



# Chapter 4

## The Processor

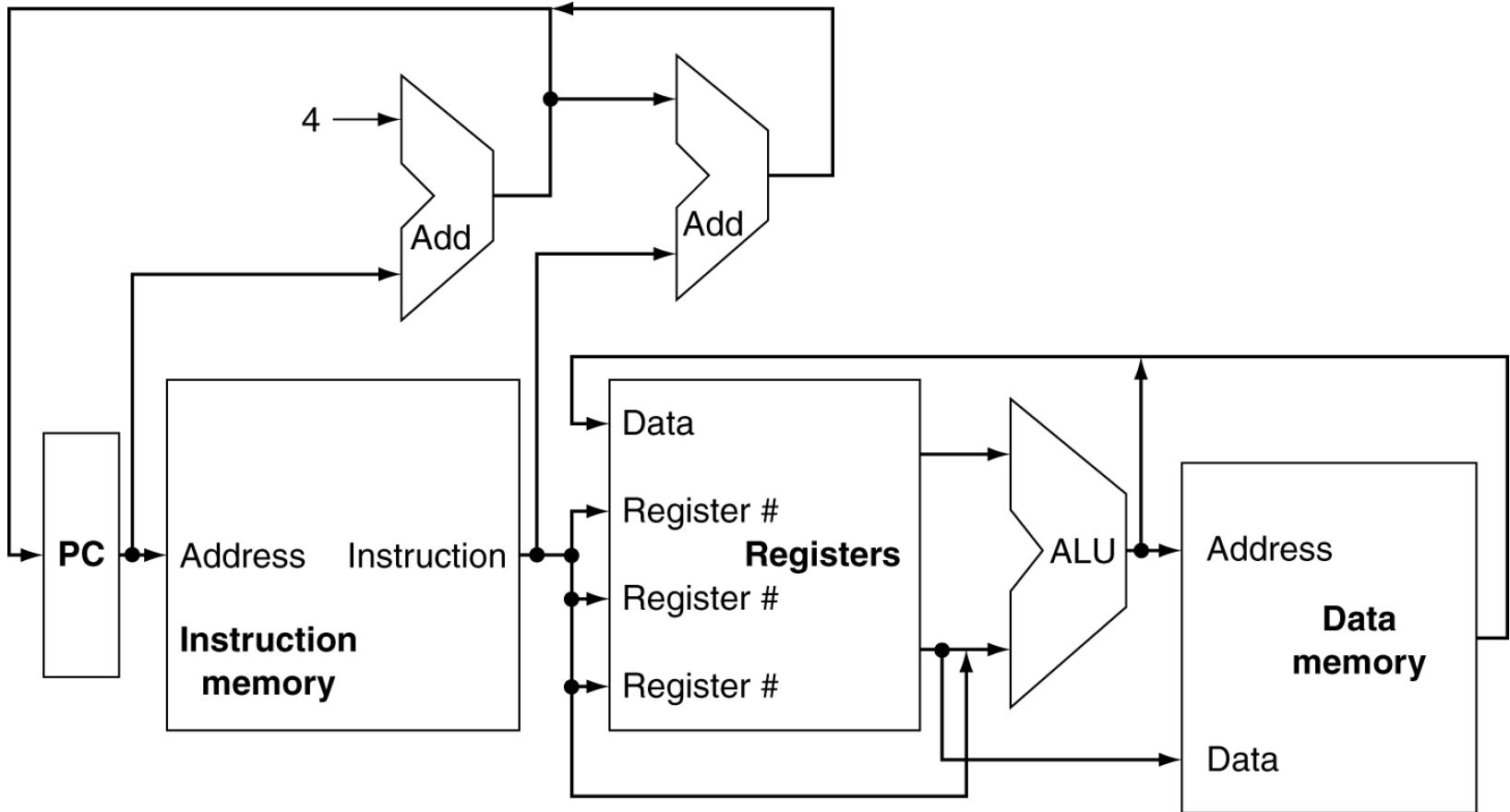
# Introduction

- CPU performance factors
  - Instruction count
    - Determined by ISA and compiler
  - CPI and Cycle time
    - Determined by CPU hardware
- We will examine two MIPS implementations
  - A simplified version
  - A more realistic pipelined version
- Simple subset, shows most aspects
  - Memory reference: lw, sw
  - Arithmetic/logical: add, sub, and, or, slt
  - Control transfer: beq, j

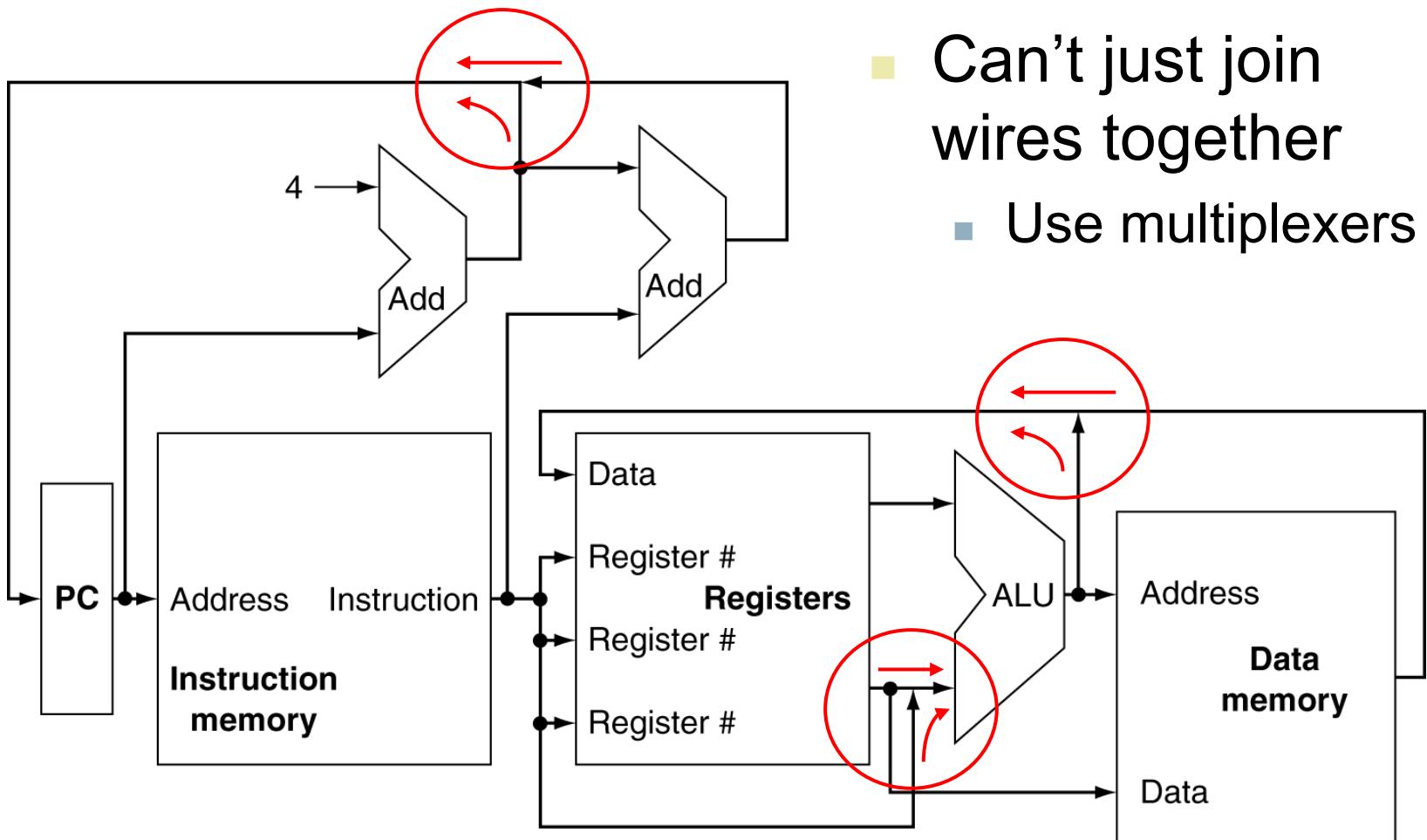
# Instruction Execution

- PC → instruction memory, fetch instruction
- Register numbers → register file, read registers
- Depending on instruction class
  - Use ALU to calculate
    - Arithmetic result
    - Memory address for load/store
    - Branch target address
  - Access data memory for load/store
  - PC ← target address or PC + 4

# CPU Overview

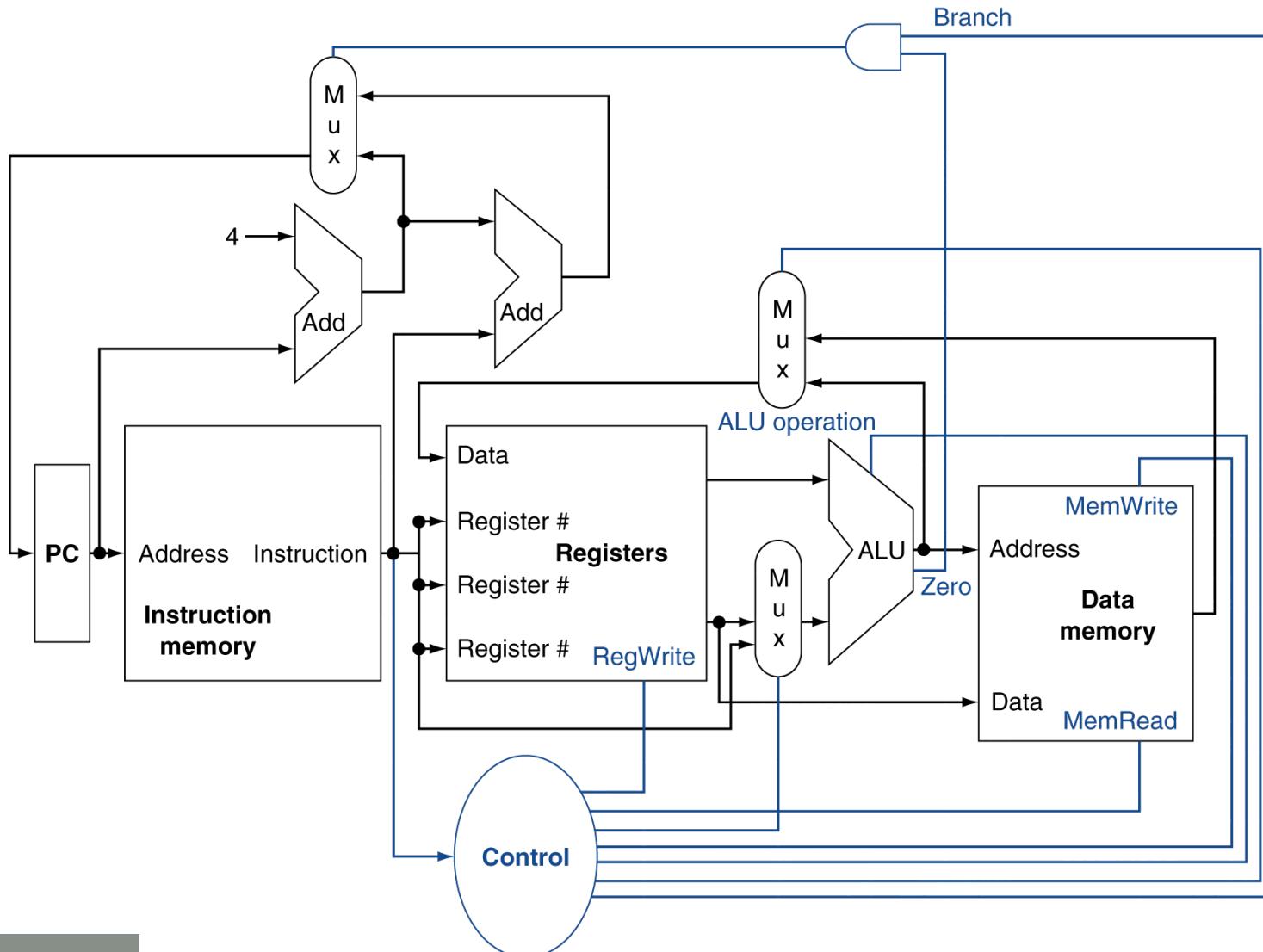


# Multiplexers



- Can't just join wires together
  - Use multiplexers

# Control

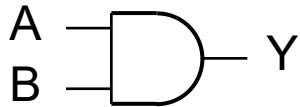


# Logic Design Basics

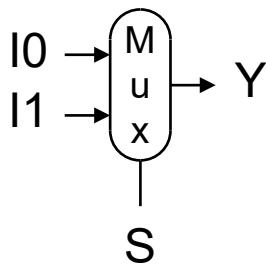
- Information encoded in binary
  - Low voltage = 0, High voltage = 1
  - One wire per bit
  - Multi-bit data encoded on multi-wire buses
- Combinational element
  - Operate on data
  - Output is a function of input
- State (sequential) elements
  - Store information

# Combinational Elements

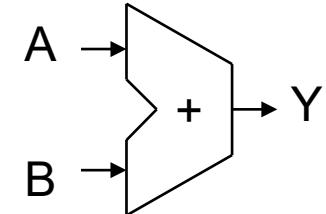
- AND-gate
  - $Y = A \& B$



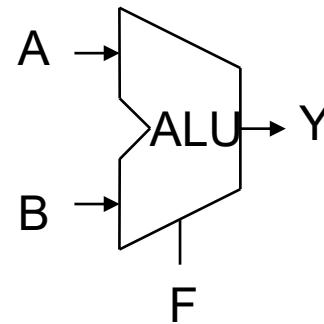
- Multiplexer
  - $Y = S ? I_1 : I_0$



- Adder
  - $Y = A + B$

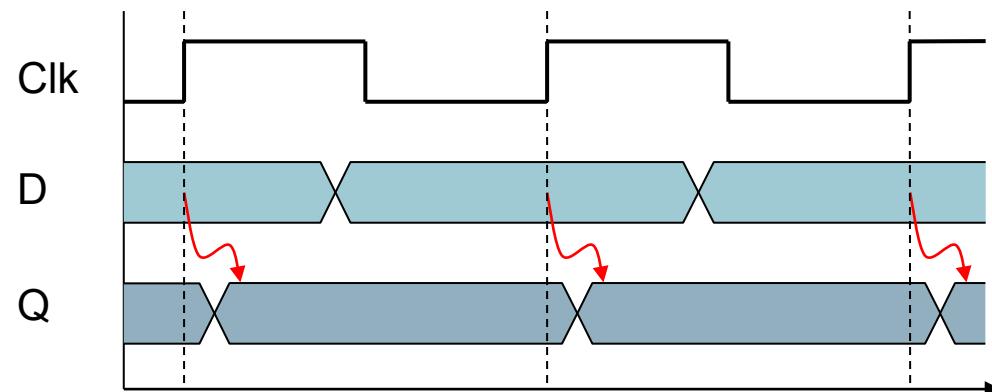
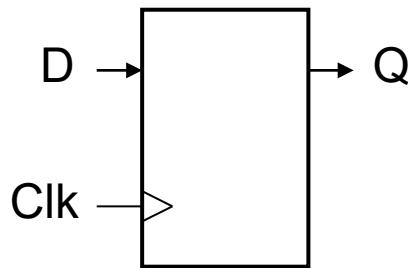


- Arithmetic/Logic Unit
  - $Y = F(A, B)$



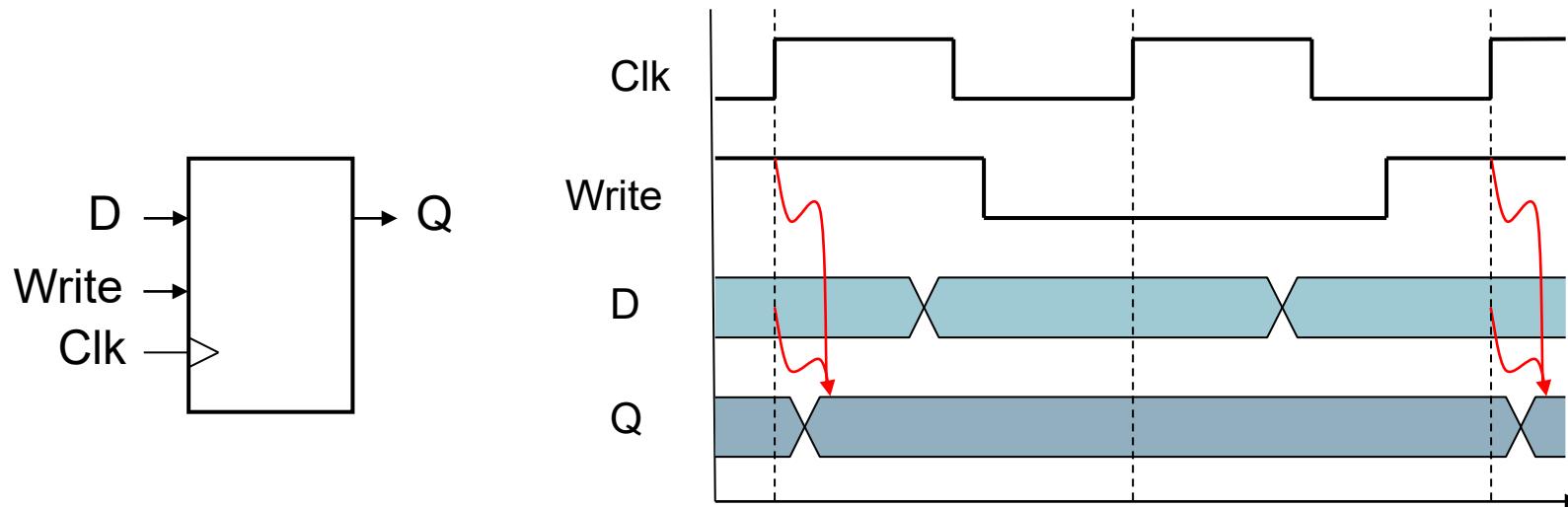
# Sequential Elements

- Register: stores data in a circuit
  - Uses a clock signal to determine when to update the stored value
  - Edge-triggered: update when Clk changes from 0 to 1



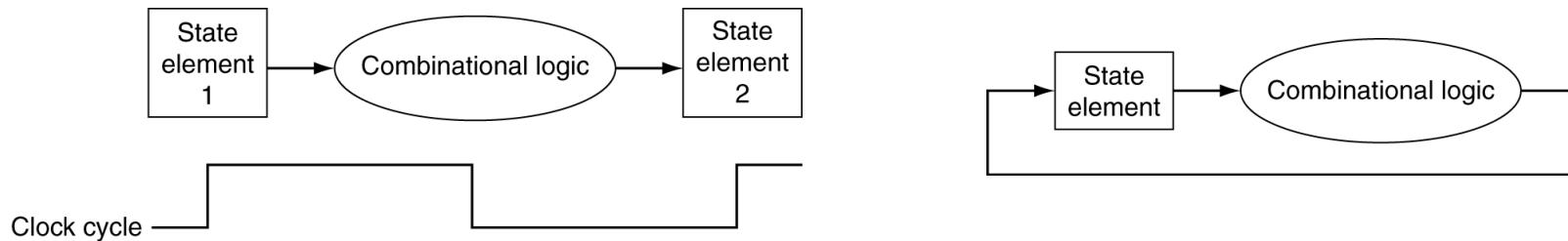
# Sequential Elements

- Register with write control
  - Only updates on clock edge when write control input is 1
  - Used when stored value is required later



# Clocking Methodology

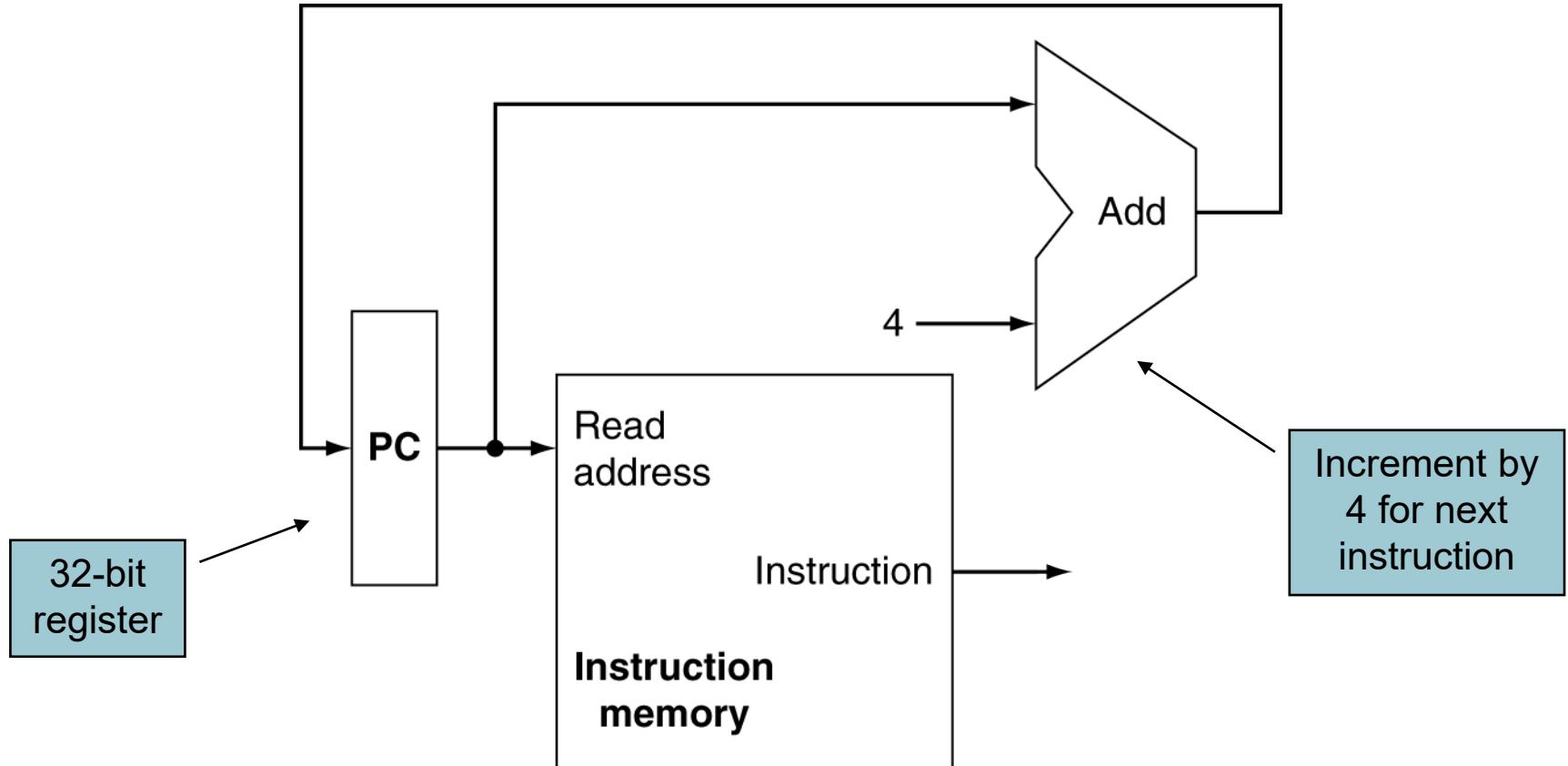
- Combinational logic transforms data during clock cycles
  - Between clock edges
  - Input from state elements, output to state element
  - Longest delay determines clock period



# Building a Datapath

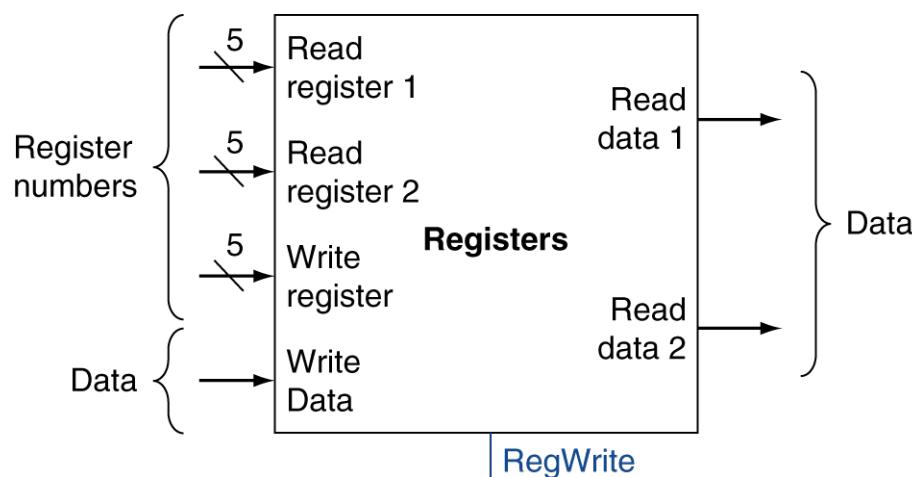
- Datapath
  - Elements that process data and addresses in the CPU
    - Registers, ALUs, mux's, memories, ...
- We will build a MIPS datapath incrementally
  - Refining the overview design

# Instruction Fetch

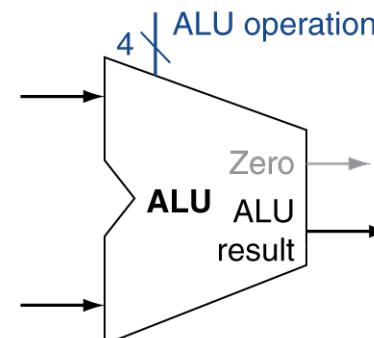


# R-Format Instructions

- Read two register operands
- Perform arithmetic/logical operation
- Write register result



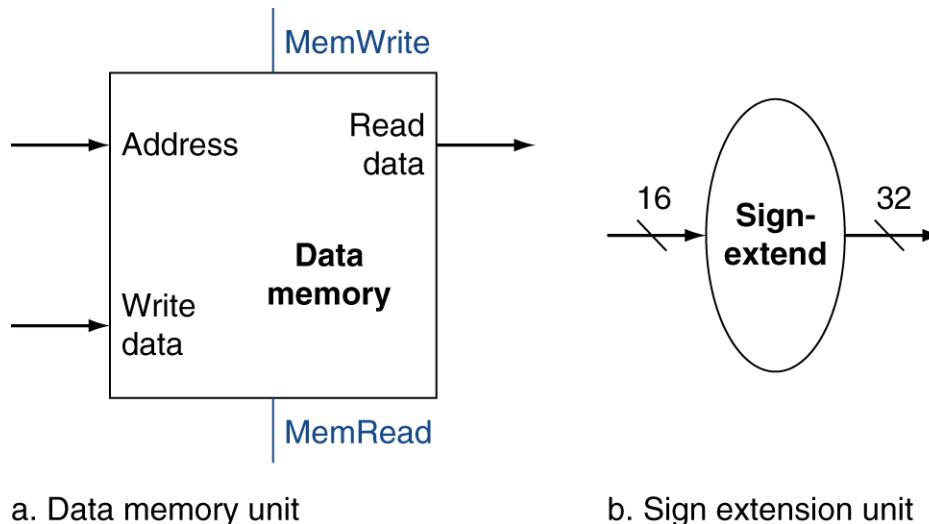
a. Registers



b. ALU

# Load/Store Instructions

- Read register operands
- Calculate address using 16-bit offset
  - Use ALU, but sign-extend offset
- Load: Read memory and update register
- Store: Write register value to memory



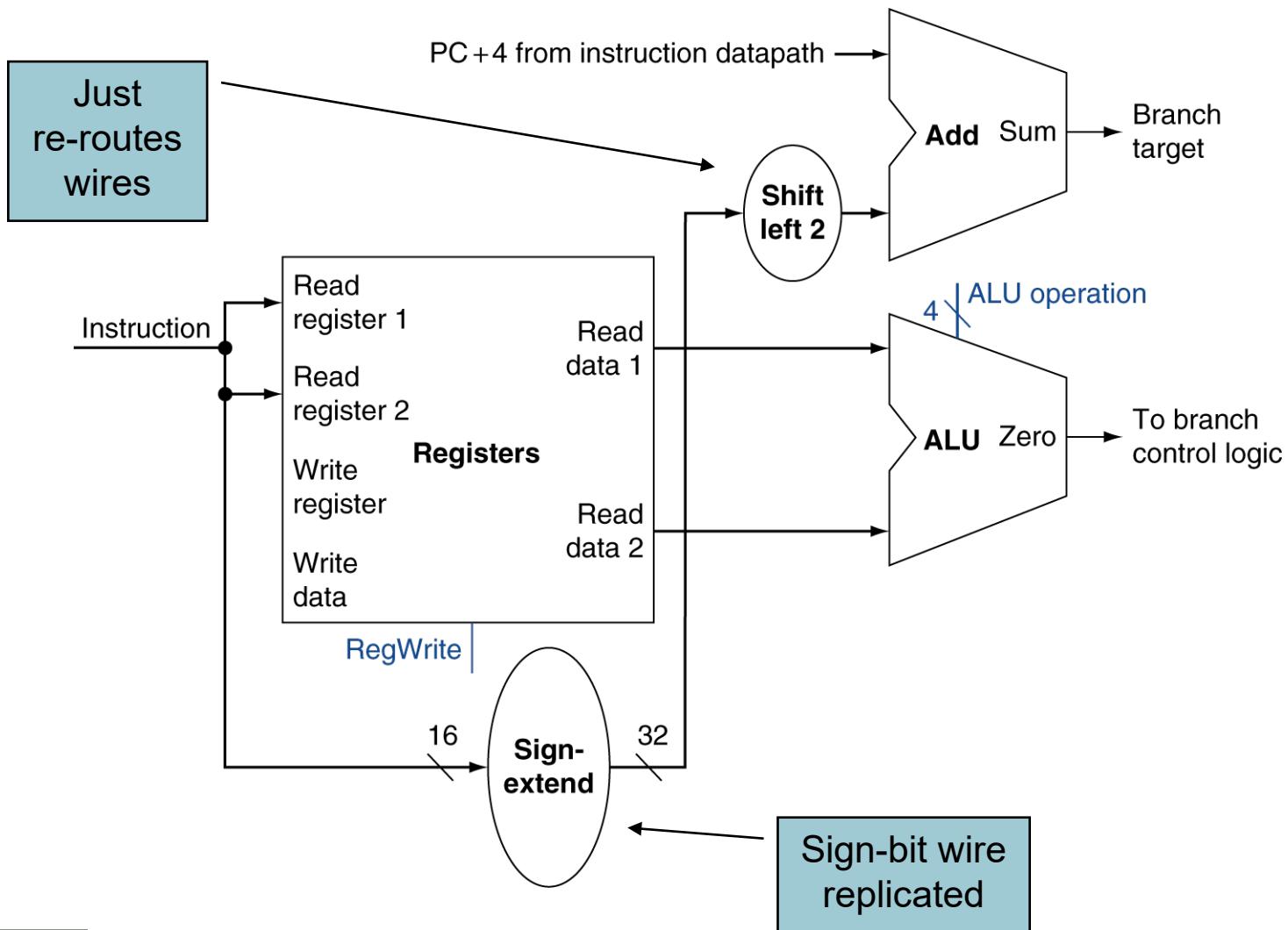
a. Data memory unit

b. Sign extension unit

# Branch Instructions

- Read register operands
- Compare operands
  - Use ALU, subtract and check Zero output
- Calculate target address
  - Sign-extend displacement
  - Shift left 2 places (word displacement)
  - Add to PC + 4
    - Already calculated by instruction fetch

# Branch Instructions



# Composing the Elements

- First-cut data path does an instruction in one clock cycle
  - Each datapath element can only do one function at a time
  - Hence, we need separate instruction and data memories
- Use multiplexers where alternate data sources are used for different instructions

