

# Arquitectura de Computadores

## **Capítulo 2.** **Procesadores segmentados**

Based on the original material of the book:  
D.A. Patterson y J.L. Hennessy “Computer Organization and Design:  
The Hardware/Software Interface” 4<sup>th</sup> edition.

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# Agenda

- The Processor: A Basic MIPS Implementation
  - Building a Datapath
  - Designing the Control Unit (single cycle)
- An Overview of Pipelining
  - MIPS five stages pipeline
  - MIPS Pipelined Datapath and Control
- Pipeline performance
  - MIPS Pipelined Hazards: Structure, Data and Control
  - Data Hazards: Forwarding vs Stalling
  - Control Hazards: Branch prediction

# 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`

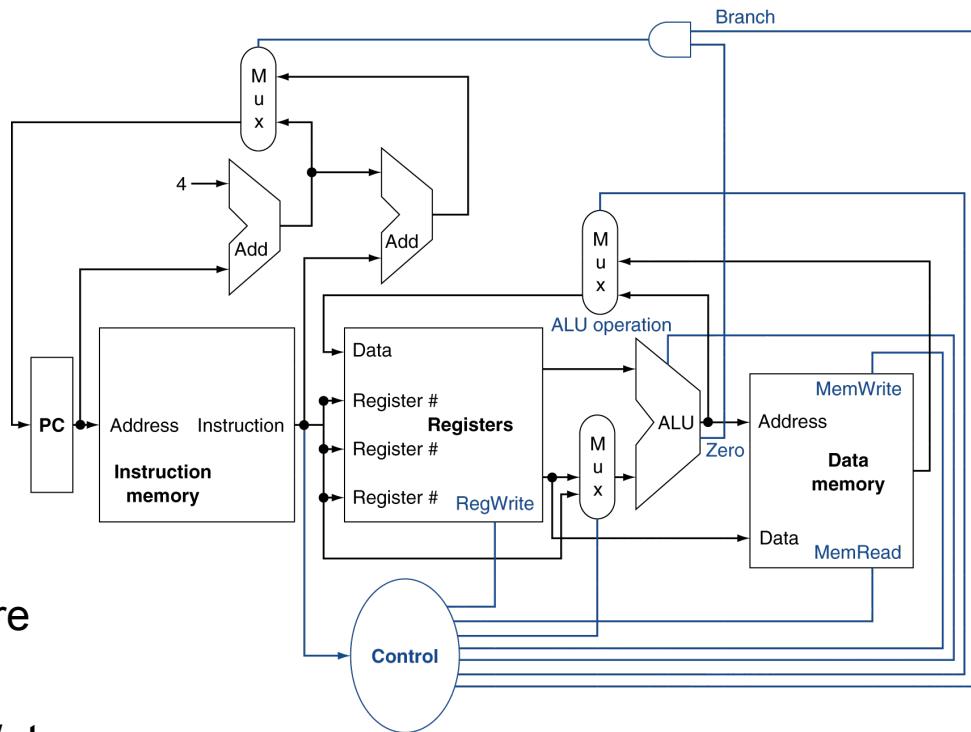
# Introduction (2)

- We will study simple RISC processor called MIPS (Microprocessor without Interlocked Pipeline Stages)
  - 32 bits processor (data, memory)
  - 32 general purpose registers
  - Separated data and code memory  
(Harvard architecture)

# CPU Overview

## Instruction Execution

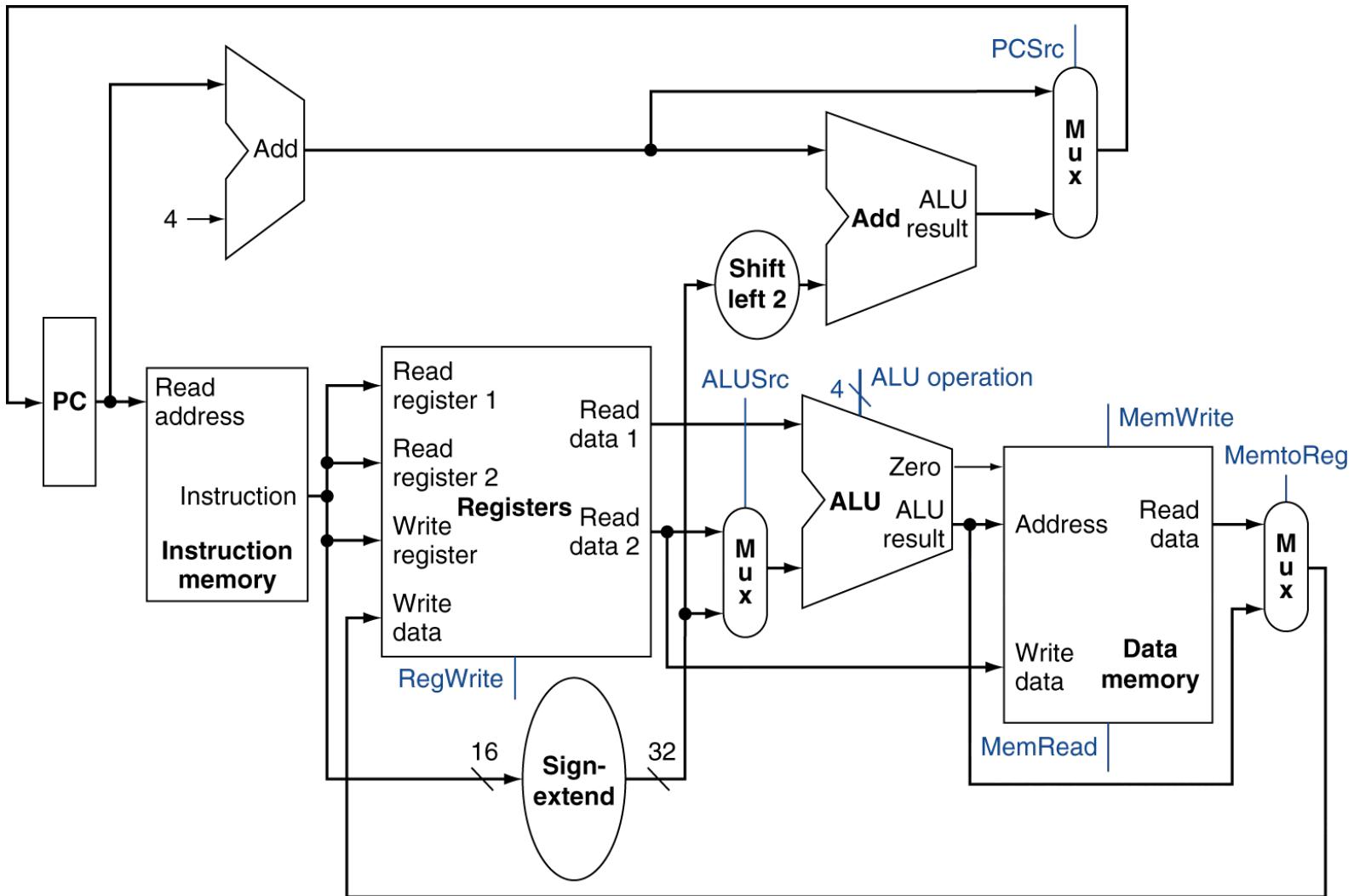
- PC → instruction memory, fetch instruction
- Register numbers → register file, read registers
- Depending on instruction class
  - Use ALU to calculate
    - Arithmetic result
    - Memory address for load/store
    - Branch target address
  - Access data memory for load/store
  - PC ← target address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



# Datapath & control design

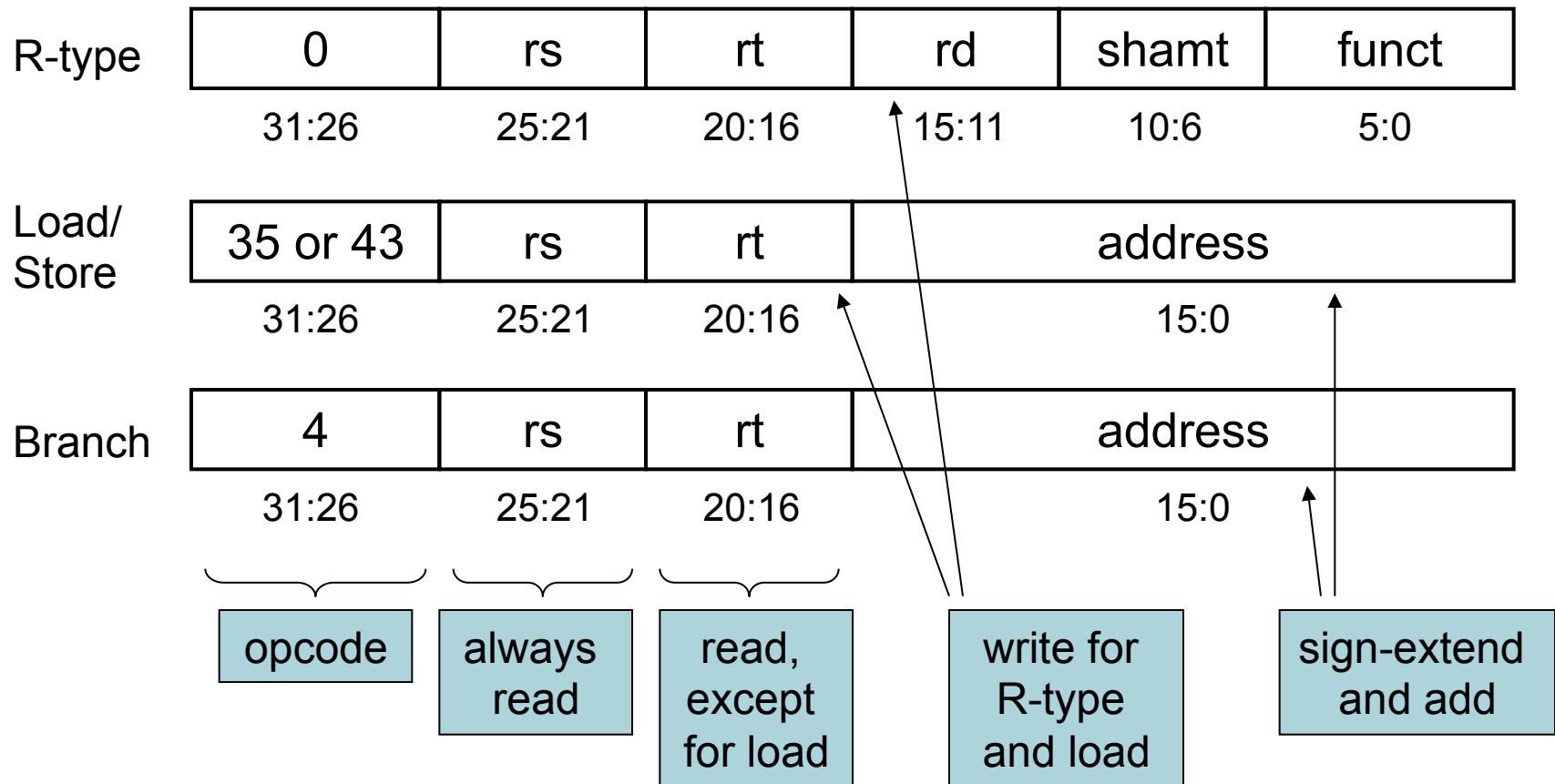
- Datapath: Elements that process data and addresses in the CPU
  - Registers, ALUs, mux's, memories, ...
  - We will build a MIPS datapath incrementally
- Control Unit: Information comes from the 32 bits of the instruction and the control lines select:
  - Registers to be read (always read two).
  - The operation to be performed by ALU
  - If data memory is to be read or written
  - What is written and where in the register file
  - What goes in PC
- Combinational Single Cycle implementation

# Full Datapath



# The Main Control Unit

- Control signals derived from instruction



# ALU Control

- ALU used for
  - Load/Store:  $F = \text{add}$
  - Branch:  $F = \text{subtract}$
  - R-type:  $F$  depends on funct field

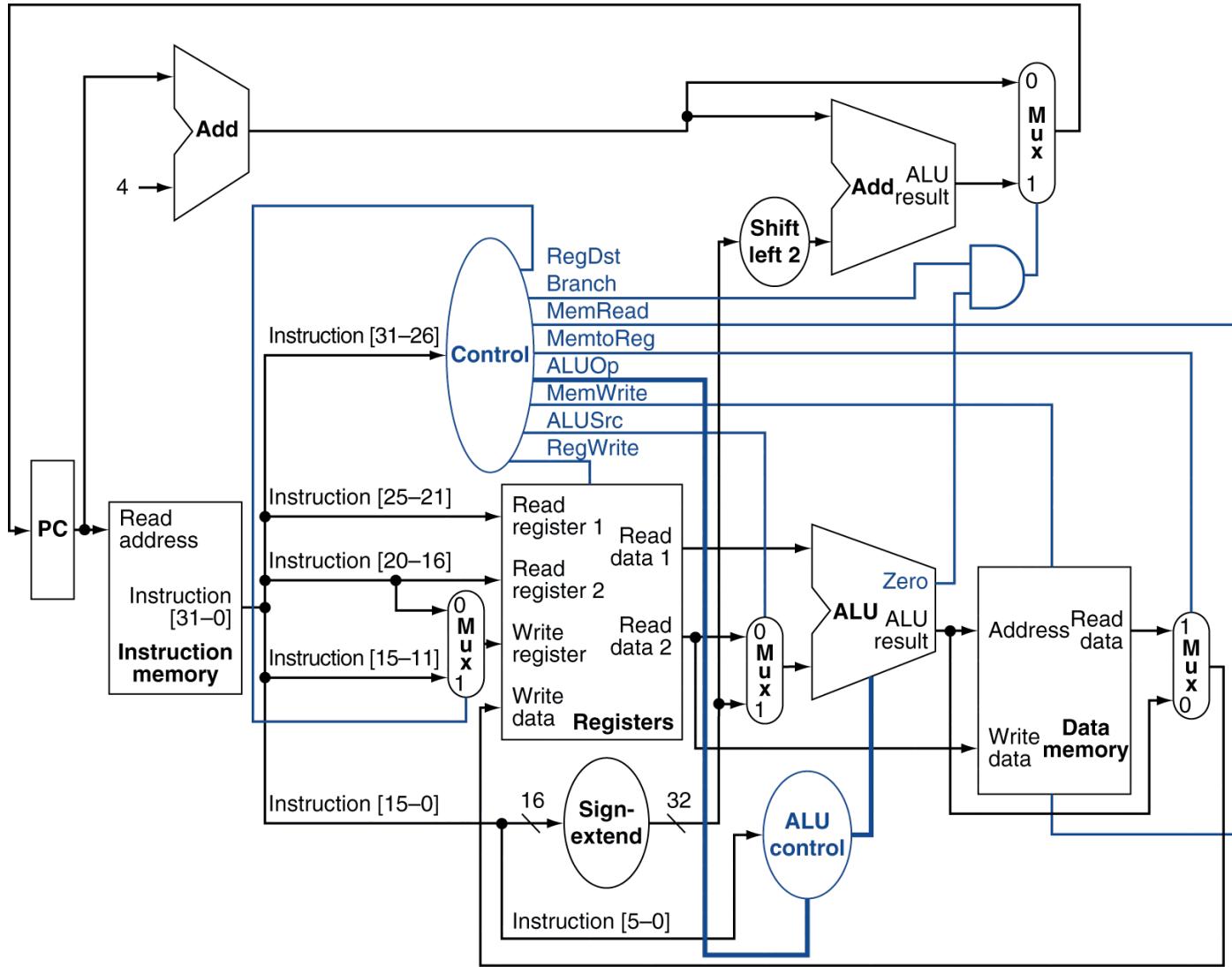
ALU control	Function
0000	AND
0001	OR
0010	add
0110	subtract
0111	set-on-less-than
1100	NOR

# ALU Control

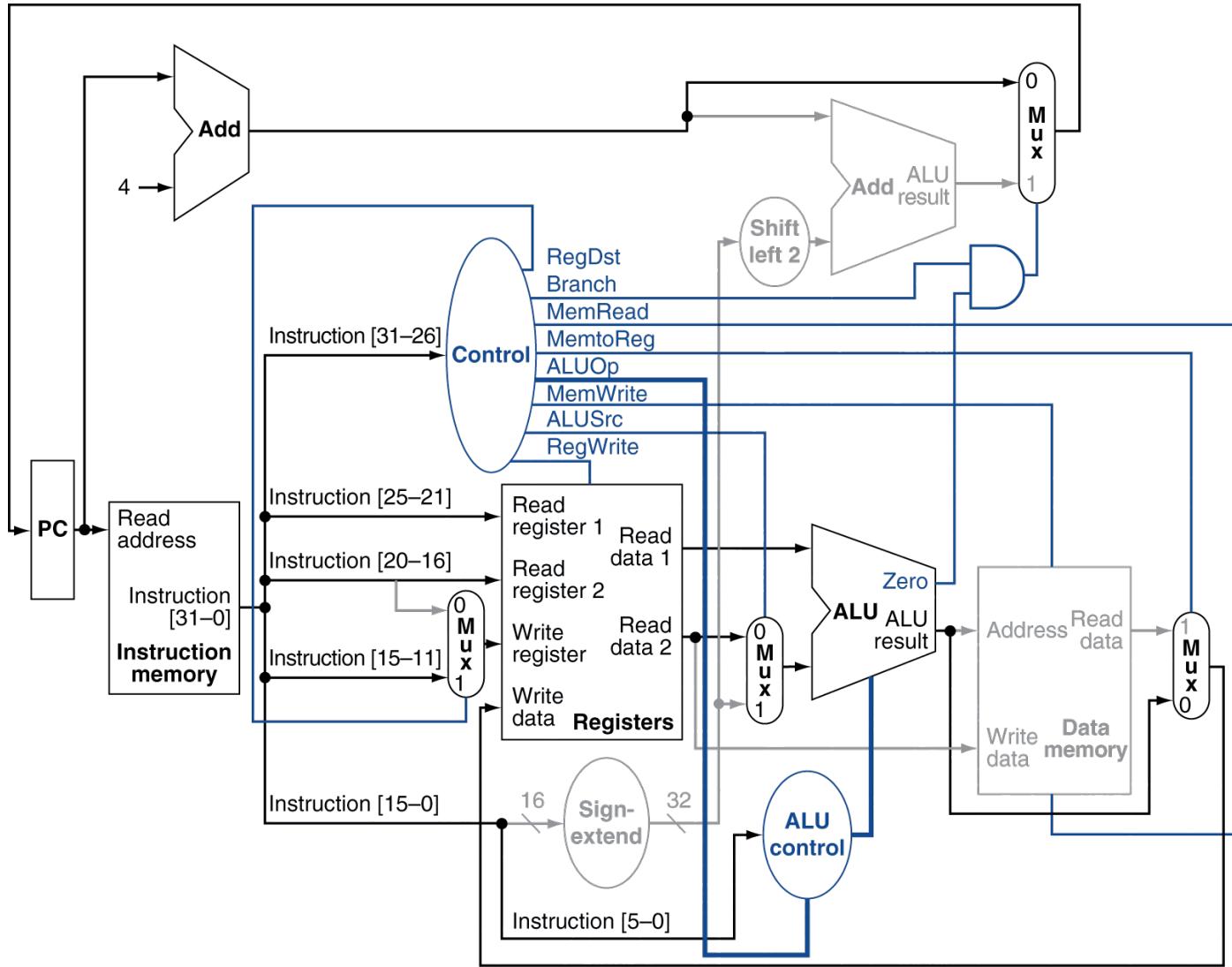
- Assume 2-bit ALUOp derived from opcode
  - Combinational logic derives ALU control

