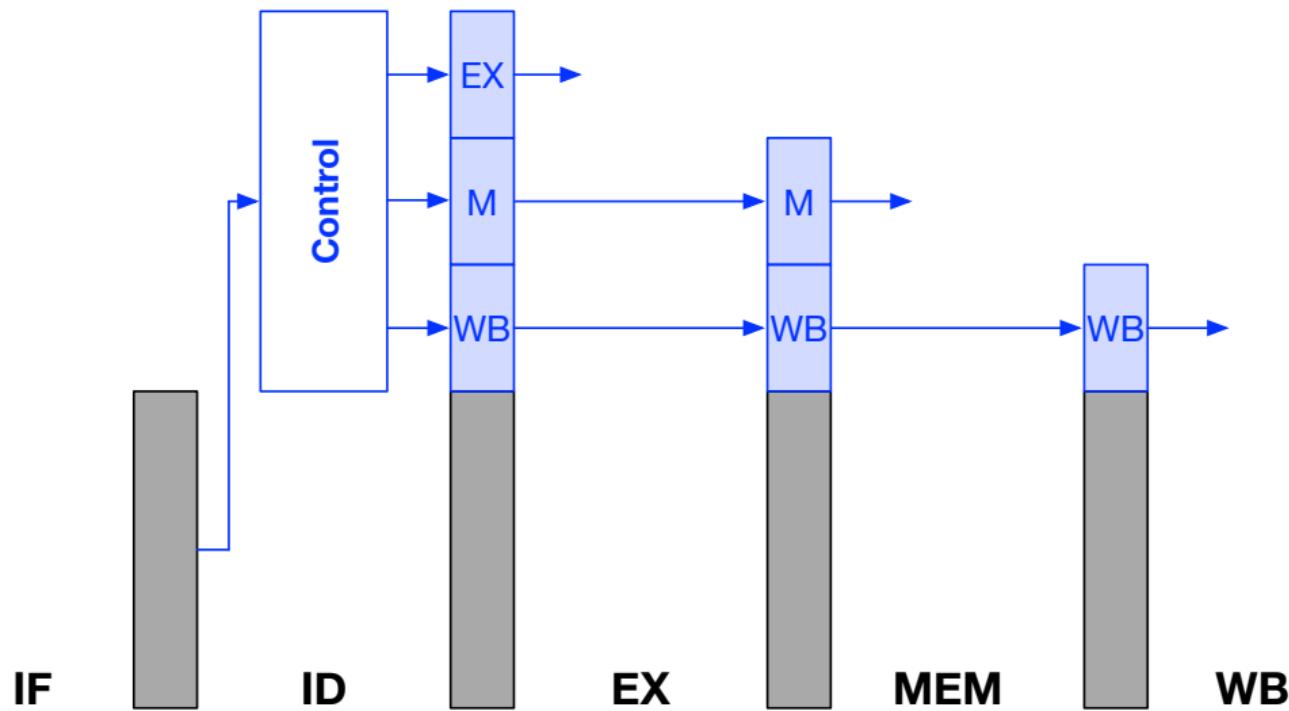


# Pipelined control

# Pipelined Control

- ▶ At each stage, information from instruction is needed
  - ▶ which ALU operation to execute
  - ▶ which memory address to consult
  - ▶ which register to write to
- ▶ This control information has to be passed through stages

# Pipelined Control



# Control Flags