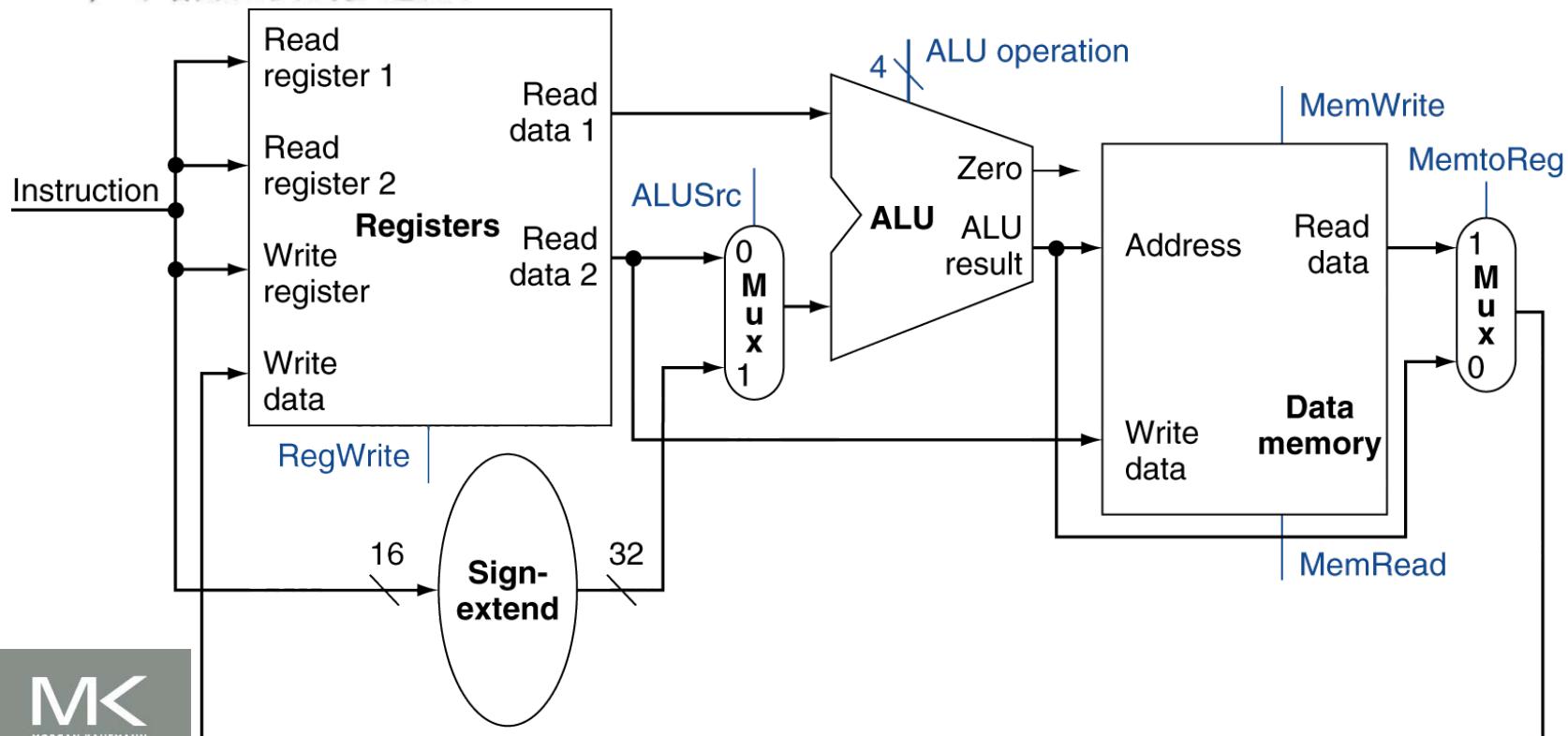
# R-Type/Load/Store Datapath

## 01 例题·建立一个数据通路

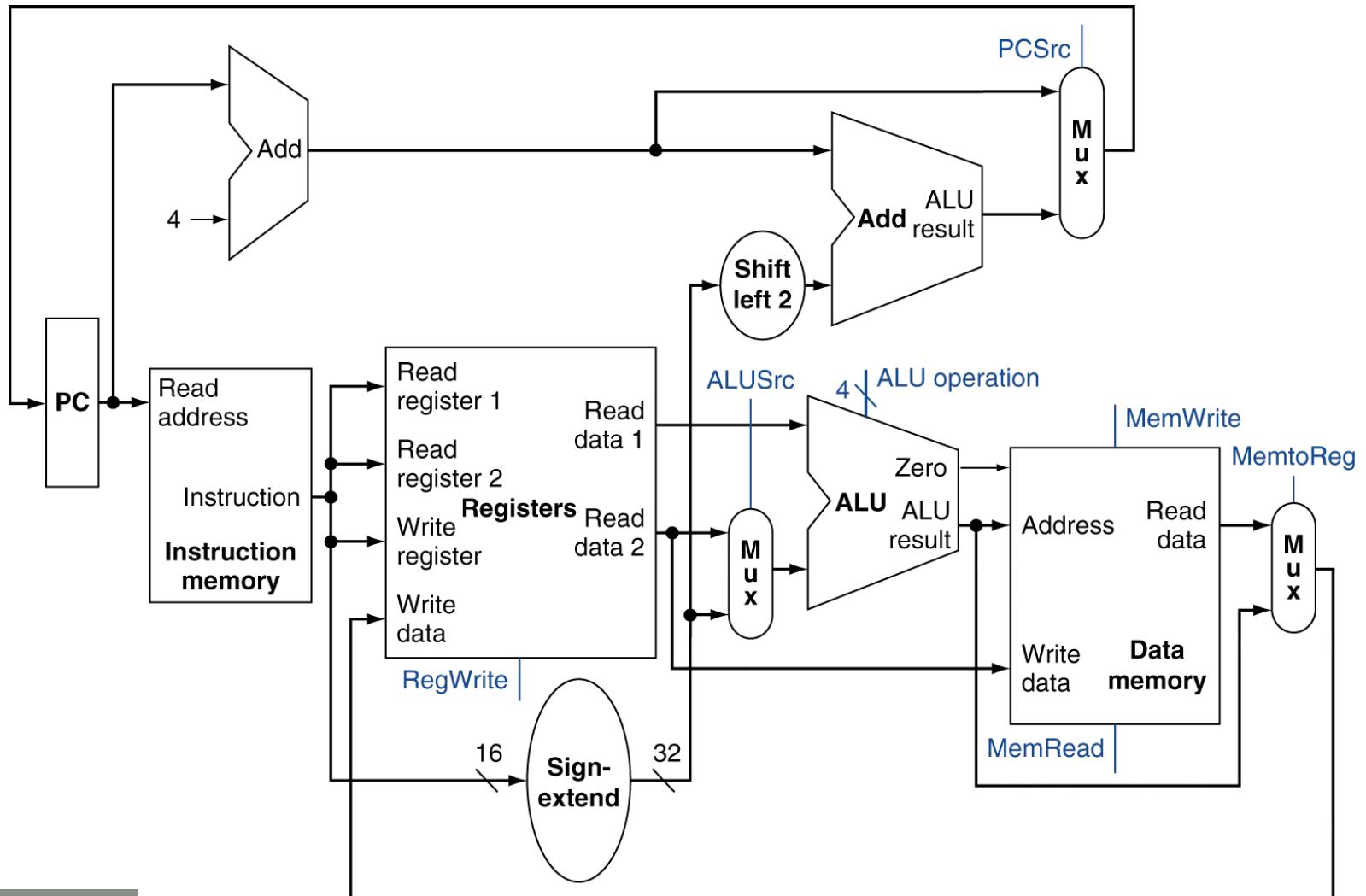
算术逻辑指令（或 R 型指令）的数据通路与访存指令的数据通路很相似。它们的主要区别为：

- 算术逻辑指令使用 ALU，并且其输入来自两个寄存器。存储指令也使用 ALU 来进行地址计算，但 ALU 的第二个输入是对指令中 16 位偏移地址进行符号扩展后的值。
- 存入目标寄存器中的值来自于 ALU（对 R 型指令而言）或者存储器（对取数操作而言）。

试设计存储指令和算术逻辑指令操作部分的数据通路，只能使用一个寄存器堆和一个 ALU，可增加必要的多选器。



# Full Datapath



# ALU Control

- ALU used for
  - Load/Store: F = add
  - Branch: F = subtract
  - R-type: F depends on funct field

ALU control	Function
0000	AND
0001	OR
0010	add
0110	subtract
0111	set-on-less-than
1100	NOR

# ALU Control

- Assume 2-bit ALUOp derived from opcode
  - Combinational logic derives ALU control

opcode	ALUOp	Operation	funct	ALU function	ALU control
lw	00	load word	XXXXXX	add	0010
sw	00	store word	XXXXXX	add	0010
beq	01	branch equal	XXXXXX	subtract	0110
R-type	10	add	100000	add	0010
		subtract	100010	subtract	0110
		AND	100100	AND	0000
		OR	100101	OR	0001
		set-on-less-than	101010	set-on-less-than	0111

# ALU Control

真值表：逻辑操作的一种表示方法，即列出输入的所有情况和每种情况下的输出。

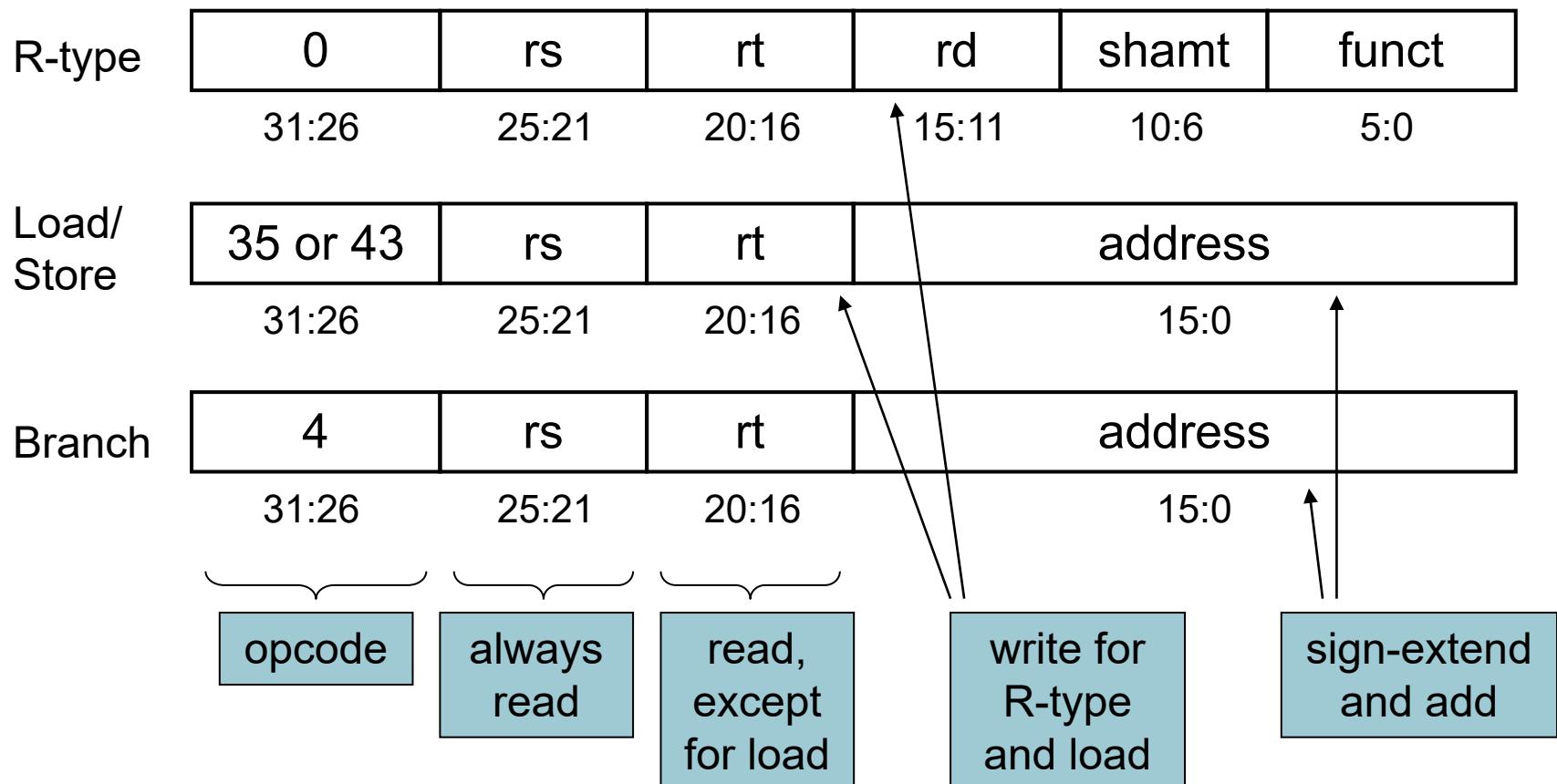
无关项：逻辑函数的一个元素，表示输出与该输入取值无关。无关项可以用不同的方式指定。

ALUOp		Funct 字段							操作
ALUOp1	ALUOp0	F5	F4	F3	F2	F1	F0		
0	0	X	X	X	X	X	X	0010	
X	1	X	X	X	X	X	X	0110	
1	X	X	X	0	0	0	0	0010	
1	X	X	X	0	0	1	0	0110	
1	X	X	X	0	1	0	0	0000	
1	X	X	X	0	1	0	1	0001	
1	X	X	X	1	0	1	0	0111	

图 4-13 4 位 ALU 控制信号（称为操作）的真值表。该真值表的输入为 ALUOp 和 funct 字段。在此只列出了 ALU 控制有效的项，也包括一些无关项。例如，ALUOp 不使用编码 11，故真值表包含 1X 和 X1 项，而不是 10 和 01 项。同样，当使用 funct 字段时指令的前两位（F4 和 F5）总是 10，所以它们是无关项，在真值表中用 XX 代替

# The Main Control Unit

## Control signals derived from instruction



# Datapath With Control

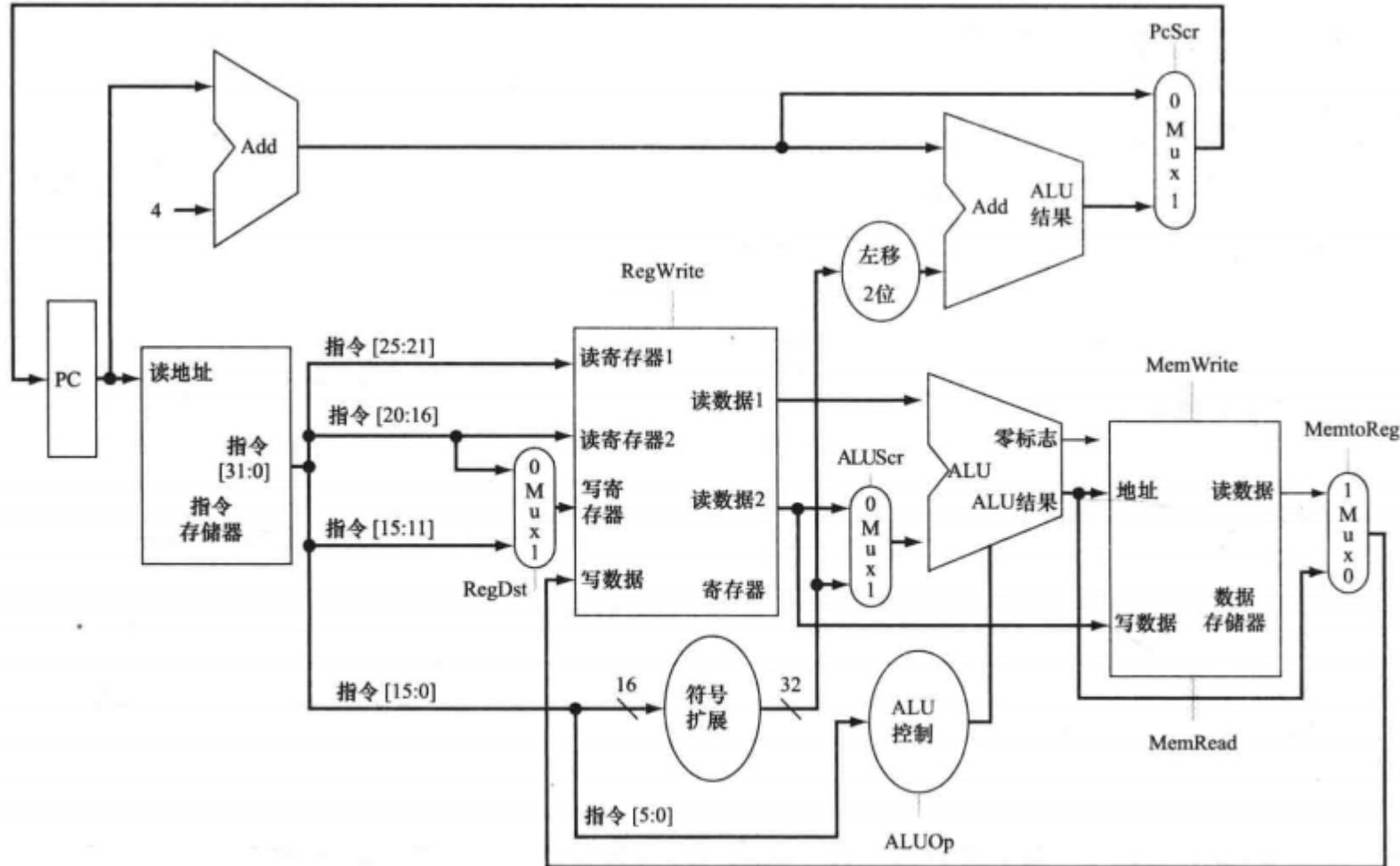
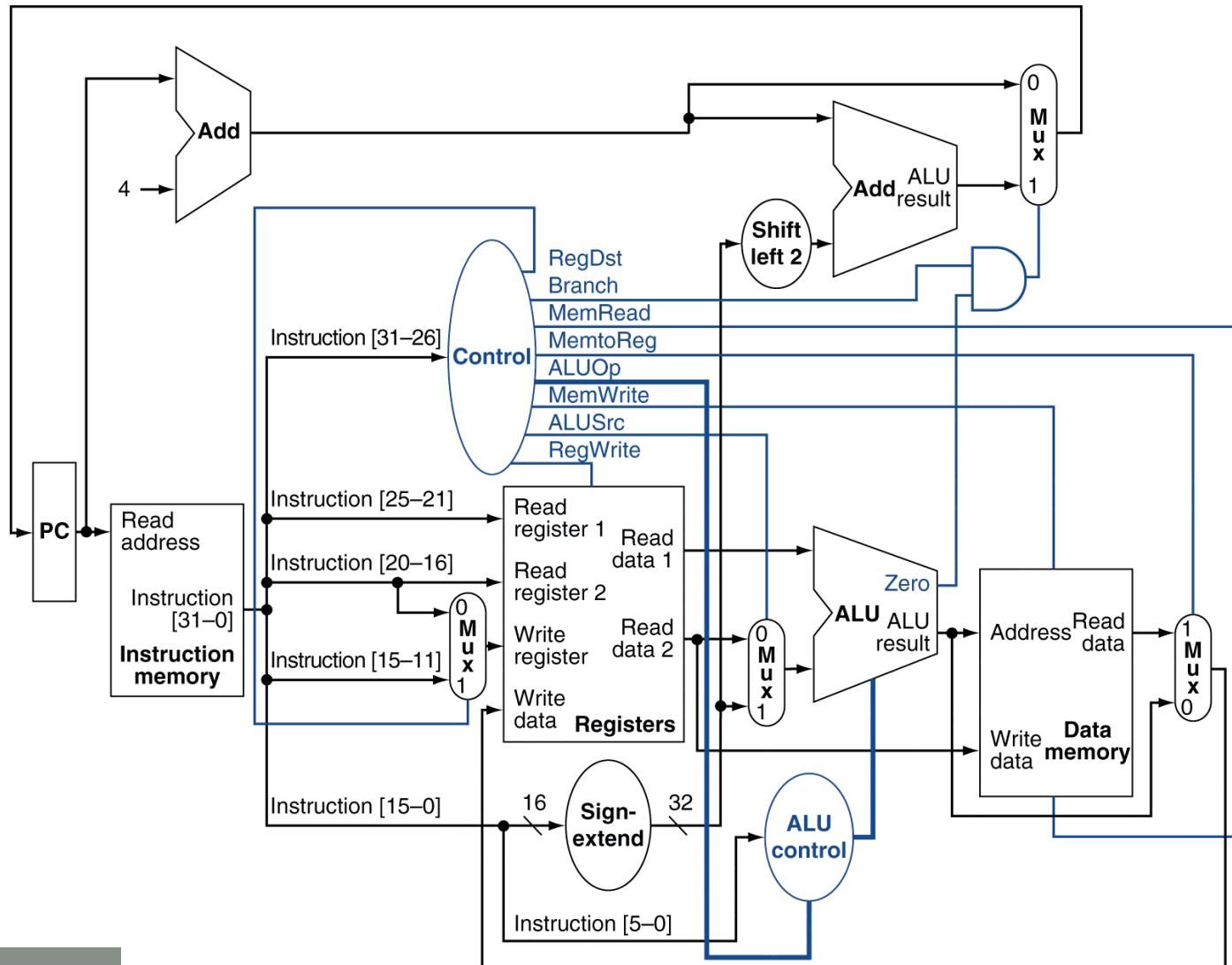
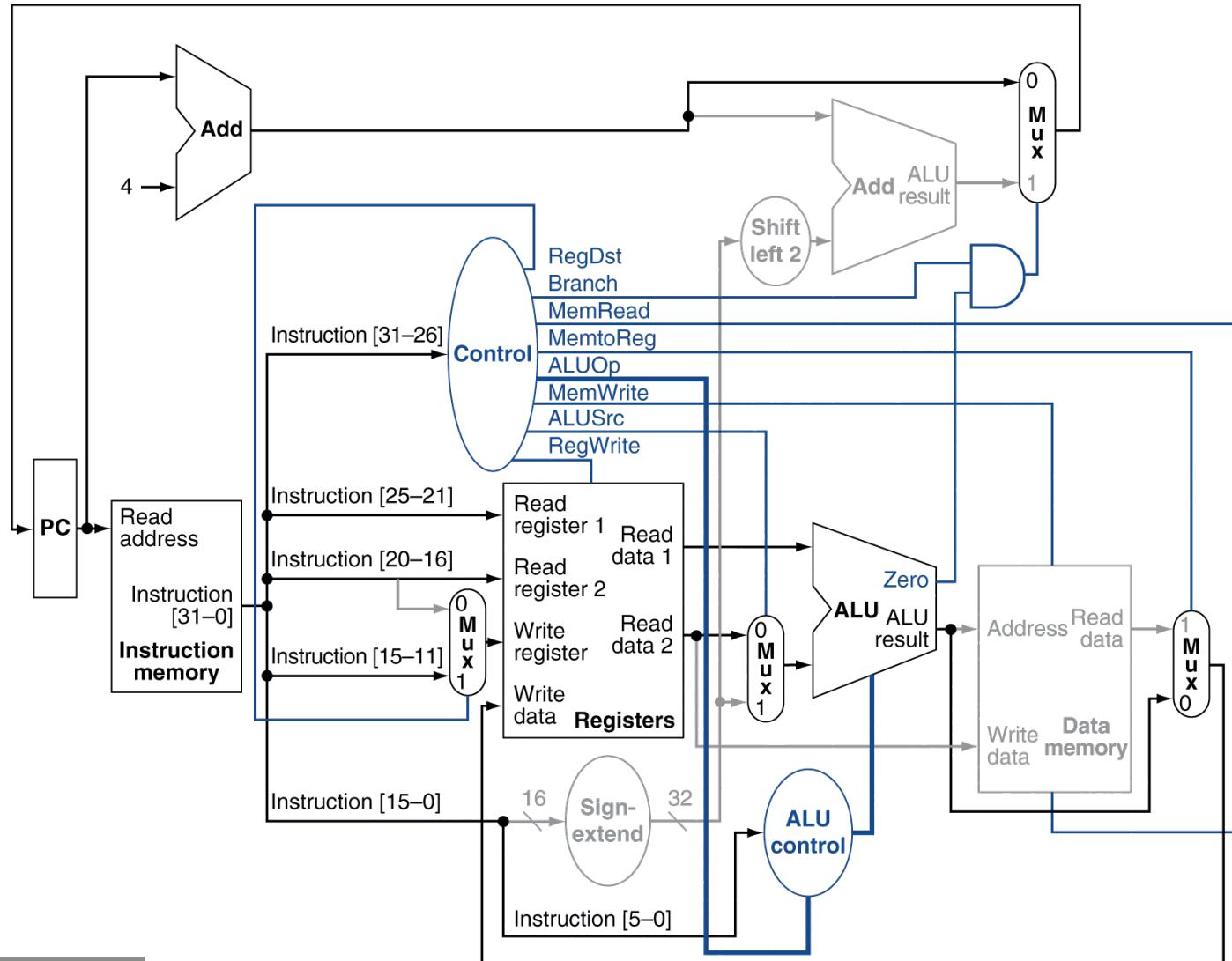


图 4-15 在图 4-11 的数据通路上增加了所有必需的多选器，并标识出了所有的控制信号。控制信

# Datapath With Control

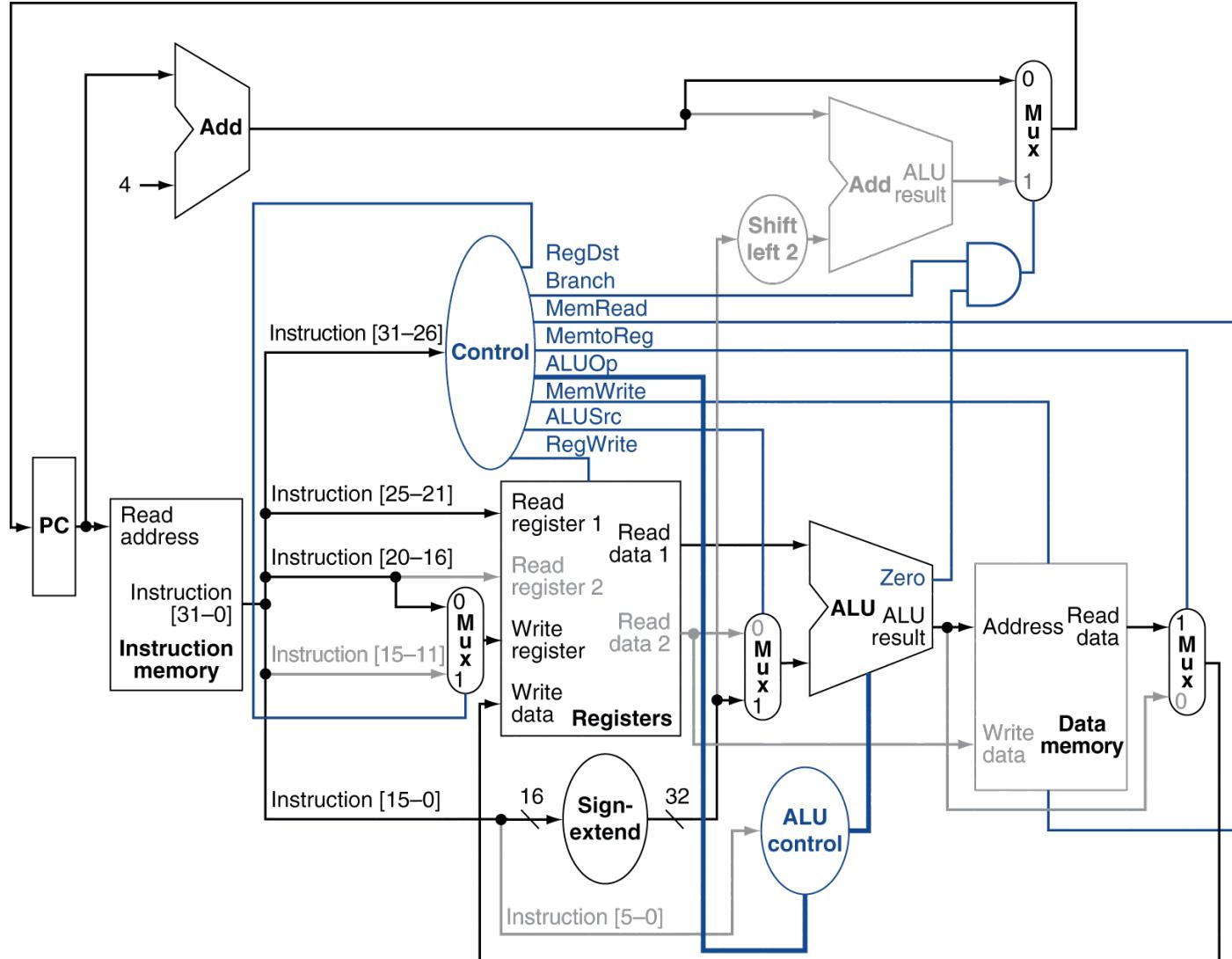


# R-Type Instruction



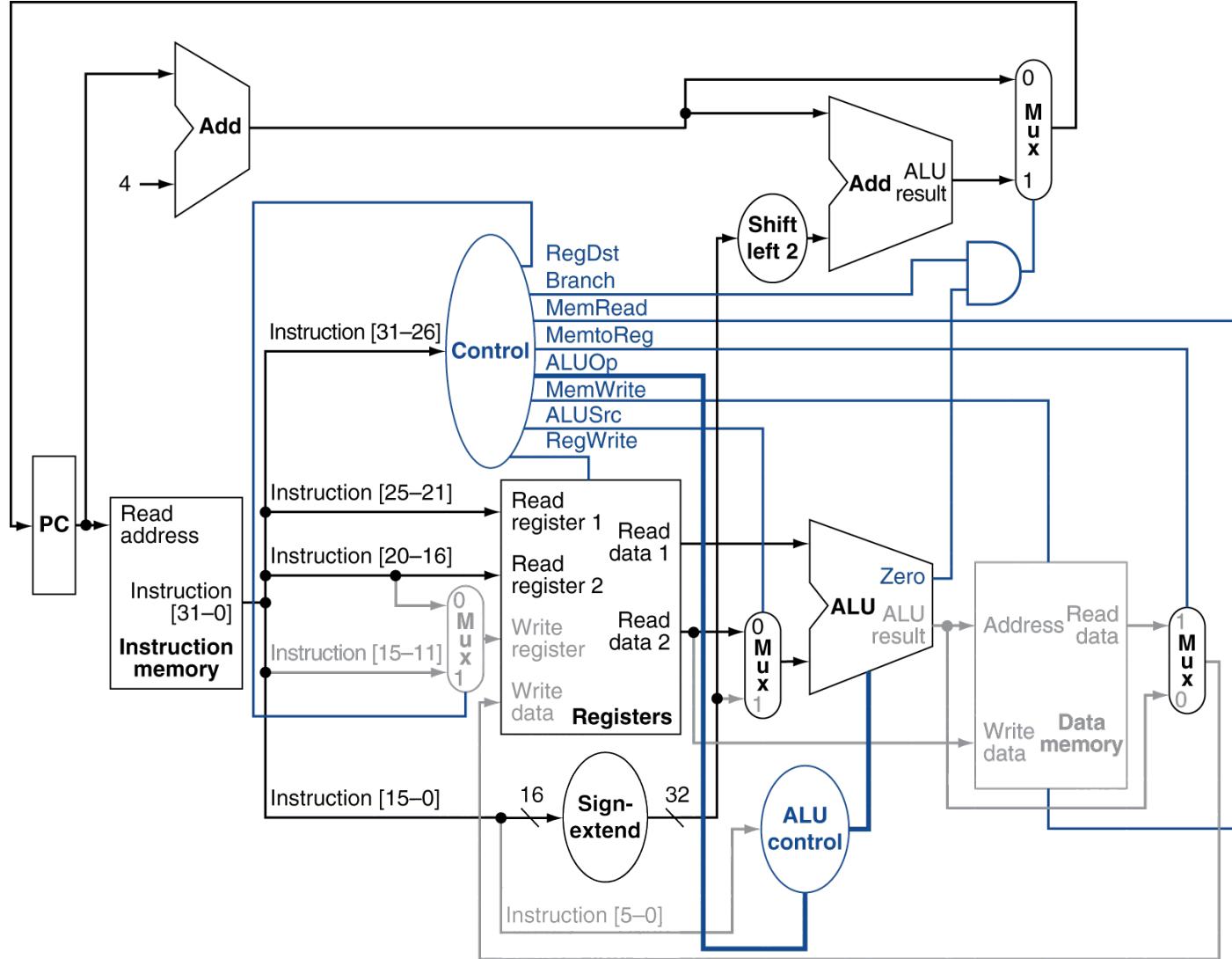
指令	RegDst	ALUSrc	MemtoReg	RegWrite	MemRead	MemWrite	Branch	ALUOp1	ALUOp0
R型	1	0	0	1	0	0	0	1	0

# Load Instruction



指令	RegDst	ALUSrc	MemtoReg	RegWrite	MemRead	MemWrite	Branch	ALUOp1	ALUOp0
lw	0	1	1	1	1	0	0	0	0

# Branch-on-Equal Instruction



指令	RegDst	ALUSrc	MemtoReg	RegWrite	MemRead	MemWrite	Branch	ALUOp1	ALUOp0
beq	X	0	X	0	0	0	1	0	1

# Truth Table

输入或输出	信号名	R型	lw	sw	beq
输入	Op5	0	1	1	0
	Op4	0	0	0	0
	Op3	0	0	1	0
	Op2	0	0	0	1
	Op1	0	1	1	0
	Op0	0	1	1	0
输入或输出	信号名	R型	lw	sw	beq
输出	RegDst	1	0	X	X
	ALUSrc	0	1	1	0
	MemtoReg	0	1	X	X
	RegWrite	1	1	0	0
	MemRead	0	1	0	0
	MemWrite	0	0	1	0
	Branch	0	0	0	1
	ALUOp1	1	0	0	0
	ALUOp0	0	0	0	1

图 4-22 简单的单周期实现的控制功能真值表。表的上半部分为输入，其包括操作码（对应于指令的 31:26 位的 Op[5:0]）的 4 种组合。表的下半部分为 4 种组合的输出。因此，RegWrite 对于两种不同的输入组合是有效的。如果只考虑这张表中的 4 个操作码，则可以用输入部分的无关项简化真值表。例如，可以由表达式  $Op5 \cdot Op2$  确定是否为 R 型指令，因为这已经足够将 R 型指令与 lw、sw 和 beq 指令区分开。之所以不用这种简化，是因为在 MIPS 指令集的完整实现中会用到其他操作码

# Implementing Jumps

Jump

2

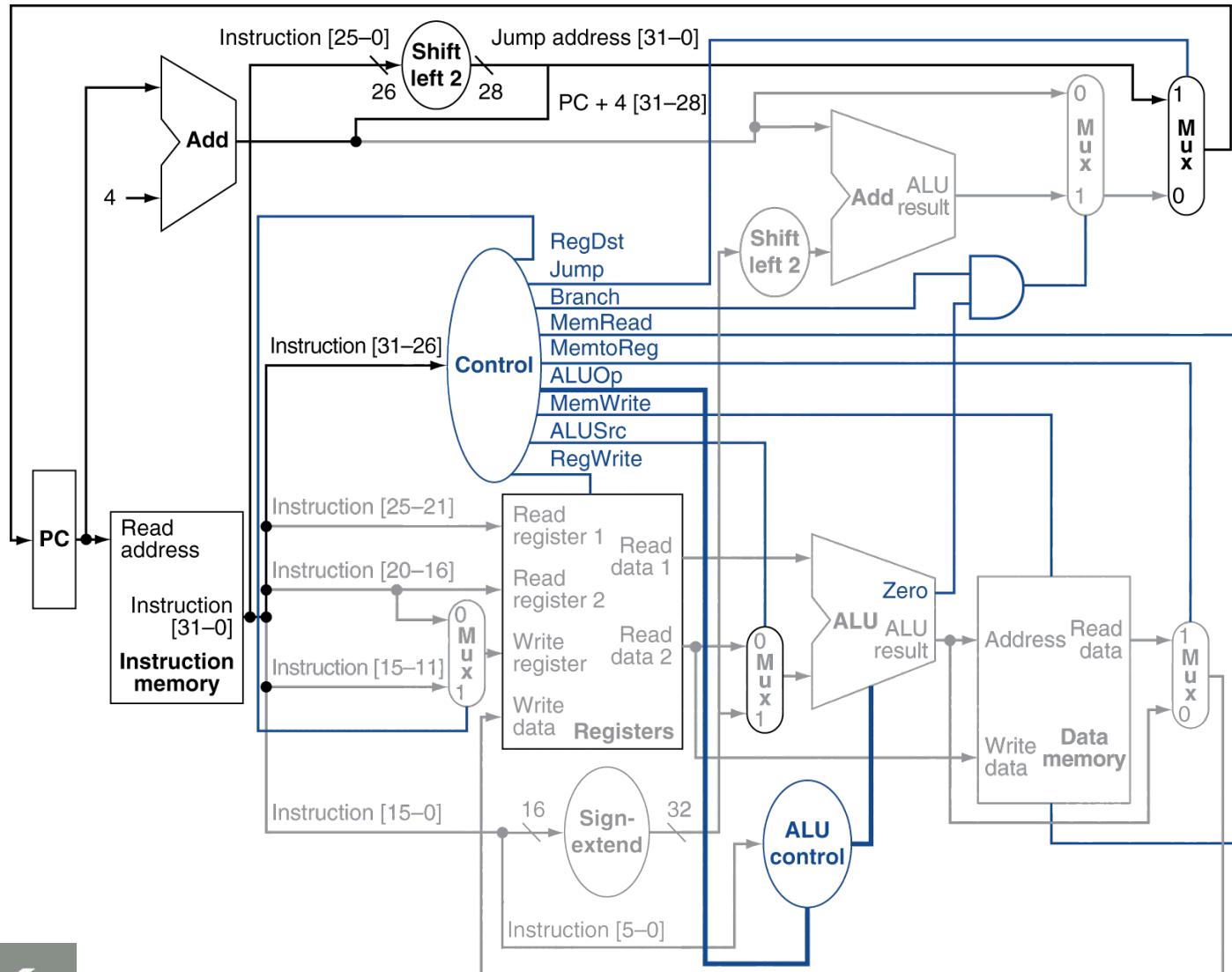
address

31:26

25:0

- Jump uses word address
- Update PC with concatenation of
  - Top 4 bits of old PC
  - 26-bit jump address
  - 00
- Need an extra control signal decoded from opcode