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

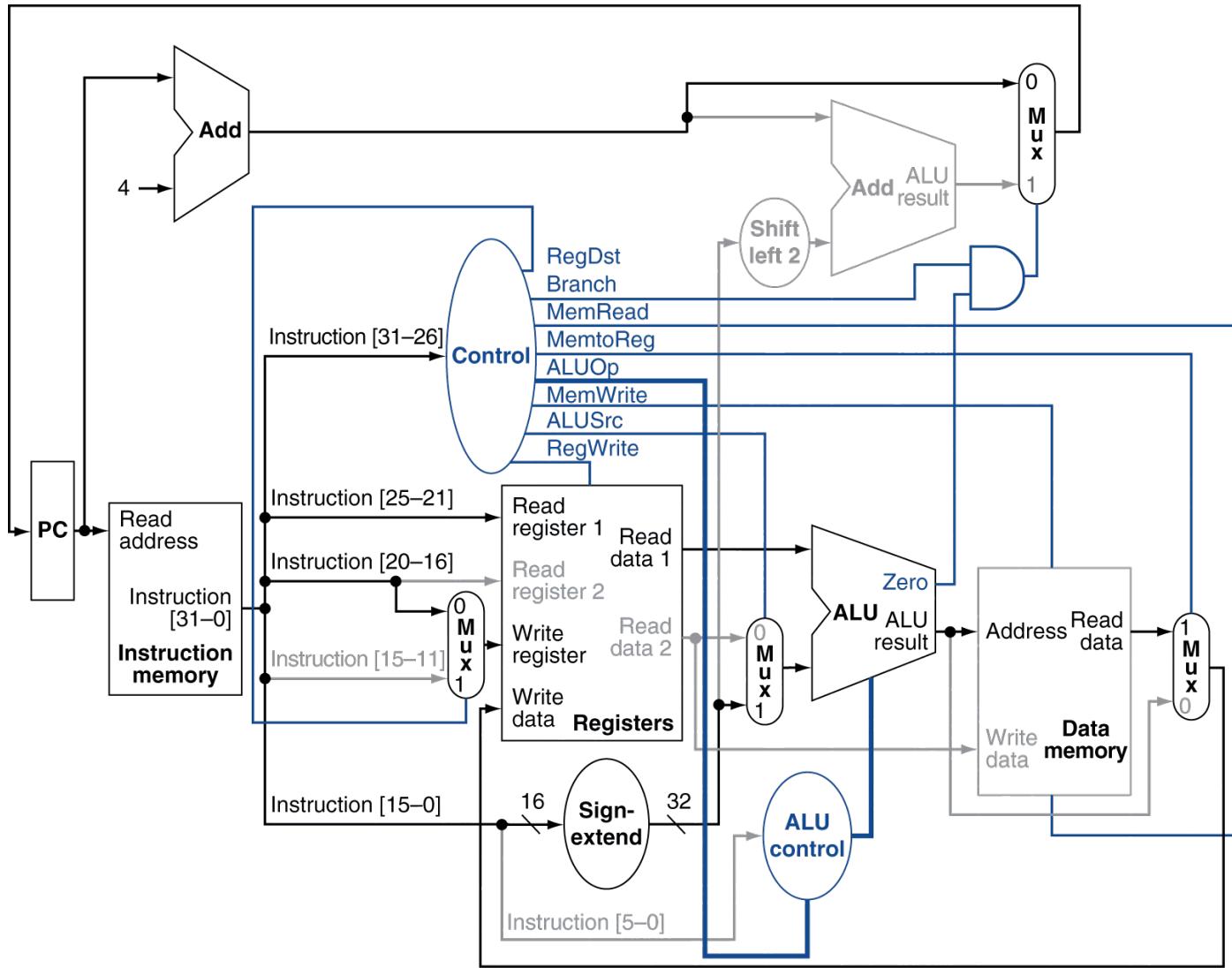
# Datapath With Control



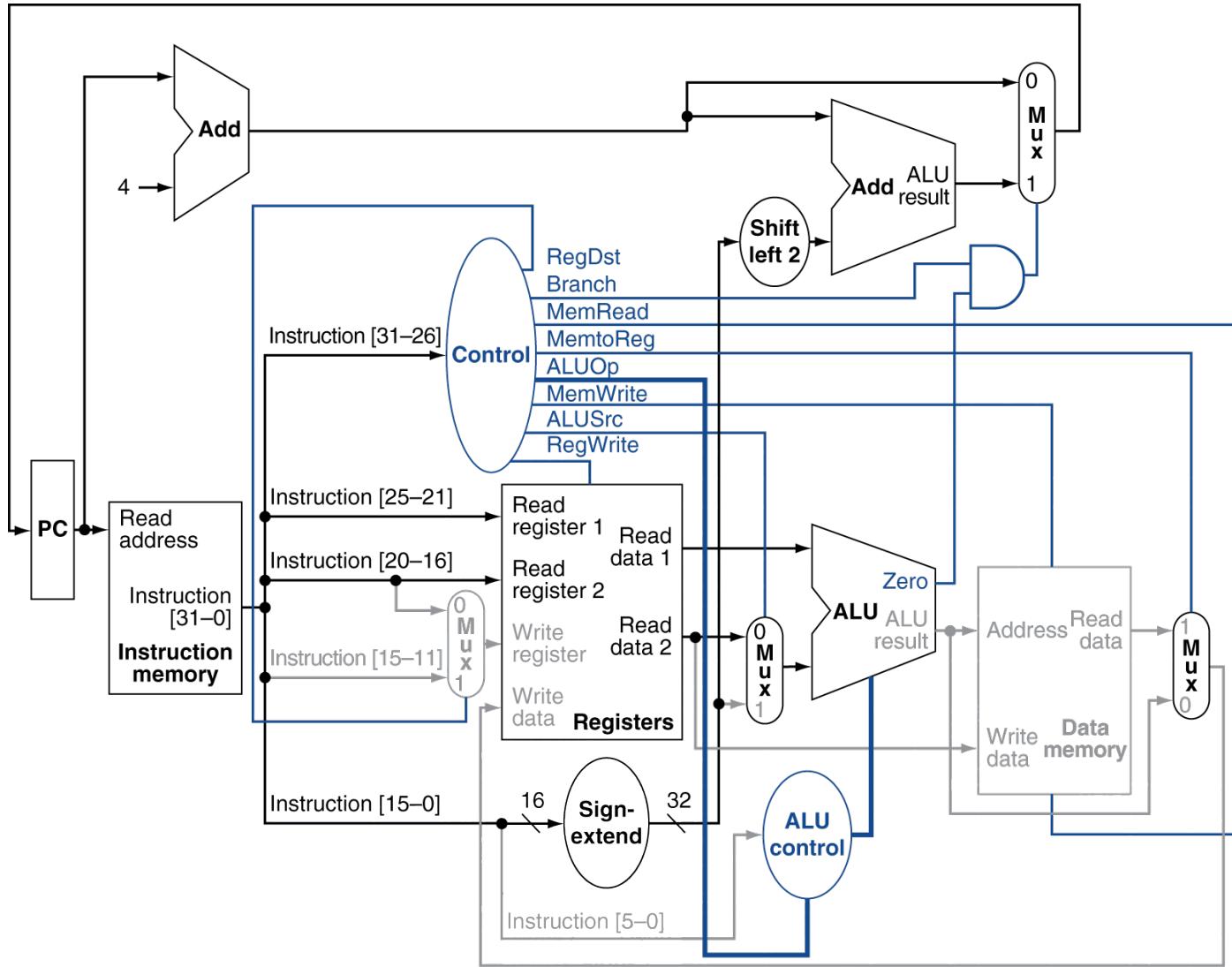
# R-Type Instruction



# Load Instruction

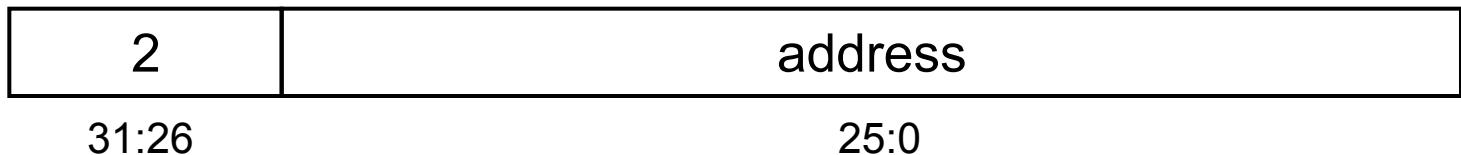


# Branch-on-Equal Instruction



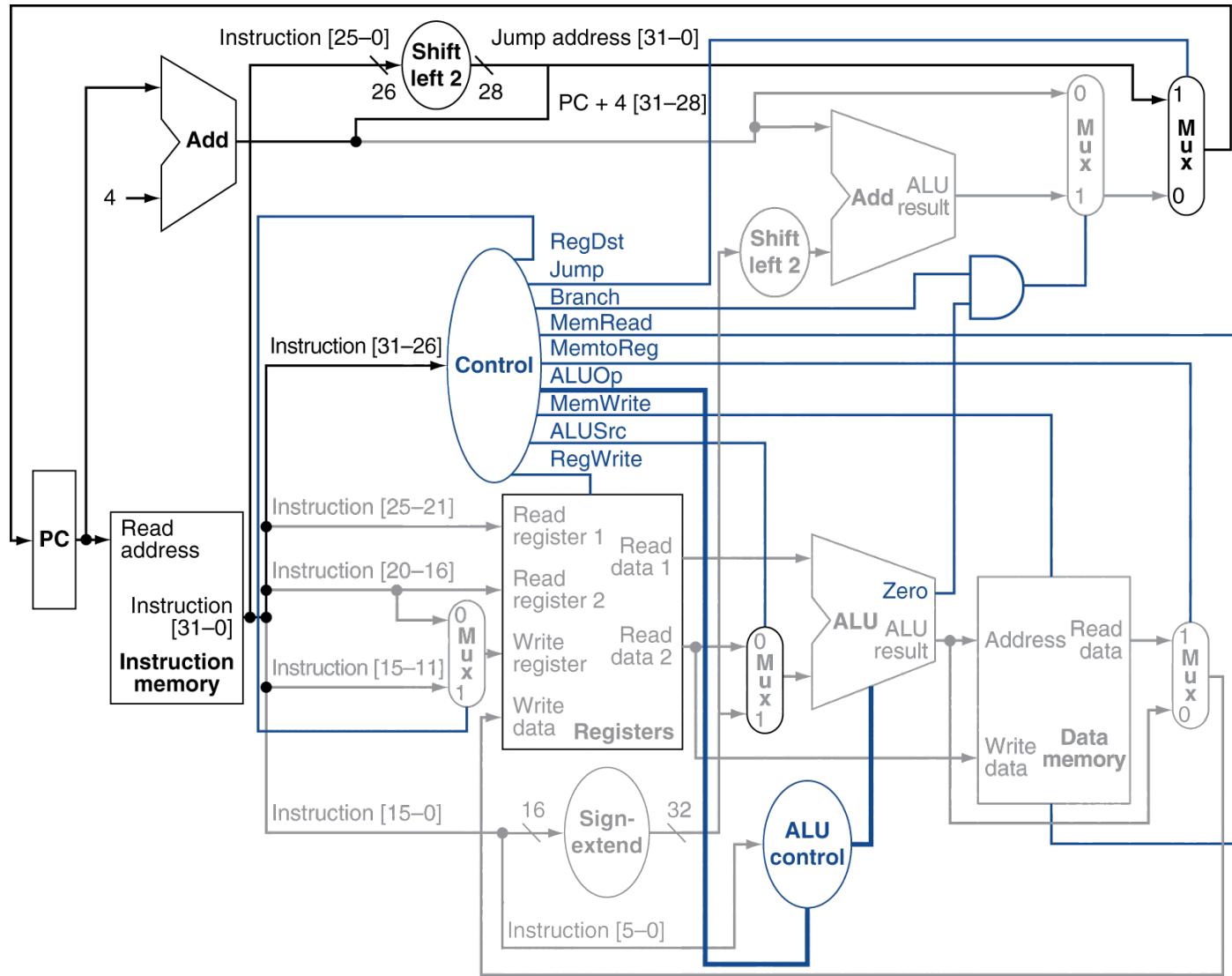
# Implementing Jumps

Jump



- 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

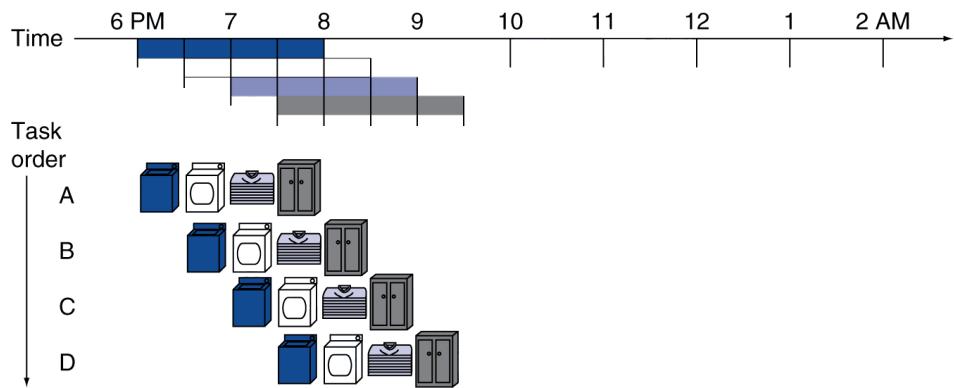
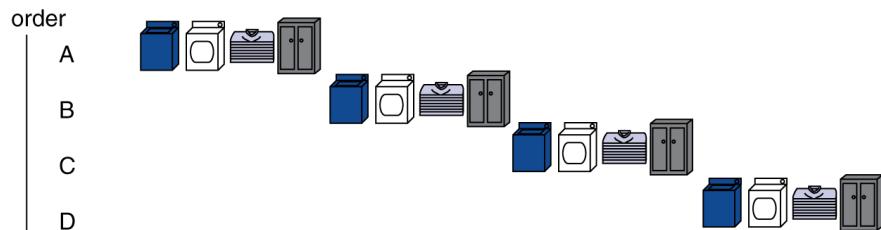
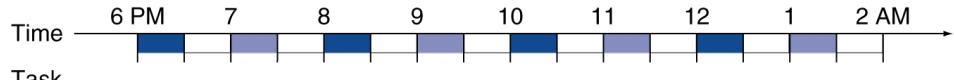
- Longest delay determines clock period
  - Critical path: load instruction
  - Instruction memory → register file → ALU → data memory → register file
- Not feasible to vary period for different instructions
- Violates design principle
  - Making the common case fast
- We will improve performance by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

# Agenda

- A Basic MIPS Implementation
  - Building a Datapath
  - Designing the Control Unit (single cycle)
- An Overview of Pipelining
  - MIPS five stages pipeline
  - MIPS Pipelined Datapath and Control
- Pipeline performance
  - MIPS Pipelined Hazards: Structure, Data and Control
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# Pipelining Analogy

- Pipelined laundry: overlapping execution
  - Parallelism improves performance

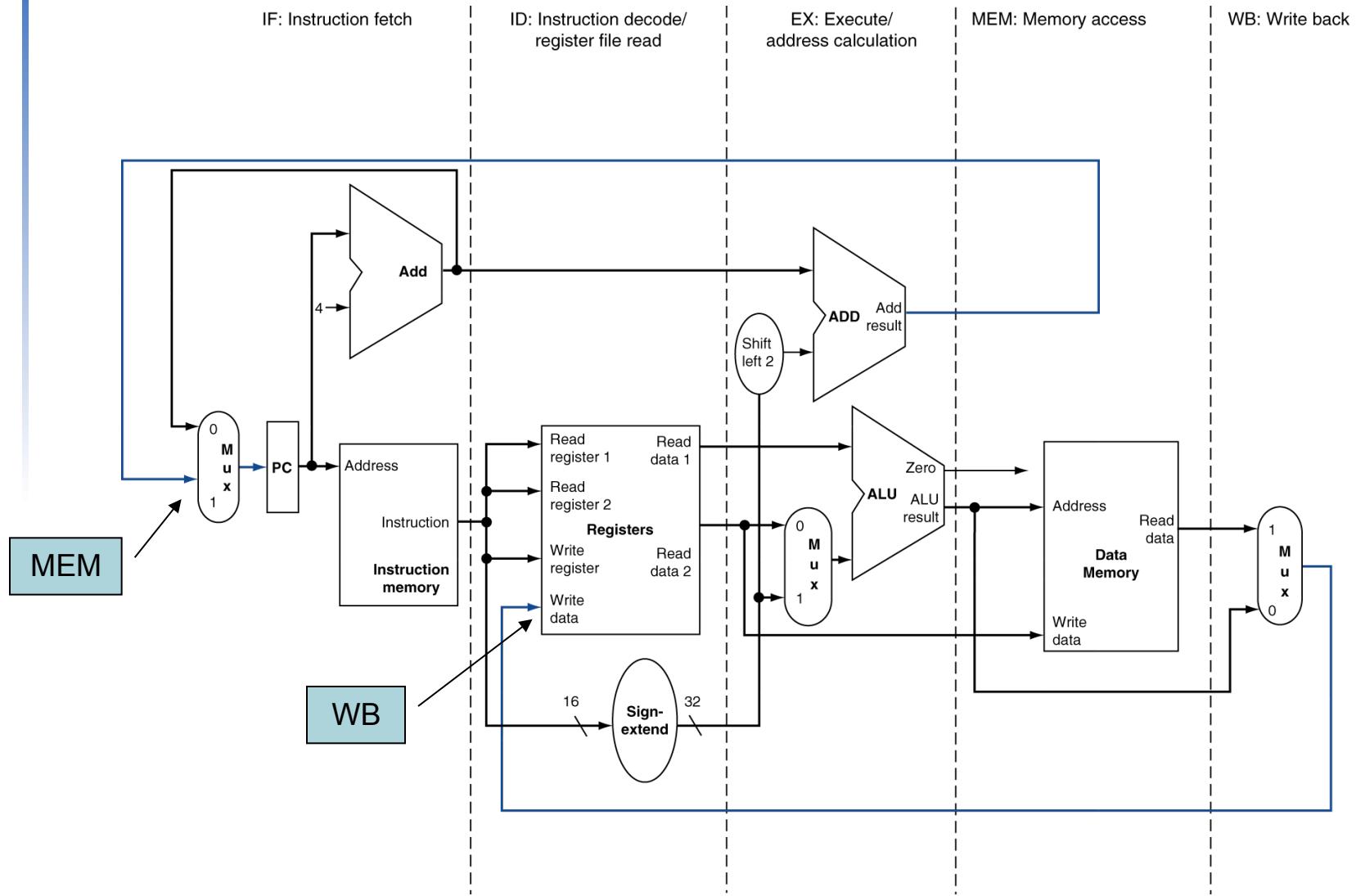


- Four loads:
  - Speedup  
 $= 8/3.5 = 2.3$
- Non-stop:
  - Speedup  
 $= 2n/0.5n + 1.5 \approx 4$   
= number of stages

# MIPS Pipeline

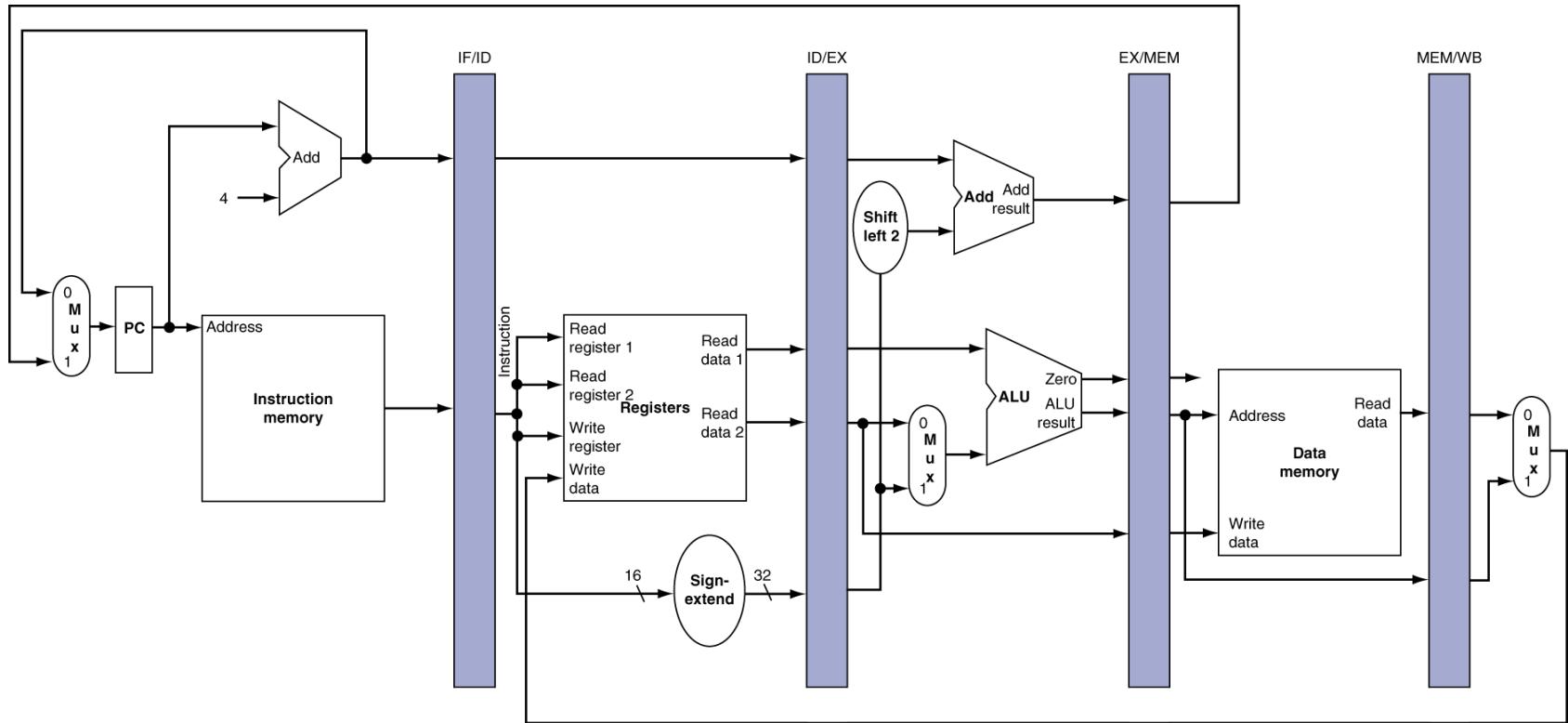
- Five stages, one step per stage
  1. IF: Instruction fetch from memory
  2. ID: Instruction decode & register read
  3. EX: Execute operation or calculate address
  4. MEM: Access memory operand or PC+IMM
  5. WB: Write result back to register