# Datapath With Jumps Added

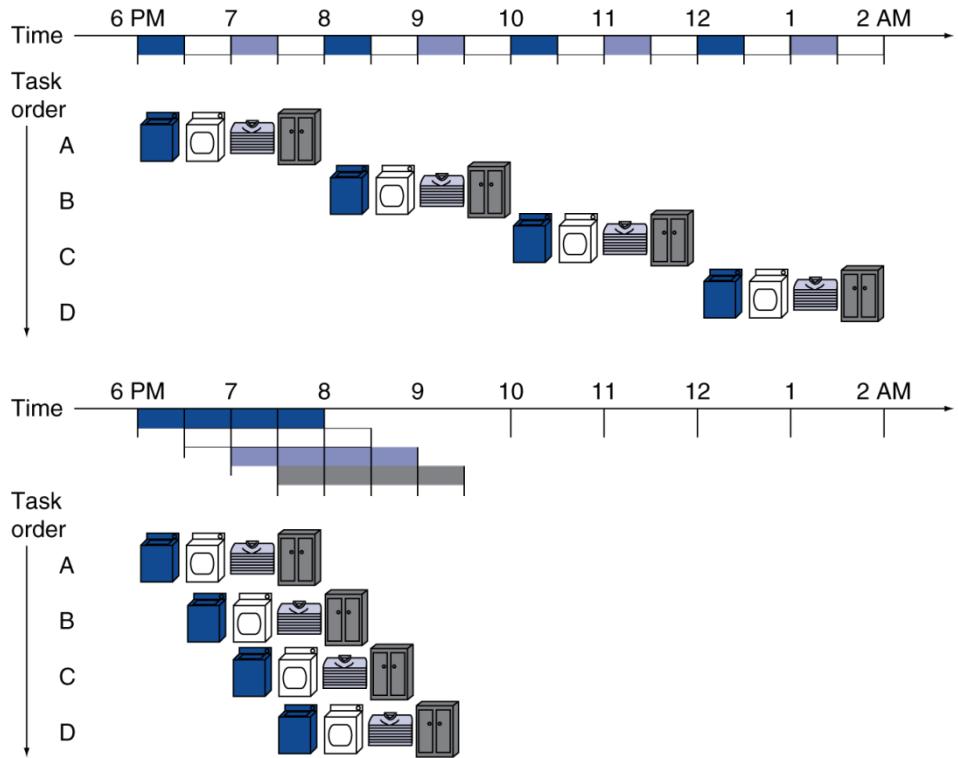


# Performance Issues

- Longest delay determines clock period
  - Critical path: load instruction
  - Instruction memory → register file → ALU → data memory → register file
- Not feasible to vary period for different instructions
- Violates design principle
  - Making the common case fast
- We will improve performance by pipelining

# Pipelining Analogy

- Pipelined laundry: overlapping execution
  - Parallelism improves performance



- Four loads:
  - Speedup  
 $= 8/3.5 = 2.3$
- Non-stop:
  - Speedup  
 $= 2n/0.5n + 1.5 \approx 4$   
= number of stages

# MIPS Pipeline

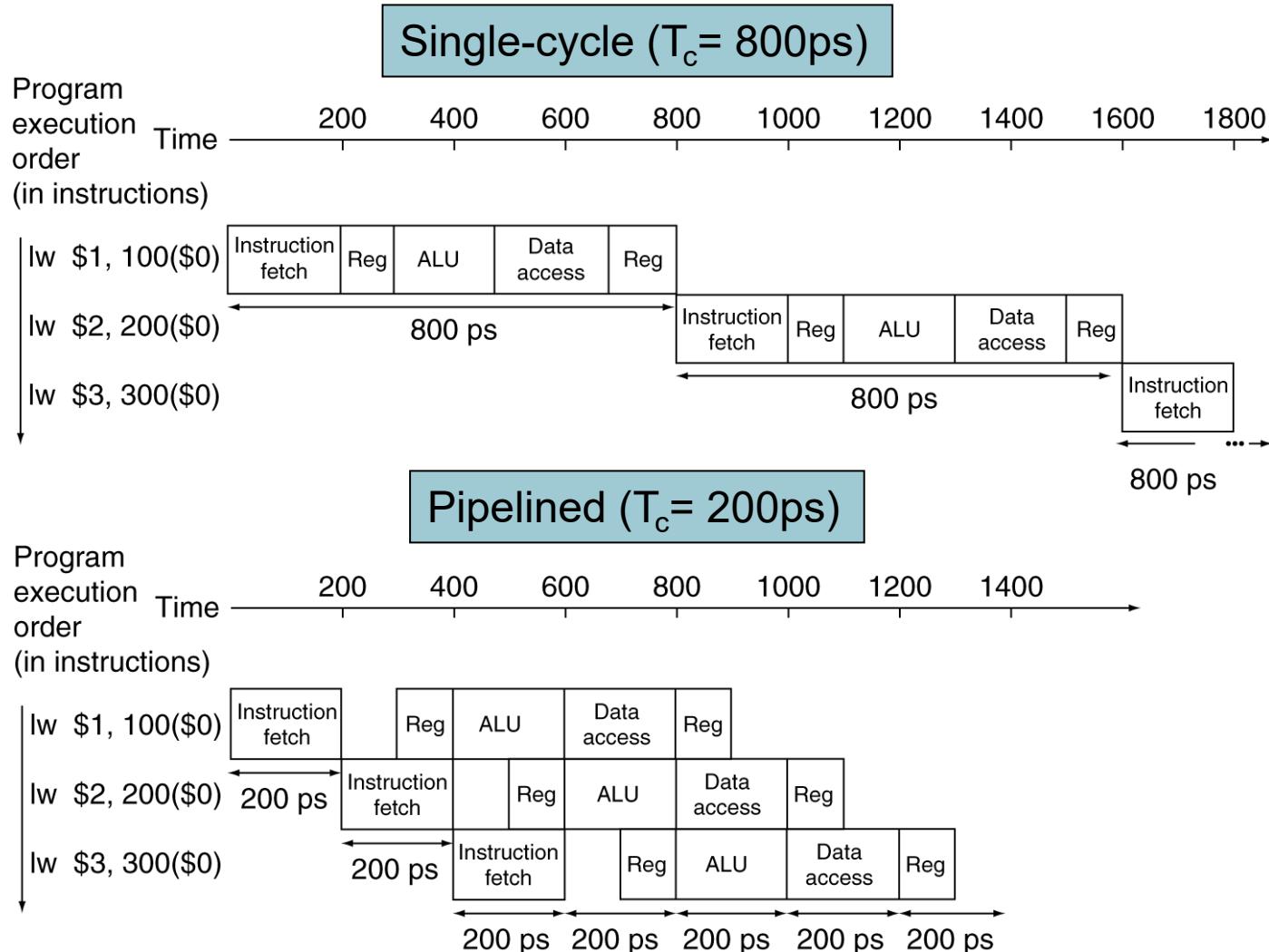
- Five stages, one step per stage
  1. IF: Instruction fetch from memory
  2. ID: Instruction decode & register read
  3. EX: Execute operation or calculate address
  4. MEM: Access memory operand
  5. WB: Write result back to register

# Pipeline Performance

- Assume time for stages is
  - 100ps for register read or write
  - 200ps for other stages
- Compare pipelined datapath with single-cycle datapath

Instr	Instr fetch	Register read	ALU op	Memory access	Register write	Total time
lw	200ps	100 ps	200ps	200ps	100 ps	800ps
sw	200ps	100 ps	200ps	200ps		700ps
R-format	200ps	100 ps	200ps		100 ps	600ps
beq	200ps	100 ps	200ps			500ps

# Pipeline Performance



# Pipeline Speedup

- If all stages are balanced
  - i.e., all take the same time
  - Time between instructions<sub>pipelined</sub>  
= Time between instructions<sub>nonpipelined</sub>  

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Number of stages
- If not balanced, speedup is less
- Speedup due to increased throughput
  - Latency (time for each instruction) does not decrease

# Pipelining and ISA Design

- MIPS ISA designed for pipelining
  - All instructions are 32-bits
    - Easier to fetch and decode in one cycle
    - c.f. x86: 1- to 17-byte instructions
  - Few and regular instruction formats
    - Can decode and read registers in one step
  - Load/store addressing
    - Can calculate address in 3<sup>rd</sup> stage, access memory in 4<sup>th</sup> stage
  - Alignment of memory operands
    - Memory access takes only one cycle

# Hazards

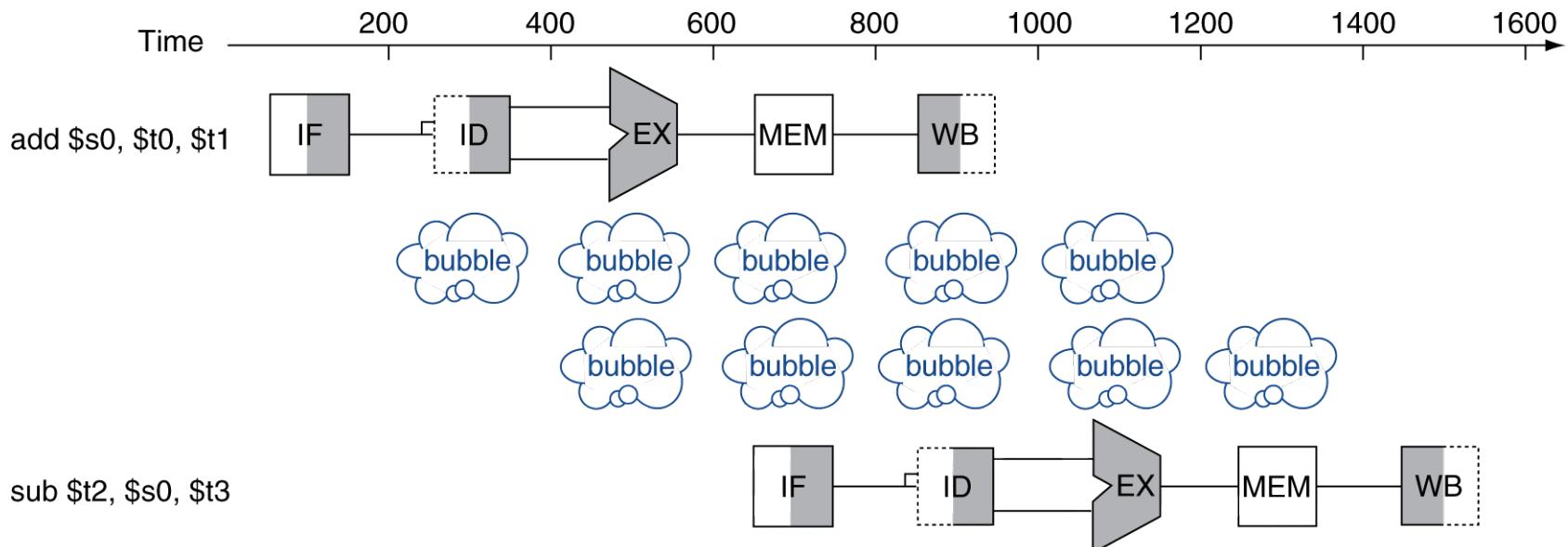
- Situations that prevent starting the next instruction in the next cycle
- Structure hazards
  - A required resource is busy
- Data hazard
  - Need to wait for previous instruction to complete its data read/write
- Control hazard
  - Deciding on control action depends on previous instruction

# Structure Hazards

- Conflict for use of a resource
- In MIPS pipeline with a single memory
  - Load/store requires data access
  - Instruction fetch would have to *stall* for that cycle
    - Would cause a pipeline “bubble”
- Hence, pipelined datapaths require separate instruction/data memories
  - Or separate instruction/data caches

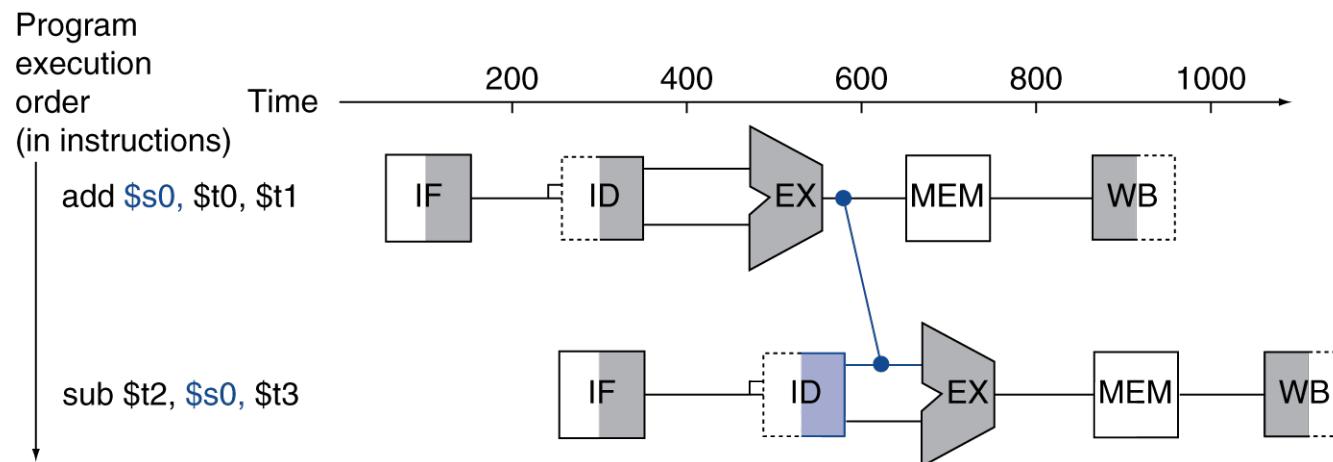
# Data Hazards

- An instruction depends on completion of data access by a previous instruction
  - add \$s0, \$t0, \$t1
  - sub \$t2, \$s0, \$t3



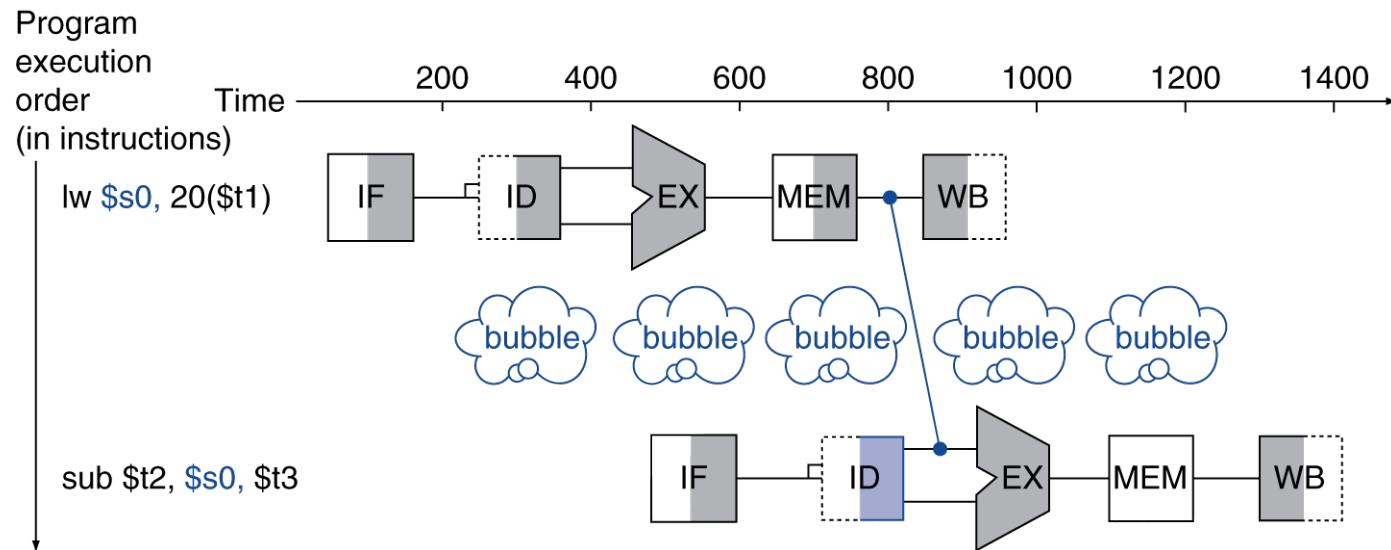
# Forwarding (aka Bypassing)

- Use result when it is computed
  - Don't wait for it to be stored in a register
  - Requires extra connections in the datapath



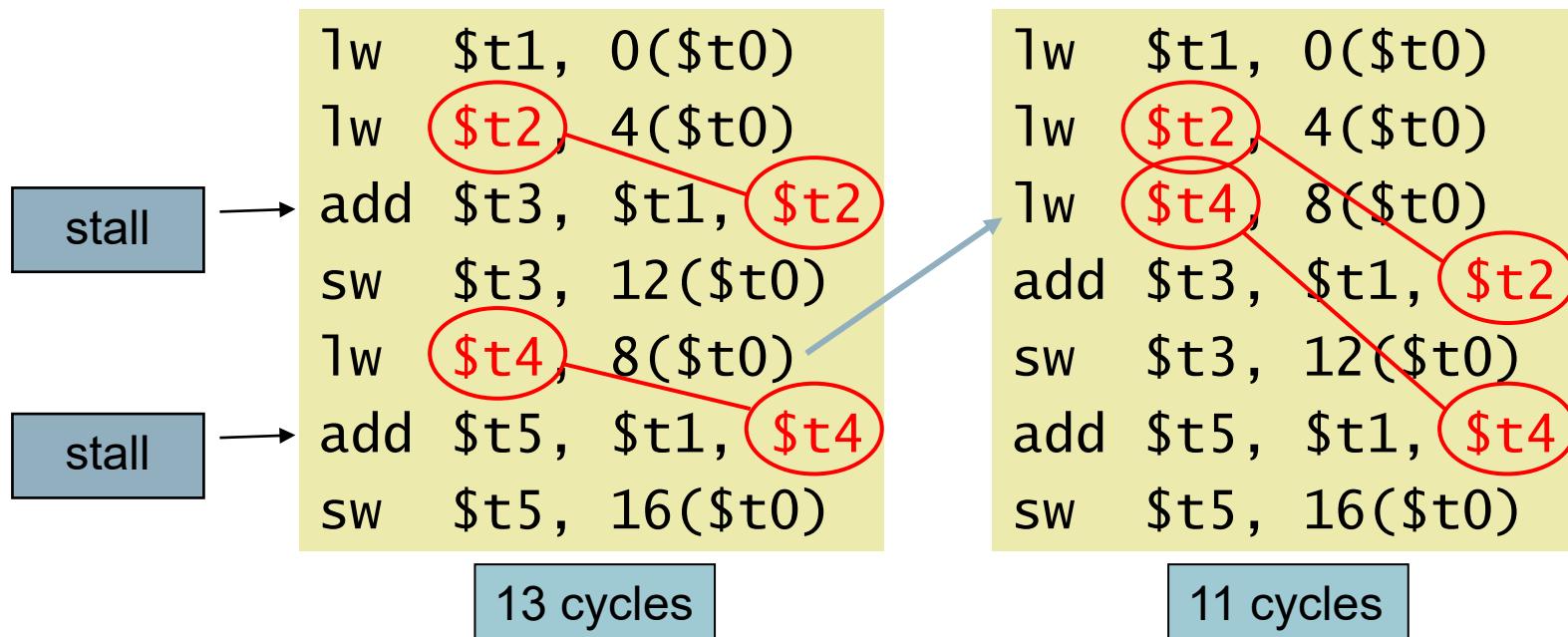
# Load-Use Data Hazard

- Can't always avoid stalls by forwarding
  - If value not computed when needed
  - Can't forward backward in time!



# Code Scheduling to Avoid Stalls

- Reorder code to avoid use of load result in the next instruction
- C code for  $A = B + E; C = B + F;$

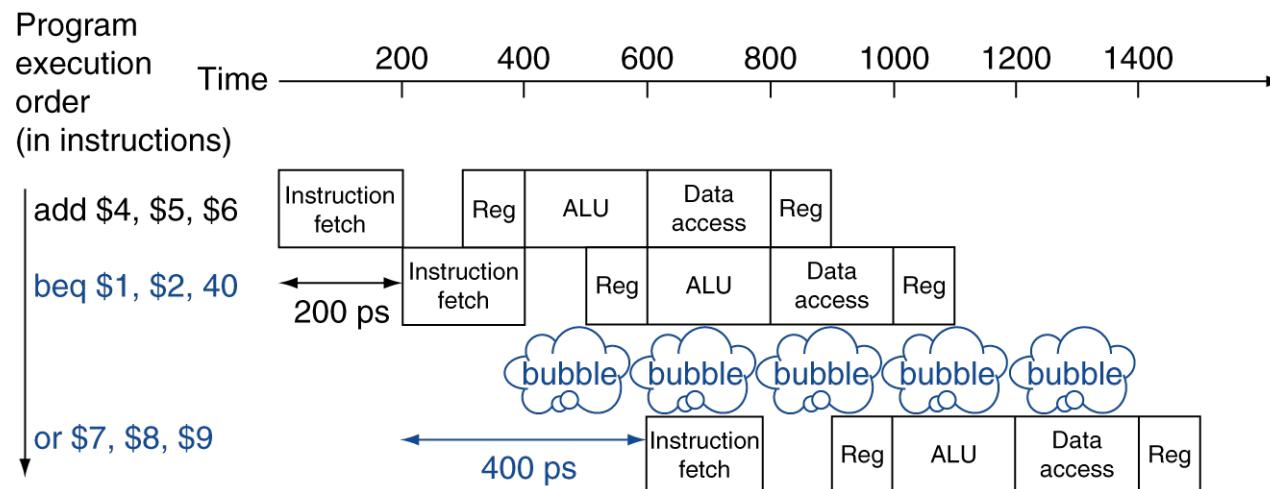


# Control Hazards

- Branch determines flow of control
  - Fetching next instruction depends on branch outcome
  - Pipeline can't always fetch correct instruction
    - Still working on ID stage of branch
- In MIPS pipeline
  - Need to compare registers and compute target early in the pipeline
  - Add hardware to do it in ID stage

# Stall on Branch

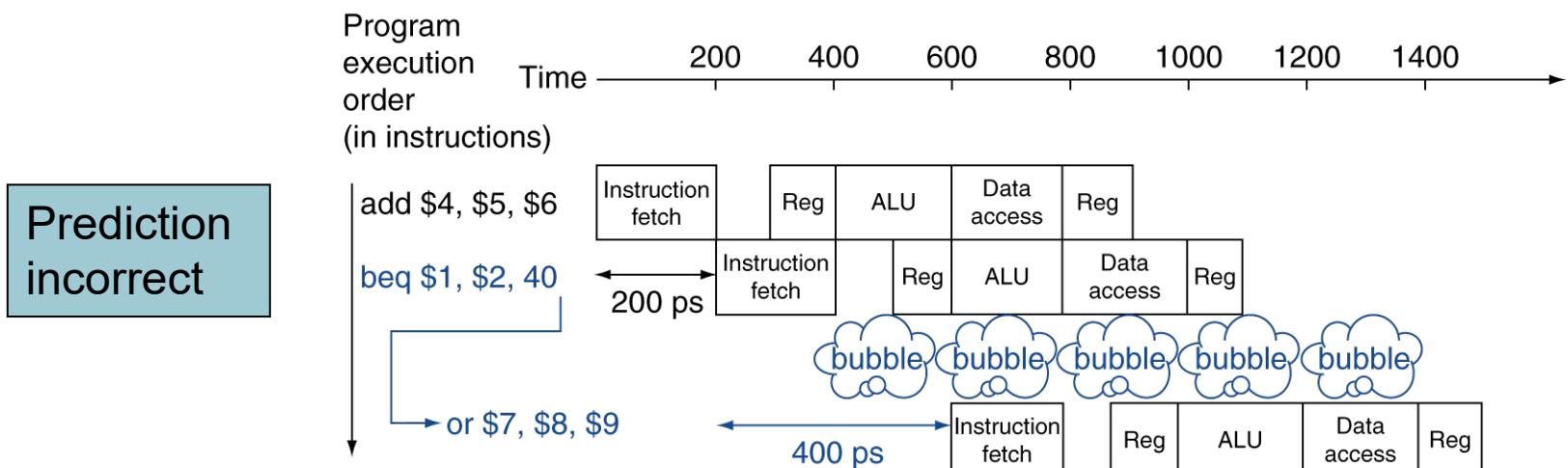
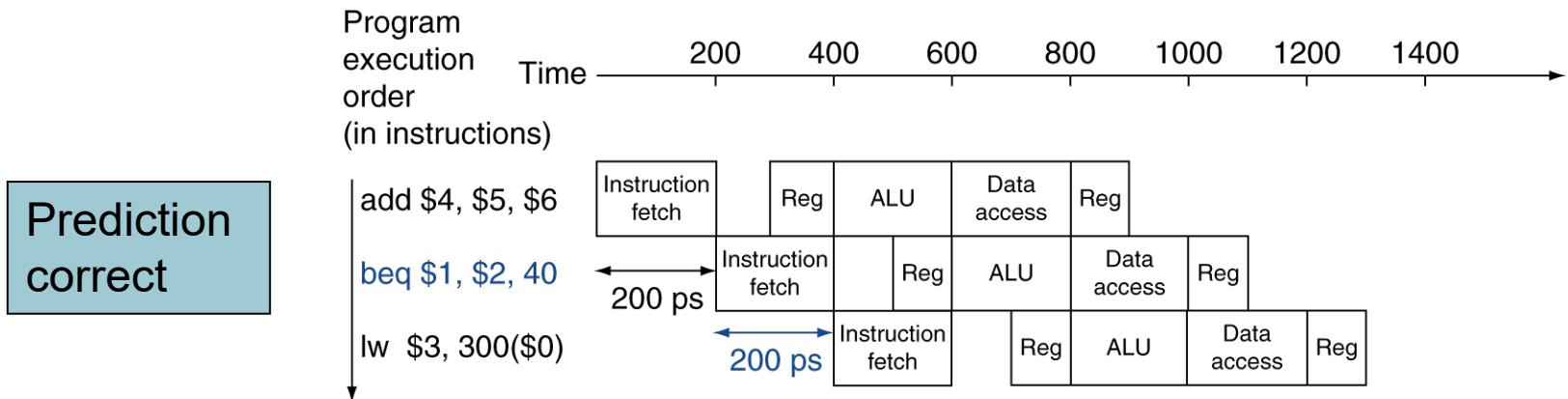
- Wait until branch outcome determined before fetching next instruction



# Branch Prediction

- Longer pipelines can't readily determine branch outcome early
  - Stall penalty becomes unacceptable
- Predict outcome of branch
  - Only stall if prediction is wrong
- In MIPS pipeline
  - Can predict branches not taken
  - Fetch instruction after branch, with no delay

# MIPS with Predict Not Taken



# More-Realistic Branch Prediction

- Static branch prediction
  - Based on typical branch behavior
  - Example: loop and if-statement branches
    - Predict backward branches taken
    - Predict forward branches not taken
- Dynamic branch prediction
  - Hardware measures actual branch behavior
    - e.g., record recent history of each branch
  - Assume future behavior will continue the trend
    - When wrong, stall while re-fetching, and update history

# Pipeline Summary

## The BIG Picture

- Pipelining improves performance by increasing instruction throughput
  - Executes multiple instructions in parallel
  - Each instruction has the same latency
- Subject to hazards
  - Structure, data, control
- Instruction set design affects complexity of pipeline implementation

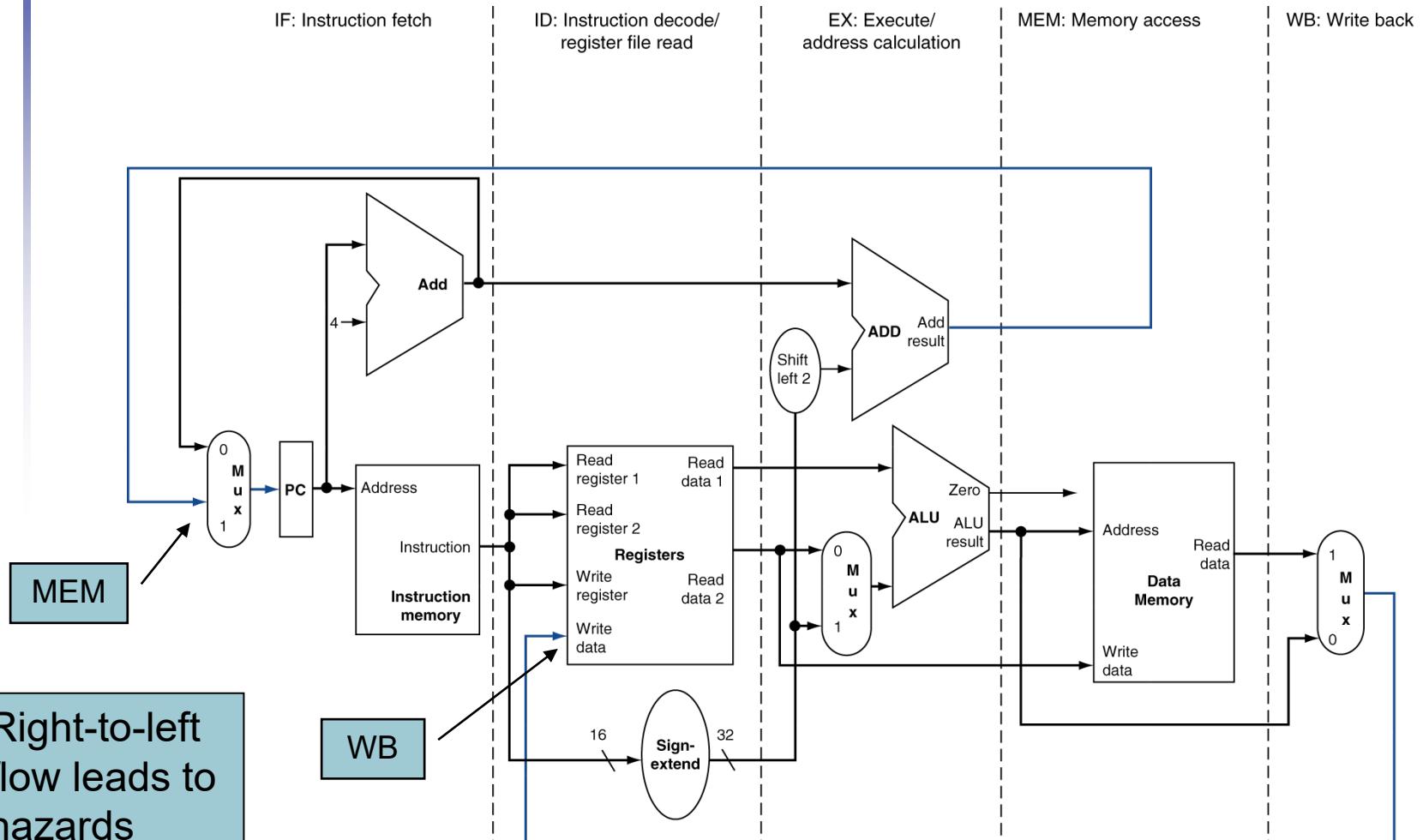
# Pipeline Summary

对下面每个指令序列，说明哪个必须阻塞，哪个只使用旁路就可以避免阻塞，而哪个既不需要阻塞也不需要旁路就可以执行。

指令序列 1	指令序列 2	指令序列 3
lw \$t0,0(\$t0) add \$t1,\$t0;\$t0	add \$t1,\$t0,\$t0 addi \$t2,\$t0,#5 addi \$t4,\$t1,#5	addi \$t1,\$t0,#1 addi \$t2,\$t0,#2 addi \$t3,\$t0,#2 addi \$t3,\$t0,#4 addi \$t5,\$t0,#5

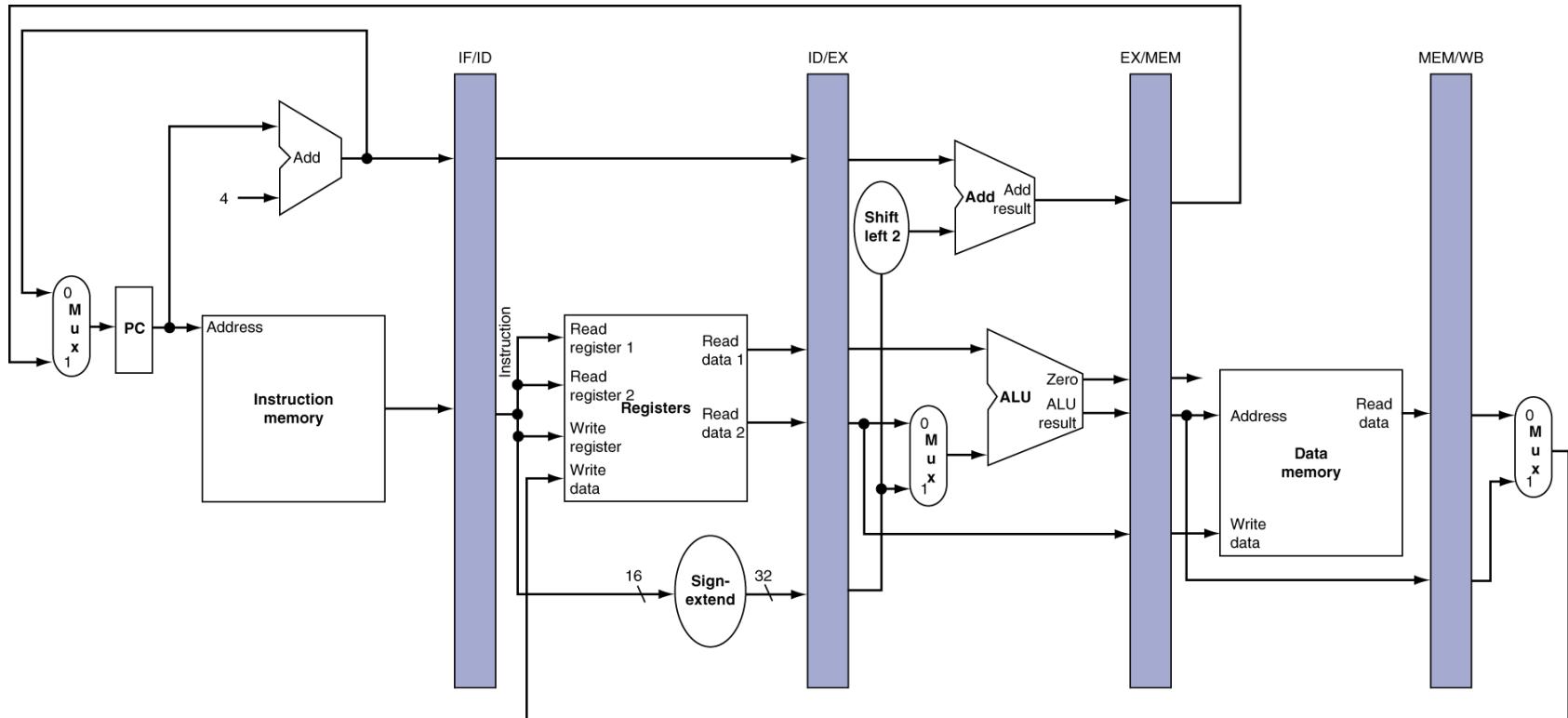


# MIPS Pipelined Datapath



# Pipeline registers

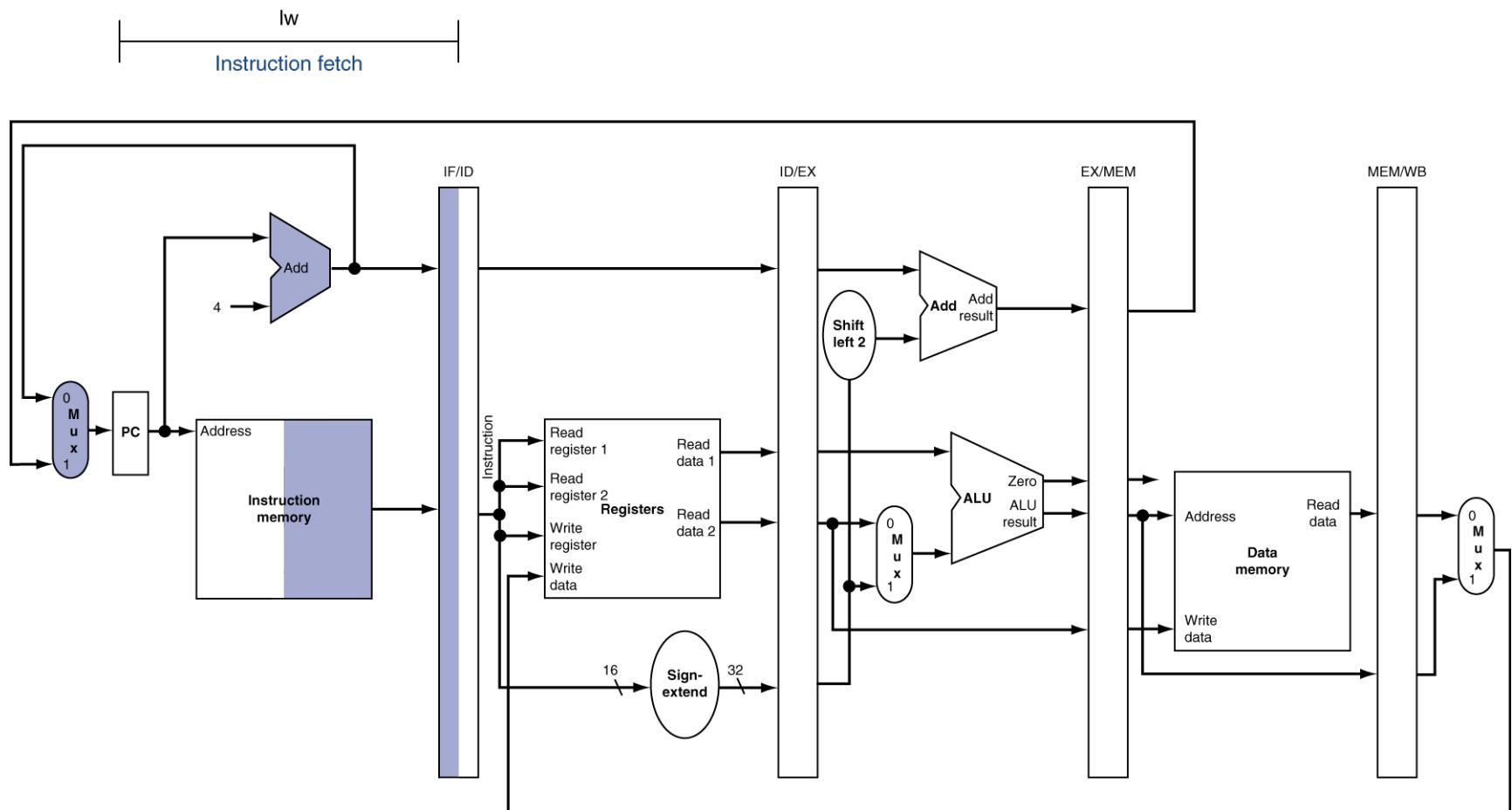
- Need registers between stages
  - To hold information produced in previous cycle



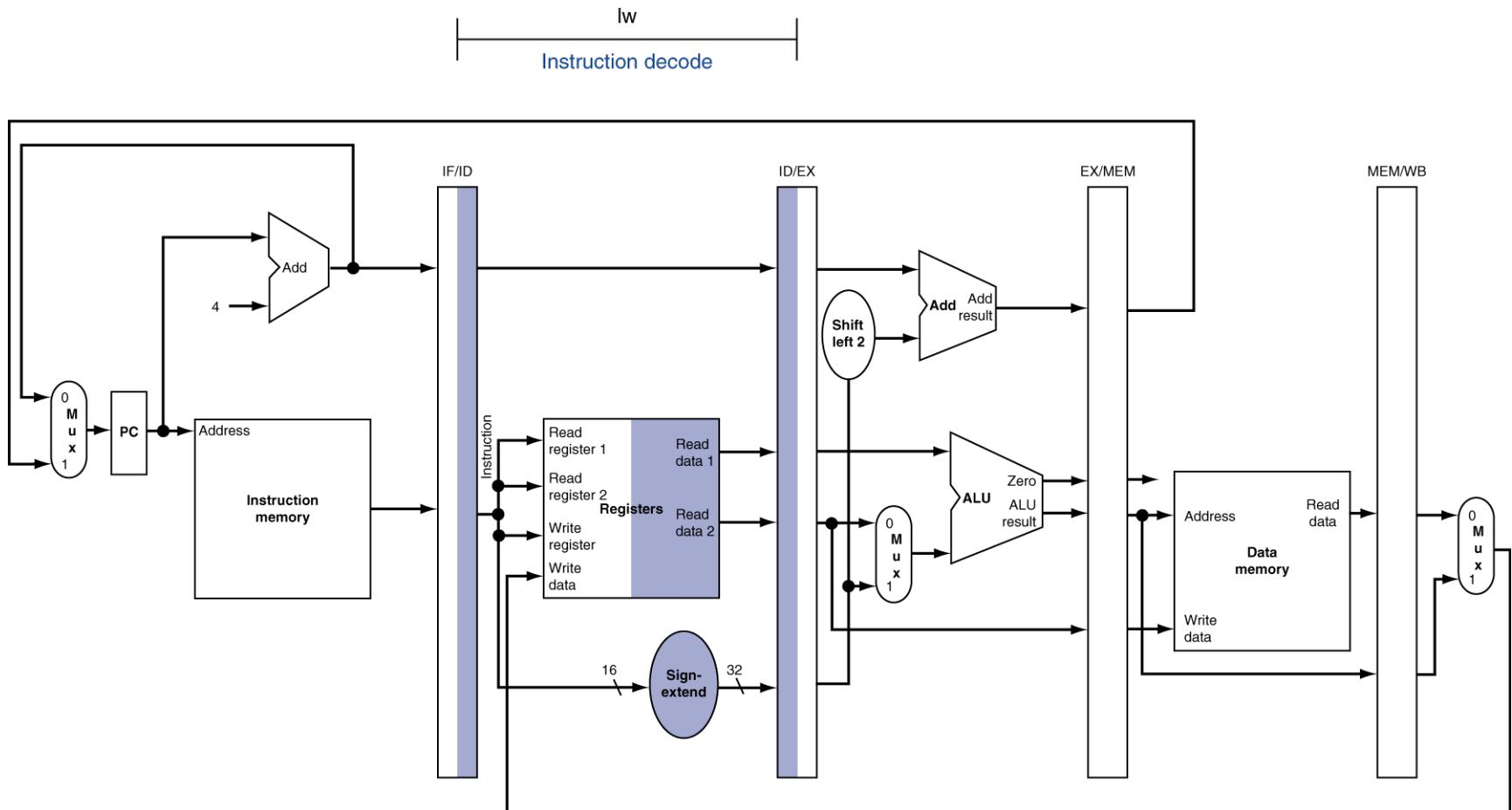
# Pipeline Operation

- Cycle-by-cycle flow of instructions through the pipelined datapath
  - “Single-clock-cycle” pipeline diagram
    - Shows pipeline usage in a single cycle
    - Highlight resources used
  - c.f. “multi-clock-cycle” diagram
    - Graph of operation over time
- We'll look at “single-clock-cycle” diagrams for load & store

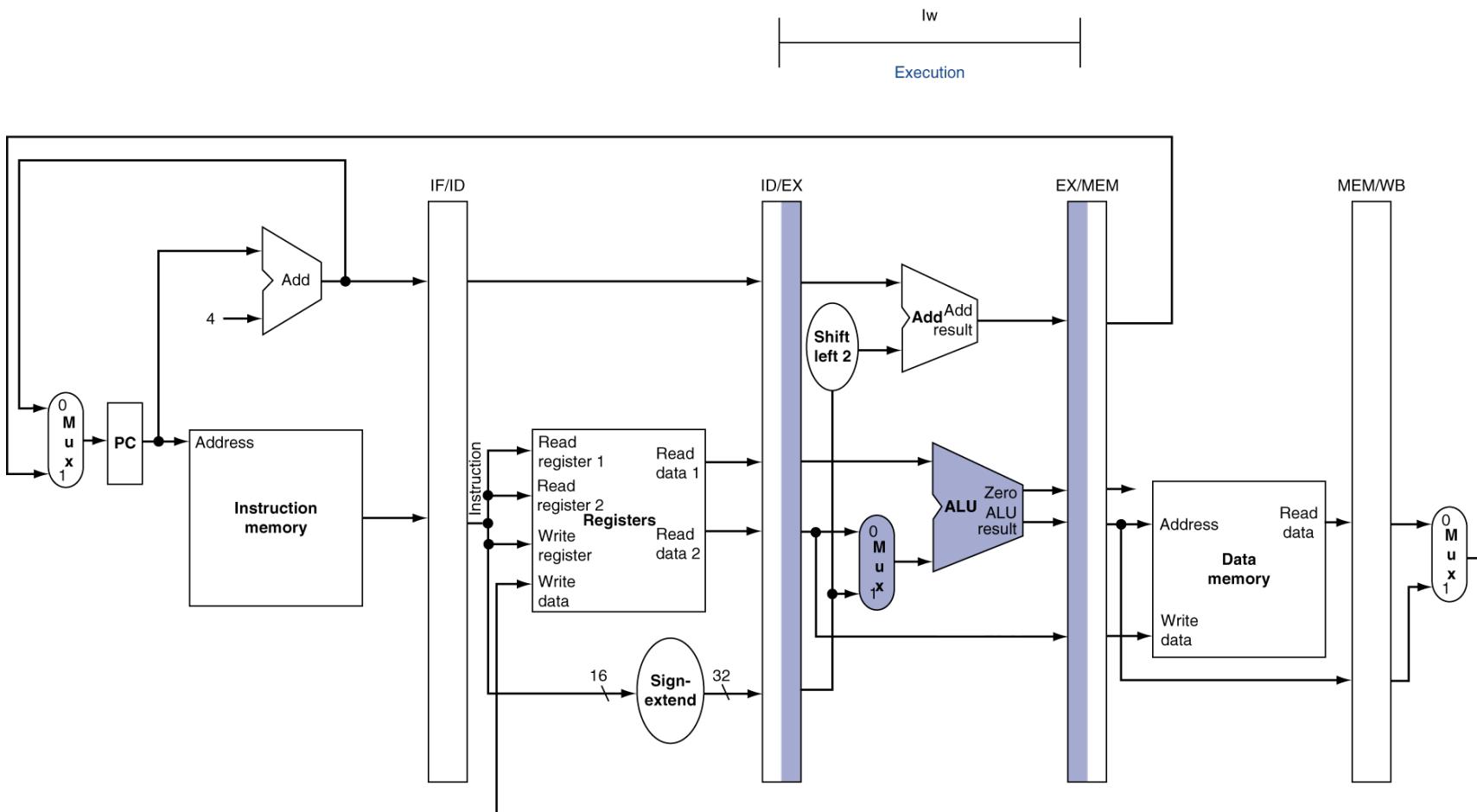
# IF for Load, Store, ...



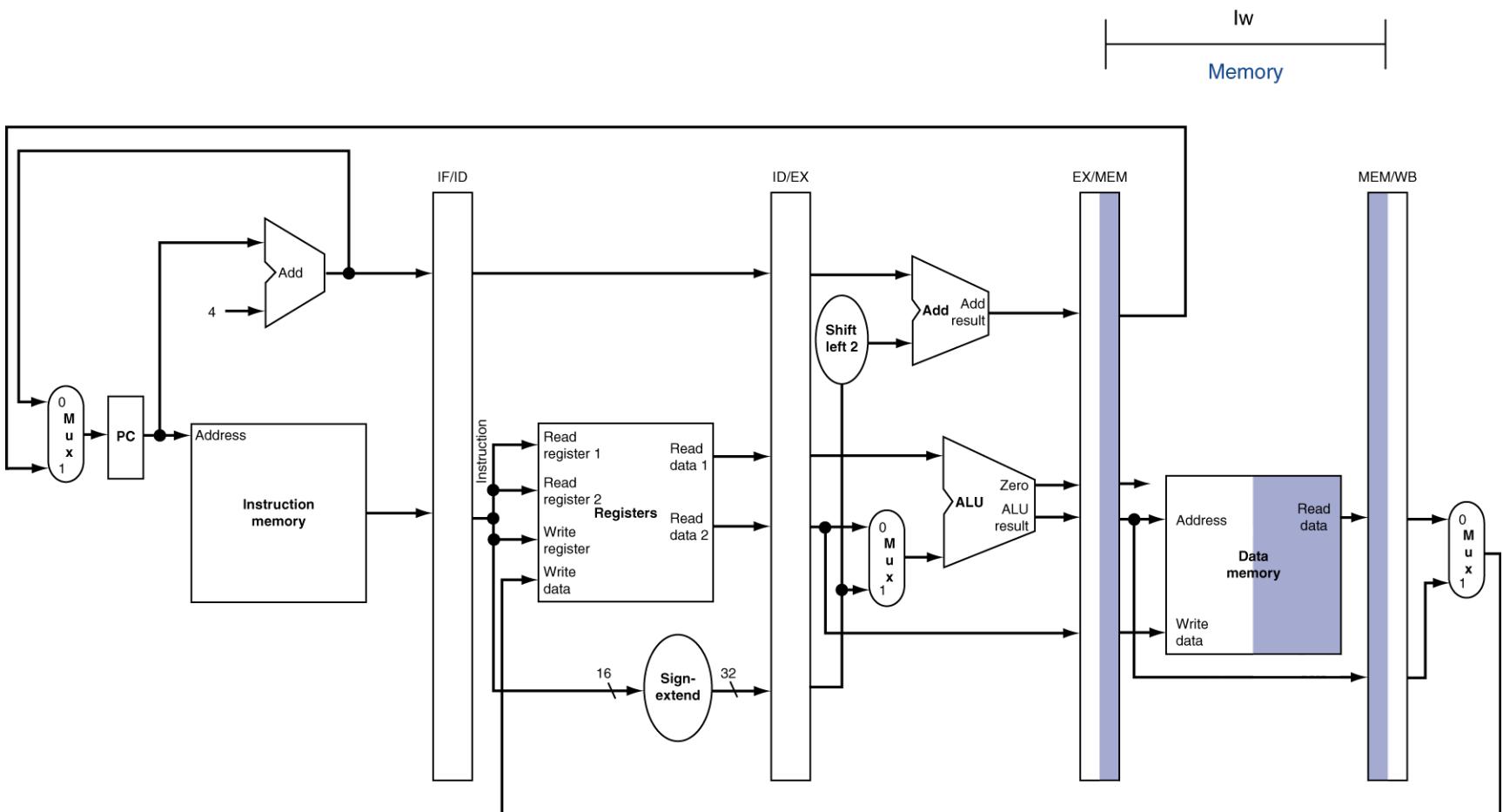
# ID for Load, Store, ...