# MIPS Pipelined Datapath



# Pipeline registers

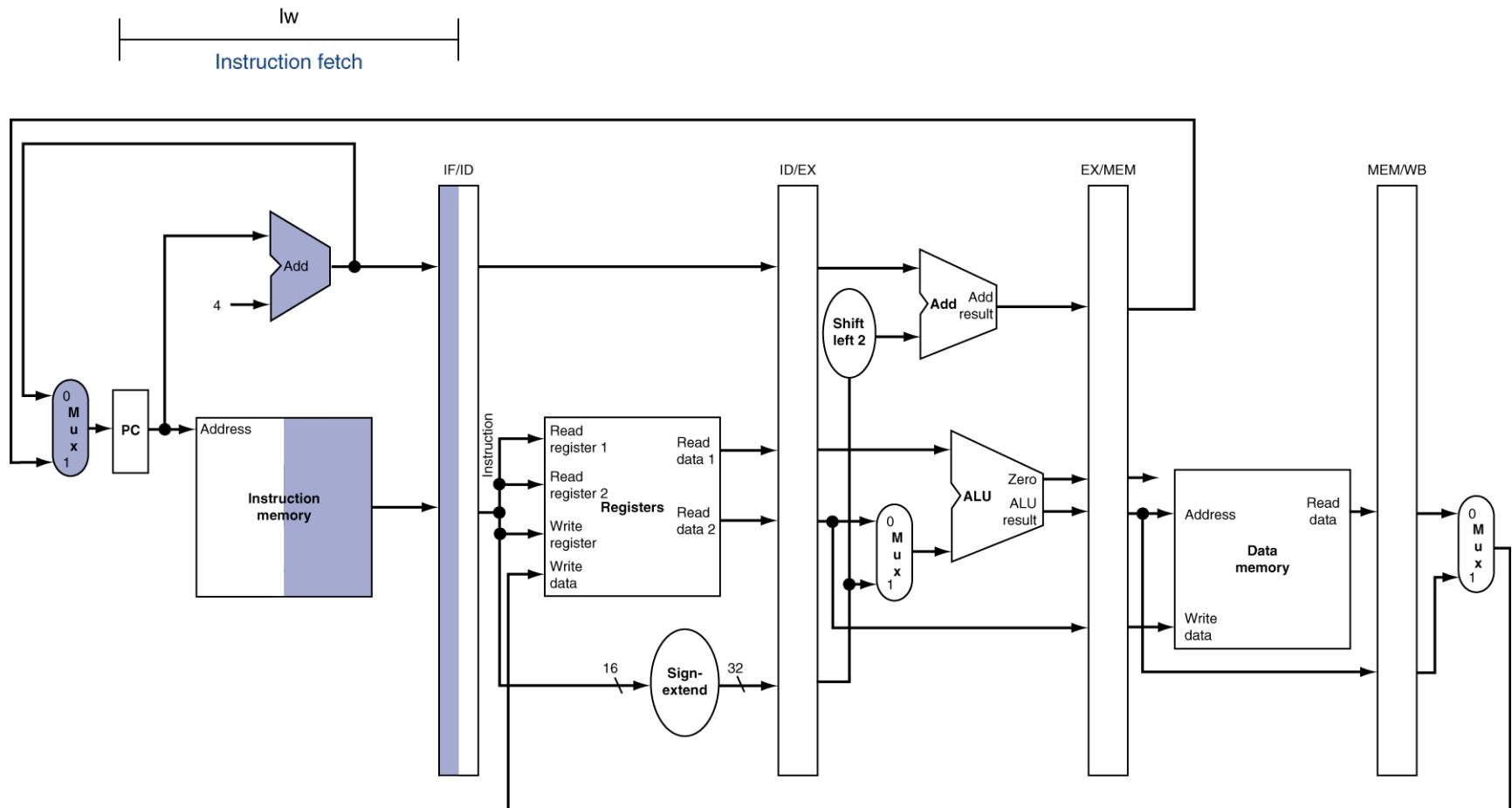
- Need registers between stages
  - To hold information produced in previous cycle



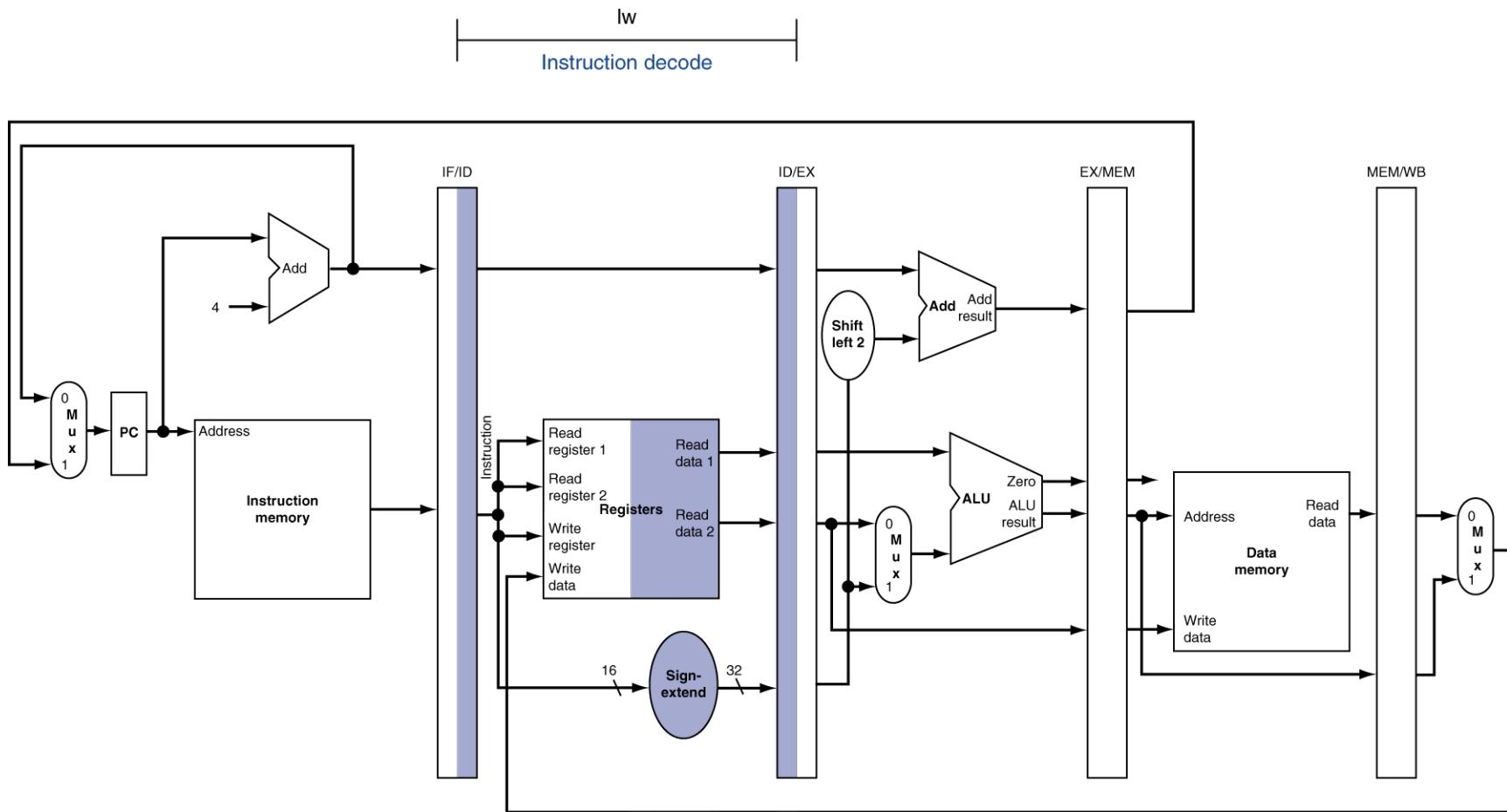
# Pipeline Operation

- 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

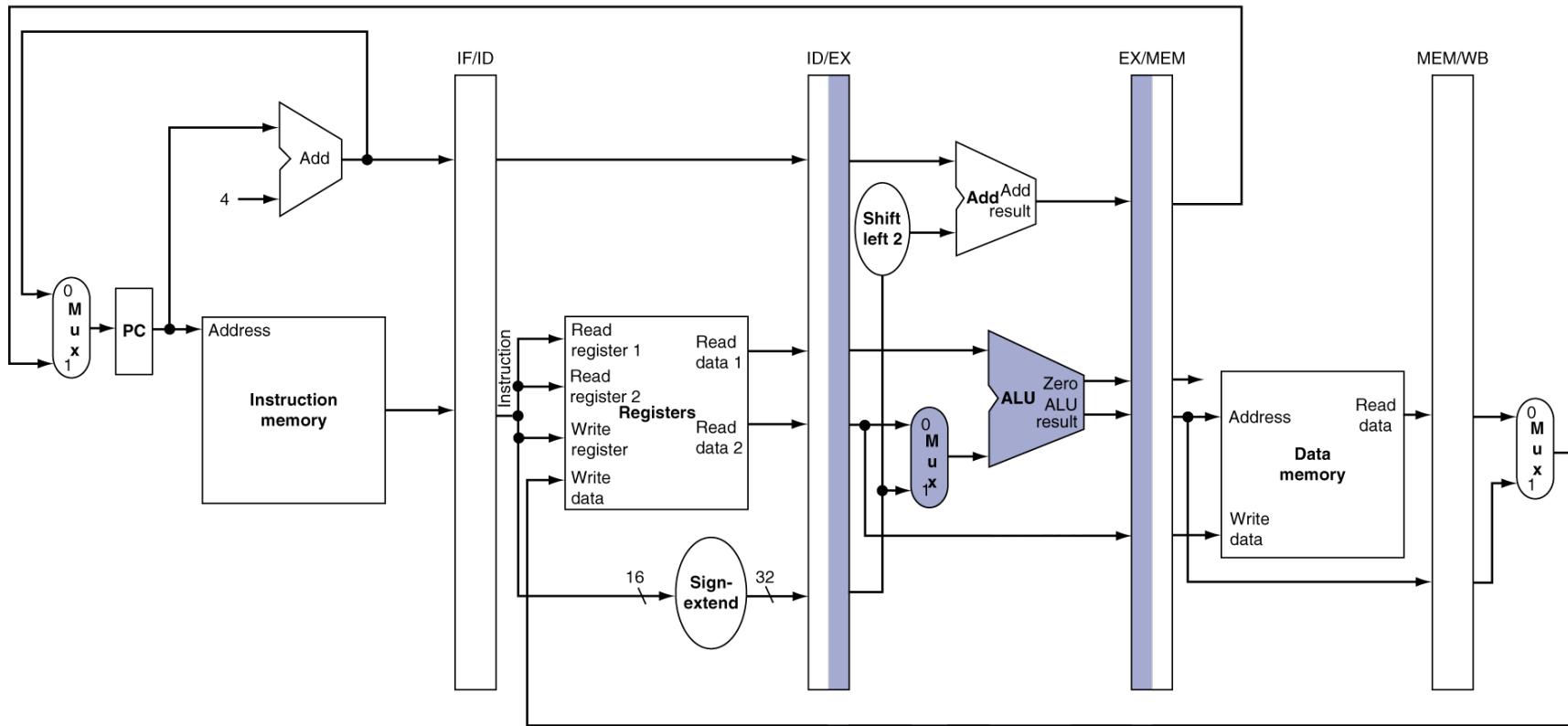
# IF for Load, Store, ...



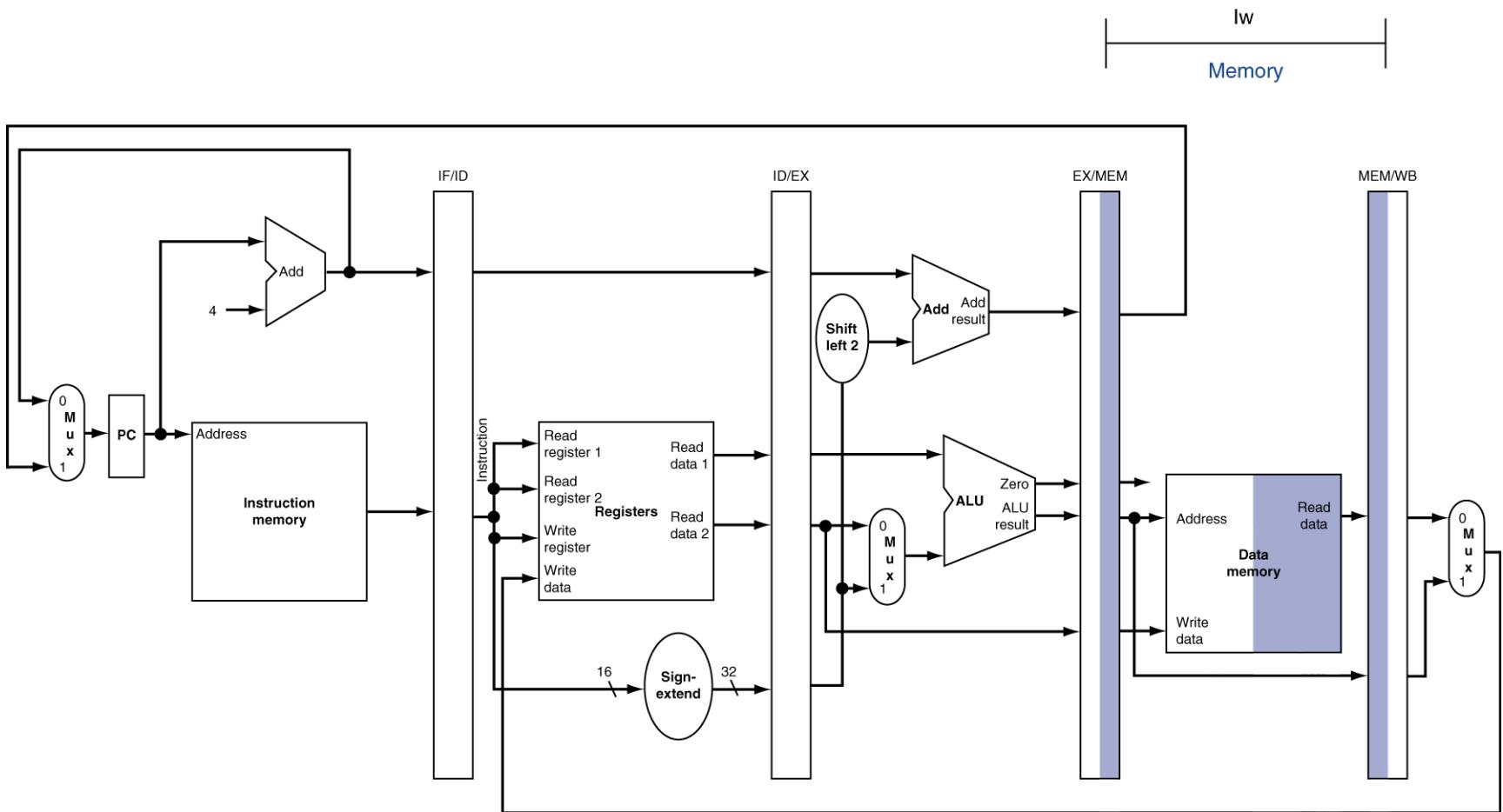
# ID for Load, Store, ...