# EX for Load

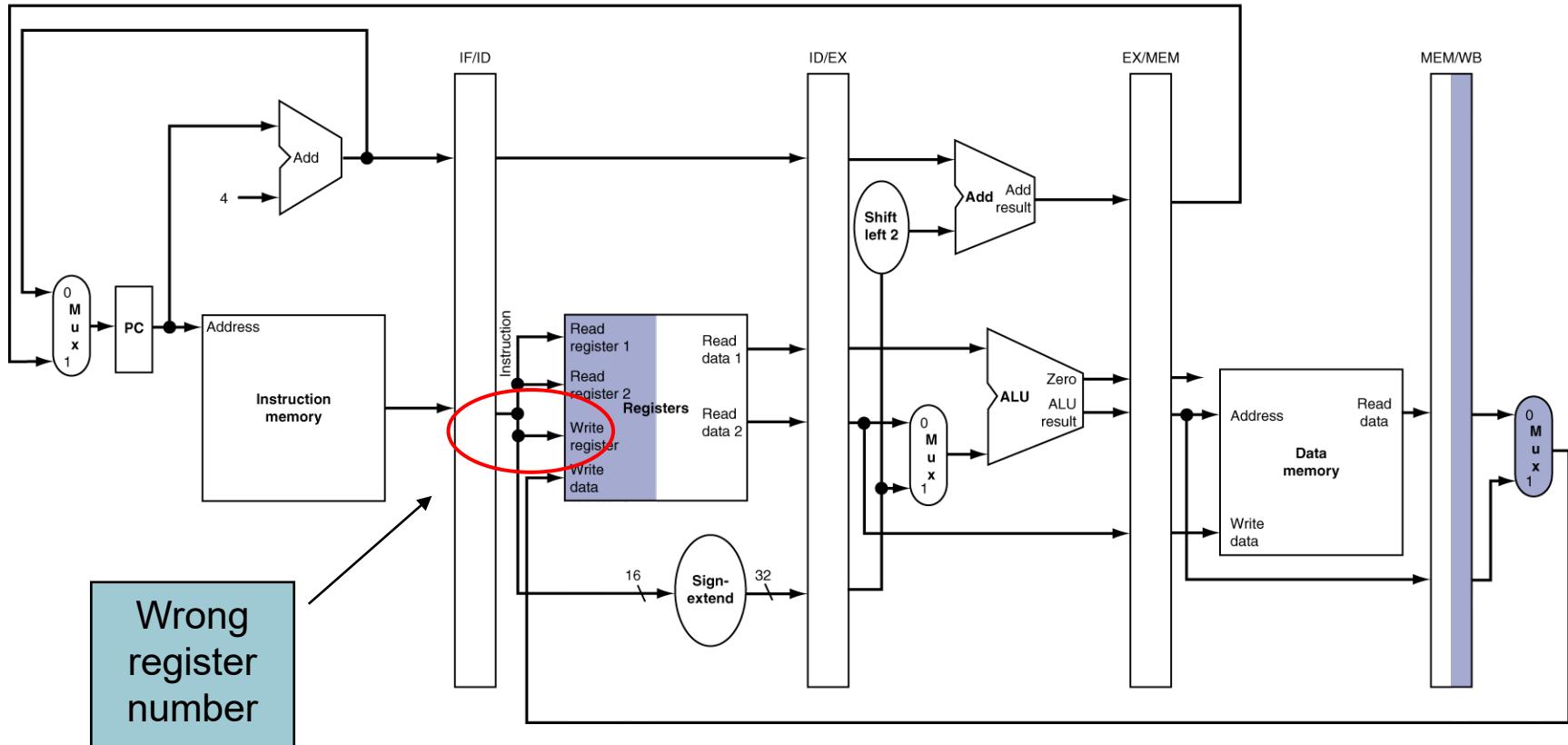


# MEM for Load

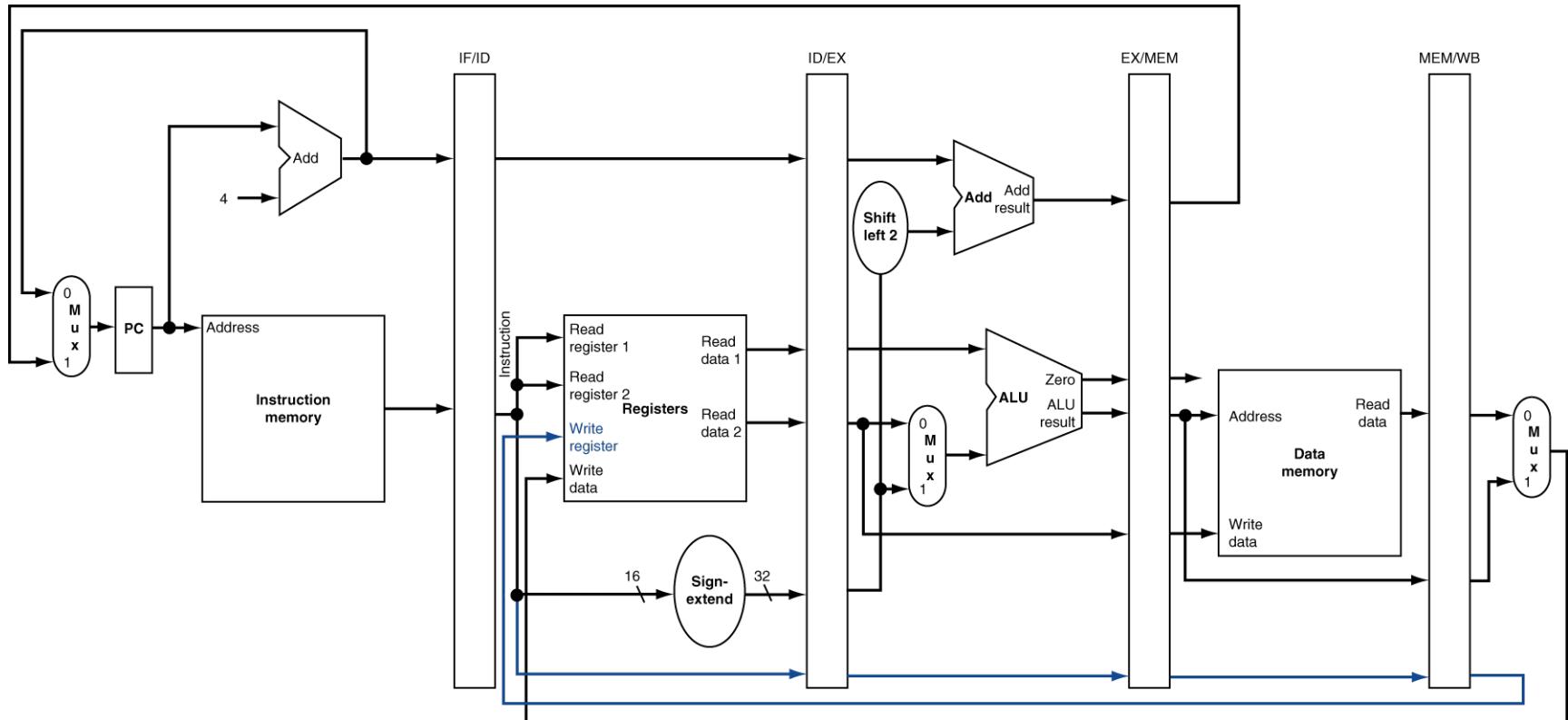


# WB for Load

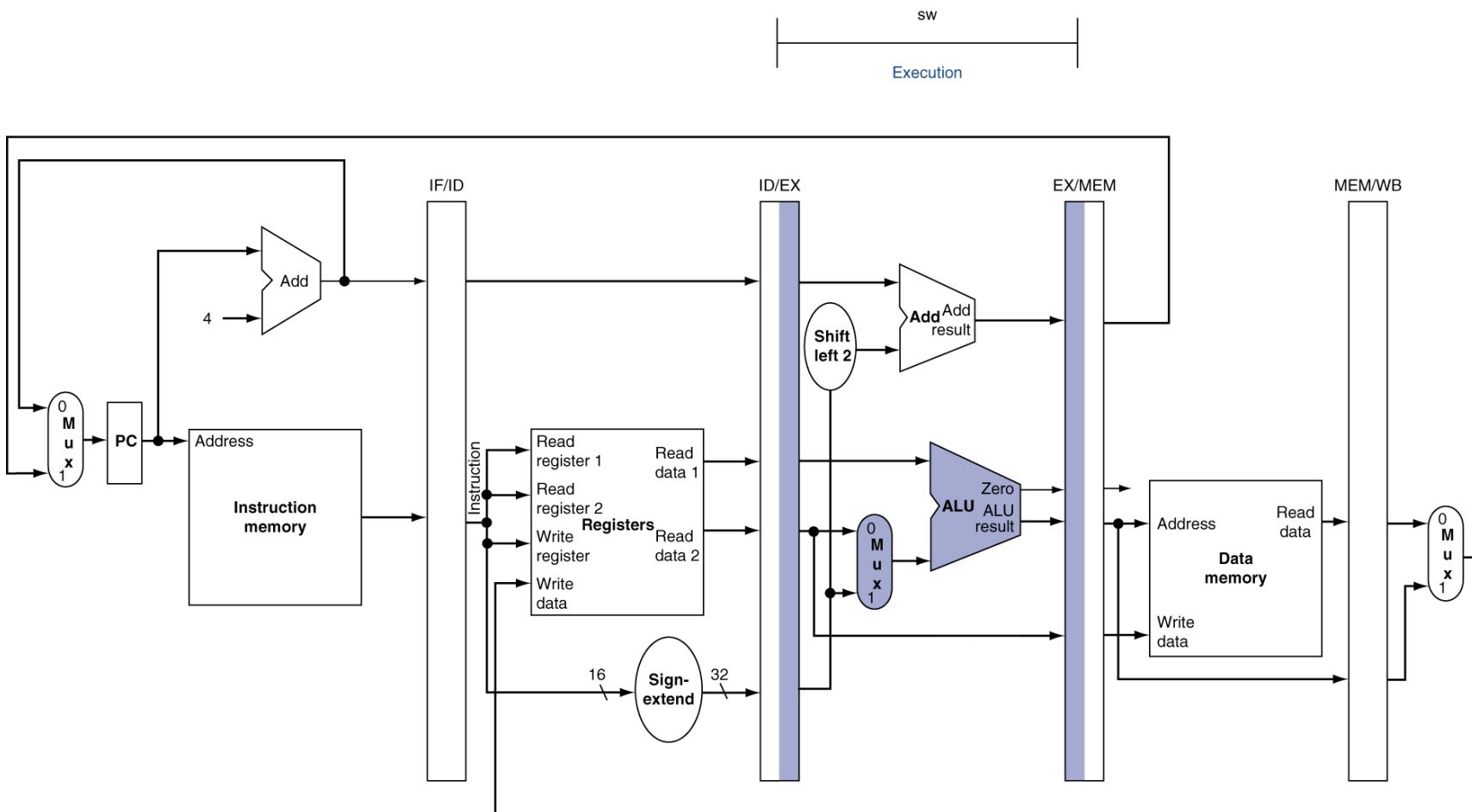
lw  
Write back



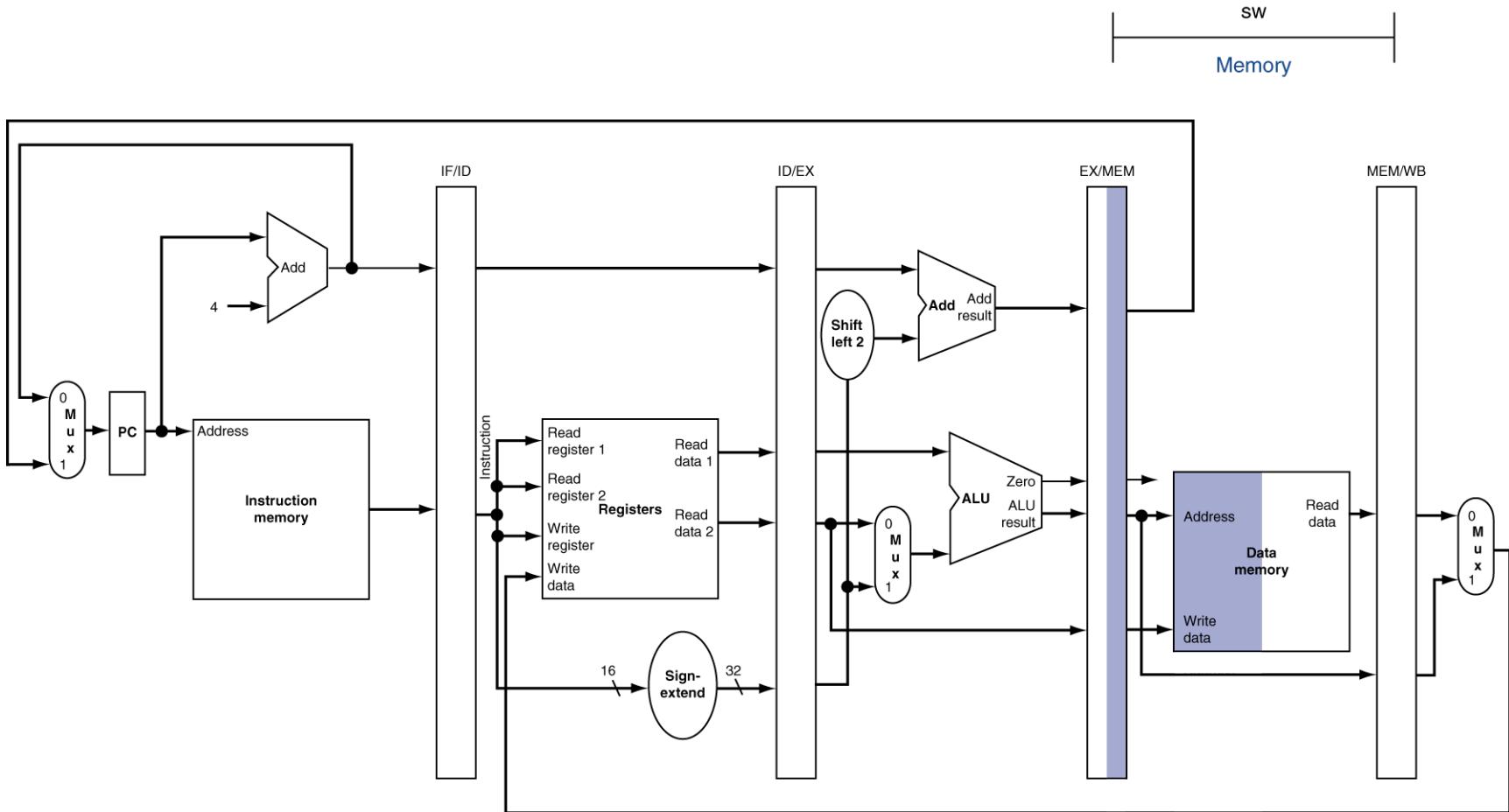
# Corrected Datapath for Load



# EX for Store

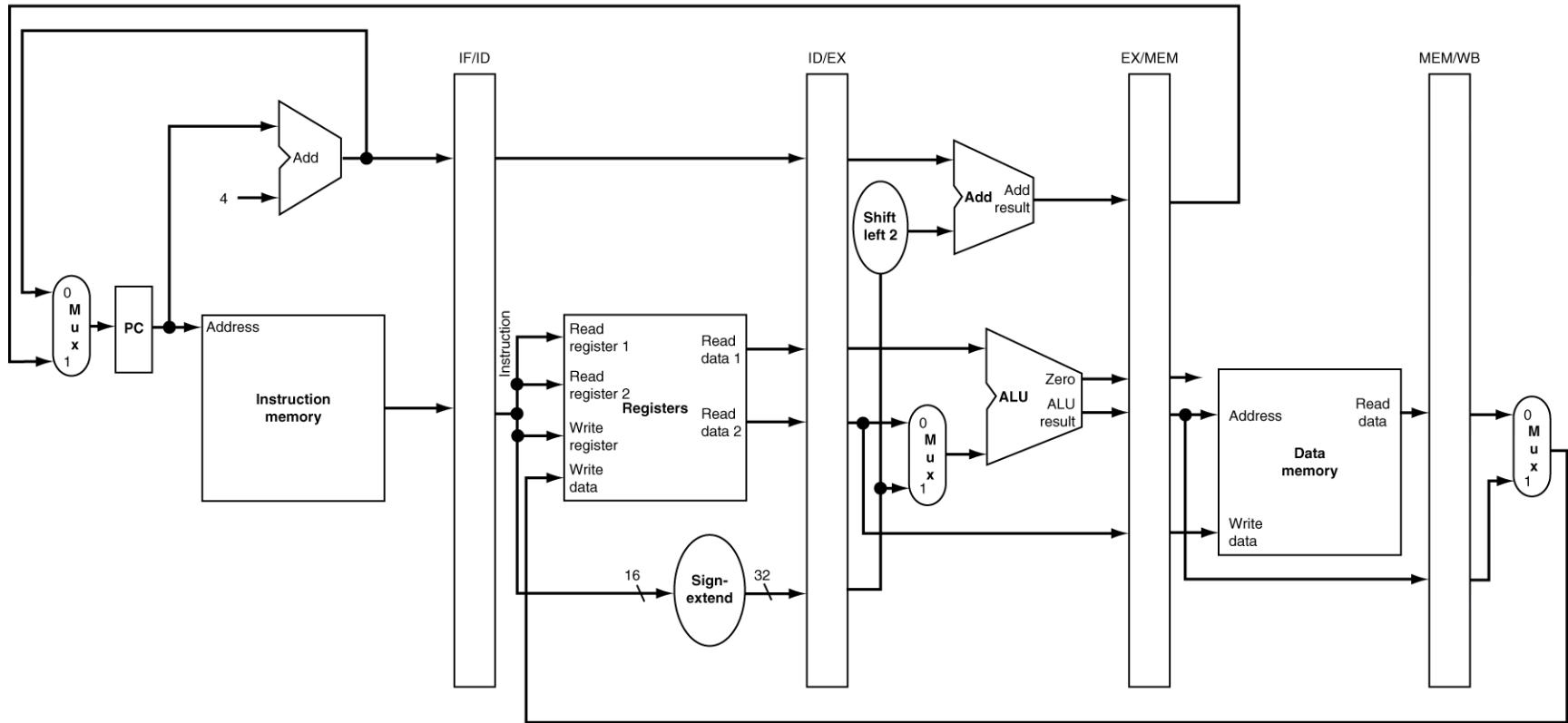


# MEM for Store



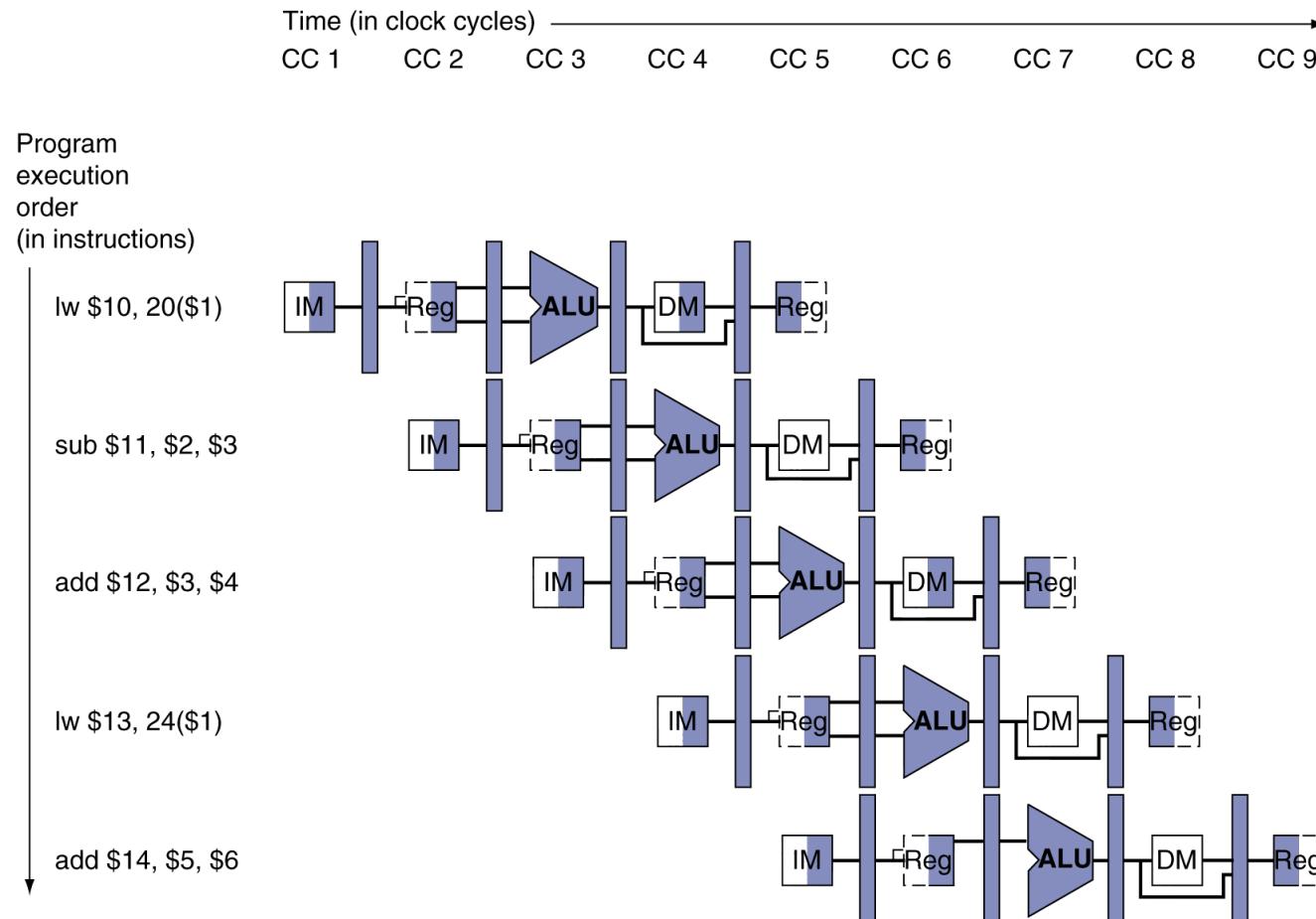
# WB for Store

SW  
Write-back



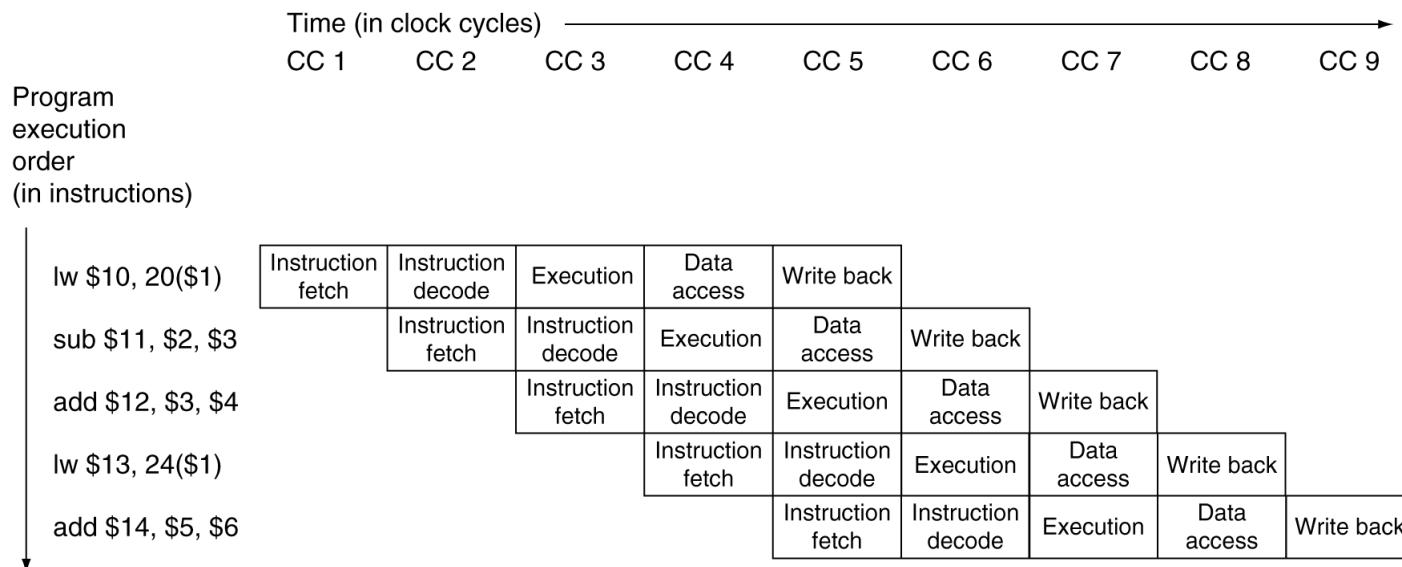
# Multi-Cycle Pipeline Diagram

- Form showing resource usage



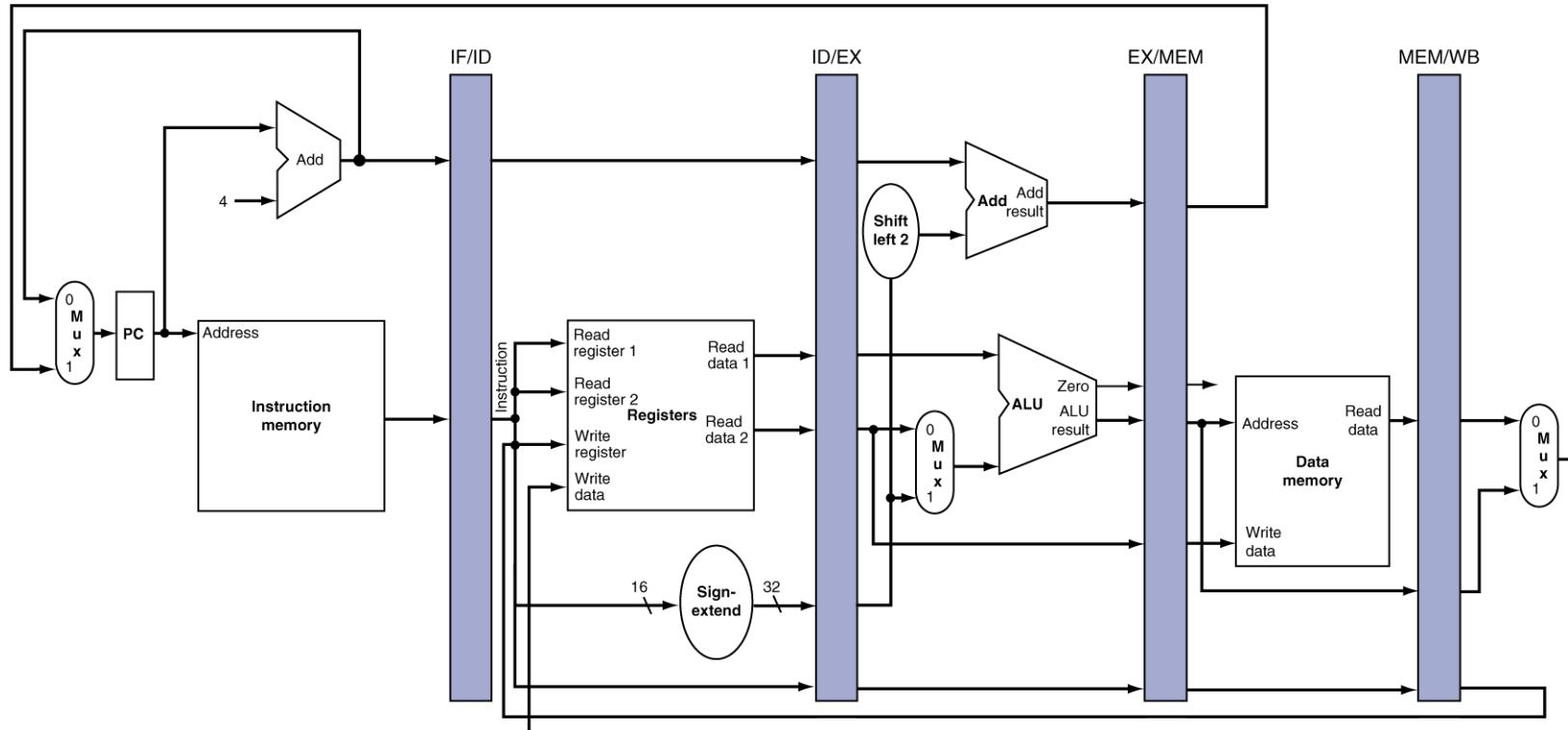
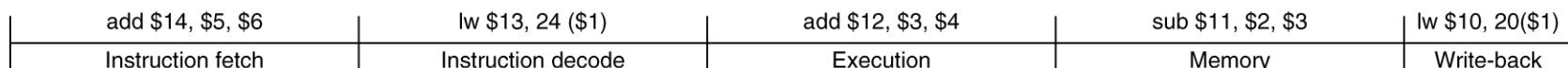
# Multi-Cycle Pipeline Diagram

## Traditional form

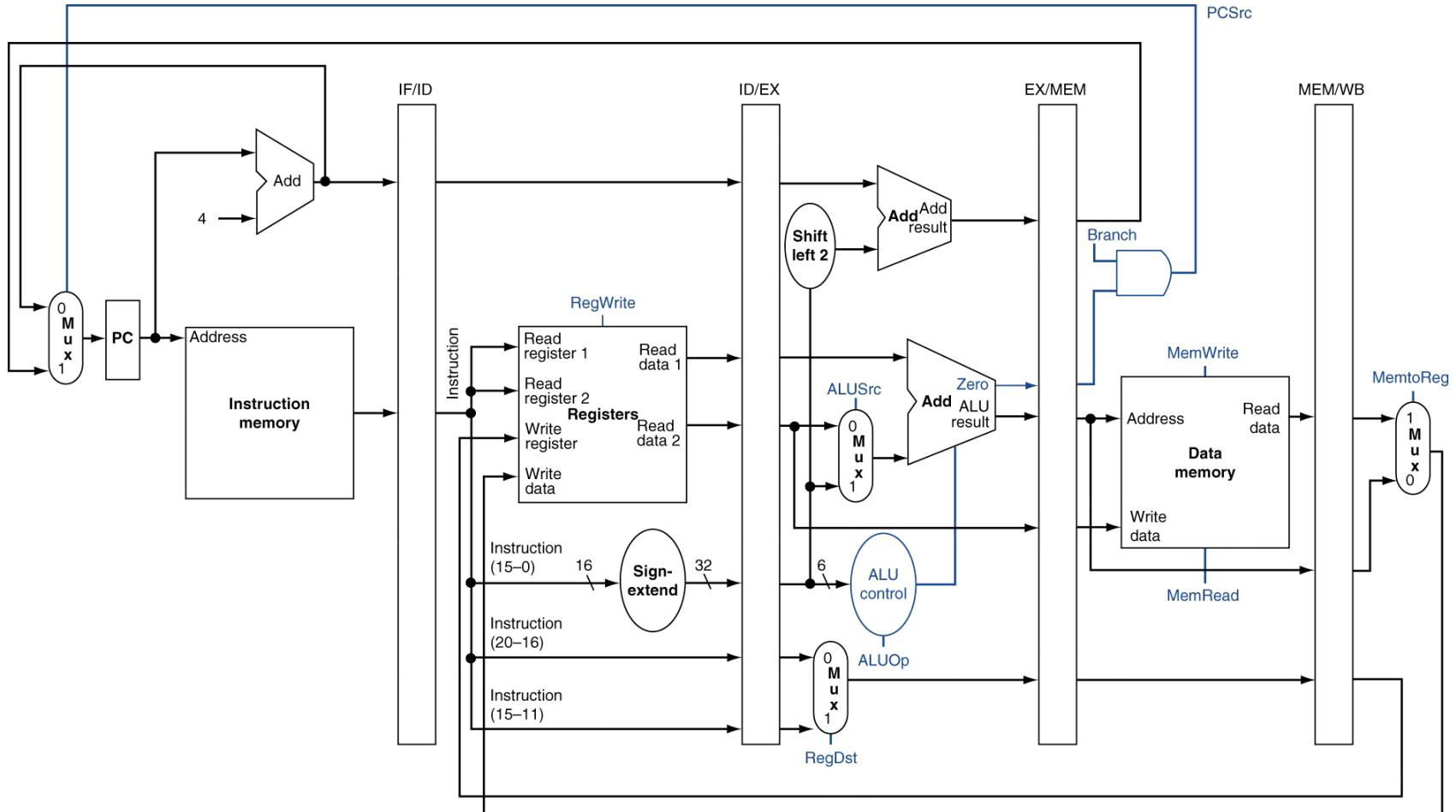


# Single-Cycle Pipeline Diagram

## State of pipeline in a given cycle (5)



# Pipelined Control (Simplified)



# Pipelined Control (Simplified)

指令操作码	ALUOp	指令操作	功能码	ALU 操作	ALU 控制信号
LW	00	取字	XXXXXX	加	0010
SW	00	存字	XXXXXX	加	0010
相等则分支	01	相等则分支	XXXXXX	减	0110
R 型	10	加	100000	加	0010
R 型	10	减	100010	减	0110
R 型	10	与	100100	与	0000
R 型	10	或	100101	或	0001
D 型	10	小于则置位	101010	小于则置位	0111
信号名	置无效时的效果 (0)			置有效时的效果 (1)	

RegDst	写入寄存器的目标号来自 rt 字段 (20:16 位)	写入寄存器的目标号来自 rd 字段 (15:11 位)
RegWrite	无	写入寄存器的源寄存器设置为输入的写入数据
ALUSrc	第二个 ALU 操作数来自第二个寄存器堆的输出 (读数据 2)	第二个 ALU 操作数是指令低 16 位的符号扩展
PCSrc	PC 被 PC + 4 替代	PC 被分支目标地址替代
MemRead	无	输入地址对应的数据存储器的内容为读数据的输出
		输入地址对应的数据存储器的内容替换为写数据

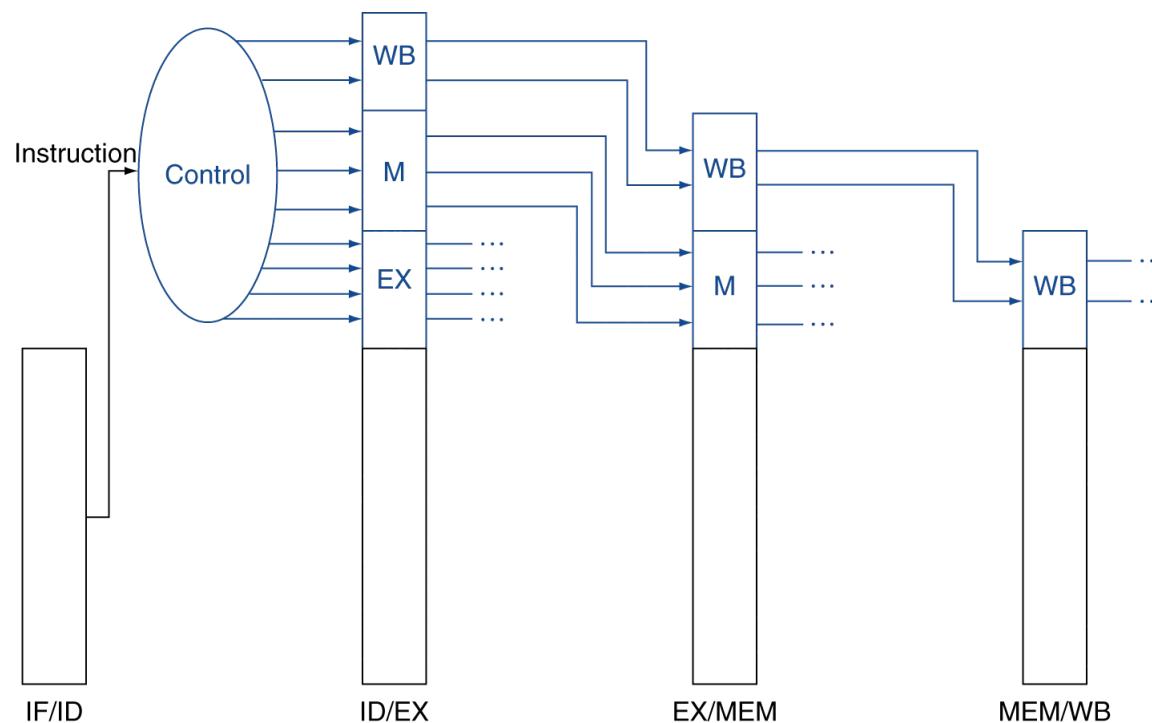
指令	执行/地址计算阶段的控制信号				存储器存取阶段的控制信号			写回阶段的控制信号	
	RegDst	ALUOp1	ALUOp0	ALUSrc	Branch	MemRead	MemWrite	RegWrite	MemtoReg

R 型	1	1	0	0	0	0	0	1	0
lw	0	0	0	1	0	1	0	1	1
sw	X	0	0	1	0	0	1	0	X
beq	X	0	1	0	1	0	0	0	X

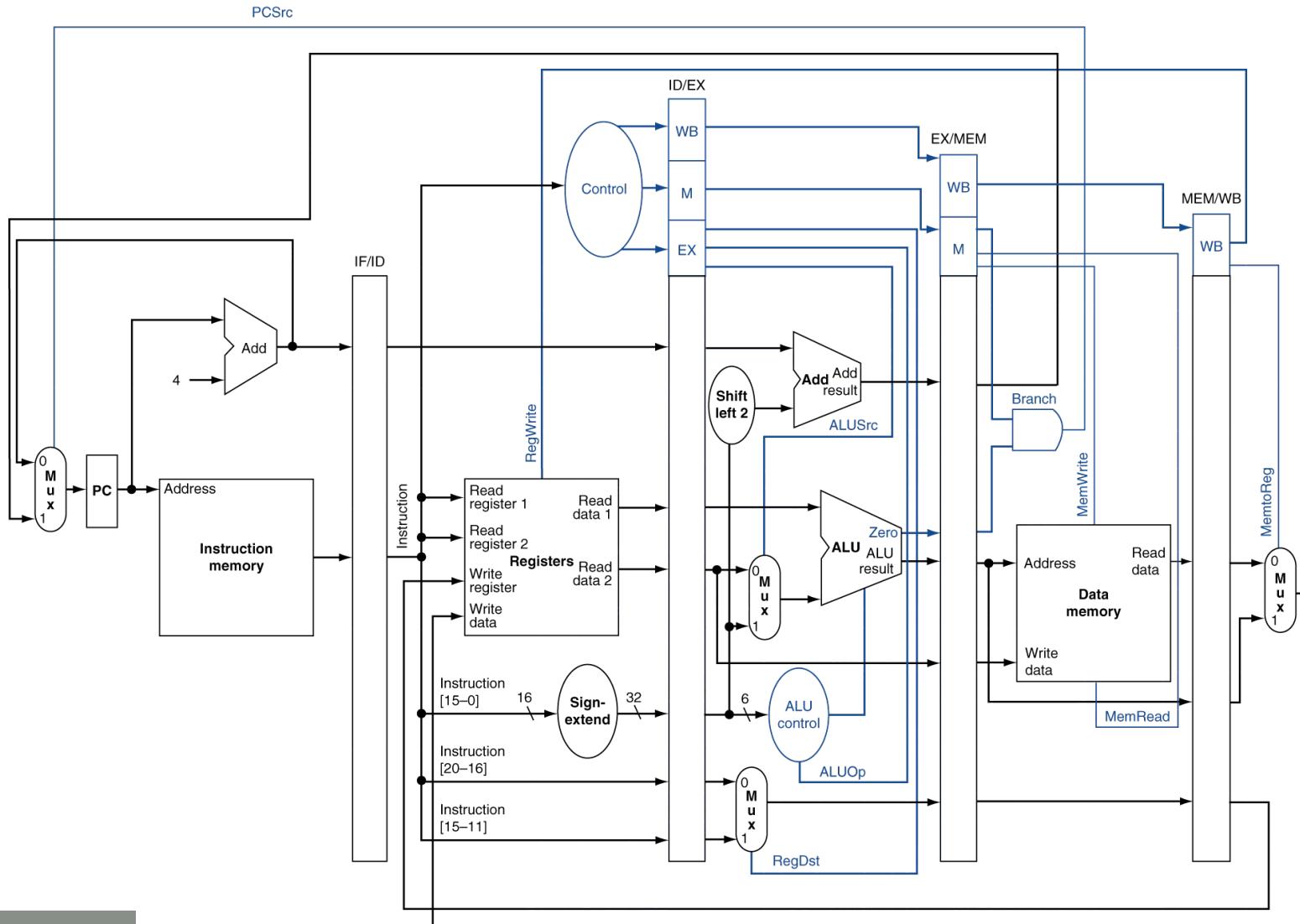


# Pipelined Control

- Control signals derived from instruction
  - As in single-cycle implementation



# Pipelined Control



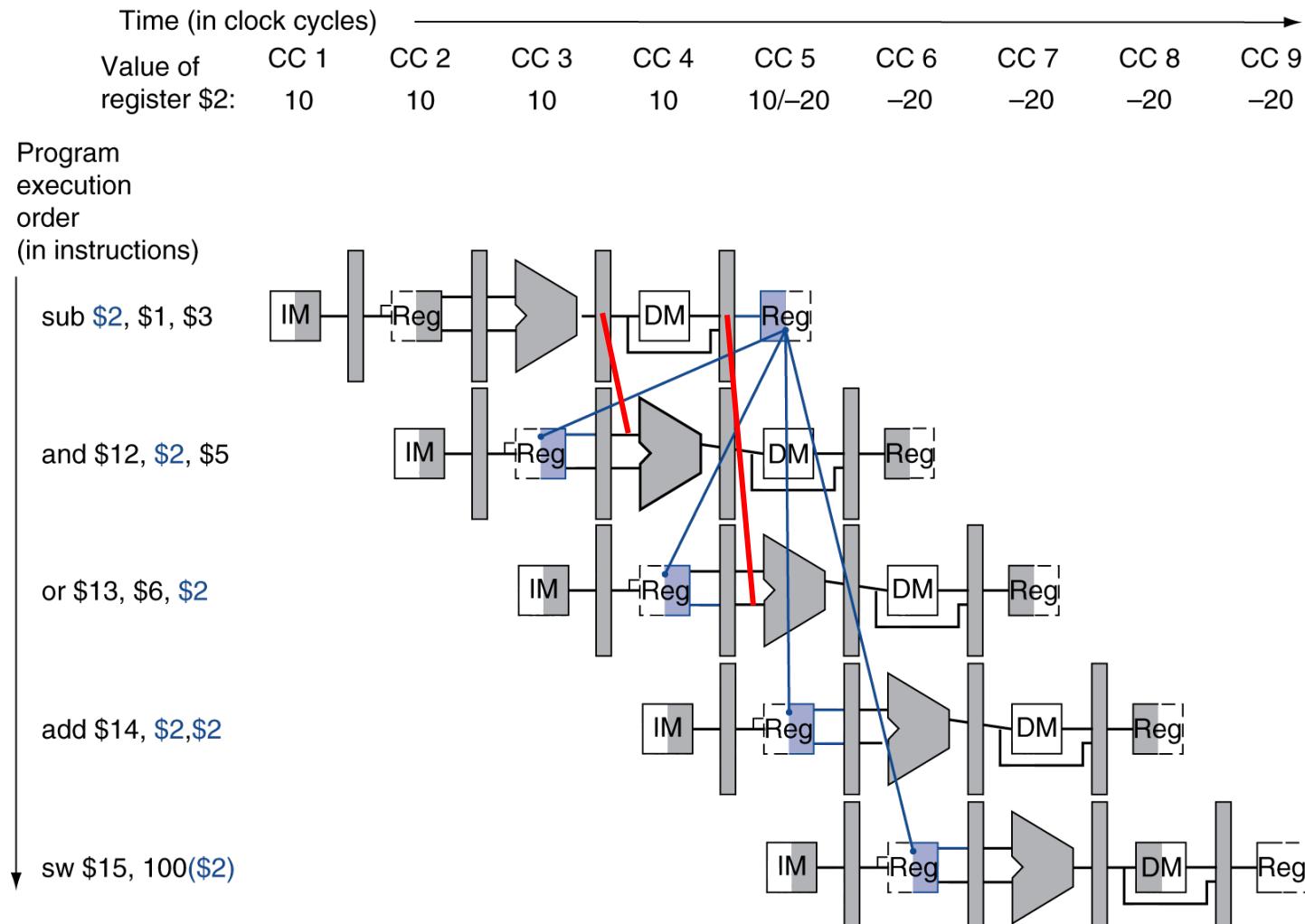
# Data Hazards in ALU Instructions

- Consider this sequence:

```
sub $2, $1, $3  
and $12, $2, $5  
or $13, $6, $2  
add $14, $2, $2  
sw $15, 100($2)
```

- We can resolve hazards with forwarding
  - How do we detect when to forward?

# Dependencies & Forwarding



# Detecting the Need to Forward

- Pass register numbers along pipeline
  - e.g., ID/EX.RegisterRs = register number for Rs sitting in ID/EX pipeline register
- ALU operand register numbers in EX stage are given by
  - ID/EX.RegisterRs, ID/EX.RegisterRt
- Data hazards when
  - 1a. EX/MEM.RegisterRd = ID/EX.RegisterRs
  - 1b. EX/MEM.RegisterRd = ID/EX.RegisterRt
  - 2a. MEM/WB.RegisterRd = ID/EX.RegisterRs
  - 2b. MEM/WB.RegisterRd = ID/EX.RegisterRt

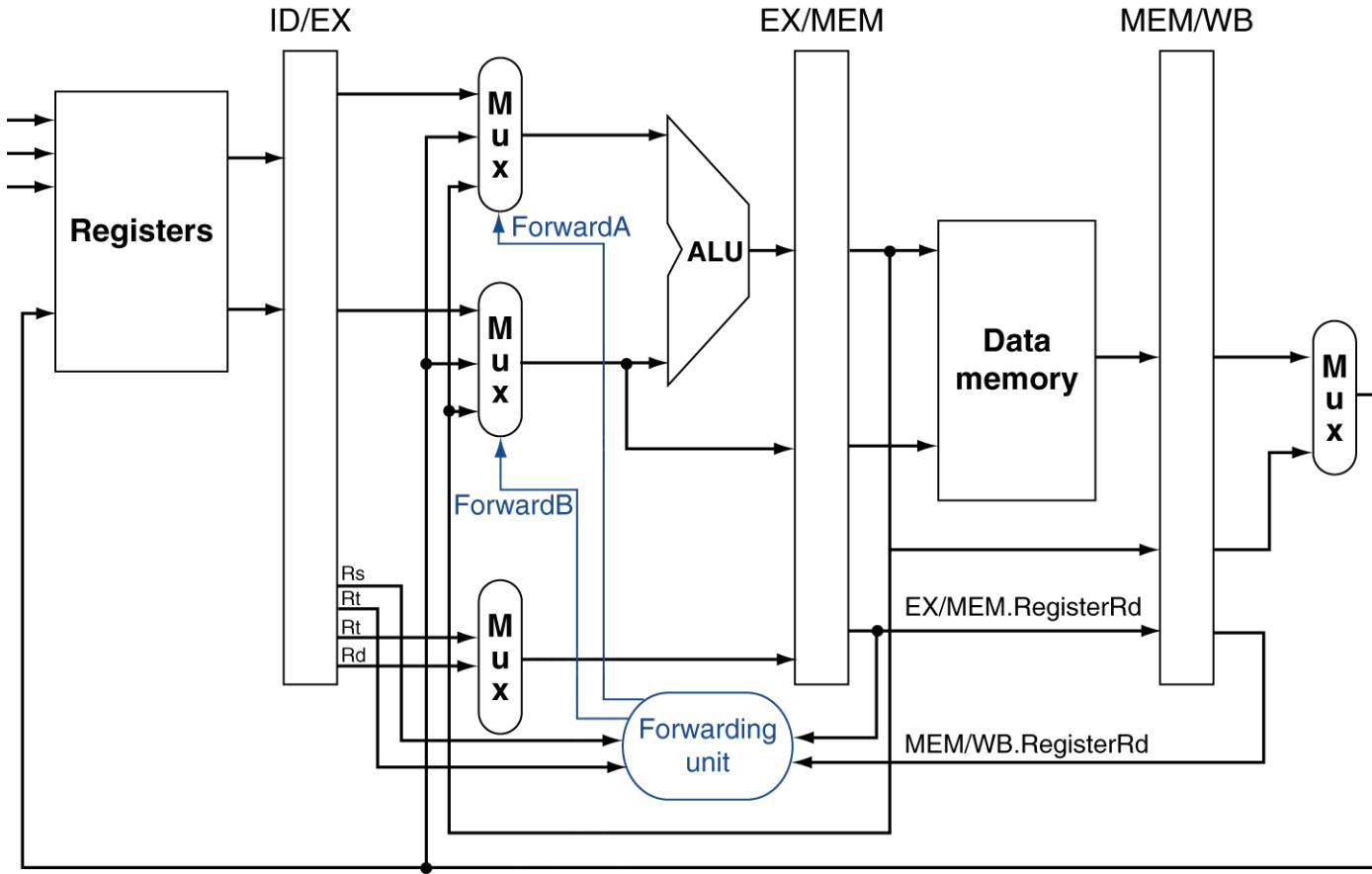
Fwd from  
EX/MEM  
pipeline reg

Fwd from  
MEM/WB  
pipeline reg

# Detecting the Need to Forward

- But only if forwarding instruction will write to a register!
  - EX/MEM.RegWrite, MEM/WB.RegWrite
- And only if Rd for that instruction is not \$zero
  - EX/MEM.RegisterRd  $\neq$  0,  
MEM/WB.RegisterRd  $\neq$  0

# Forwarding Paths



b. With forwarding

# Forwarding Conditions

- EX hazard
  - if (EX/MEM.RegWrite and (EX/MEM.RegisterRd ≠ 0)  
and (EX/MEM.RegisterRd = ID/EX.RegisterRs))  
*ForwardA = 10*
  - if (EX/MEM.RegWrite and (EX/MEM.RegisterRd ≠ 0)  
and (EX/MEM.RegisterRd = ID/EX.RegisterRt))  
*ForwardB = 10*
- MEM hazard
  - if (MEM/WB.RegWrite and (MEM/WB.RegisterRd ≠ 0)  
and (MEM/WB.RegisterRd = ID/EX.RegisterRs))  
*ForwardA = 01*
  - if (MEM/WB.RegWrite and (MEM/WB.RegisterRd ≠ 0)  
and (MEM/WB.RegisterRd = ID/EX.RegisterRt))  
*ForwardB = 01*



# Double Data Hazard

- Consider the sequence:

add \$1, \$1, \$2

add \$1, \$1, \$3

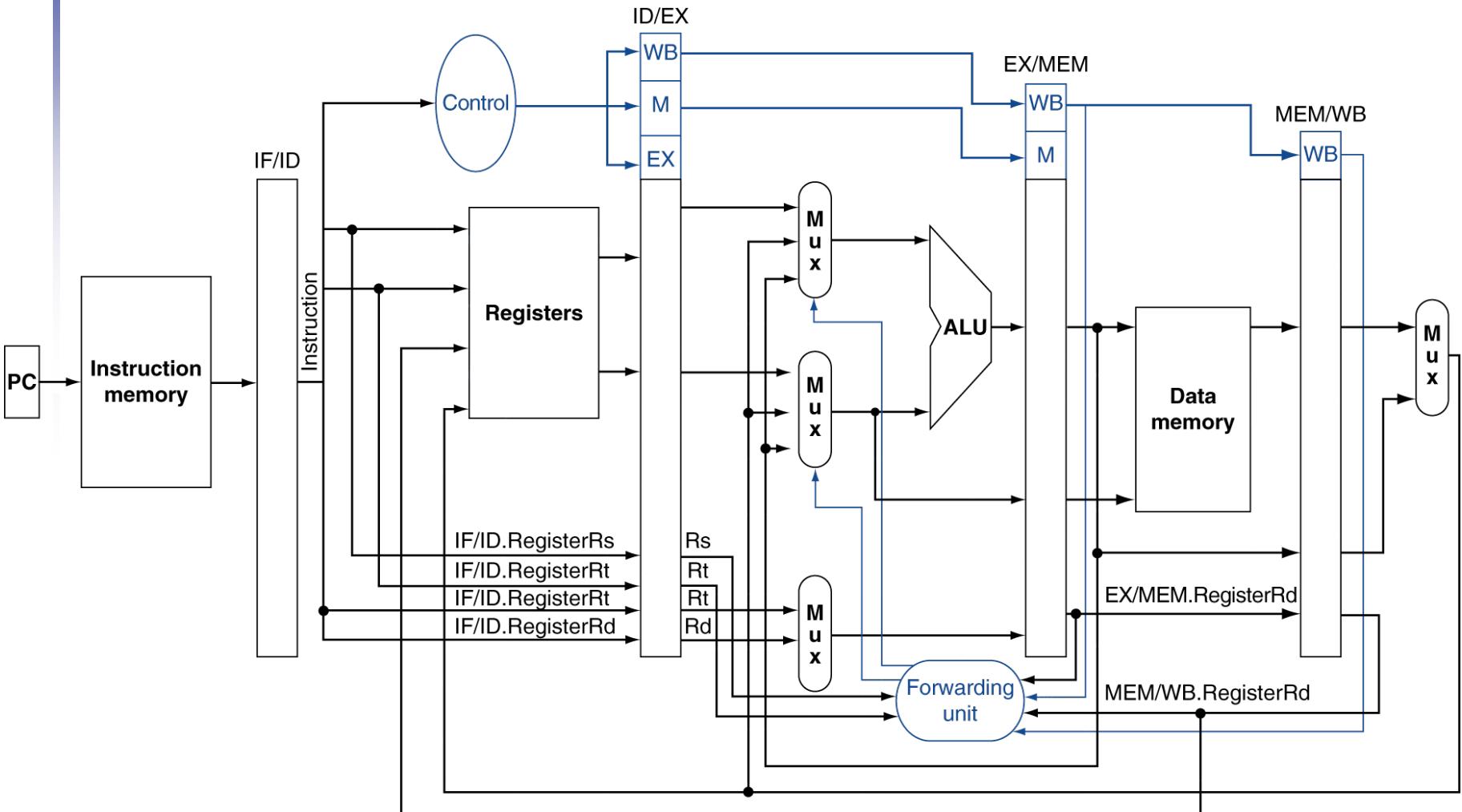
add \$1, \$1, \$4

- Both hazards occur
  - Want to use the most recent
- Revise MEM hazard condition
  - Only fwd if EX hazard condition isn't true

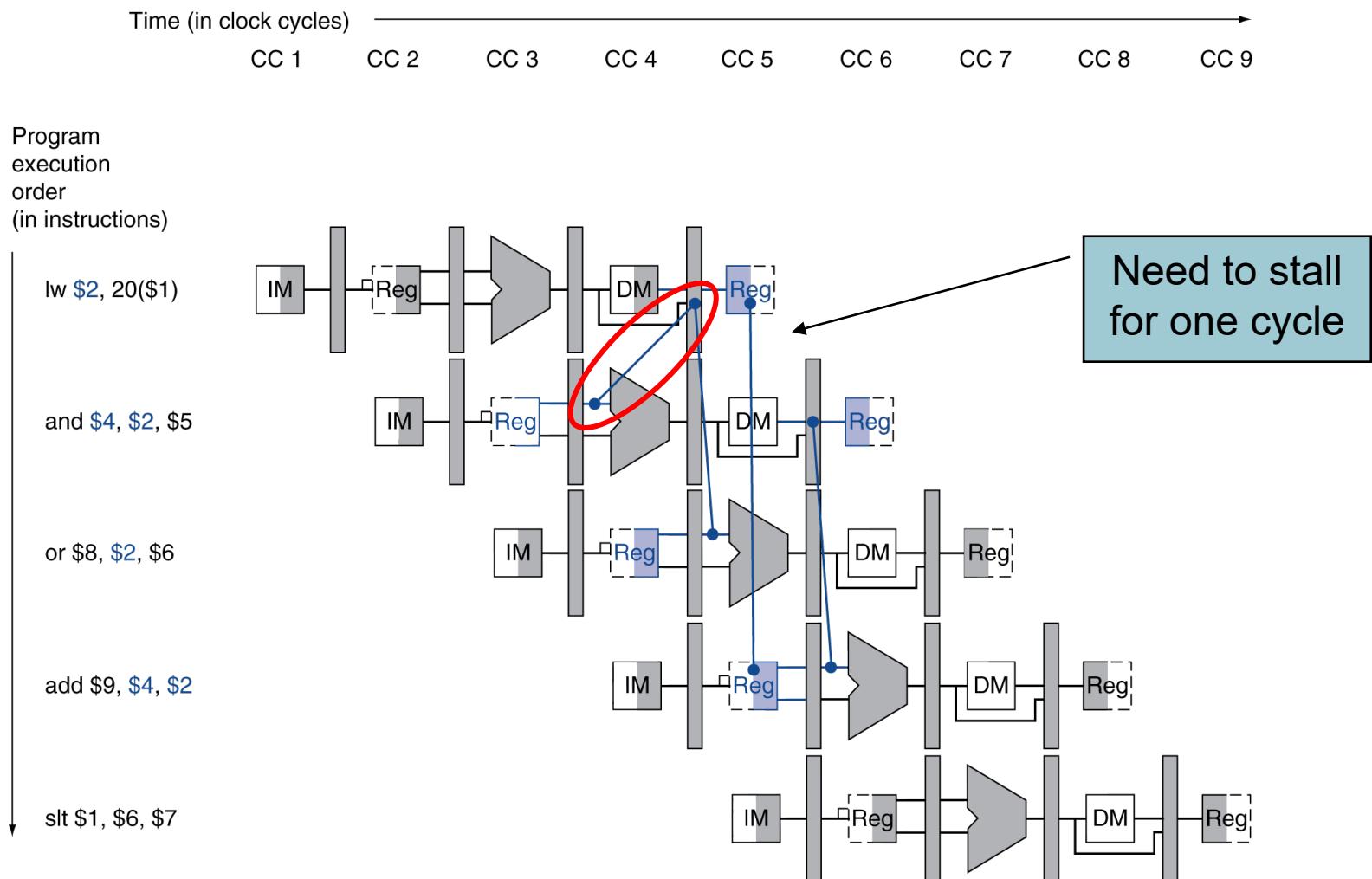
# Revised Forwarding Condition

- MEM hazard
  - if (MEM/WB.RegWrite and (MEM/WB.RegisterRd ≠ 0)  
and not (EX/MEM.RegWrite and (EX/MEM.RegisterRd ≠ 0)  
and (EX/MEM.RegisterRd = ID/EX.RegisterRs))  
and (MEM/WB.RegisterRd = ID/EX.RegisterRs))  
ForwardA = 01
  - if (MEM/WB.RegWrite and (MEM/WB.RegisterRd ≠ 0)  
and not (EX/MEM.RegWrite and (EX/MEM.RegisterRd ≠ 0)  
and (EX/MEM.RegisterRd = ID/EX.RegisterRt))  
and (MEM/WB.RegisterRd = ID/EX.RegisterRt))  
ForwardB = 01

# Datapath with Forwarding



# Load-Use Data Hazard



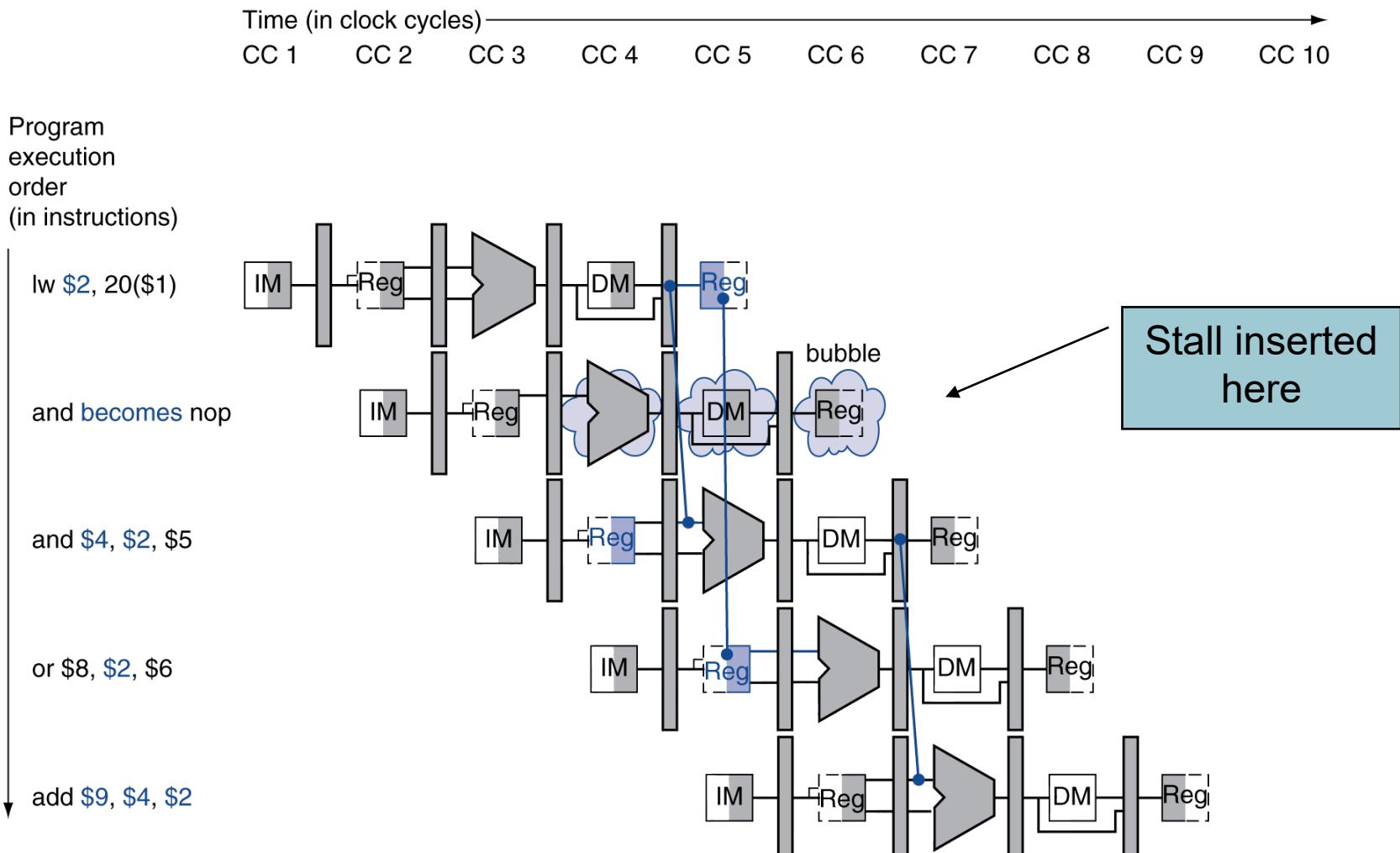
# Load-Use Hazard Detection

- Check when using instruction is decoded in ID stage
- ALU operand register numbers in ID stage are given by
  - IF/ID.RegisterRs, IF/ID.RegisterRt
- Load-use hazard when
  - ID/EX.MemRead and
$$((ID/EX.RegisterRt = IF/ID.RegisterRs) \text{ or } (ID/EX.RegisterRt = IF/ID.RegisterRt))$$
- If detected, stall and insert bubble

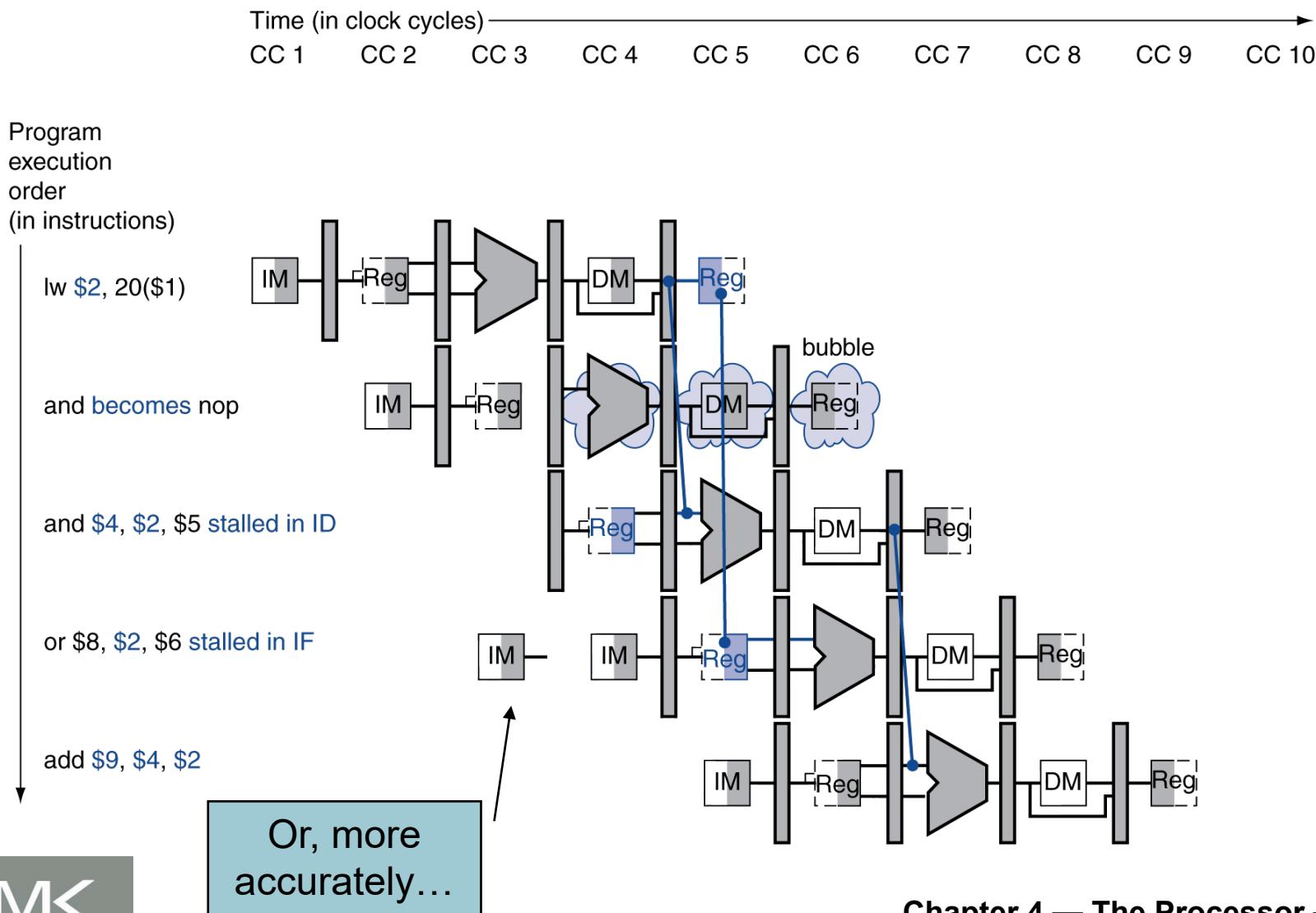
# How to Stall the Pipeline

- Force control values in ID/EX register to 0
  - EX, MEM and WB do nop (no-operation)
- Prevent update of PC and IF/ID register
  - Using instruction is decoded again
  - Following instruction is fetched again
  - 1-cycle stall allows MEM to read data for 1w
    - Can subsequently forward to EX stage

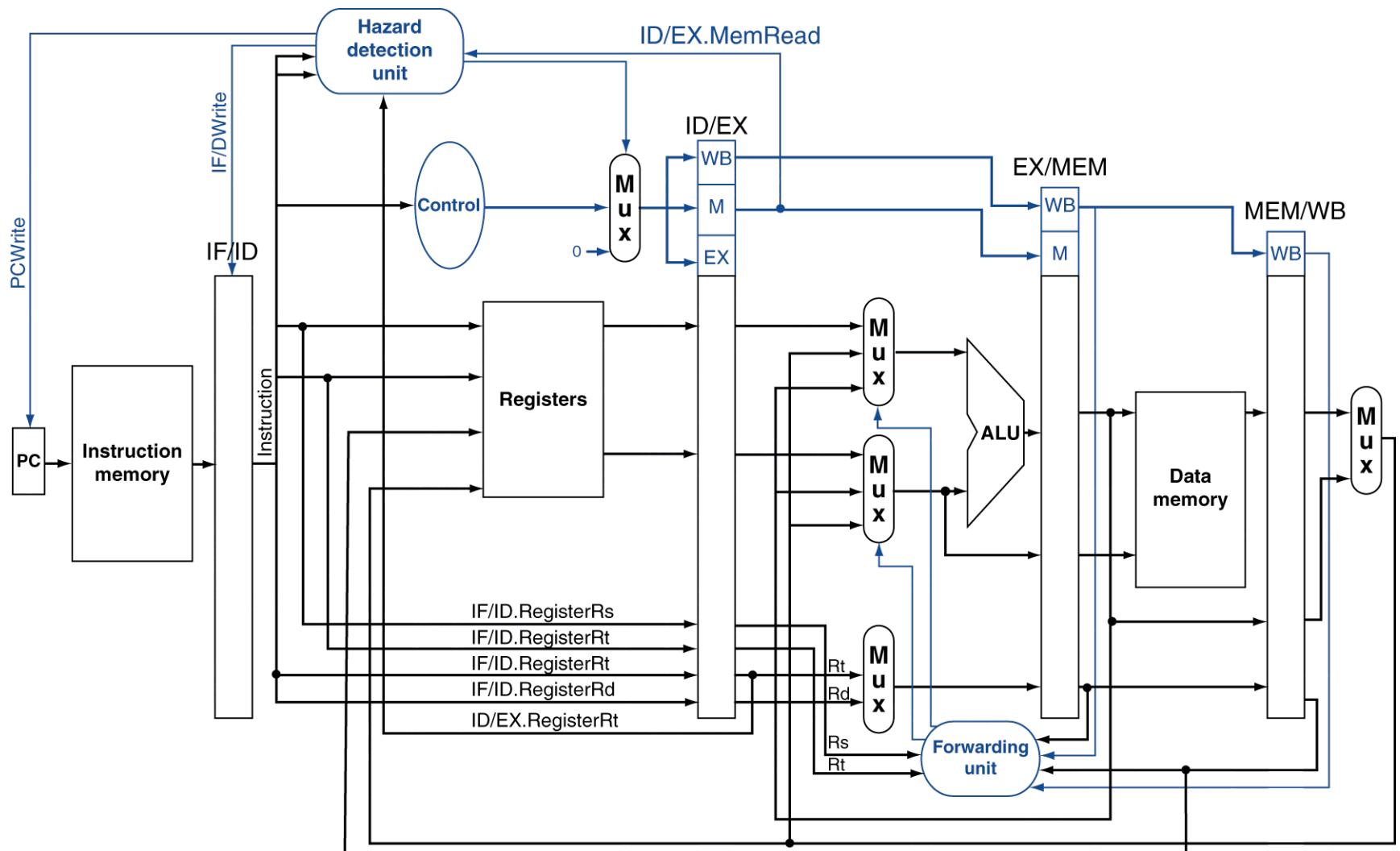
# Stall/Bubble in the Pipeline



# Stall/Bubble in the Pipeline



# Datapath with Hazard Detection



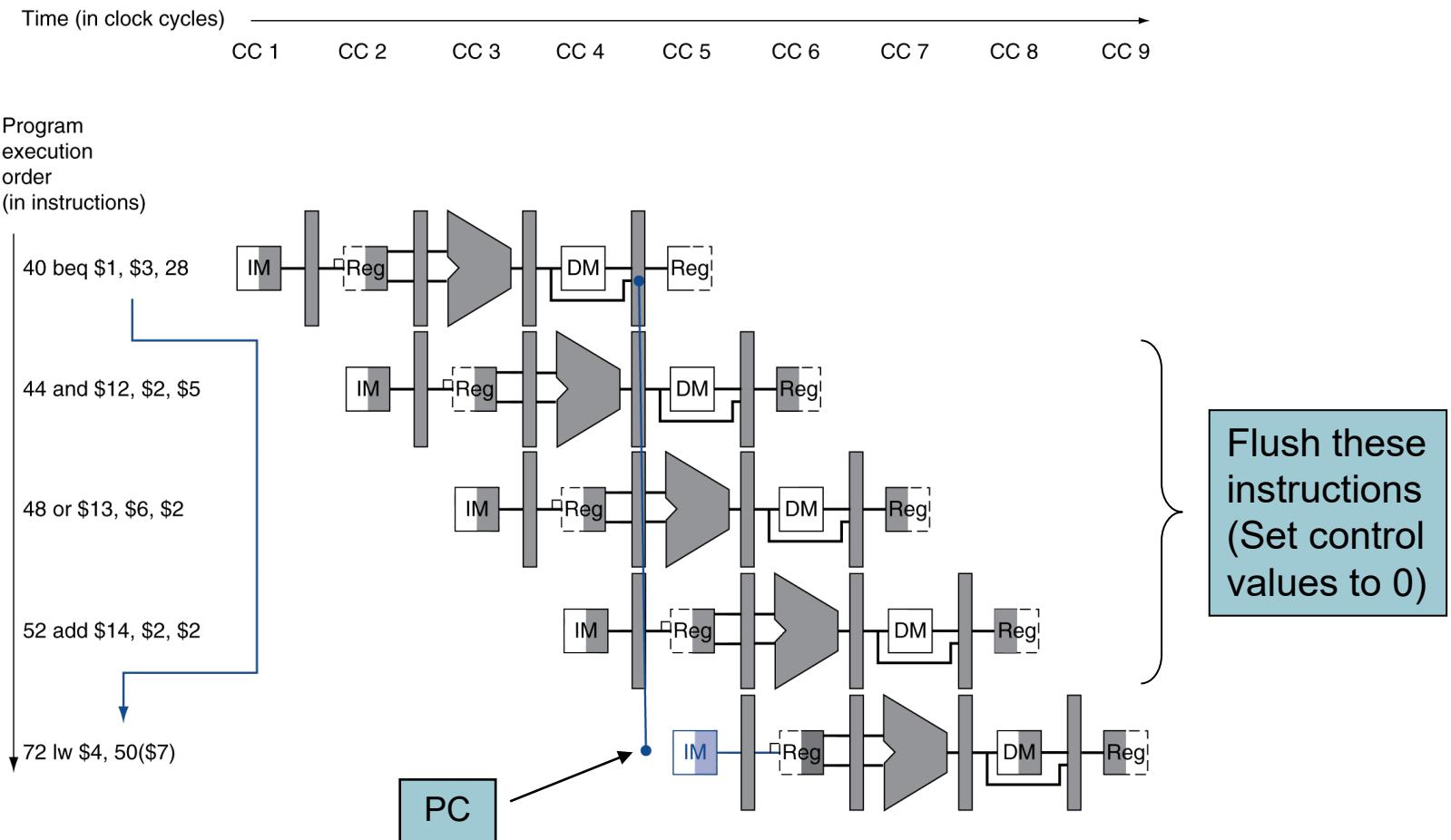
# Stalls and Performance

## The BIG Picture

- Stalls reduce performance
  - But are required to get correct results
- Compiler can arrange code to avoid hazards and stalls
  - Requires knowledge of the pipeline structure

# Branch Hazards

- If branch outcome determined in MEM

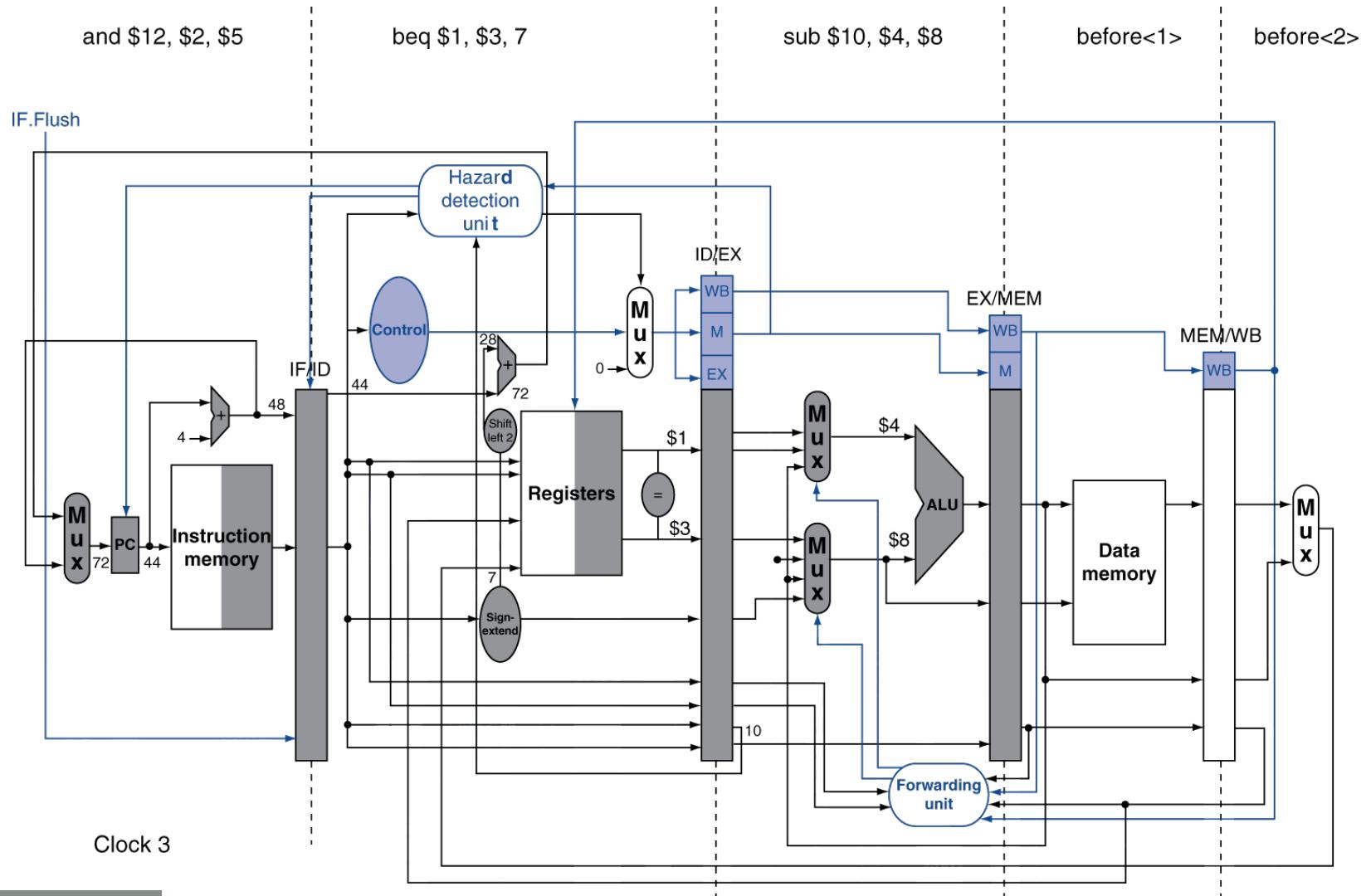


# Reducing Branch Delay

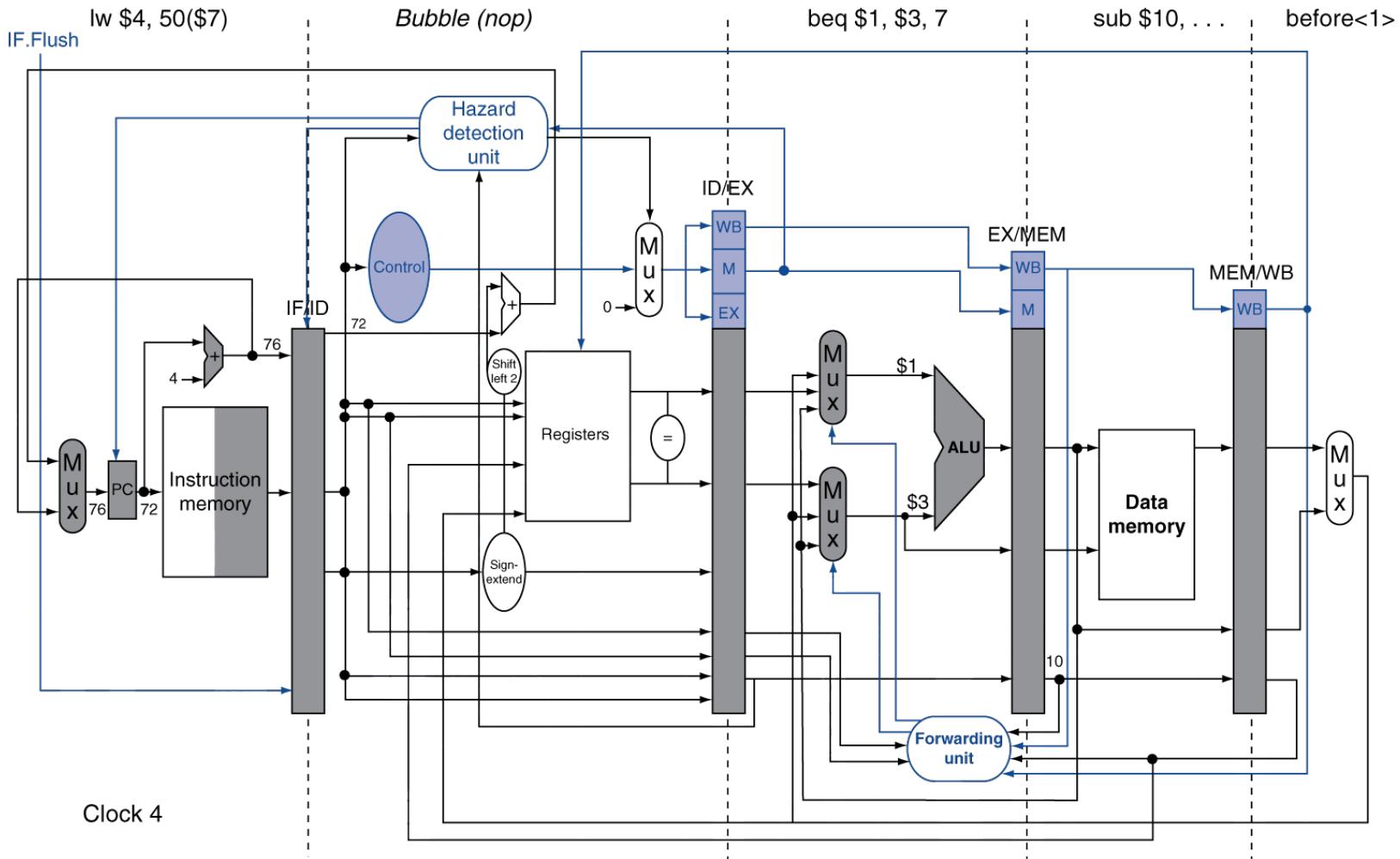
- Move hardware to determine outcome to ID stage
  - Target address adder
  - Register comparator
- Example: branch taken

```
36:    sub   $10, $4, $8  
40:    beq   $1,  $3, 7  
44:    and   $12, $2, $5  
48:    or    $13, $2, $6  
52:    add   $14, $4, $2  
56:    slt   $15, $6, $7  
      ...  
72:    lw    $4, 50($7)
```