# EX for Load

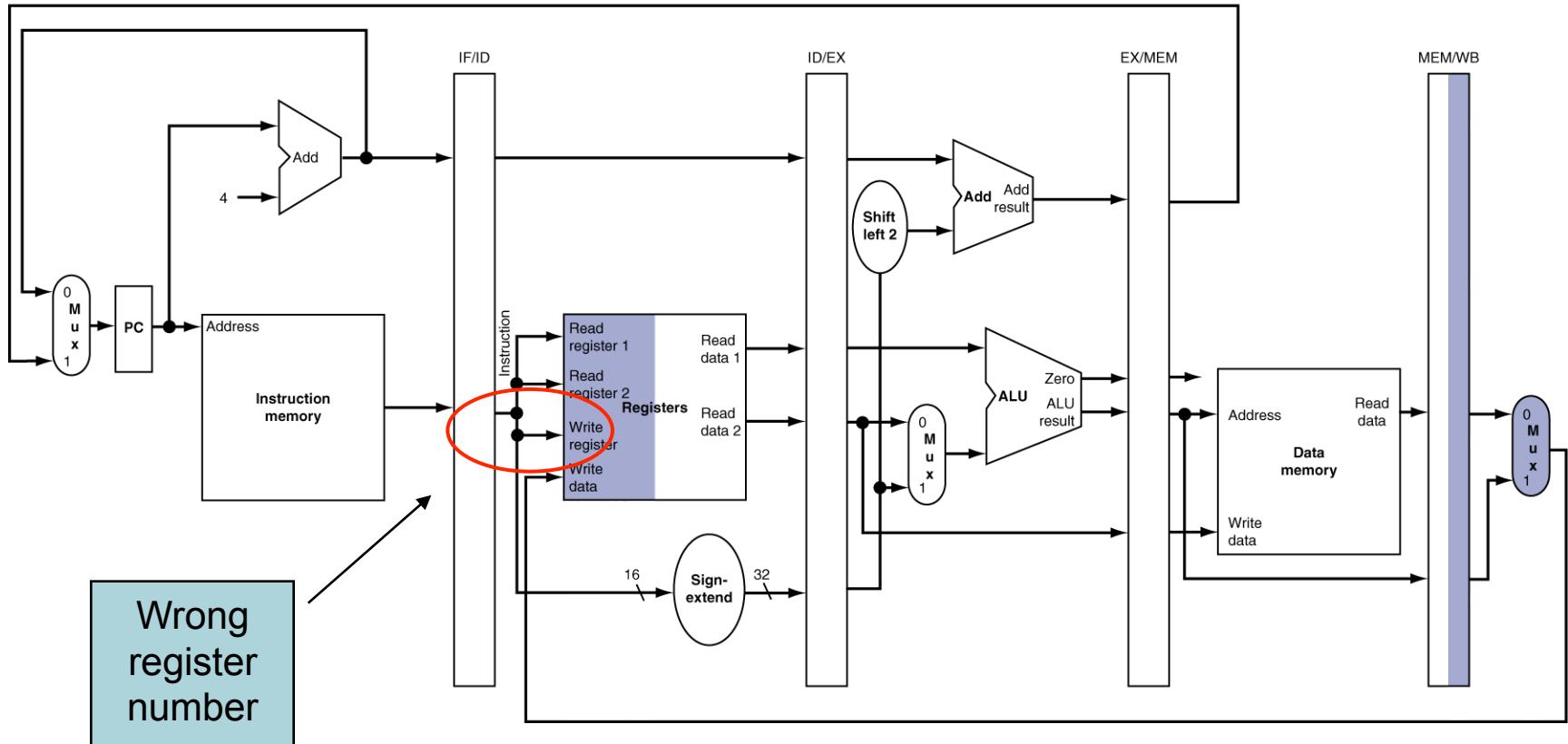


# MEM for Load

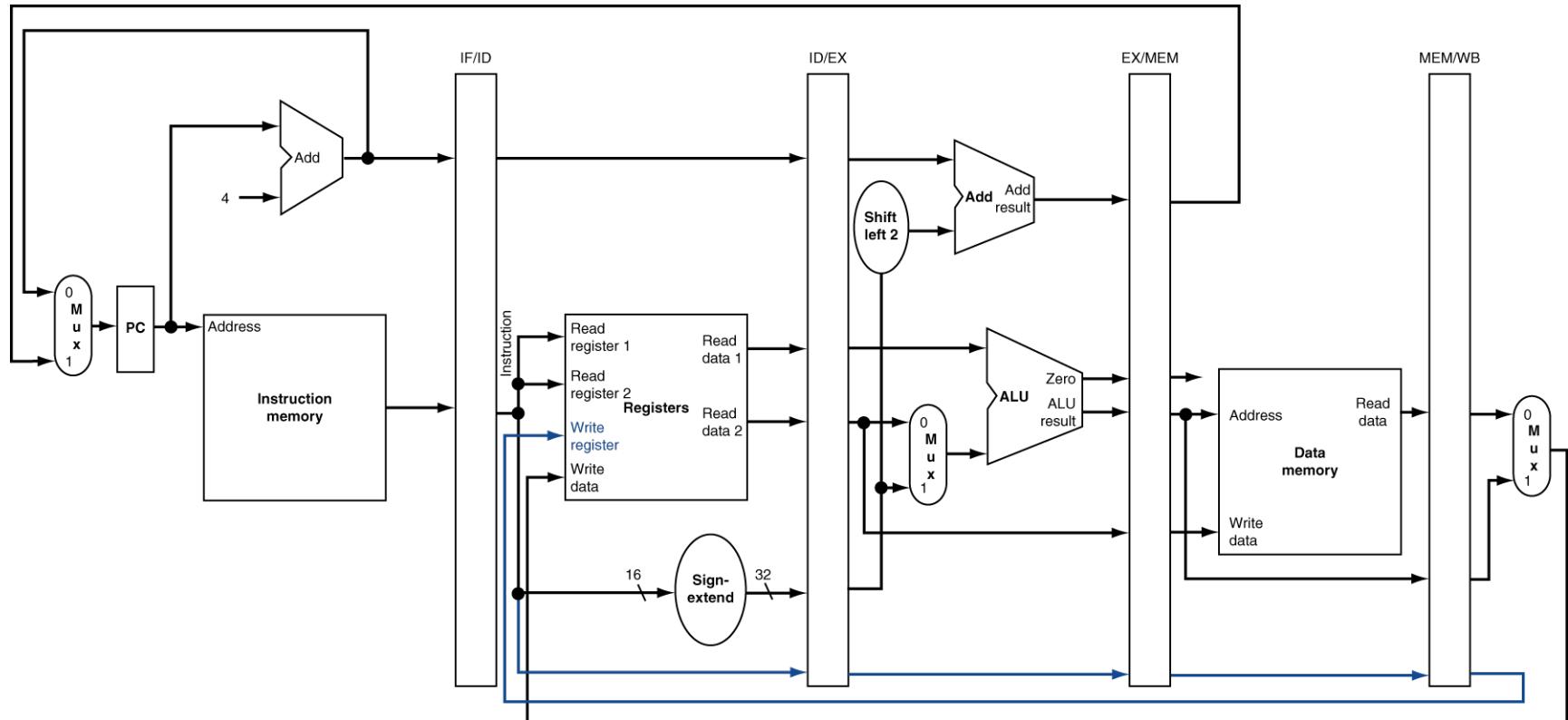


# WB for Load

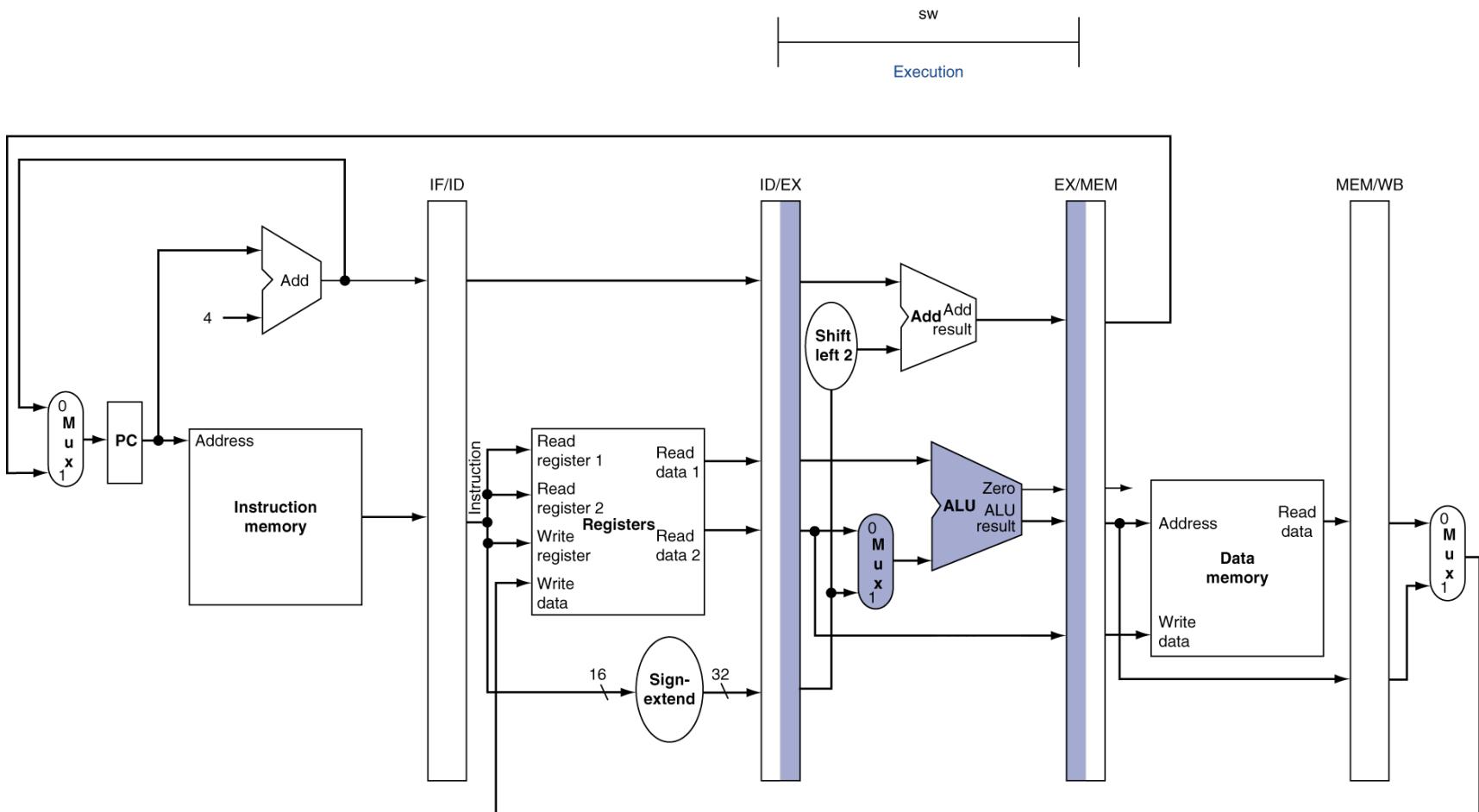
Iw  
Write back



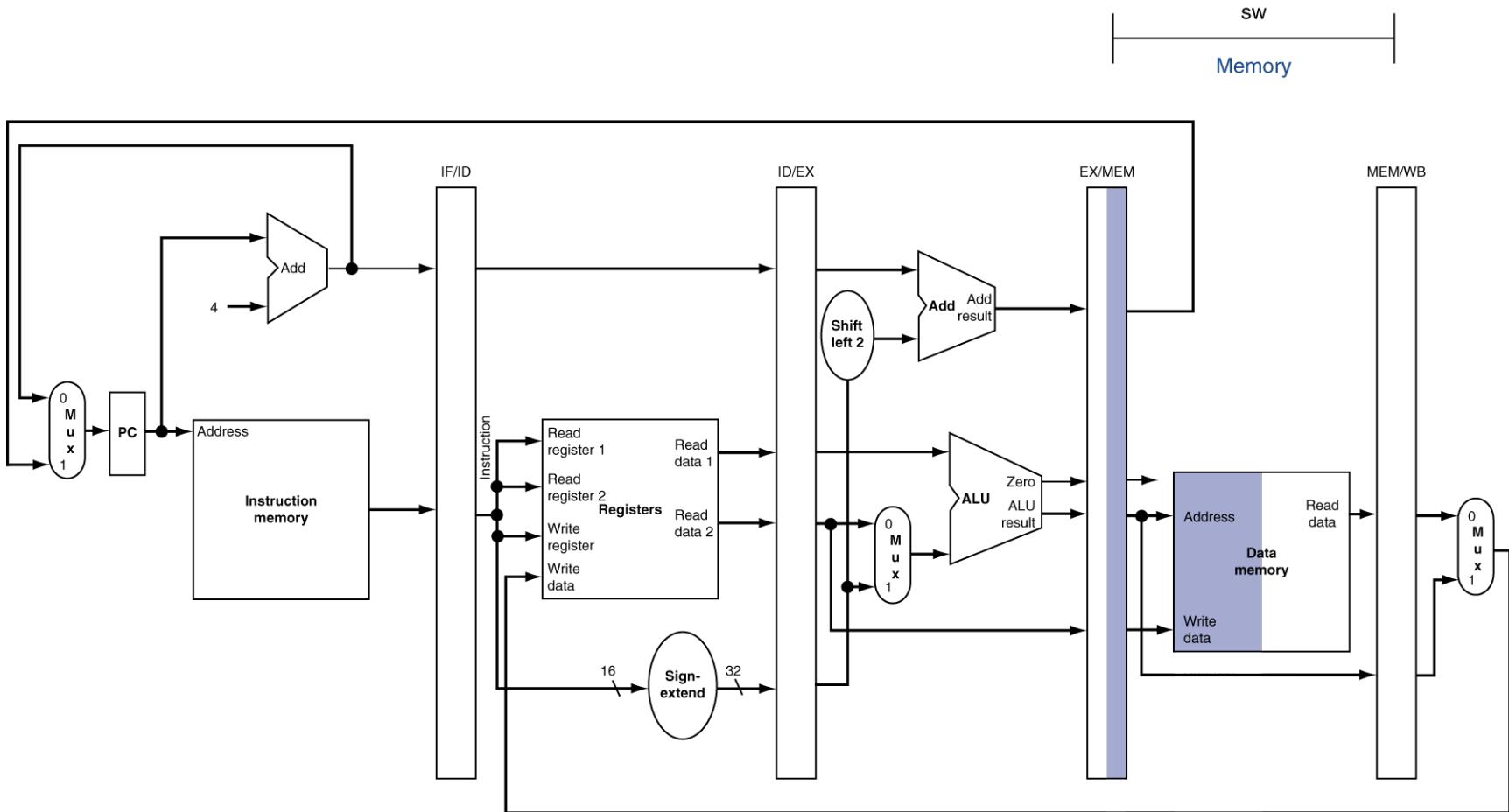
# Corrected Datapath for Load



# EX for Store

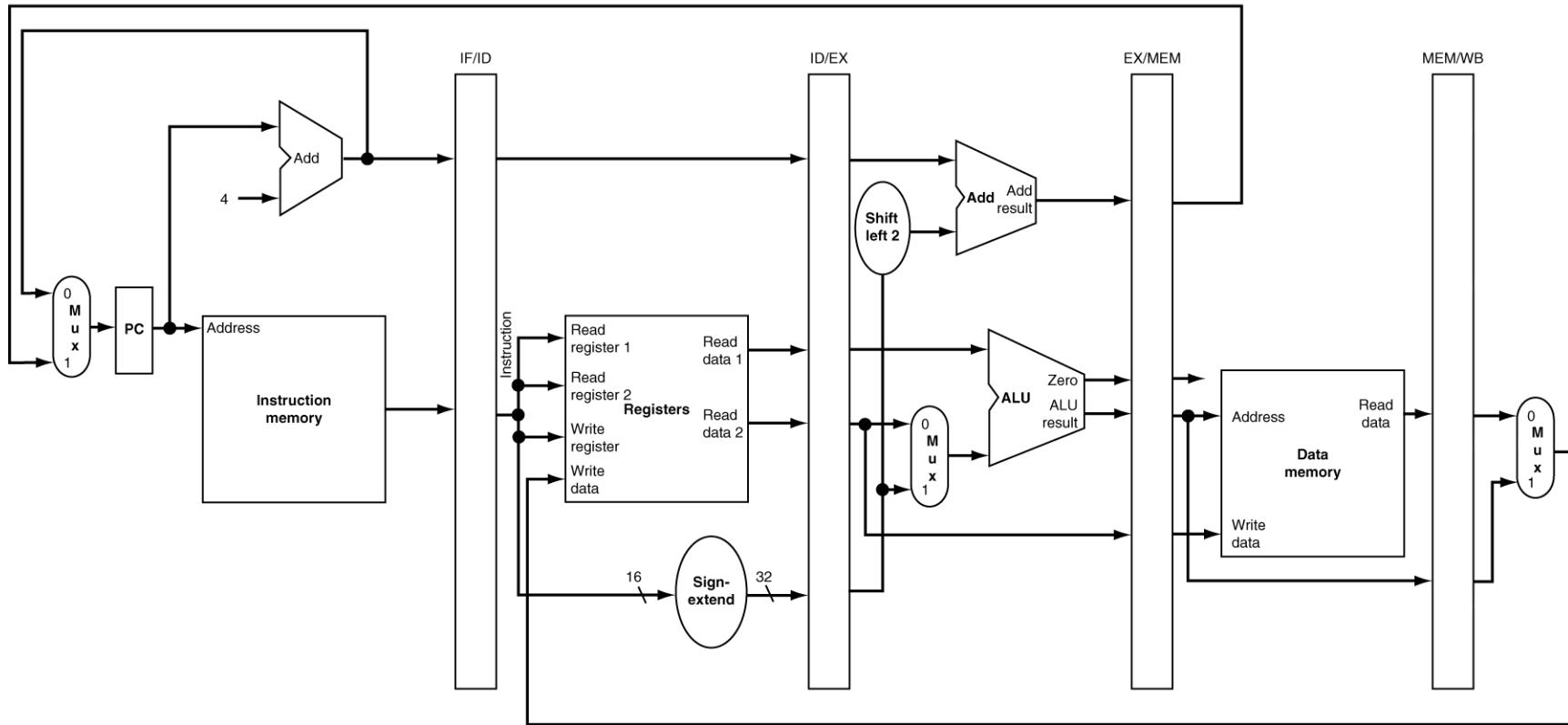


# MEM for Store



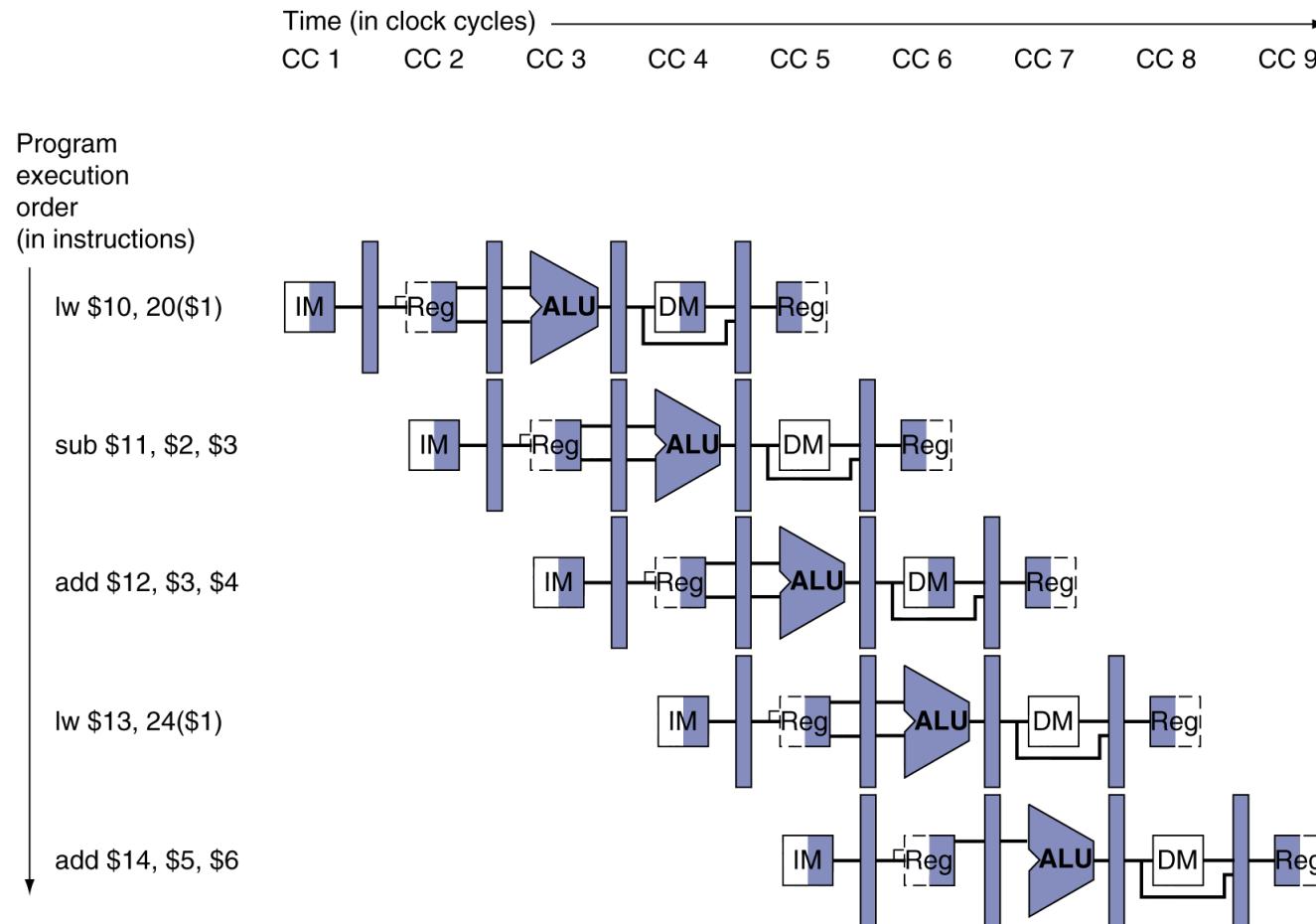
# WB for Store

SW  
Write-back



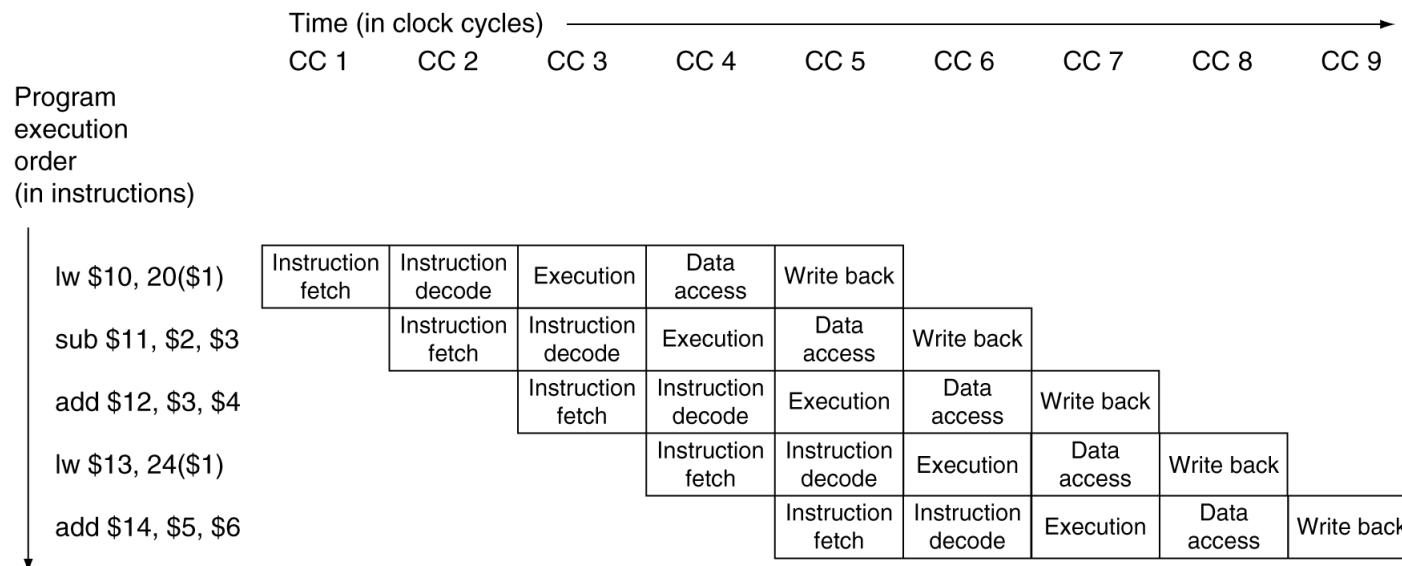
# Multi-Cycle Pipeline Diagram

## Form showing resource usage



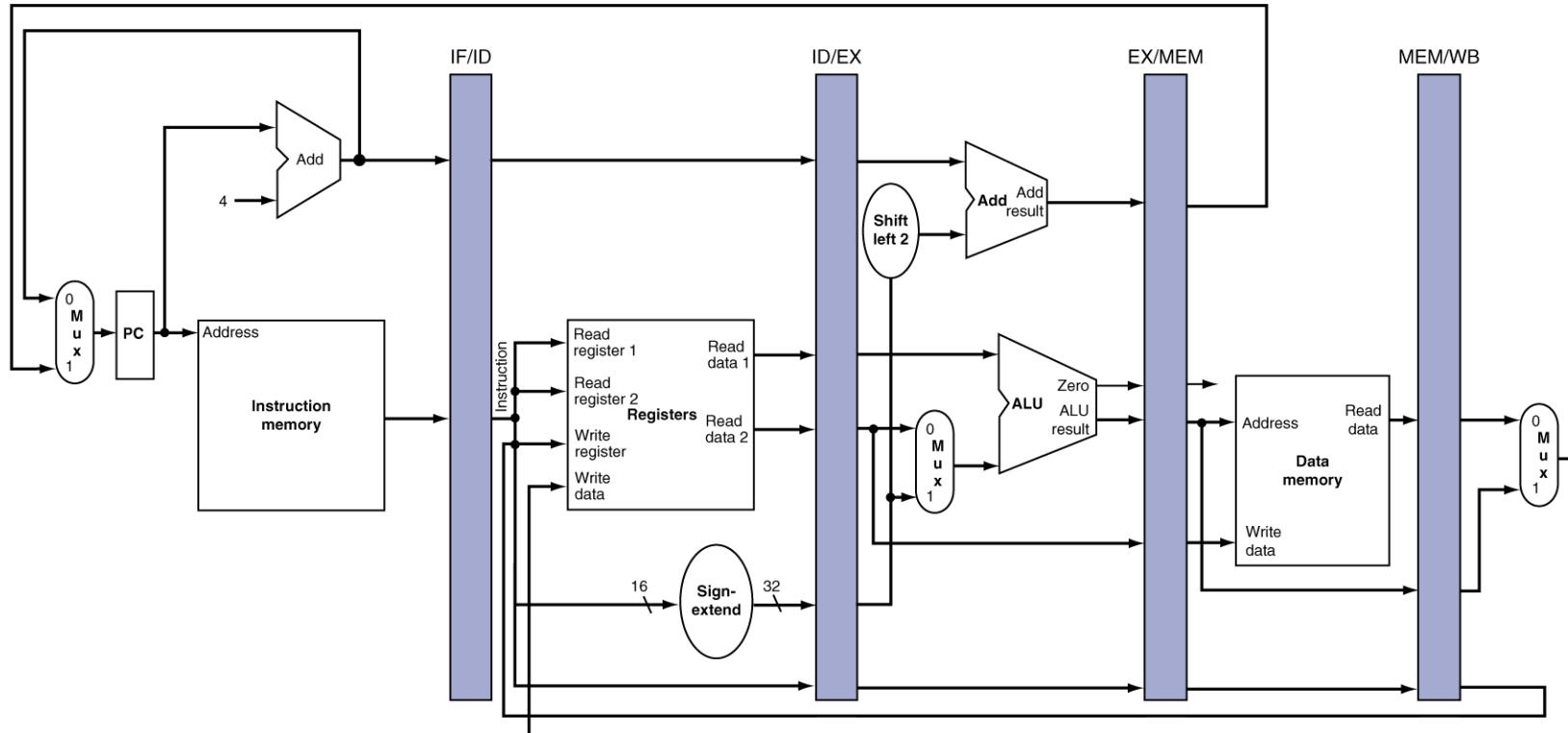
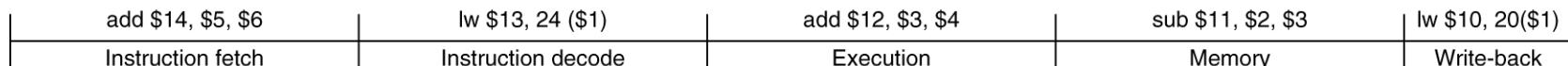