# Example: Branch Taken



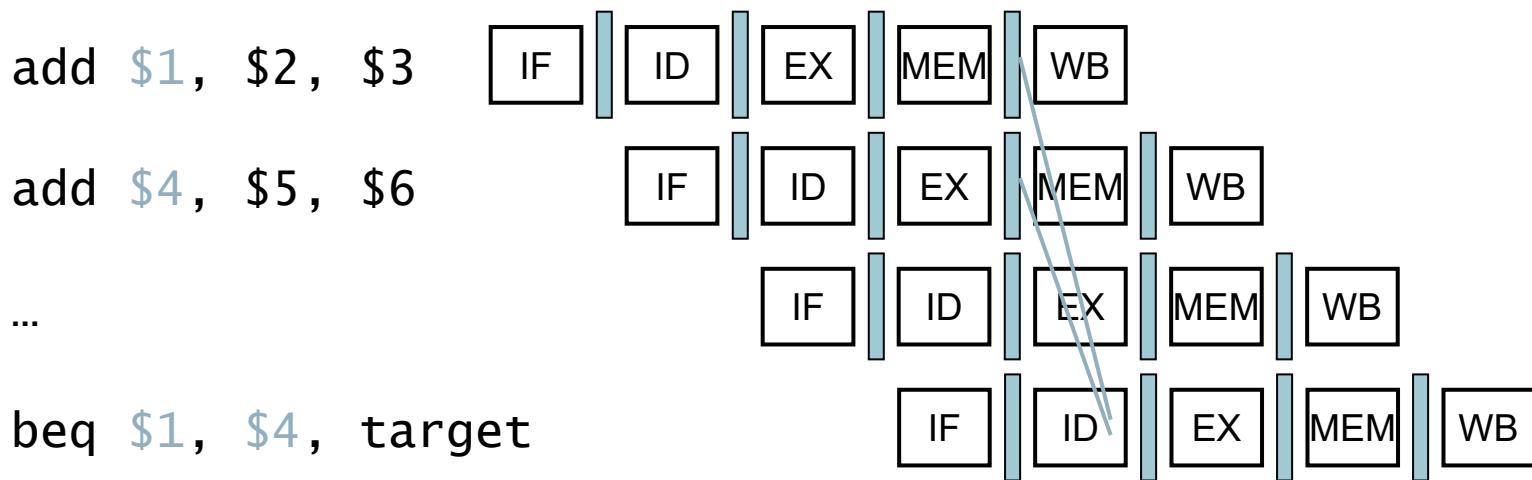
# Example: Branch Taken



Clock 4

# Data Hazards for Branches

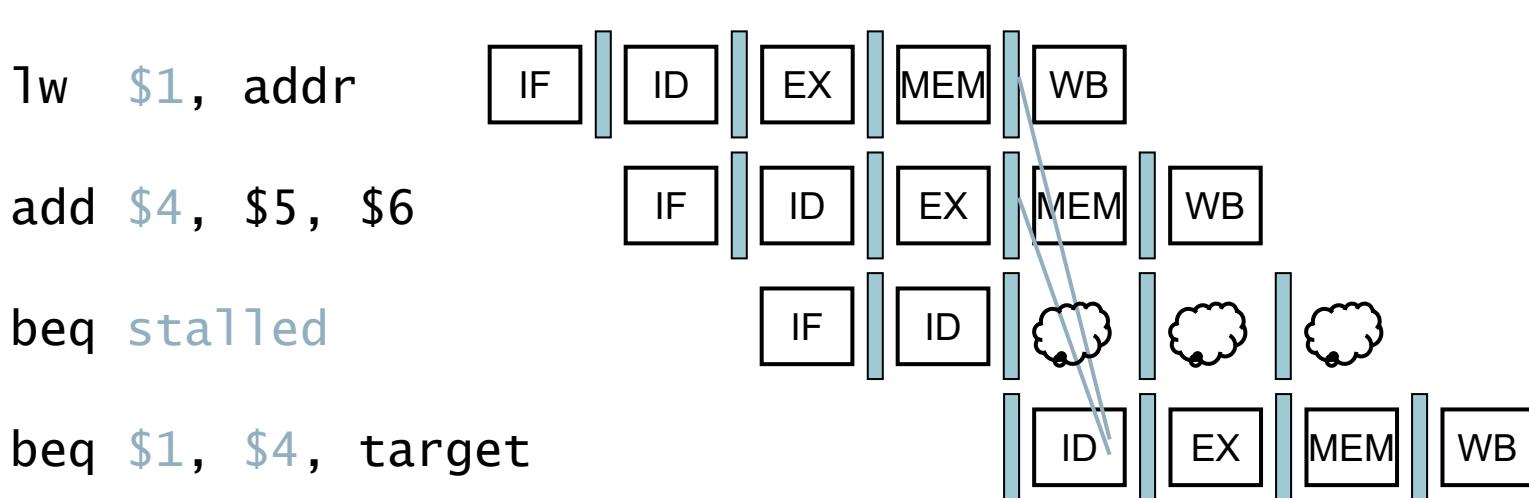
- If a comparison register is a destination of 2<sup>nd</sup> or 3<sup>rd</sup> preceding ALU instruction



- Can resolve using forwarding

# Data Hazards for Branches

- If a comparison register is a destination of preceding ALU instruction or 2<sup>nd</sup> preceding load instruction
  - Need 1 stall cycle



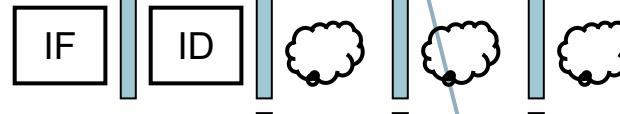
# Data Hazards for Branches

- If a comparison register is a destination of immediately preceding load instruction
  - Need 2 stall cycles

lw \$1, addr



beq stalled



beq stalled



beq \$1, \$0, target



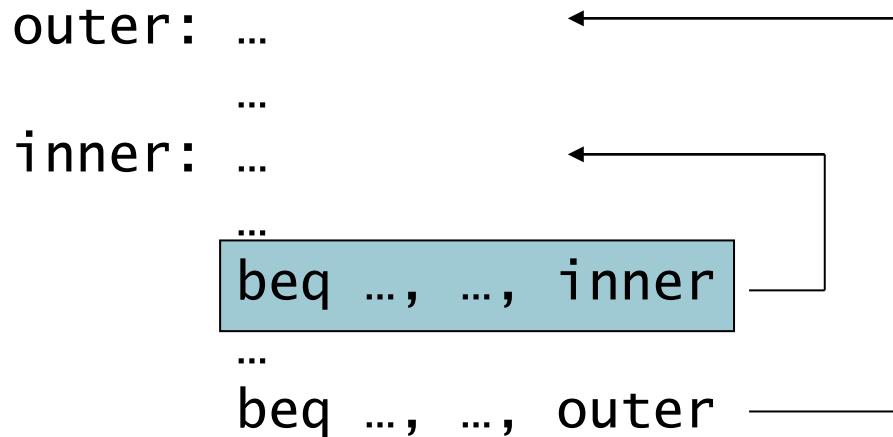
# Dynamic Branch Prediction

- In deeper and superscalar pipelines, branch penalty is more significant
- Use dynamic prediction
  - Branch prediction buffer (aka branch history table)
  - Indexed by recent branch instruction addresses
  - Stores outcome (taken/not taken)
  - To execute a branch
    - Check table, expect the same outcome
    - Start fetching from fall-through or target
    - If wrong, flush pipeline and flip prediction



# 1-Bit Predictor: Shortcoming

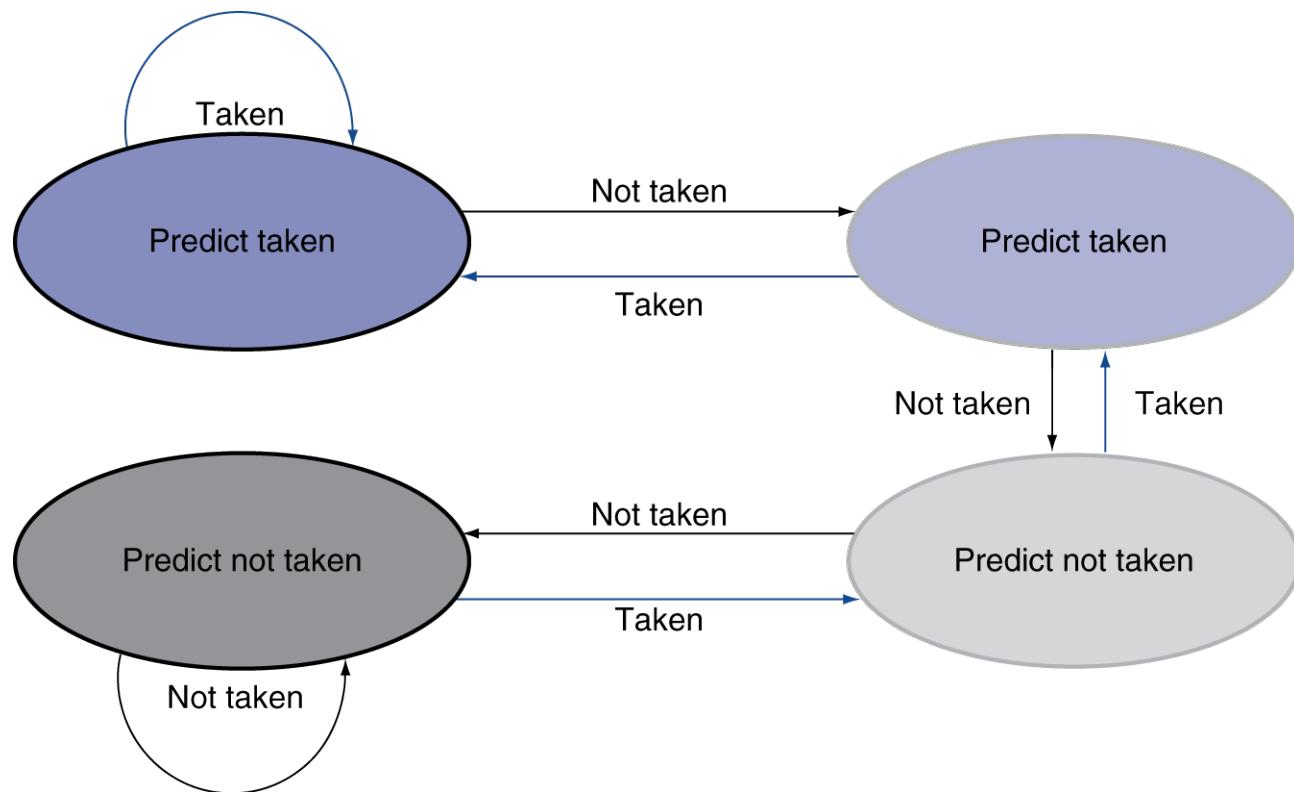
- Inner loop branches mispredicted twice!



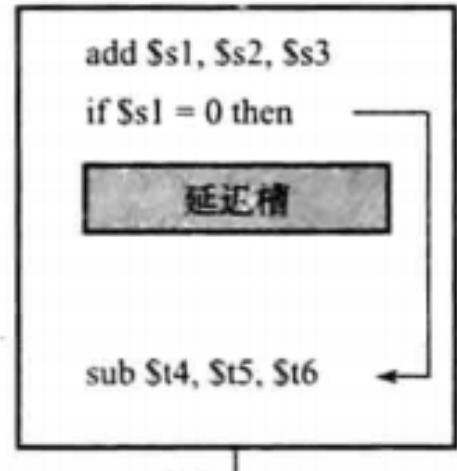
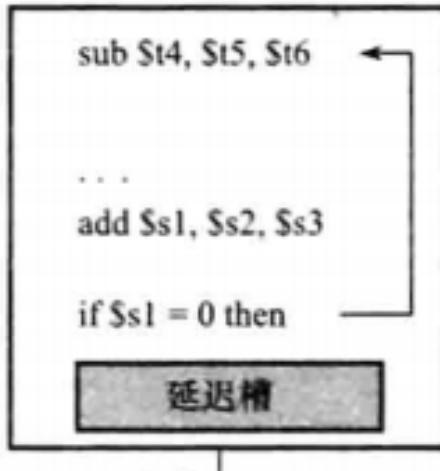
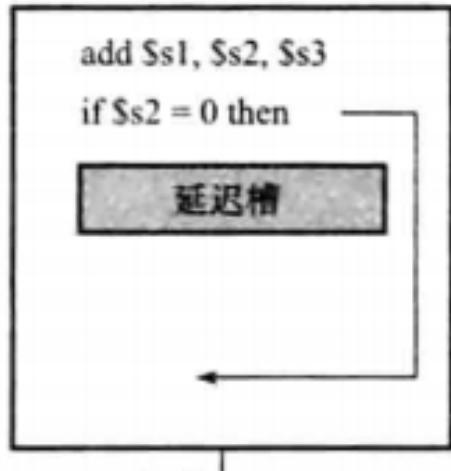
- Mispredict as taken on last iteration of inner loop
- Then mispredict as not taken on first iteration of inner loop next time around

# 2-Bit Predictor

- Only change prediction on two successive mispredictions



# Branch delay slot



a) 从前面调度

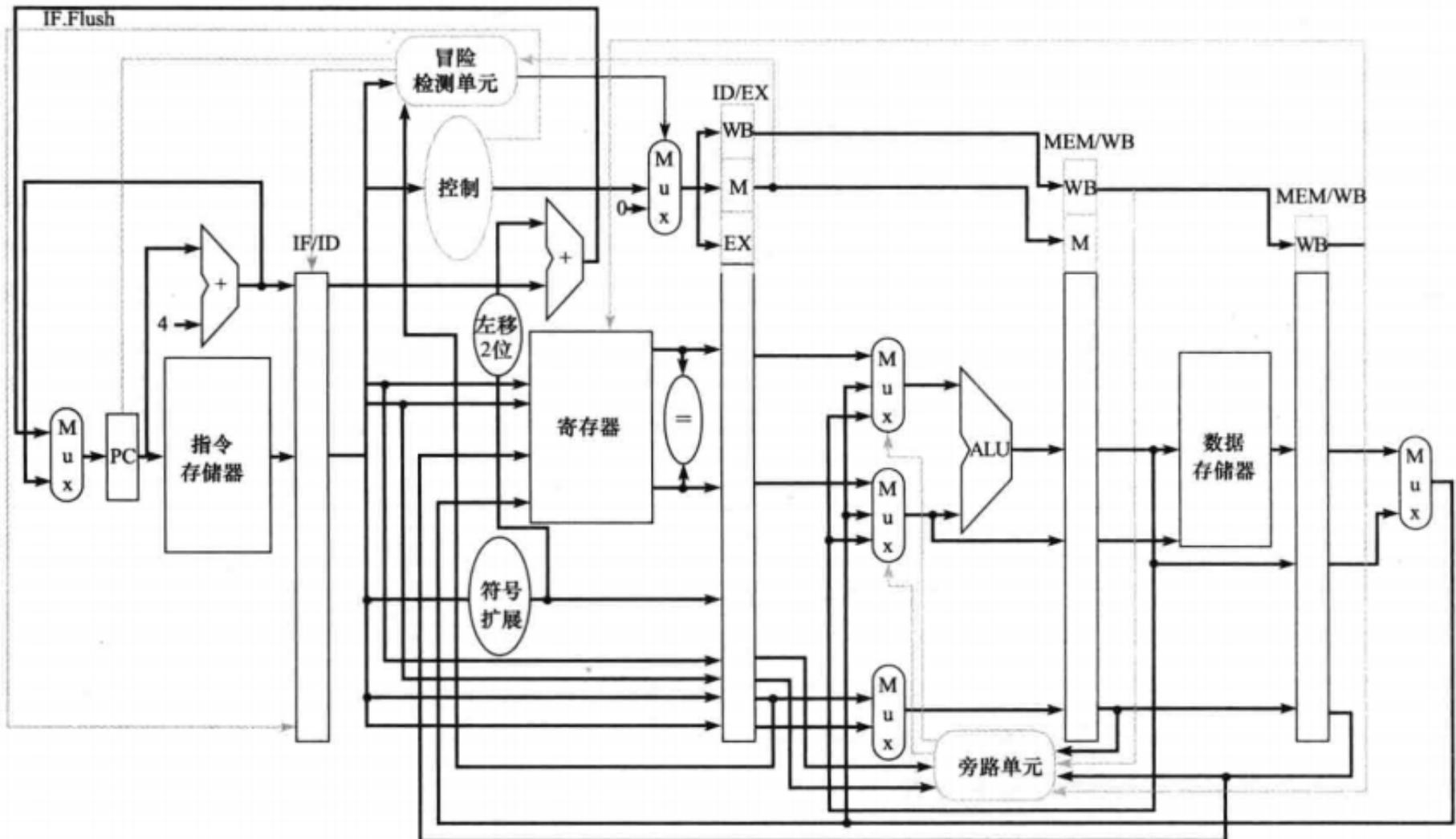
b) 从目标处调度

c) 从不发生转移处调度

# Calculating the Branch Target

- Even with predictor, still need to calculate the target address
  - 1-cycle penalty for a taken branch
- Branch target buffer
  - Cache of target addresses
  - Indexed by PC when instruction fetched
    - If hit and instruction is branch predicted taken, can fetch target immediately
  - Correlating predictor
  - Tournament branch predictor

# Pipeline Summary



# Exceptions and Interrupts

- “Unexpected” events requiring change in flow of control
  - Different ISAs use the terms differently
- Exception
  - Arises within the CPU
    - e.g., undefined opcode, overflow, syscall, ...
- Interrupt
  - From an external I/O controller
- Dealing with them without sacrificing performance is hard

# Handling Exceptions

- In MIPS, exceptions managed by a System Control Coprocessor (CP0)
- Save PC of offending (or interrupted) instruction
  - In MIPS: Exception Program Counter (EPC)
- Save indication of the problem
  - In MIPS: Cause register
  - We'll assume 1-bit
    - 0 for undefined opcode, 1 for overflow
- Jump to handler at 8000 00180

# An Alternate Mechanism

- Vectored Interrupts
  - Handler address determined by the cause
- Example:
  - Undefined opcode: C000 0000
  - Overflow: C000 0020
  - .... C000 0040
- Instructions either
  - Deal with the interrupt, or
  - Jump to real handler

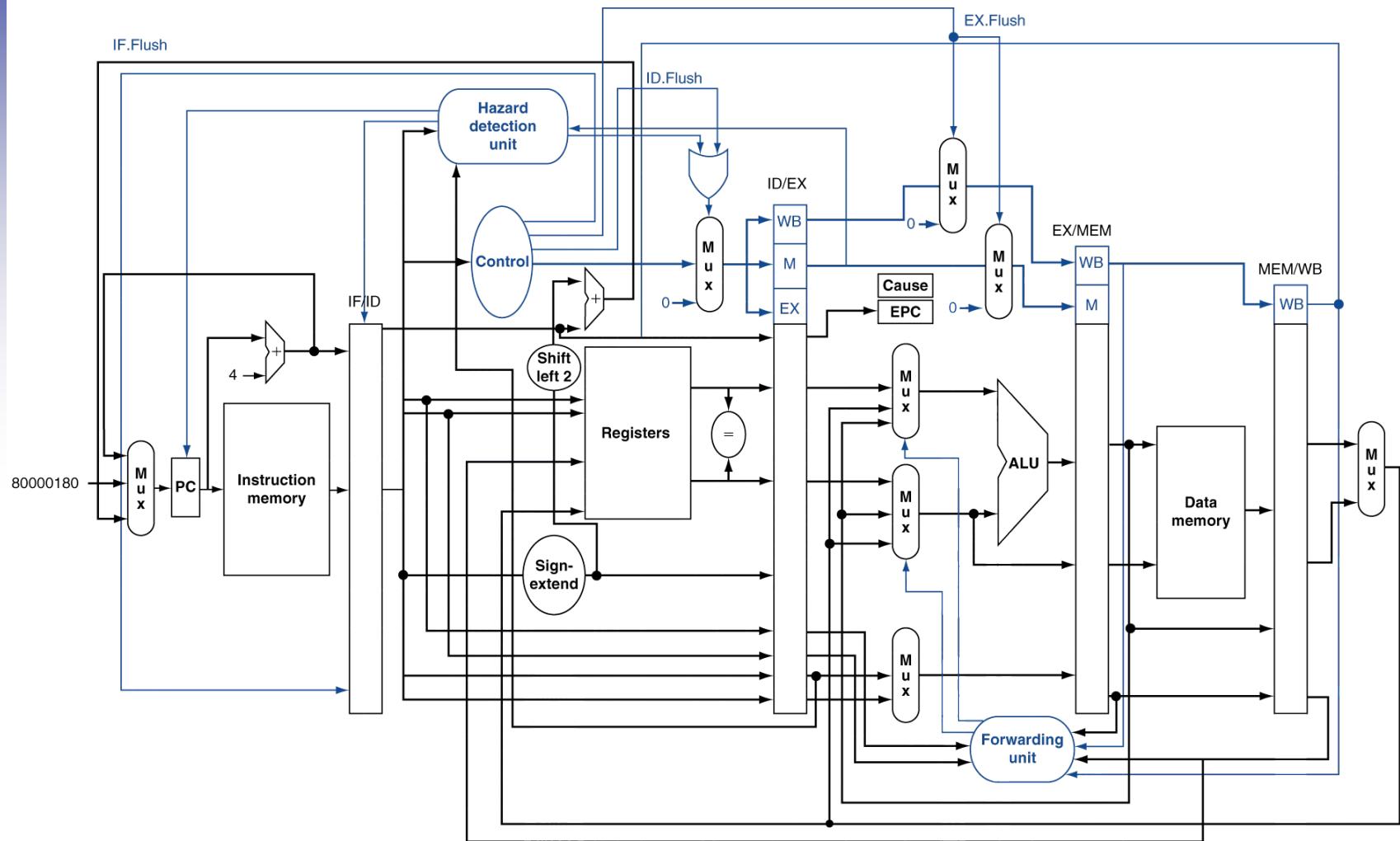
# Handler Actions

- Read cause, and transfer to relevant handler
- Determine action required
- If restartable
  - Take corrective action
  - use EPC to return to program
- Otherwise
  - Terminate program
  - Report error using EPC, cause, ...

# Exceptions in a Pipeline

- Another form of control hazard
- Consider overflow on add in EX stage
  - add \$1, \$2, \$1
    - Prevent \$1 from being clobbered
    - Complete previous instructions
    - Flush add and subsequent instructions
    - Set Cause and EPC register values
    - Transfer control to handler
- Similar to mispredicted branch
  - Use much of the same hardware

# Pipeline with Exceptions



# Exception Properties

- Restartable exceptions
  - Pipeline can flush the instruction
  - Handler executes, then returns to the instruction
    - Refetched and executed from scratch
- PC saved in EPC register
  - Identifies causing instruction
  - Actually  $PC + 4$  is saved
    - Handler must adjust

# Exception Example

- Exception on add in

```
40      sub    $11, $2, $4
44      and    $12, $2, $5
48      or     $13, $2, $6
4C      add    $1,   $2,   $1
50      slt    $15, $6, $7
54      lw     $16, 50($7)
```

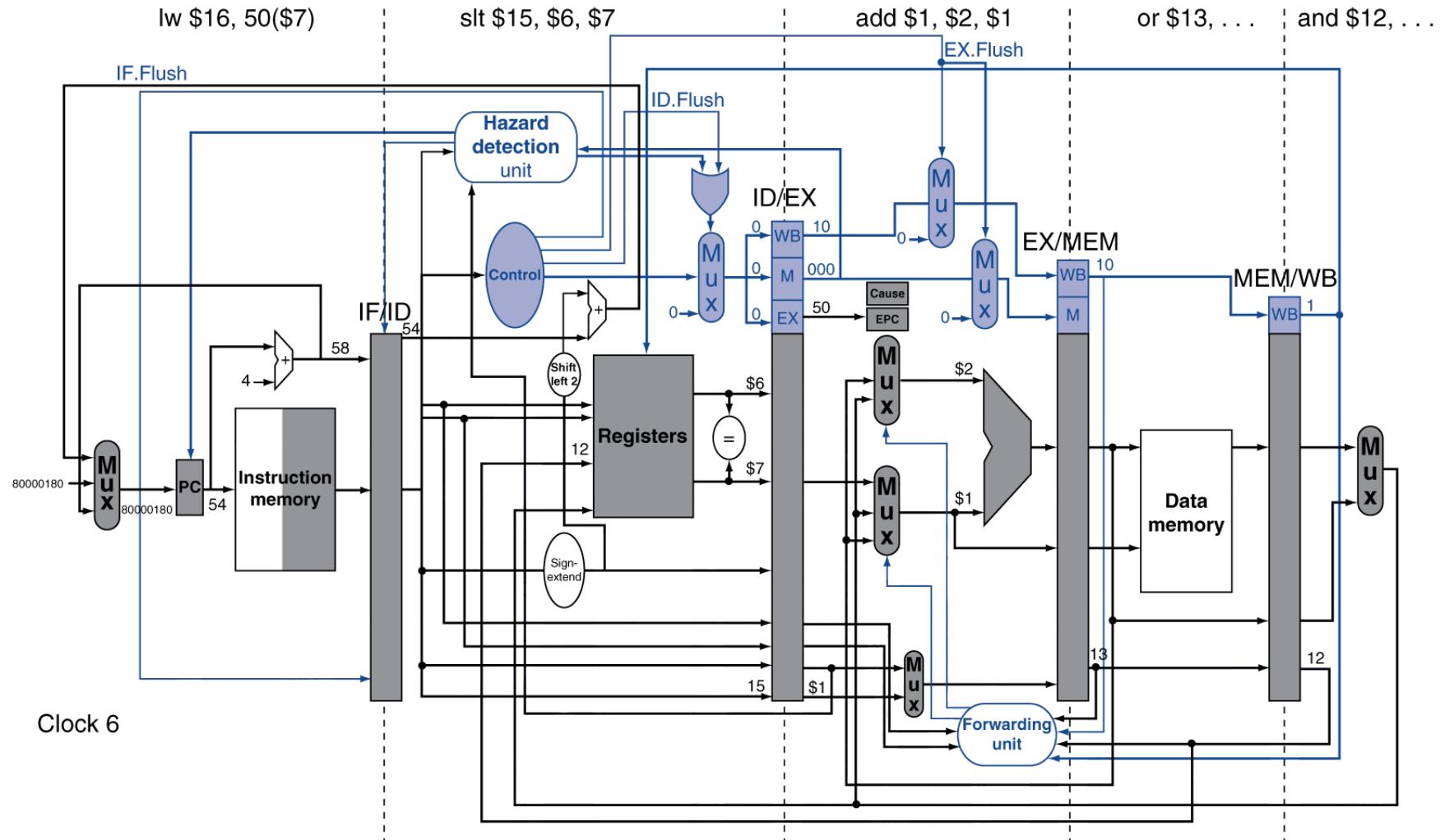
...

- Handler

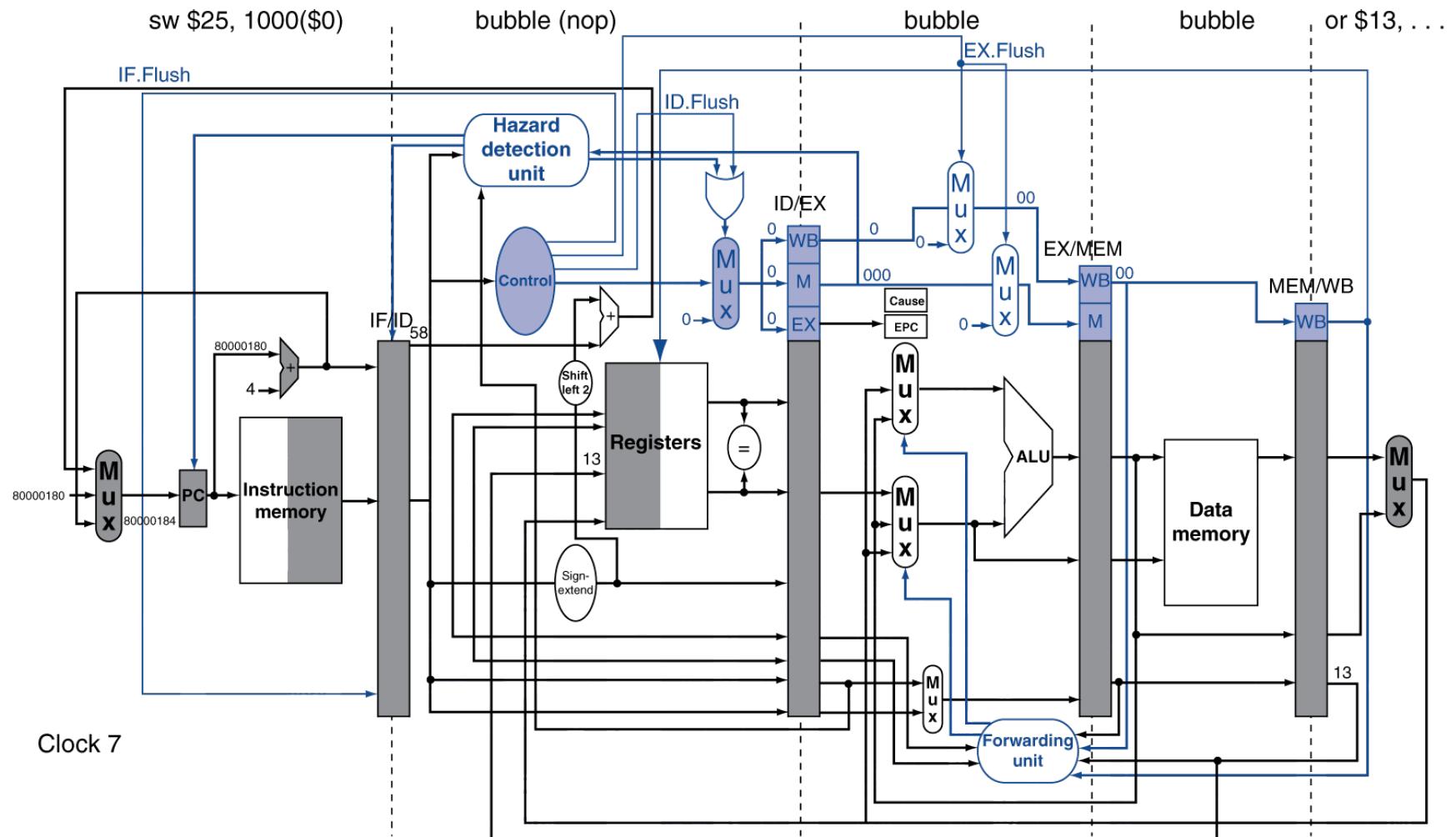
```
80000180    sw    $25, 1000($0)
80000184    sw    $26, 1004($0)
```

...

# Exception Example



# Exception Example



# Multiple Exceptions

- Pipelining overlaps multiple instructions
  - Could have multiple exceptions at once
- Simple approach: deal with exception from earliest instruction
  - Flush subsequent instructions
  - “Precise” exceptions
- In complex pipelines
  - Multiple instructions issued per cycle
  - Out-of-order completion
  - Maintaining precise exceptions is difficult!