# Multi-Cycle Pipeline Diagram

## Traditional form

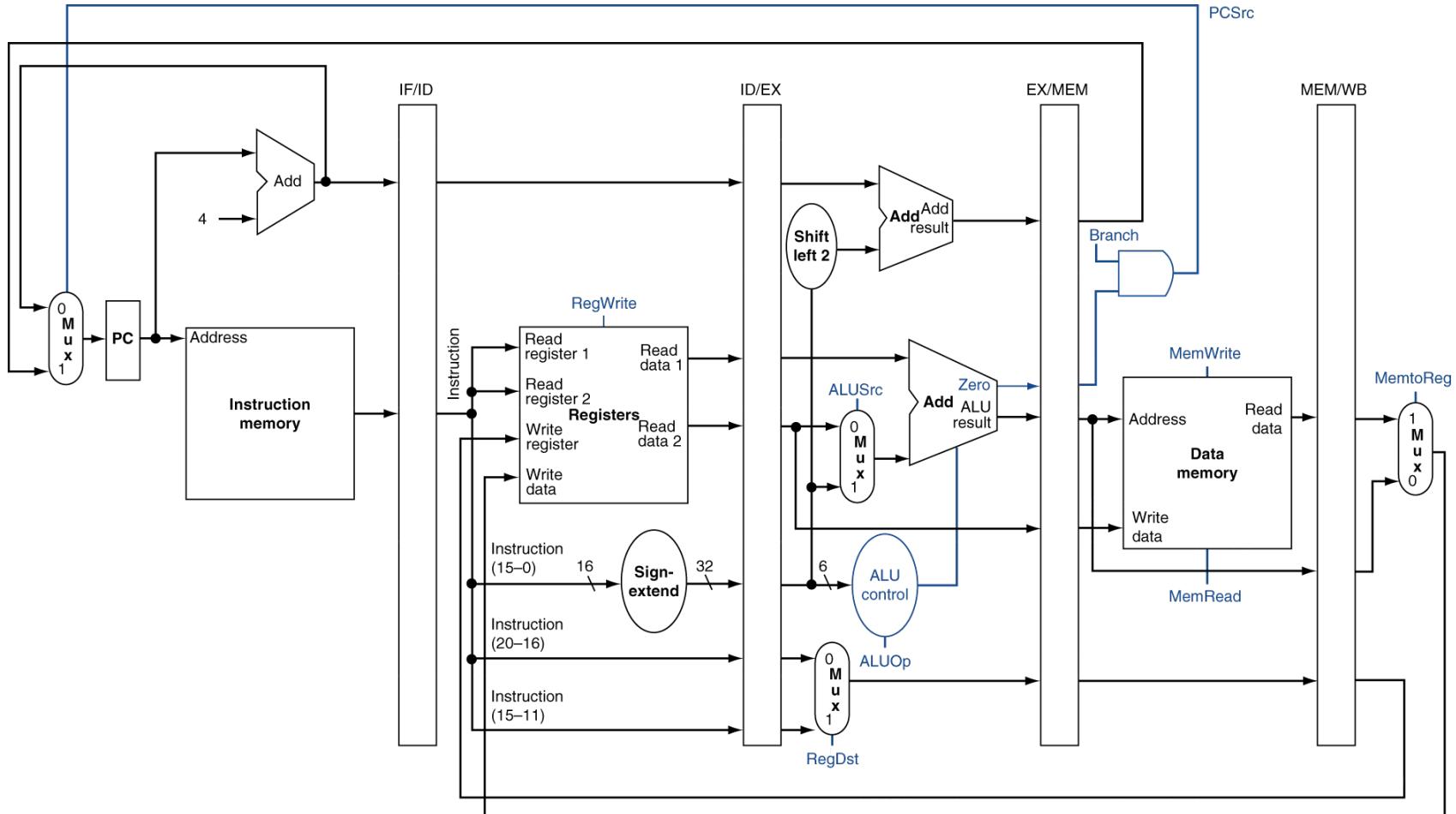


# Single-Cycle Pipeline Diagram

## State of pipeline in a given cycle

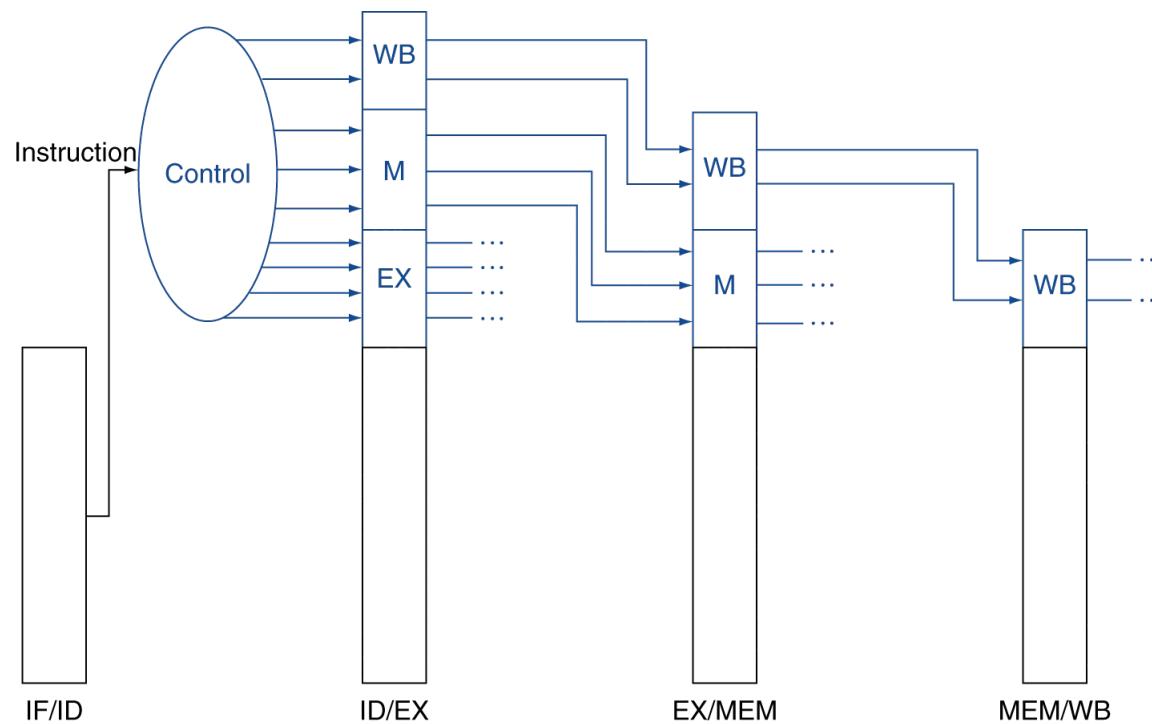


# Pipelined Control (Simplified)

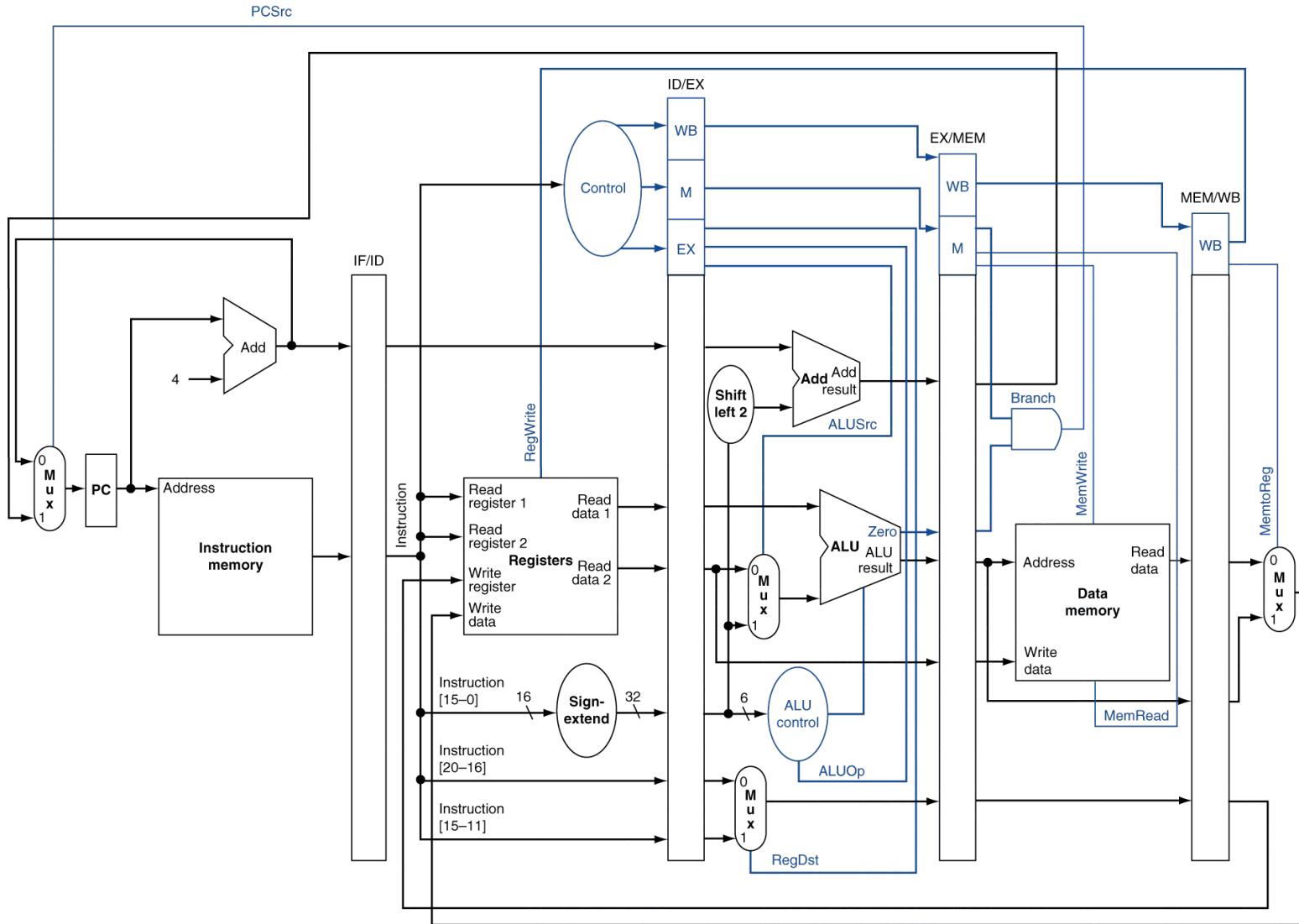


# Pipelined Control

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



# Pipelined Control



# Agenda

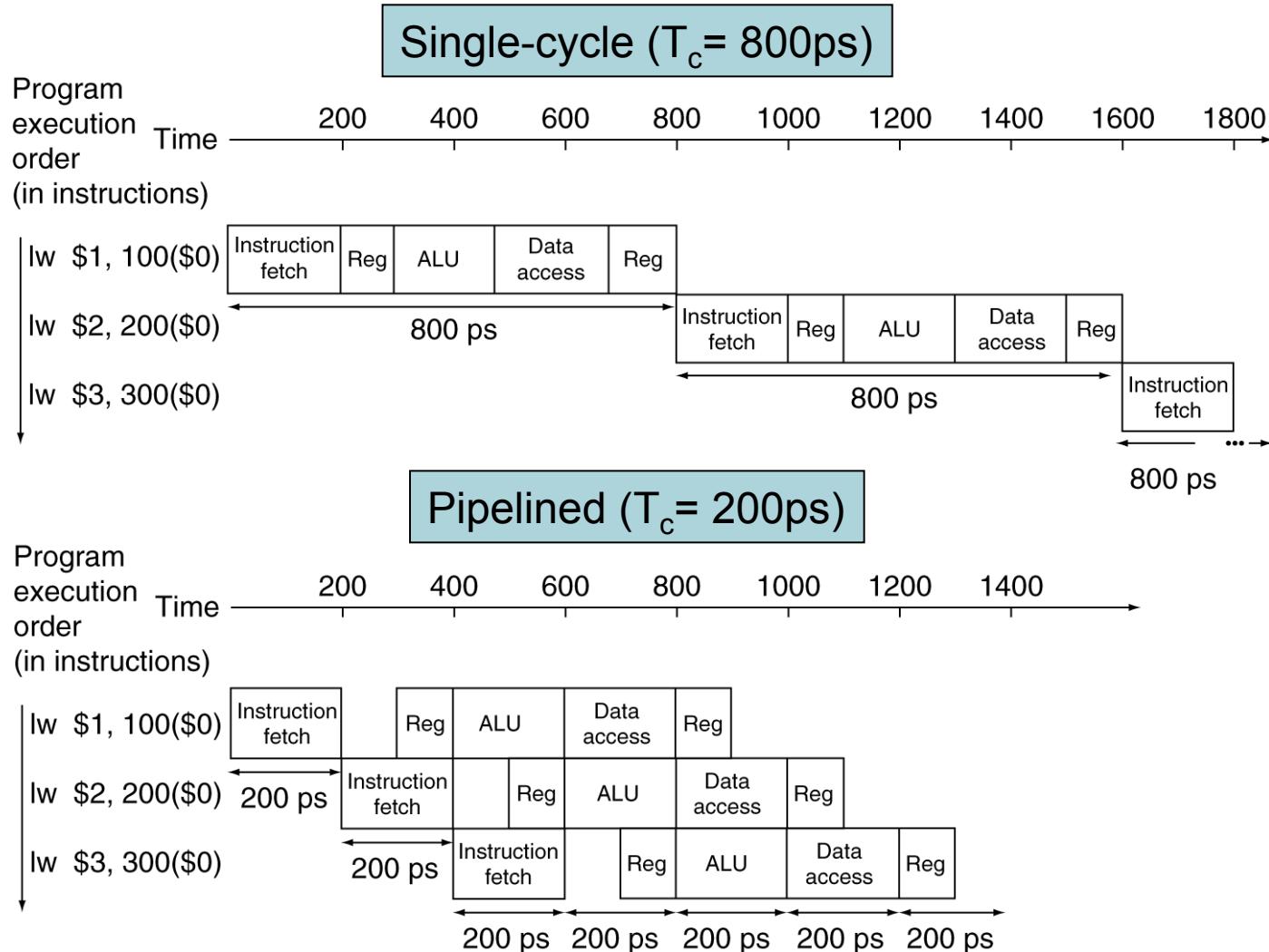
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# Pipeline Performance

- 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>  
$$\frac{\text{Number of stages}}{}$$
- 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

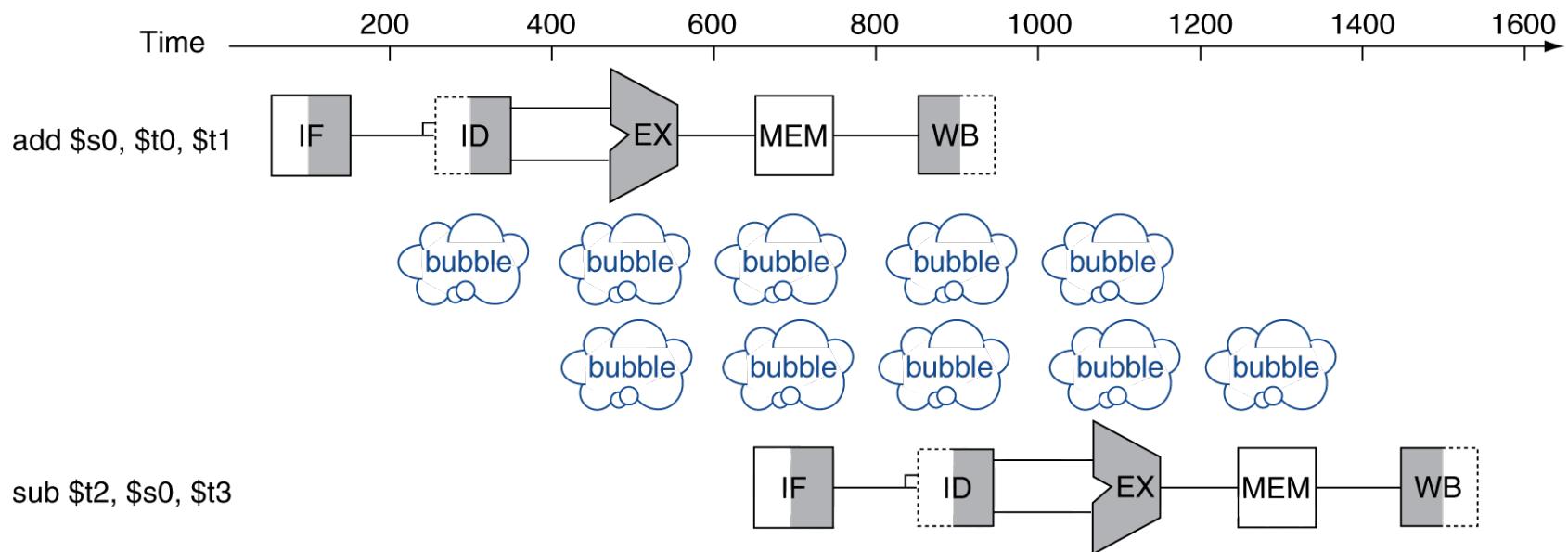
- Situations that prevent starting the next instruction in the next cycle
- Structure hazards
  - A required resource is busy
- Data hazard
  - Need to wait for previous instruction to complete its data read/write
- Control hazard
  - Deciding on control action depends on previous instruction

# 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

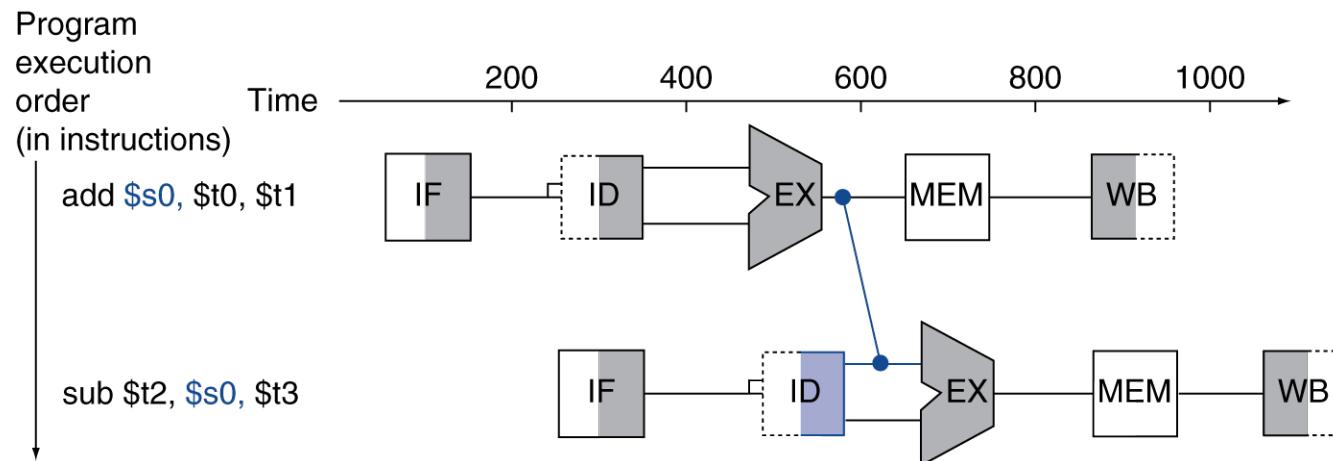
# Data Hazards

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



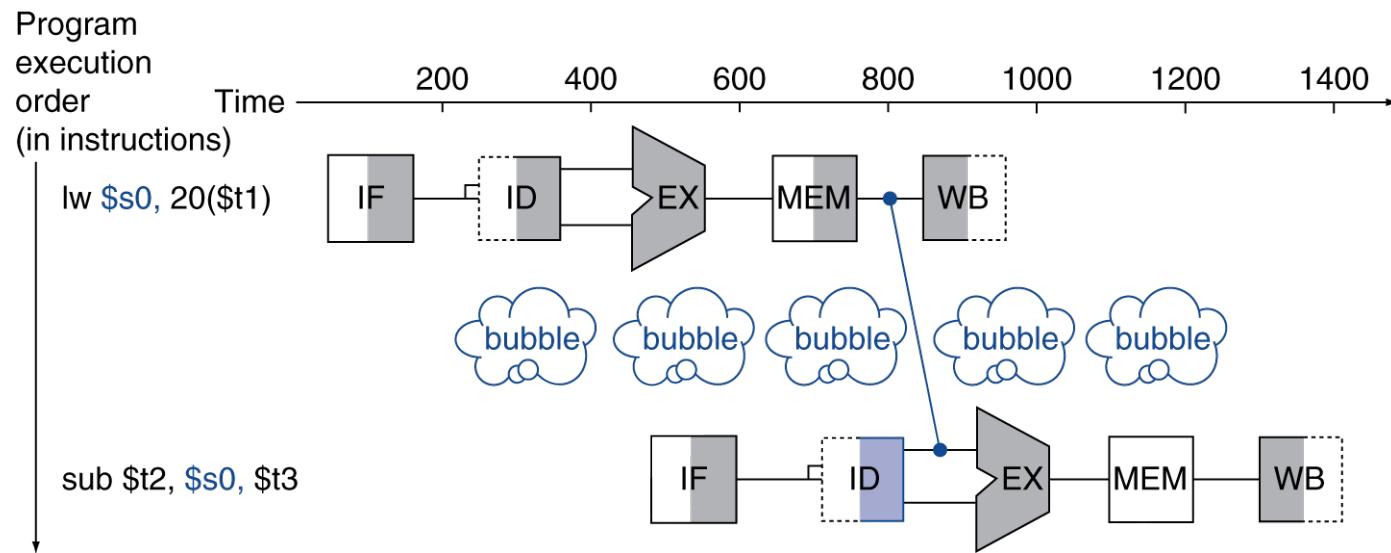
# Forwarding (aka Bypassing)

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



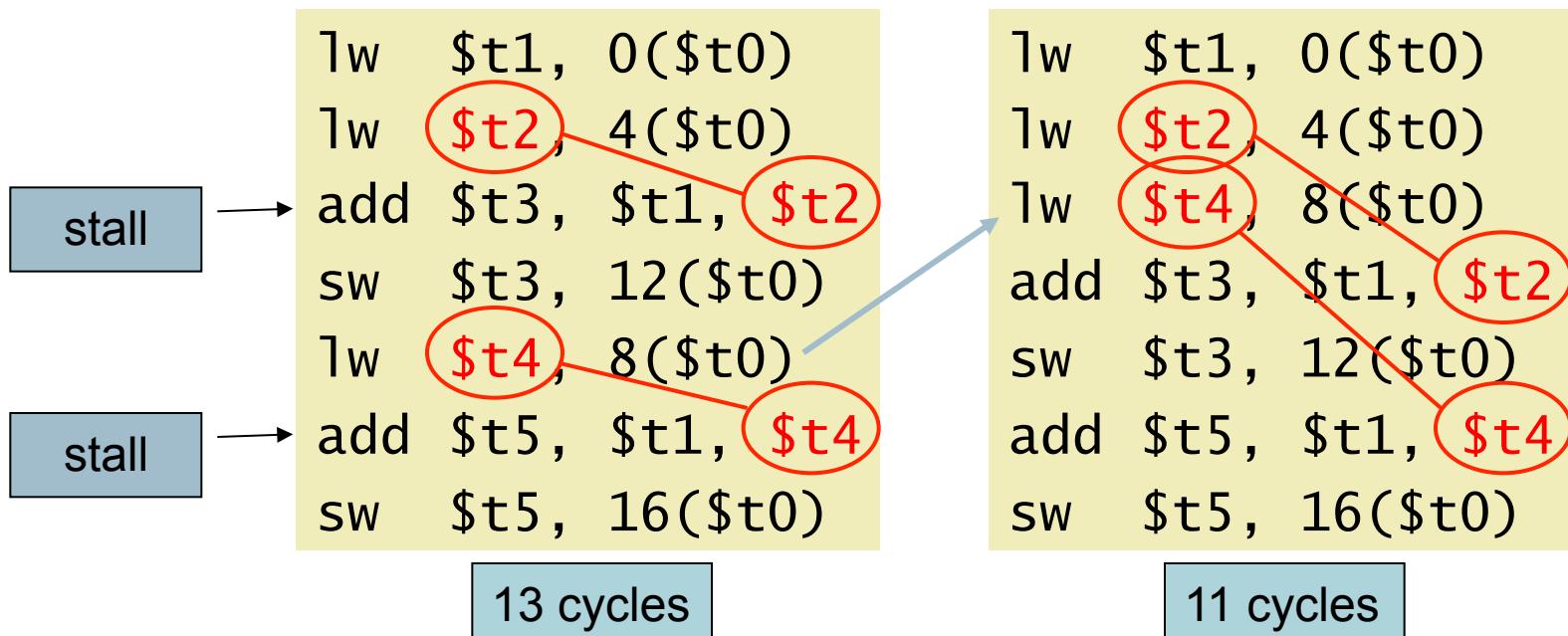
# Load-Use Data Hazard

- 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  $A = B + E; C = B + F;$

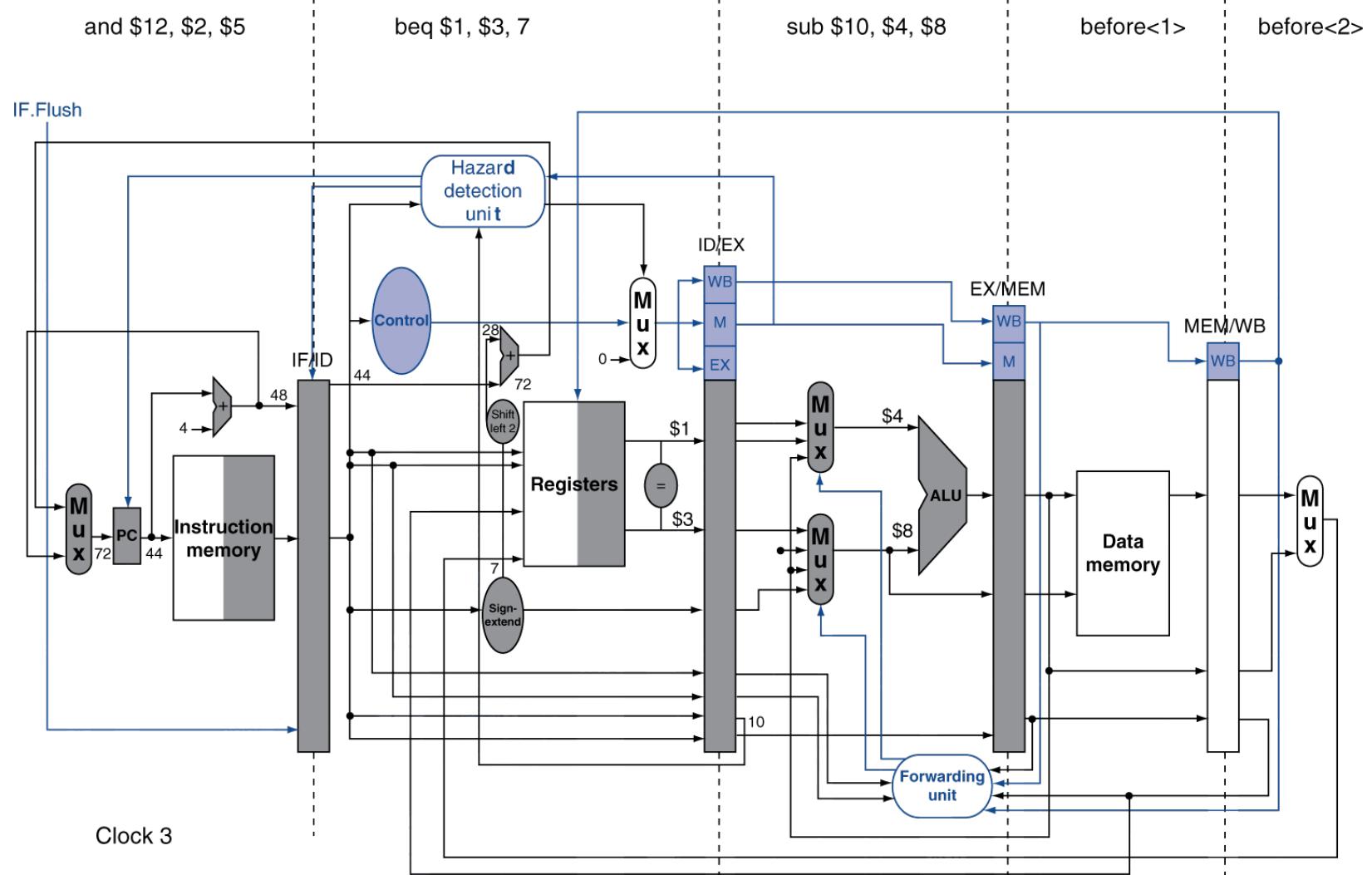


# Control Hazards

- 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**

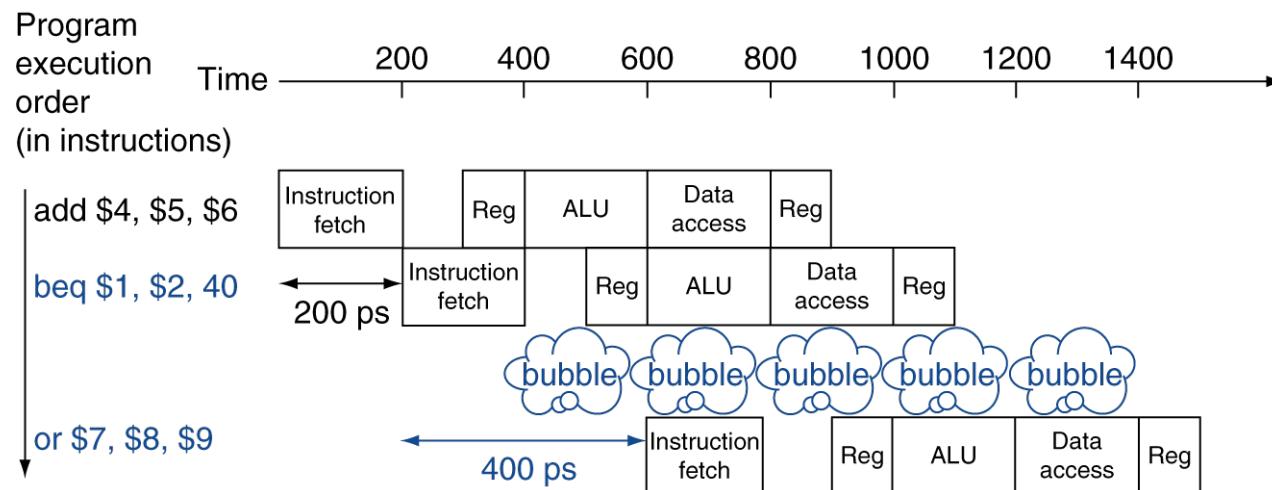
# Control Hazards:

## Branch compare register in ID stage



# Stall on Branch

- Wait until branch outcome determined before fetching next instruction

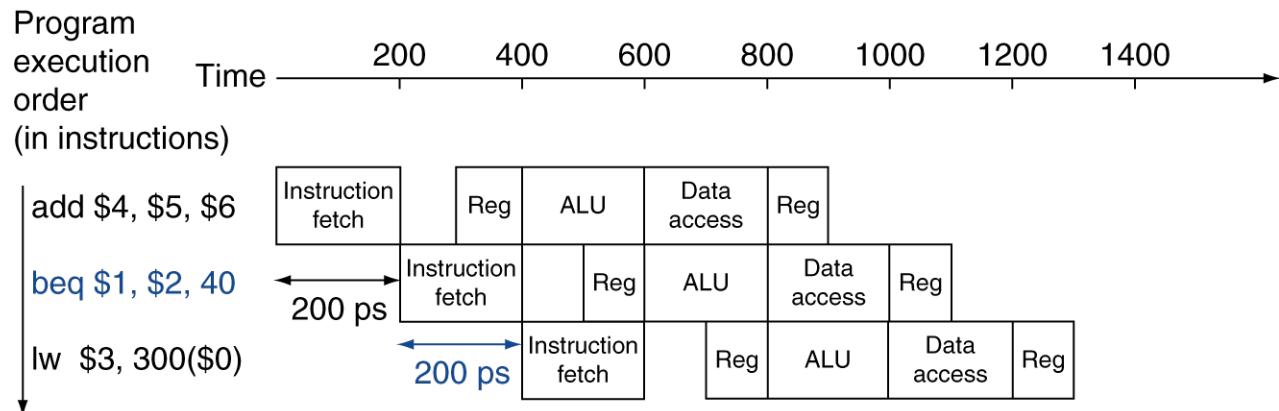


# Branch Prediction

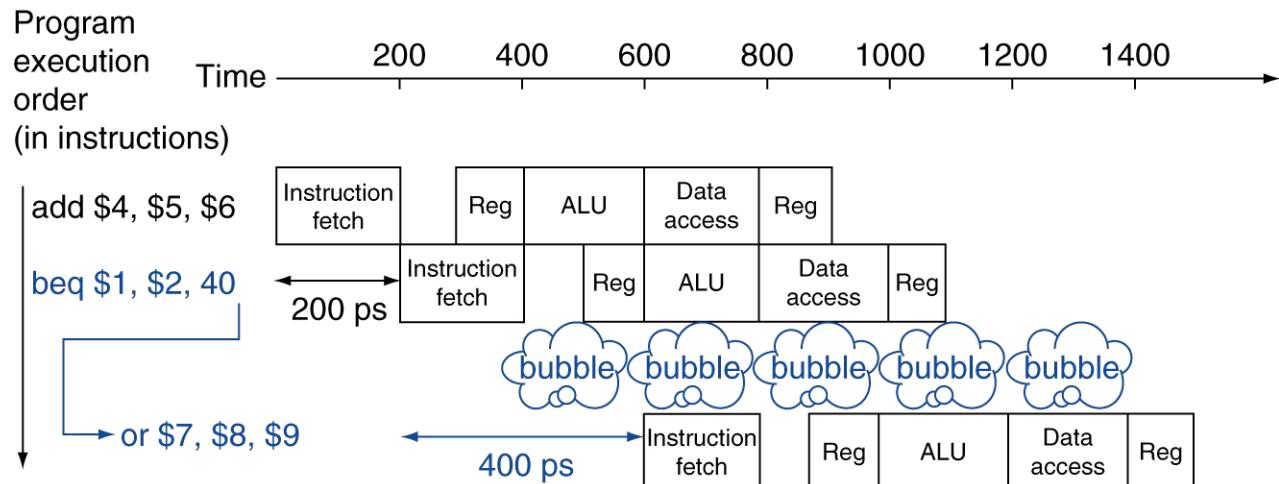
- Longer pipelines can't readily determine branch outcome early
  - Stall penalty becomes unacceptable
- Predict outcome of branch
  - Only stall if prediction is wrong
- In MIPS pipeline
  - Can predict branches not taken
  - Fetch instruction after branch, with no delay