# Imprecise Exceptions

- Just stop pipeline and save state
  - Including exception cause(s)
- Let the handler work out
  - Which instruction(s) had exceptions
  - Which to complete or flush
    - May require “manual” completion
- Simplifies hardware, but more complex handler software
- Not feasible for complex multiple-issue out-of-order pipelines

# Instruction-Level Parallelism (ILP)

- Pipelining: executing multiple instructions in parallel
- To increase ILP
  - Deeper pipeline
    - Less work per stage  $\Rightarrow$  shorter clock cycle
  - Multiple issue
    - Replicate pipeline stages  $\Rightarrow$  multiple pipelines
    - Start multiple instructions per clock cycle
    - CPI < 1, so use Instructions Per Cycle (IPC)
    - E.g., 4GHz 4-way multiple-issue
      - 16 BIPS, peak CPI = 0.25, peak IPC = 4
    - But dependencies reduce this in practice

# Multiple Issue

- Static multiple issue
  - Compiler groups instructions to be issued together
  - Packages them into “issue slots”
  - Compiler detects and avoids hazards
- Dynamic multiple issue
  - CPU examines instruction stream and chooses instructions to issue each cycle
  - Compiler can help by reordering instructions
  - CPU resolves hazards using advanced techniques at runtime

# Speculation

- “Guess” what to do with an instruction
  - Start operation as soon as possible
  - Check whether guess was right
    - If so, complete the operation
    - If not, roll-back and do the right thing
- Common to static and dynamic multiple issue
- Examples
  - Speculate on branch outcome
    - Roll back if path taken is different
  - Speculate on load
    - Roll back if location is updated

# Compiler/Hardware Speculation

- Compiler can reorder instructions
  - e.g., move load before branch
  - Can include “fix-up” instructions to recover from incorrect guess
- Hardware can look ahead for instructions to execute
  - Buffer results until it determines they are actually needed
  - Flush buffers on incorrect speculation

# Speculation and Exceptions

- What if exception occurs on a speculatively executed instruction?
  - e.g., speculative load before null-pointer check
- Static speculation
  - Can add ISA support for deferring exceptions
- Dynamic speculation
  - Can buffer exceptions until instruction completion (which may not occur)

# Static Multiple Issue

- Compiler groups instructions into “issue packets”
  - Group of instructions that can be issued on a single cycle
  - Determined by pipeline resources required
- Think of an issue packet as a very long instruction
  - Specifies multiple concurrent operations
  - ⇒ Very Long Instruction Word (VLIW)

# Scheduling Static Multiple Issue

- Compiler must remove some/all hazards
  - Reorder instructions into issue packets
  - No dependencies with a packet
  - Possibly some dependencies between packets
    - Varies between ISAs; compiler must know!
  - Pad with nop if necessary

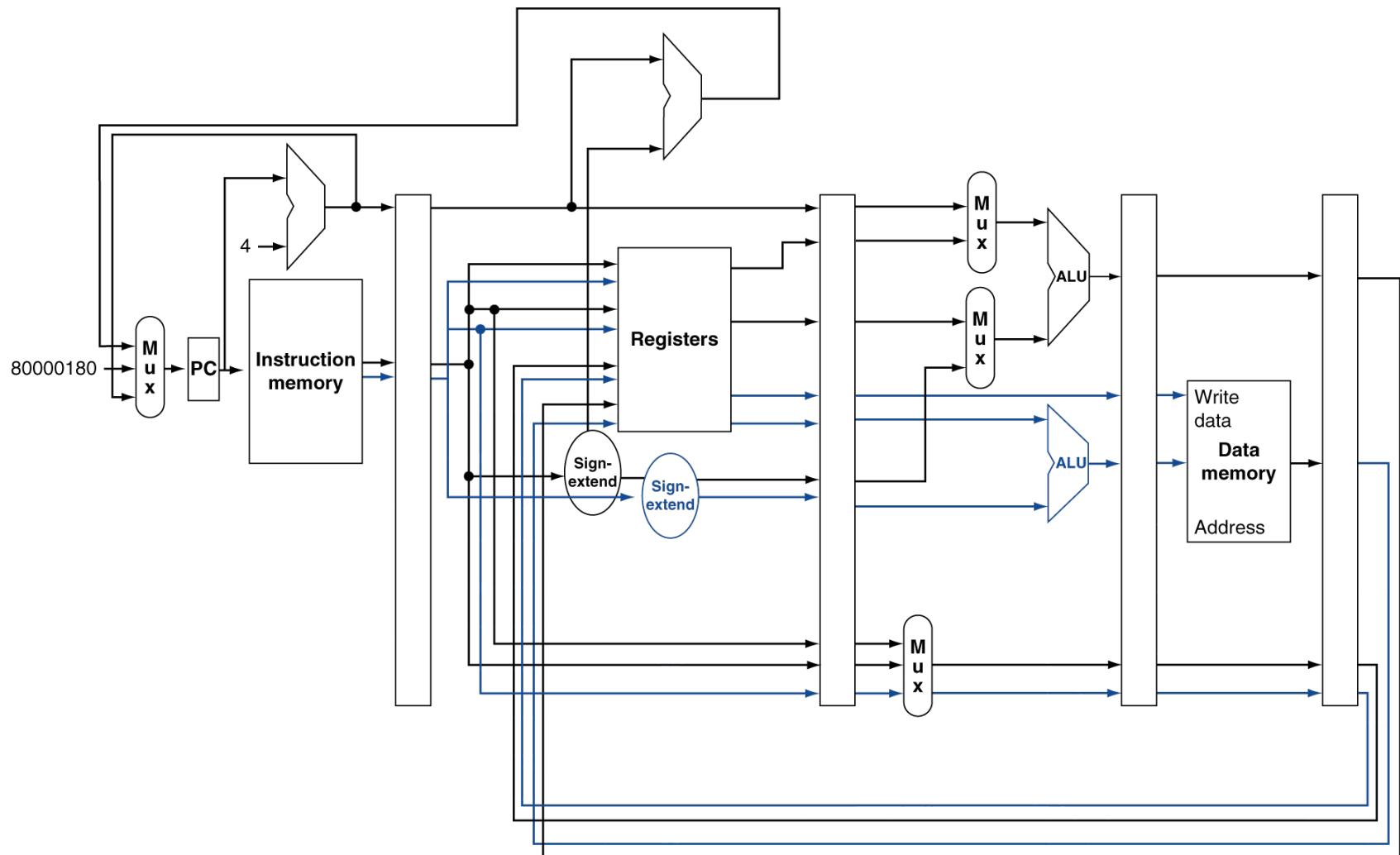
# MIPS with Static Dual Issue

## Two-issue packets

- One ALU/branch instruction
- One load/store instruction
- 64-bit aligned
  - ALU/branch, then load/store
  - Pad an unused instruction with nop

Address	Instruction type	Pipeline Stages						
		IF	ID	EX	MEM	WB		
n	ALU/branch	IF	ID	EX	MEM	WB		
n + 4	Load/store	IF	ID	EX	MEM	WB		
n + 8	ALU/branch		IF	ID	EX	MEM	WB	
n + 12	Load/store		IF	ID	EX	MEM	WB	
n + 16	ALU/branch			IF	ID	EX	MEM	WB
n + 20	Load/store			IF	ID	EX	MEM	WB

# MIPS with Static Dual Issue



# Hazards in the Dual-Issue MIPS

- More instructions executing in parallel
- EX data hazard
  - Forwarding avoided stalls with single-issue
  - Now can't use ALU result in load/store in same packet
    - add \$t0, \$s0, \$s1
    - load \$s2, 0(\$t0)
    - Split into two packets, effectively a stall
- Load-use hazard
  - Still one cycle use latency, but now two instructions
- More aggressive scheduling required

# Scheduling Example

- Schedule this for dual-issue MIPS

```
Loop:  lw    $t0, 0($s1)      # $t0=array element
        addu $t0, $t0, $s2      # add scalar in $s2
        sw   $t0, 0($s1)      # store result
        addi $s1, $s1,-4       # decrement pointer
        bne $s1, $zero, Loop  # branch $s1!=0
```

	ALU/branch	Load/store	cycle
Loop:	nop	lw \$t0, 0(\$s1)	1
	addi \$s1, \$s1,-4	nop	2
	addu \$t0, \$t0, \$s2	nop	3
	bne \$s1, \$zero, Loop	sw \$t0, 4(\$s1)	4

- IPC = 5/4 = 1.25 (c.f. peak IPC = 2)

# Loop Unrolling

- Replicate loop body to expose more parallelism
  - Reduces loop-control overhead
- Use different registers per replication
  - Called “register renaming”
  - Avoid loop-carried “anti-dependencies”
    - Store followed by a load of the same register
    - Aka “name dependence”
      - Reuse of a register name

# Loop Unrolling Example

	ALU/branch	Load/store	cycle
Loop:	addi \$s1, \$s1,-16	lw \$t0, 0(\$s1)	1
	nop	lw \$t1, 12(\$s1)	2
	addu \$t0, \$t0, \$s2	lw \$t2, 8(\$s1)	3
	addu \$t1, \$t1, \$s2	lw \$t3, 4(\$s1)	4
	addu \$t2, \$t2, \$s2	sw \$t0, 16(\$s1)	5
	addu \$t3, \$t4, \$s2	sw \$t1, 12(\$s1)	6
	nop	sw \$t2, 8(\$s1)	7
	bne \$s1, \$zero, Loop	sw \$t3, 4(\$s1)	8

- $\text{IPC} = 14/8 = 1.75$ 
  - Closer to 2, but at cost of registers and code size

# Dynamic Multiple Issue

- “Superscalar” processors
- CPU decides whether to issue 0, 1, 2, ... each cycle
  - Avoiding structural and data hazards
- Avoids the need for compiler scheduling
  - Though it may still help
  - Code semantics ensured by the CPU

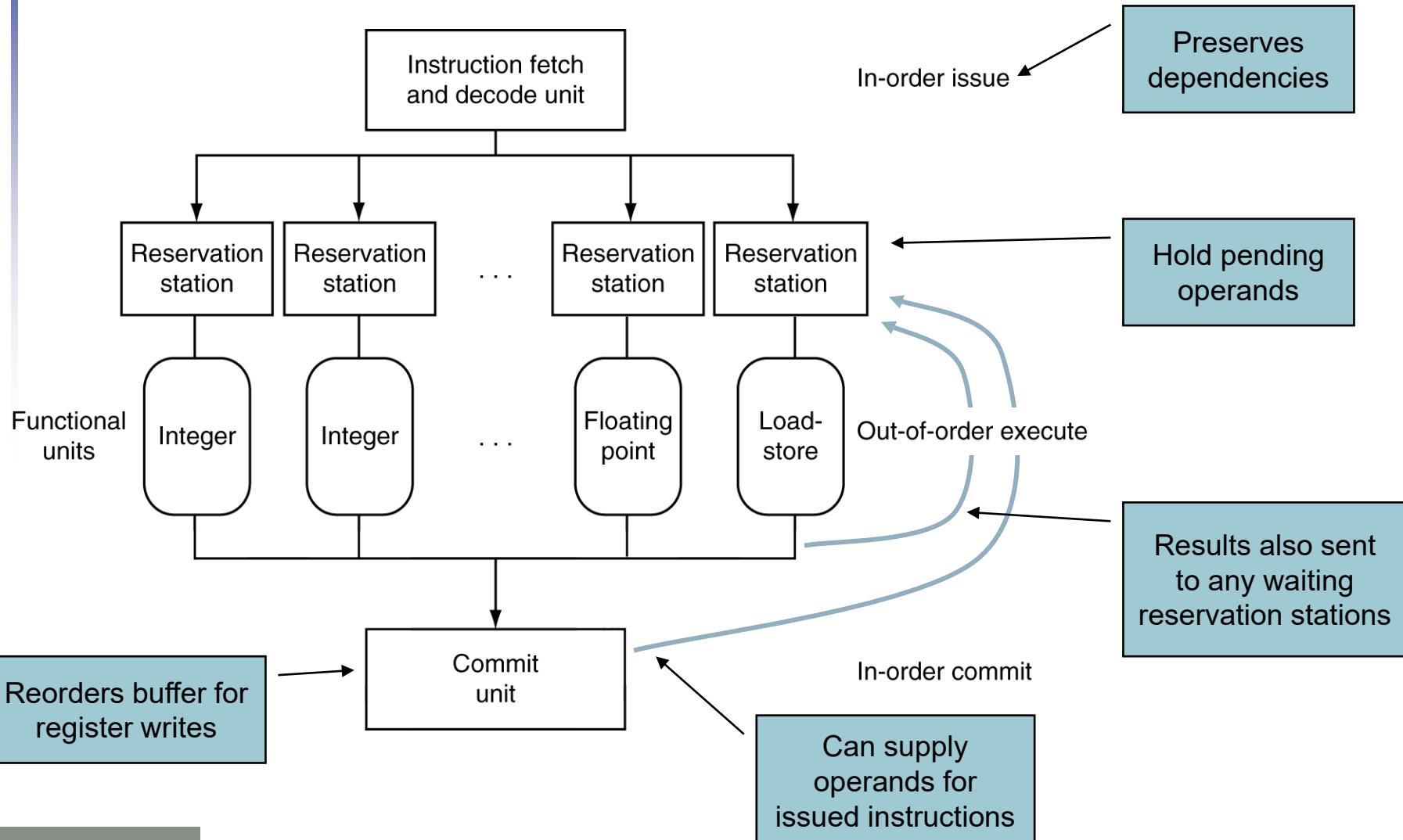
# Dynamic Pipeline Scheduling

- Allow the CPU to execute instructions out of order to avoid stalls
  - But commit result to registers in order
- Example

```
lw      $t0, 20($s2)
addu   $t1, $t0, $t2
sub    $s4, $s4, $t3
slti   $t5, $s4, 20
```

- Can start sub while addu is waiting for lw

# Dynamically Scheduled CPU



# Register Renaming

- Reservation stations and reorder buffer effectively provide register renaming
- On instruction issue to reservation station
  - If operand is available in register file or reorder buffer
    - Copied to reservation station
    - No longer required in the register; can be overwritten
  - If operand is not yet available
    - It will be provided to the reservation station by a function unit
    - Register update may not be required

# Speculation

- Predict branch and continue issuing
  - Don't commit until branch outcome determined
- Load speculation
  - Avoid load and cache miss delay
    - Predict the effective address
    - Predict loaded value
    - Load before completing outstanding stores
    - Bypass stored values to load unit
  - Don't commit load until speculation cleared

# Why Do Dynamic Scheduling?

- Why not just let the compiler schedule code?
- Not all stalls are predictable
  - e.g., cache misses
- Can't always schedule around branches
  - Branch outcome is dynamically determined
- Different implementations of an ISA have different latencies and hazards

# Does Multiple Issue Work?

## The BIG Picture

- Yes, but not as much as we'd like
- Programs have real dependencies that limit ILP
- Some dependencies are hard to eliminate
  - e.g., pointer aliasing
- Some parallelism is hard to expose
  - Limited window size during instruction issue
- Memory delays and limited bandwidth
  - Hard to keep pipelines full
- Speculation can help if done well

# Power Efficiency

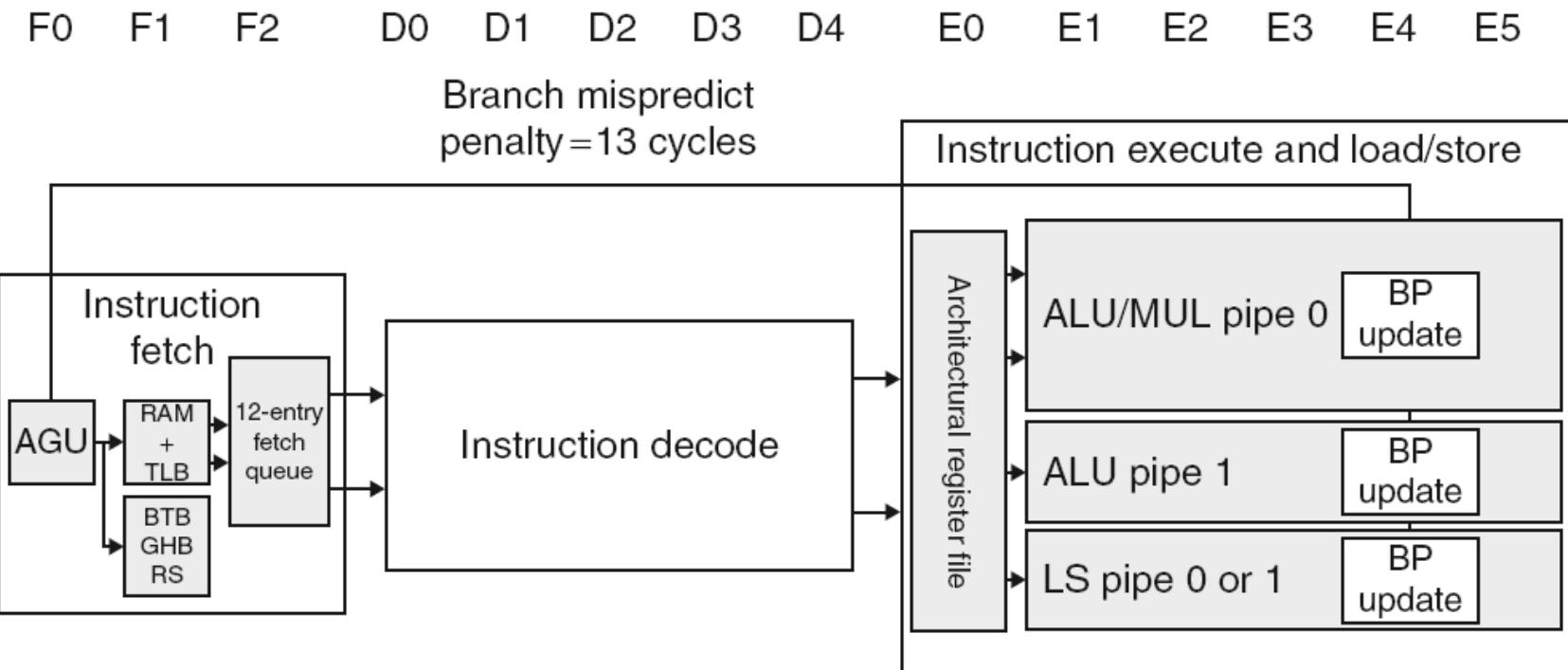
- Complexity of dynamic scheduling and speculations requires power (power wall)
- Multiple simpler cores may be better

Microprocessor	Year	Clock Rate	Pipeline Stages	Issue width	Out-of-order/Speculation	Cores	Power
i486	1989	25MHz	5	1	No	1	5W
Pentium	1993	66MHz	5	2	No	1	10W
Pentium Pro	1997	200MHz	10	3	Yes	1	29W
P4 Willamette	2001	2000MHz	22	3	Yes	1	75W
P4 Prescott	2004	3600MHz	31	3	Yes	1	103W
Core	2006	2930MHz	14	4	Yes	2	75W
UltraSparc III	2003	1950MHz	14	4	No	1	90W
UltraSparc T1	2005	1200MHz	6	1	No	8	70W

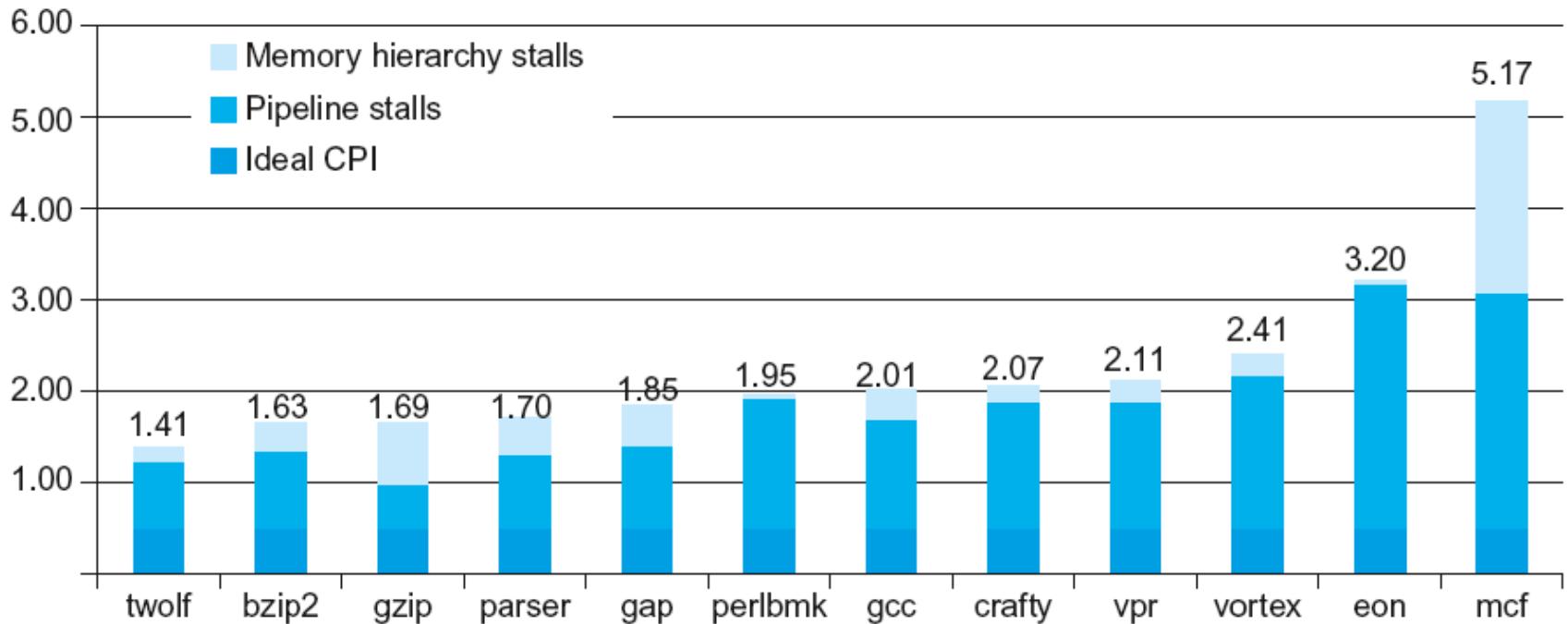
# Cortex A8 and Intel i7

Processor	ARM A8	Intel Core i7 920
Market	Personal Mobile Device	Server, cloud
Thermal design power	2 Watts	130 Watts
Clock rate	1 GHz	2.66 GHz
Cores/Chip	1	4
Floating point?	No	Yes
Multiple issue?	Dynamic	Dynamic
Peak instructions/clock cycle	2	4
Pipeline stages	14	14
Pipeline schedule	Static in-order	Dynamic out-of-order with speculation
Branch prediction	2-level	2-level
1 <sup>st</sup> level caches/core	32 KiB I, 32 KiB D	32 KiB I, 32 KiB D
2 <sup>nd</sup> level caches/core	128-1024 KiB	256 KiB
3 <sup>rd</sup> level caches (shared)	-	2- 8 MB

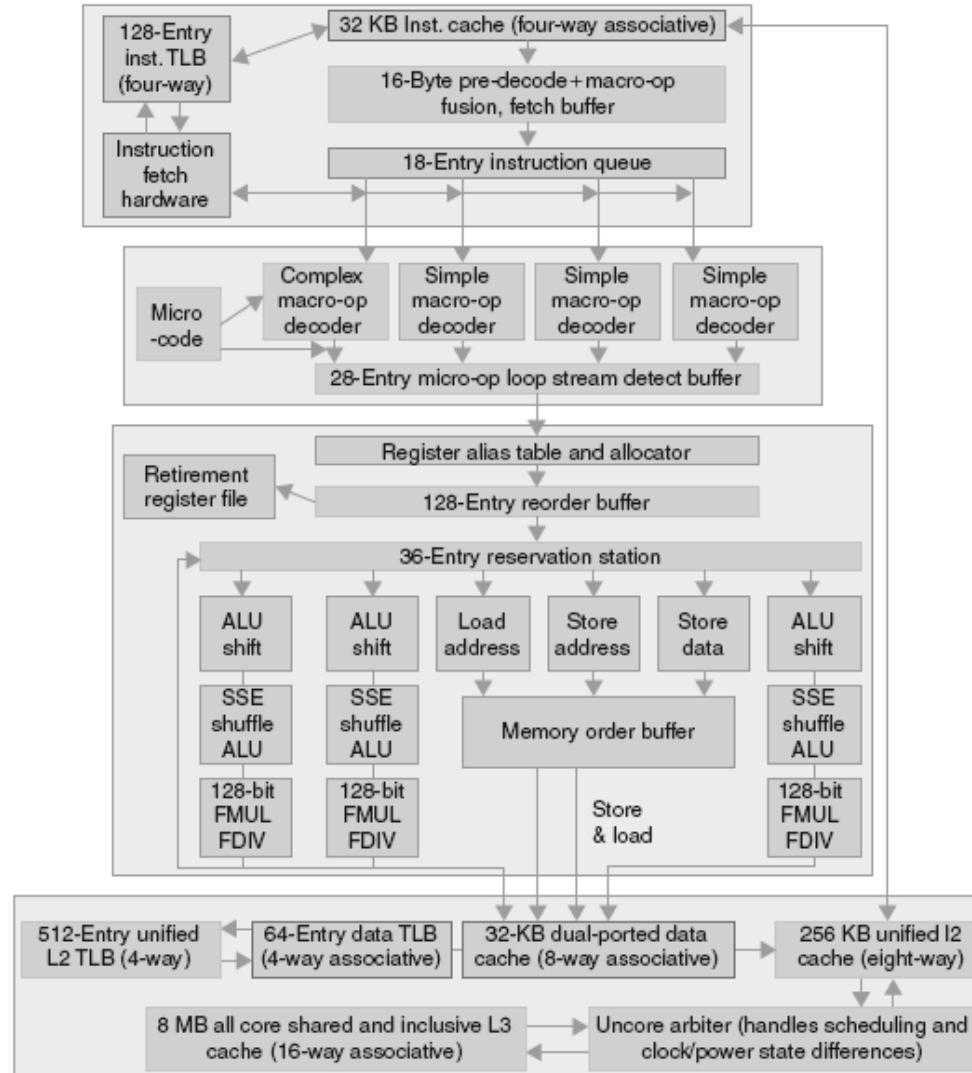
# ARM Cortex-A8 Pipeline



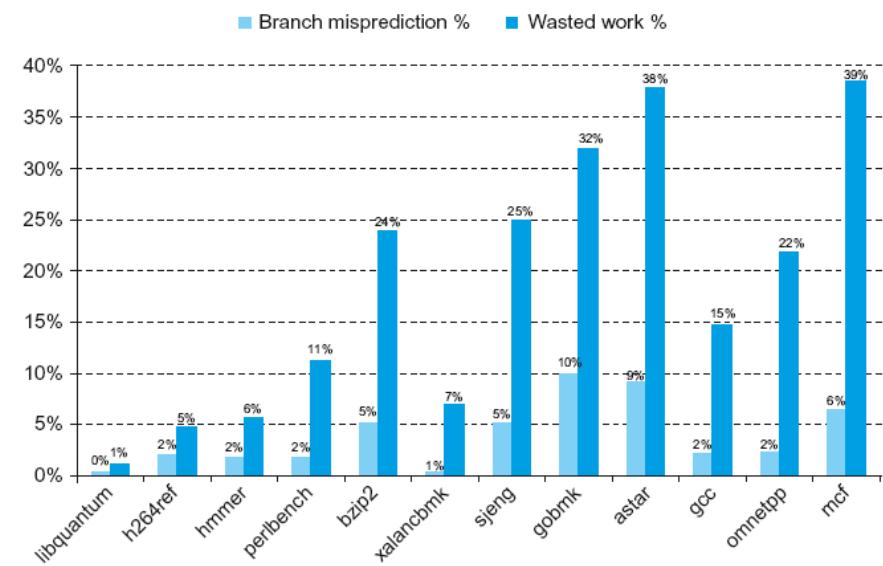
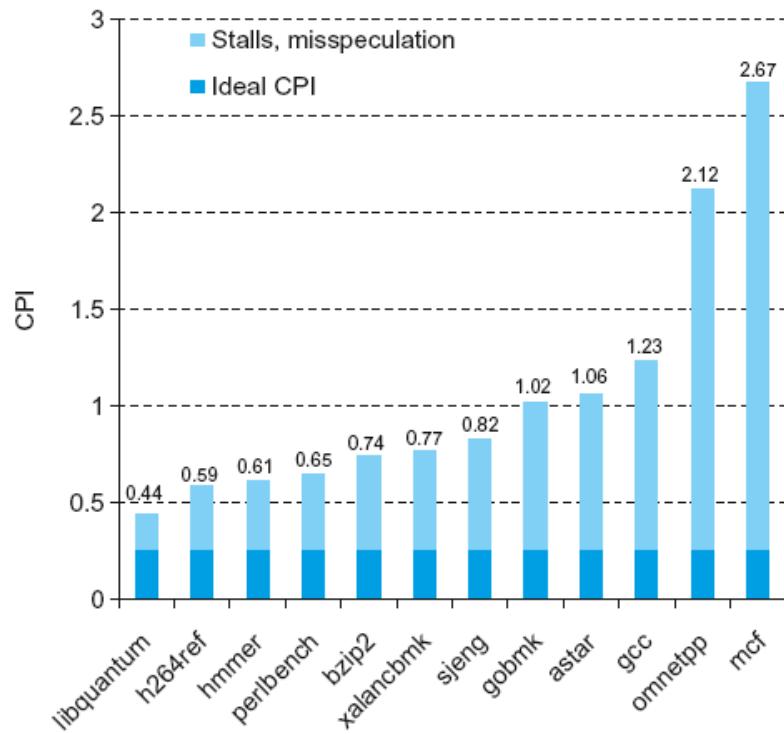
# ARM Cortex-A8 Performance



# Core i7 Pipeline



# Core i7 Performance



# Matrix Multiply

## ■ Unrolled C code

```
1 #include <x86intrin.h>
2 #define UNROLL (4)
3
4 void dgemm (int n, double* A, double* B, double* C)
5 {
6     for ( int i = 0; i < n; i+=UNROLL*4 )
7         for ( int j = 0; j < n; j++ ) {
8             __m256d c[4];
9             for ( int x = 0; x < UNROLL; x++ )
10                c[x] = _mm256_load_pd(C+i+x*4+j*n);
11
12            for( int k = 0; k < n; k++ )
13            {
14                __m256d b = _mm256_broadcast_sd(B+k+j*n);
15                for (int x = 0; x < UNROLL; x++)
16                    c[x] = _mm256_add_pd(c[x],
17                                         _mm256_mul_pd(_mm256_load_pd(A+n*k+x*4+i), b));
18            }
19
20            for ( int x = 0; x < UNROLL; x++ )
21                _mm256_store_pd(C+i+x*4+j*n, c[x]);
22        }
23 }
```

# Matrix Multiply

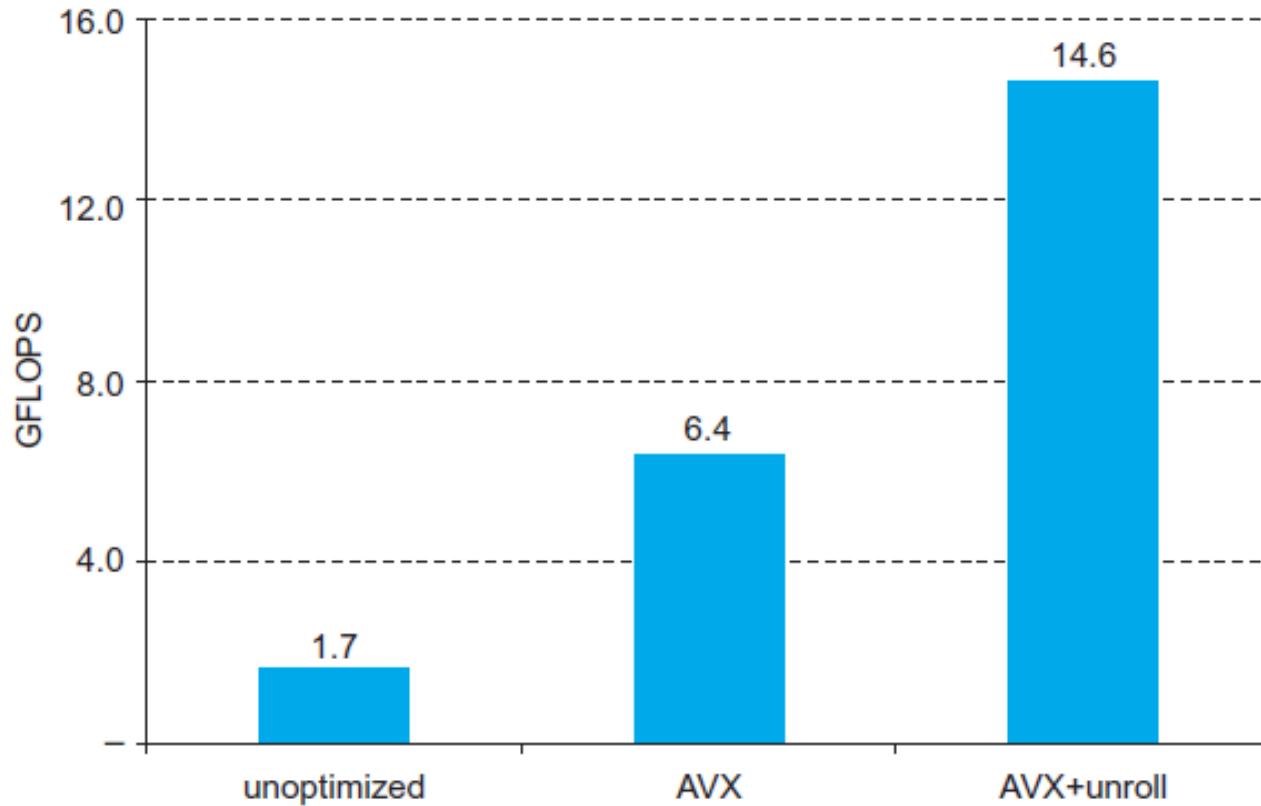
## Assembly code:

```

1 vmovapd (%r11),%ymm4          # Load 4 elements of C into %ymm4
2 mov %rbx,%rax                # register %rax = %rbx
3 xor %ecx,%ecx                # register %ecx = 0
4 vmovapd 0x20(%r11),%ymm3      # Load 4 elements of C into %ymm3
5 vmovapd 0x40(%r11),%ymm2      # Load 4 elements of C into %ymm2
6 vmovapd 0x60(%r11),%ymm1      # Load 4 elements of C into %ymm1
7 vbroadcastsd (%rcx,%r9,1),%ymm0 # Make 4 copies of B element
8 add $0x8,%rcx # register %rcx = %rcx + 8
9 vmulpd (%rax),%ymm0,%ymm5    # Parallel mul %ymm1,4 A elements
10 vaddpd %ymm5,%ymm4,%ymm4     # Parallel add %ymm5, %ymm4
11 vmulpd 0x20(%rax),%ymm0,%ymm5 # Parallel mul %ymm1,4 A elements
12 vaddpd %ymm5,%ymm3,%ymm3     # Parallel add %ymm5, %ymm3
13 vmulpd 0x40(%rax),%ymm0,%ymm5 # Parallel mul %ymm1,4 A elements
14 vmulpd 0x60(%rax),%ymm0,%ymm0 # Parallel mul %ymm1,4 A elements
15 add %r8,%rax                # register %rax = %rax + %r8
16 cmp %r10,%rcx                # compare %r8 to %rax
17 vaddpd %ymm5,%ymm2,%ymm2     # Parallel add %ymm5, %ymm2
18 vaddpd %ymm0,%ymm1,%ymm1     # Parallel add %ymm0, %ymm1
19 jne 68 <dgemm+0x68>         # jump if not %r8 != %rax
20 add $0x1,%esi                # register %esi = %esi + 1
21 vmovapd %ymm4,(%r11)          # Store %ymm4 into 4 C elements
22 vmovapd %ymm3,0x20(%r11)      # Store %ymm3 into 4 C elements
23 vmovapd %ymm2,0x40(%r11)      # Store %ymm2 into 4 C elements
24 vmovapd %ymm1,0x60(%r11)      # Store %ymm1 into 4 C elements

```

# Performance Impact



# Fallacies

- Pipelining is easy (!)
  - The basic idea is easy
  - The devil is in the details
    - e.g., detecting data hazards
- Pipelining is independent of technology
  - So why haven't we always done pipelining?
  - More transistors make more advanced techniques feasible
  - Pipeline-related ISA design needs to take account of technology trends
    - e.g., predicated instructions

# Pitfalls

- Poor ISA design can make pipelining harder
  - e.g., complex instruction sets (VAX, IA-32)
    - Significant overhead to make pipelining work
    - IA-32 micro-op approach
  - e.g., complex addressing modes
    - Register update side effects, memory indirection
  - e.g., delayed branches
    - Advanced pipelines have long delay slots

# Concluding Remarks

- ISA influences design of datapath and control
- Datapath and control influence design of ISA
- Pipelining improves instruction throughput using parallelism
  - More instructions completed per second
  - Latency for each instruction not reduced
- Hazards: structural, data, control
- Multiple issue and dynamic scheduling (ILP)
  - Dependencies limit achievable parallelism
  - Complexity leads to the power wall