# MIPS with Predict Not Taken

Prediction correct



Prediction incorrect



# 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

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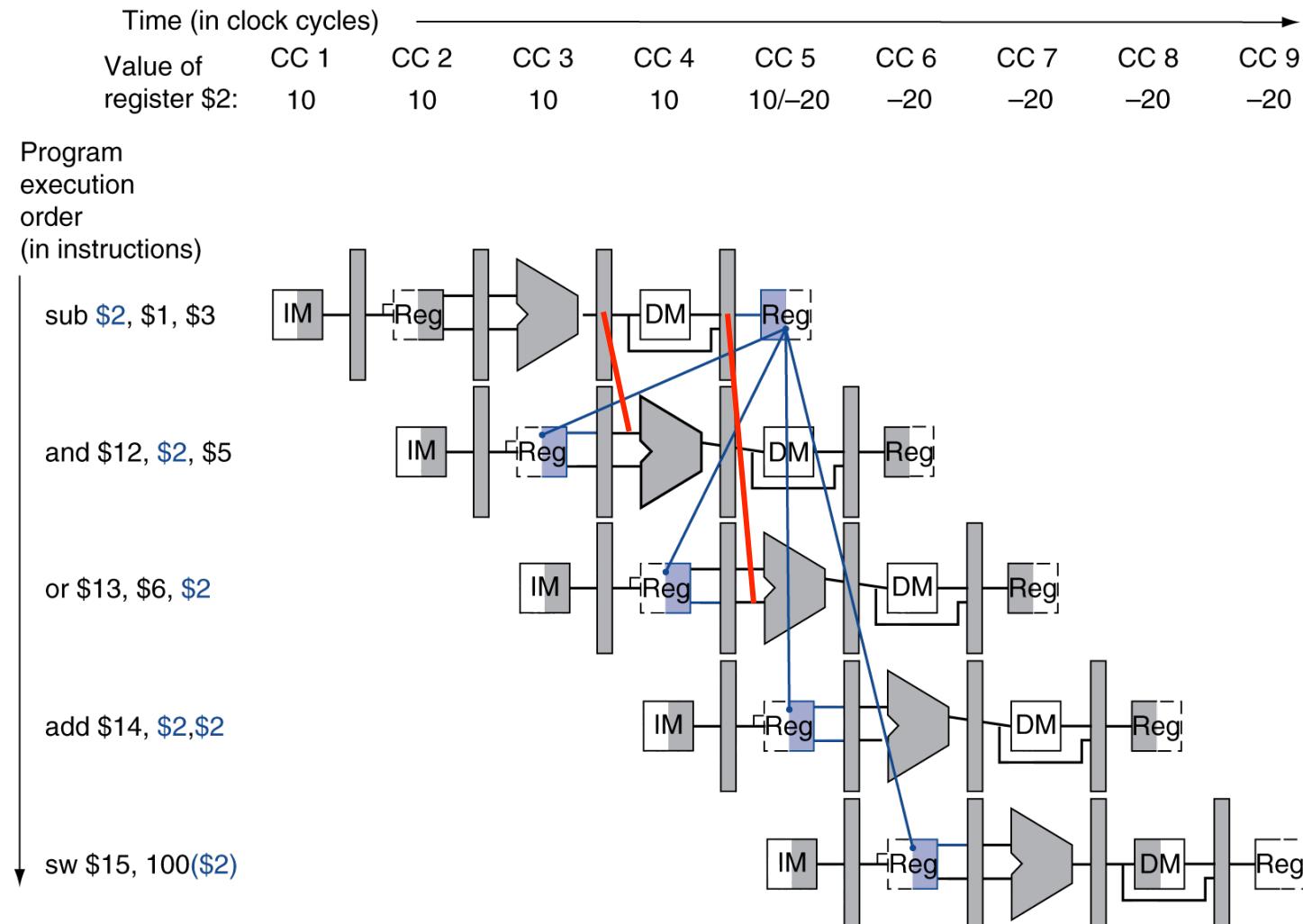
# Data Hazards in ALU Instructions

- 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

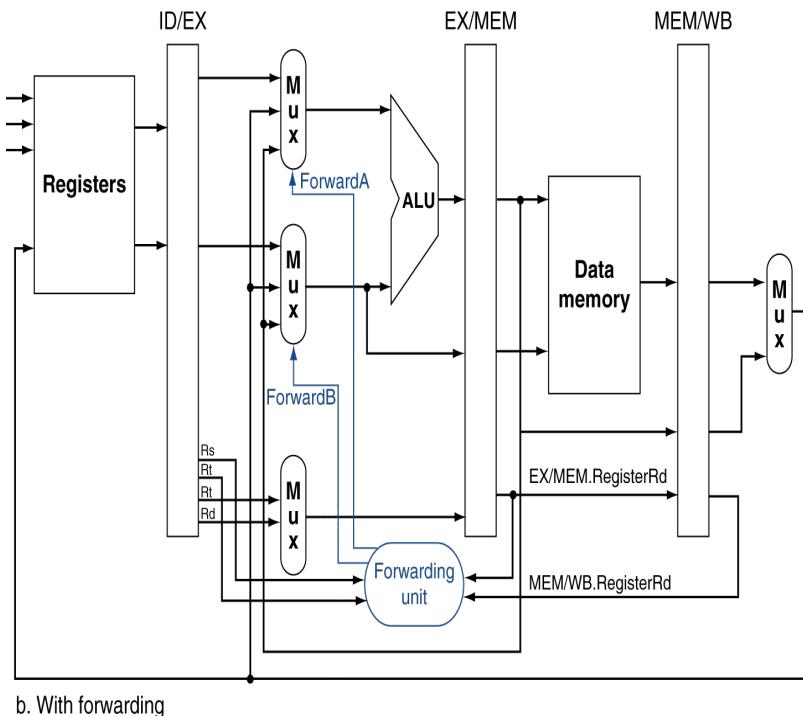
Fwd from  
EX/MEM  
pipeline reg

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 & 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

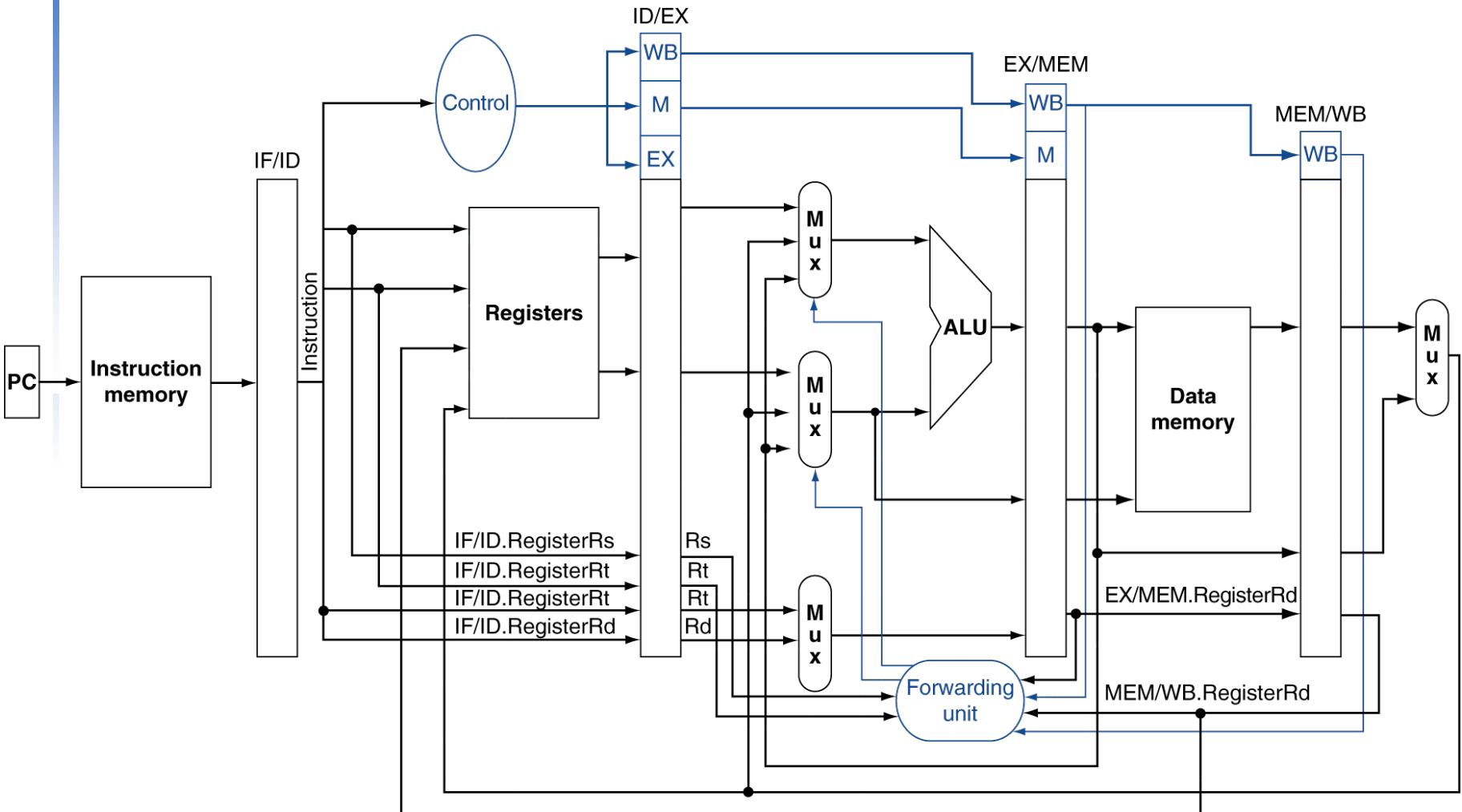
add \$1, \$1, \$4

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

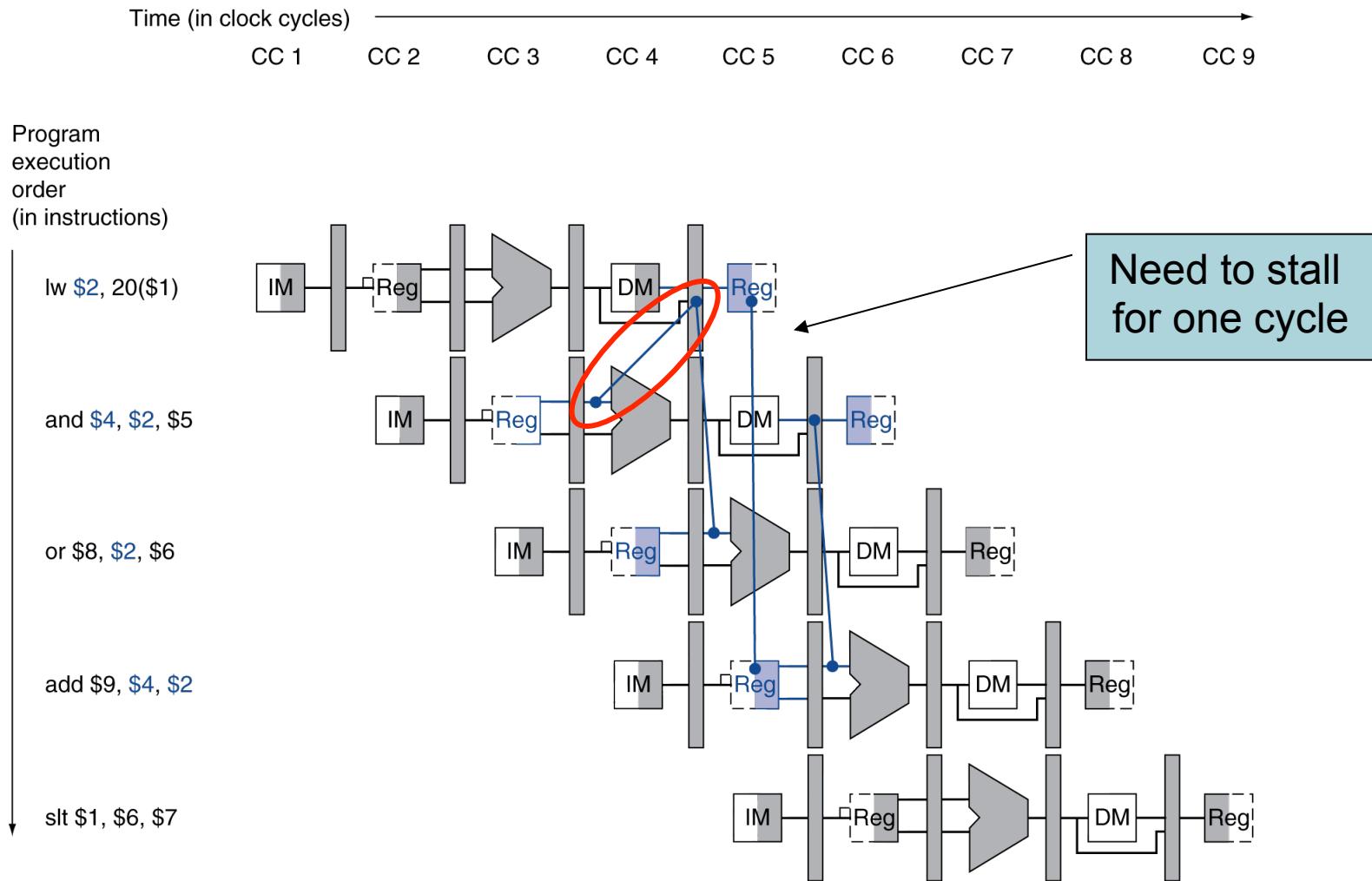
# Revised Forwarding Condition

- 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



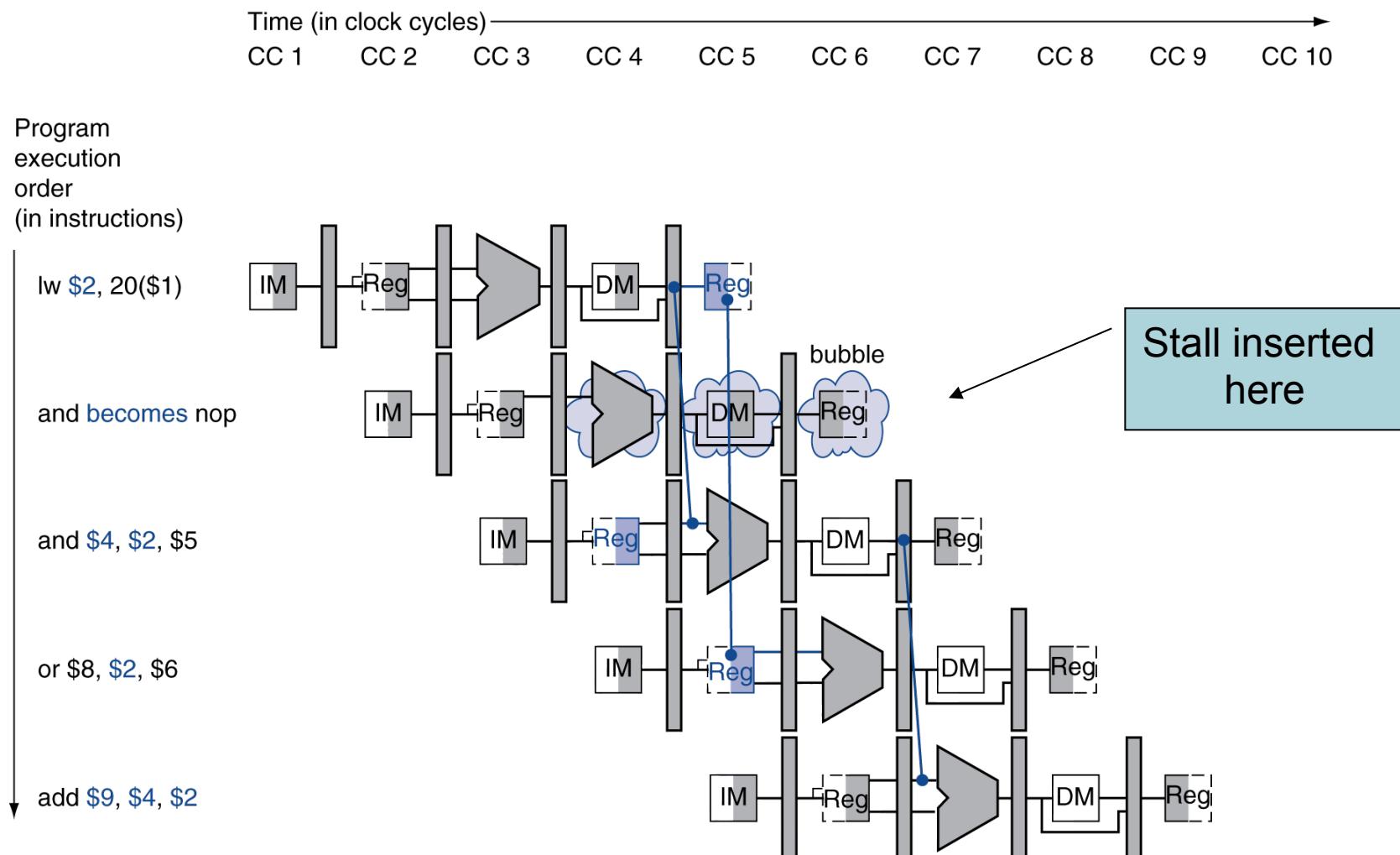
# Load-Use Hazard Detection

- 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

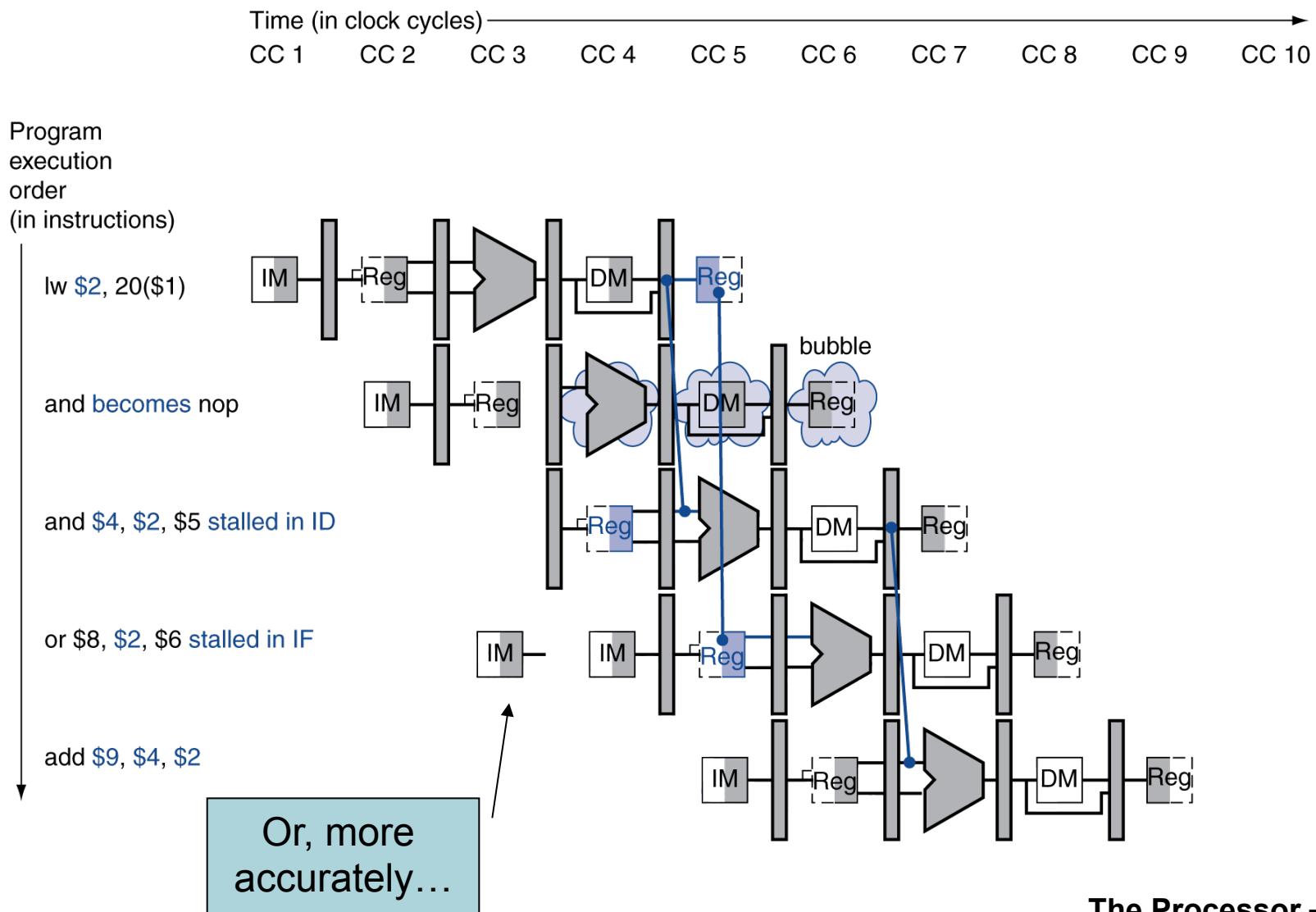
# How to Stall the Pipeline

- 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

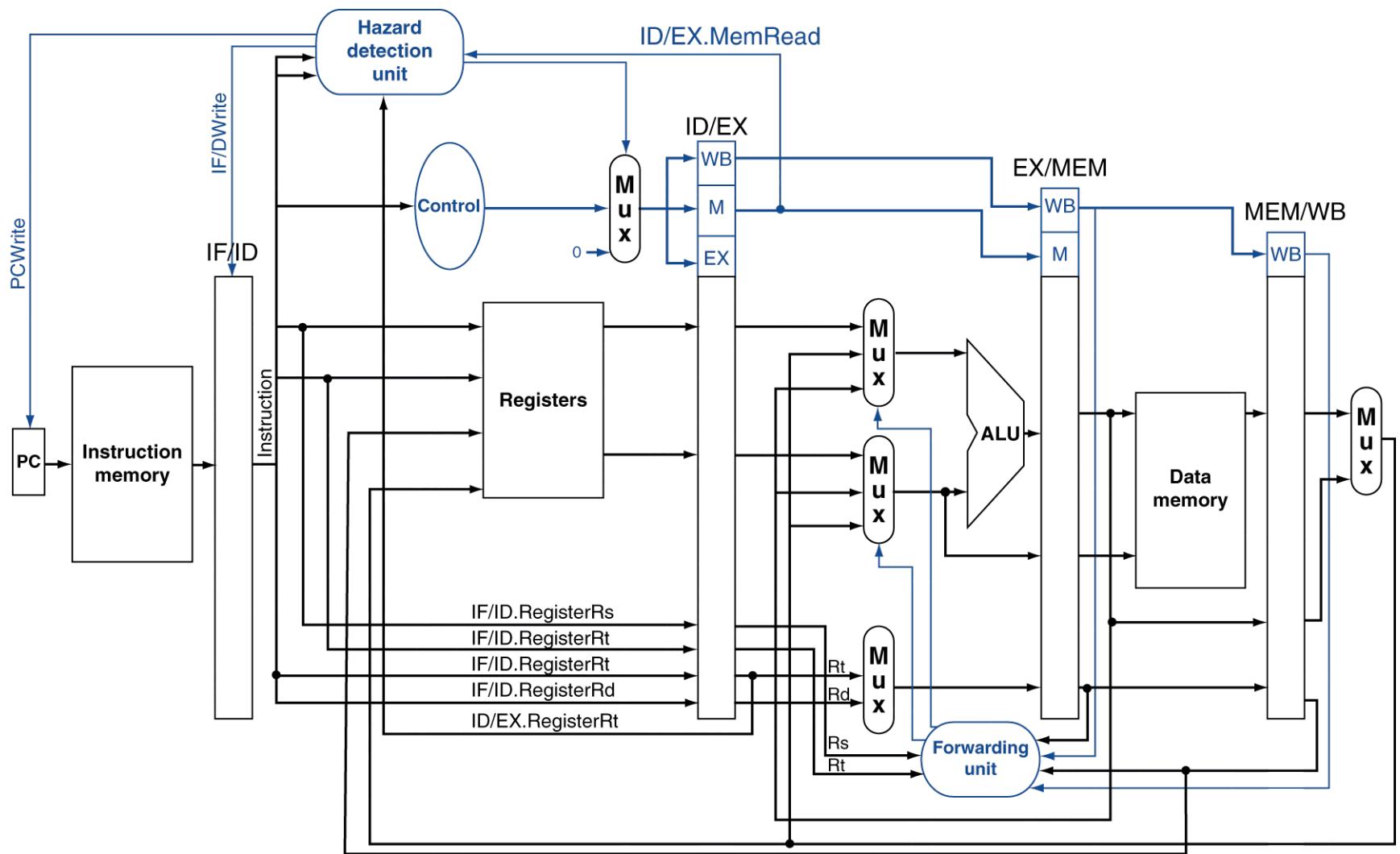
# Stall/Bubble in the Pipeline



# Stall/Bubble in the Pipeline



# Datapath with Hazard Detection



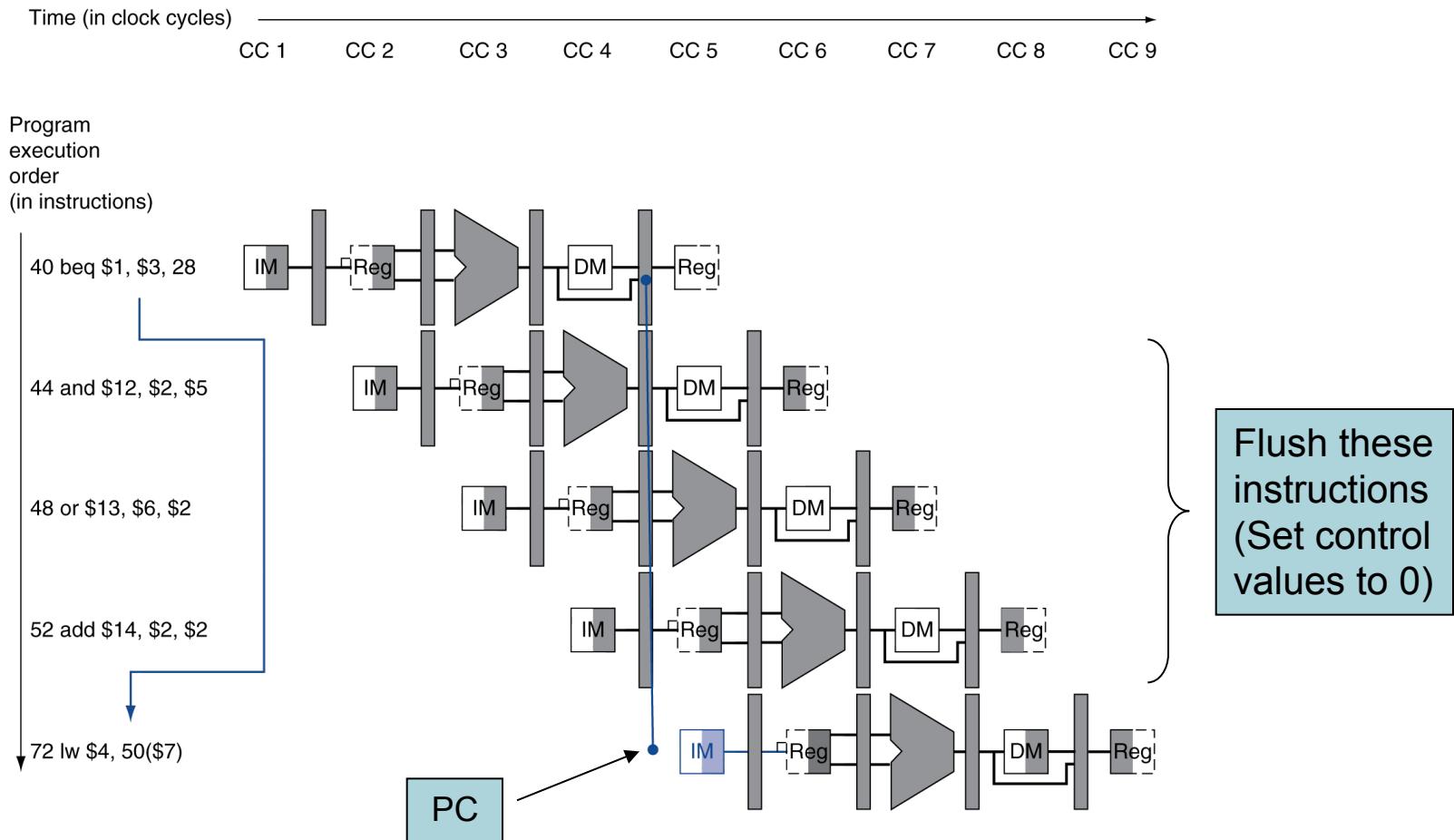
# Stalls and Performance

## 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

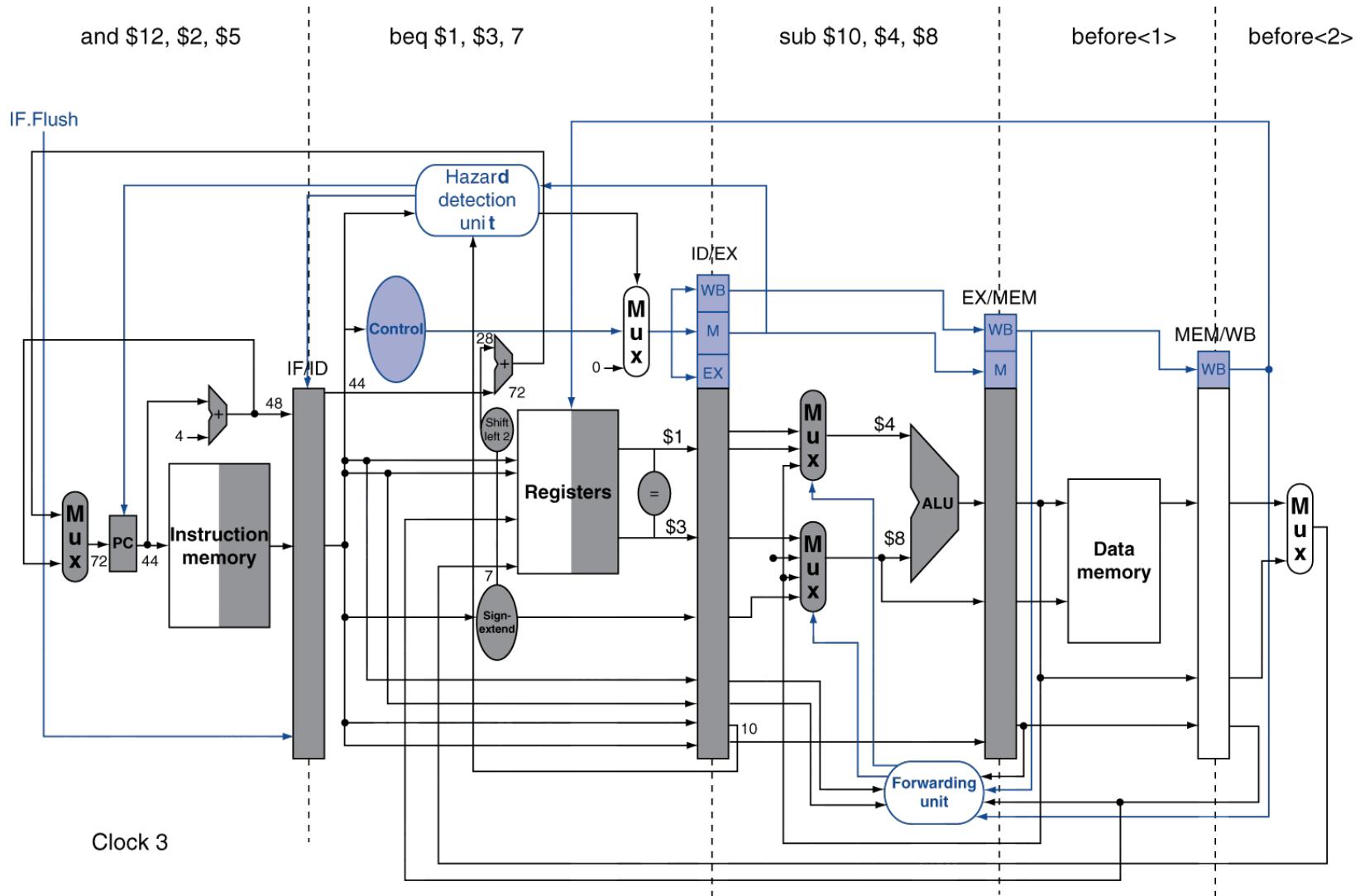


# Reducing Branch Delay

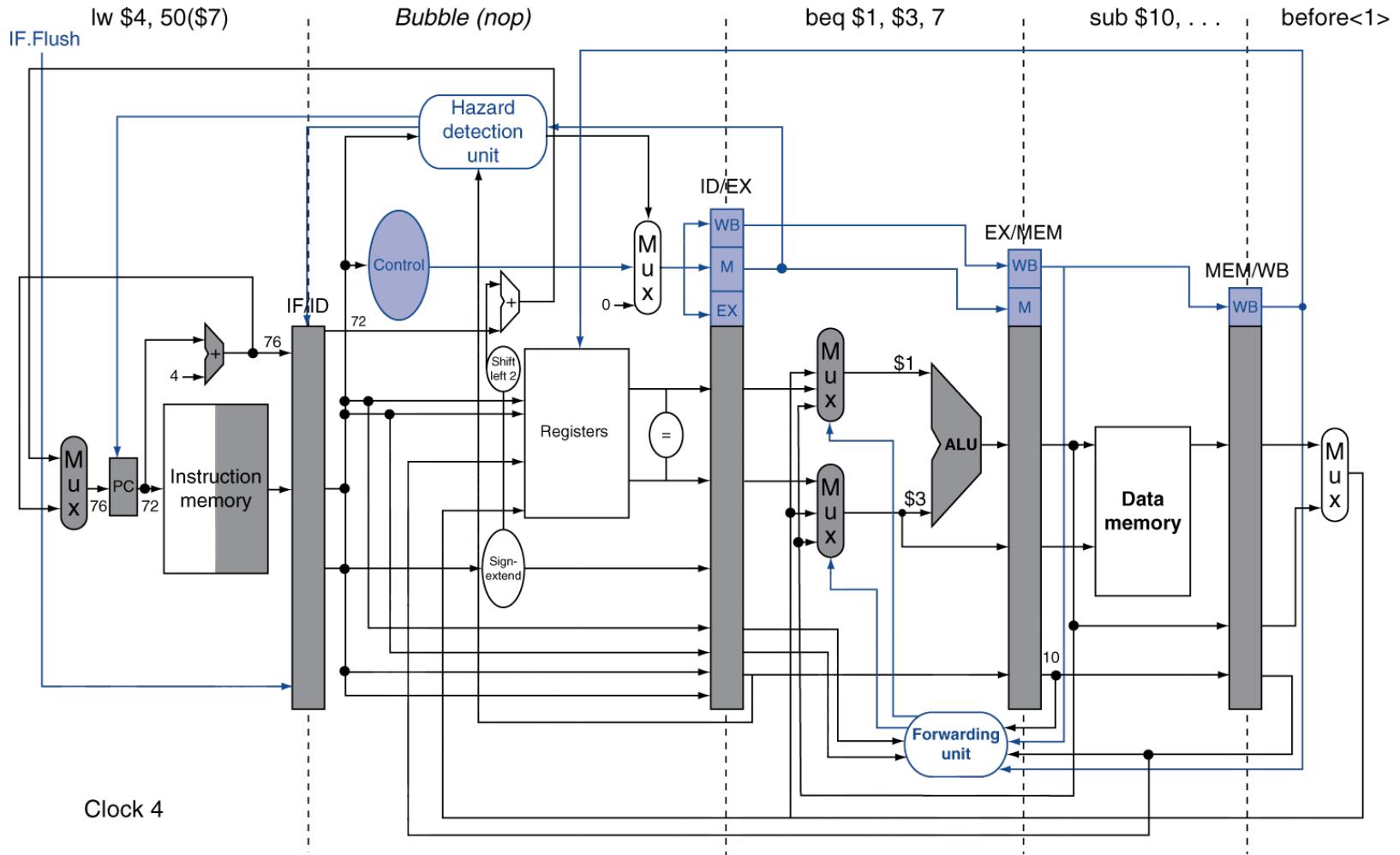
- Move hardware to determine outcome to ID stage
  - Target address adder
  - Register comparator
- Example: branch taken

```
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

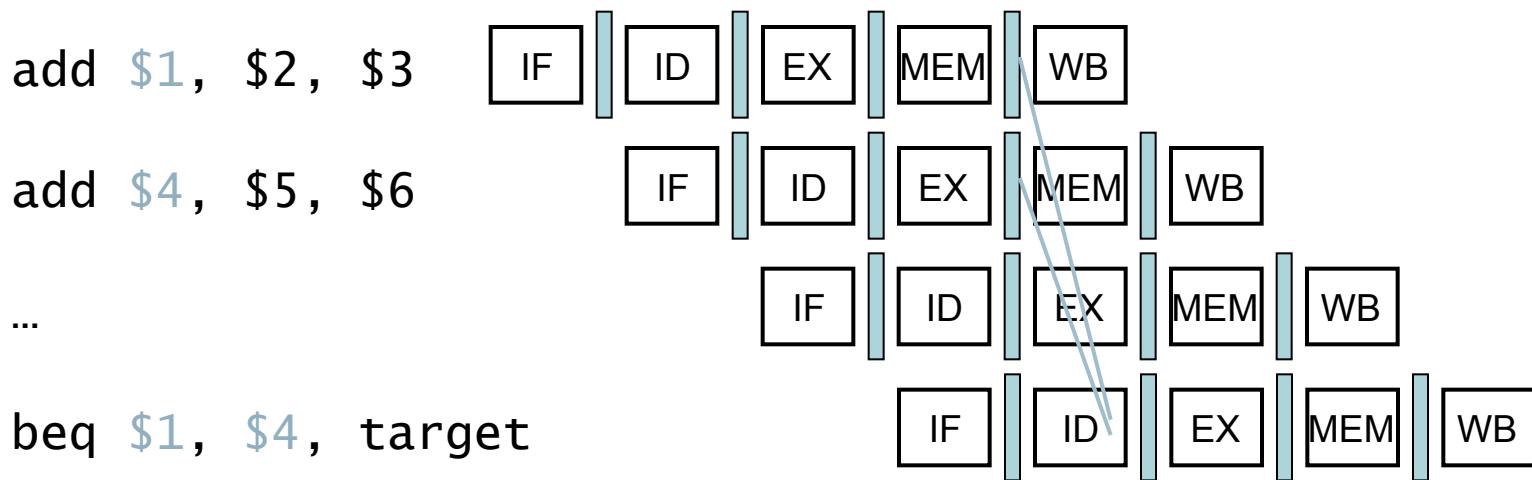


# Example: Branch Taken



# Data Hazards for Branches

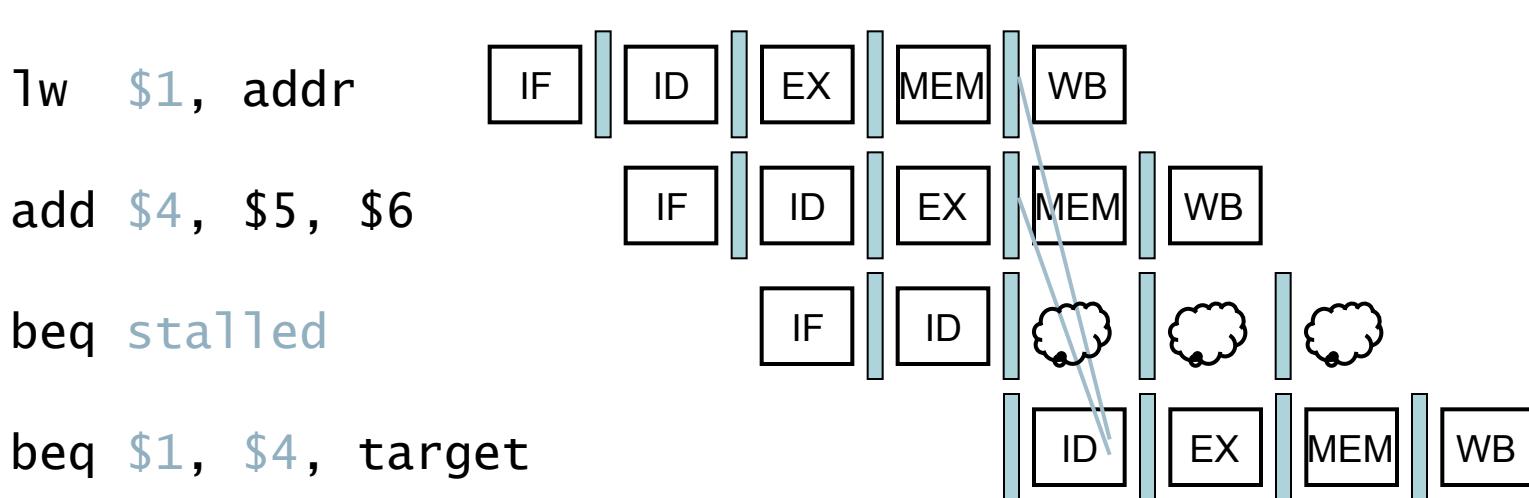
- If a comparison register is a destination of 2<sup>nd</sup> or 3<sup>rd</sup> preceding ALU instruction



- Can resolve using forwarding

# Data Hazards for Branches

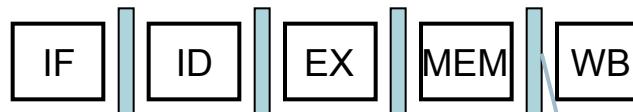
- If a comparison register is a destination of preceding ALU instruction or 2<sup>nd</sup> preceding load instruction
  - Need 1 stall cycle



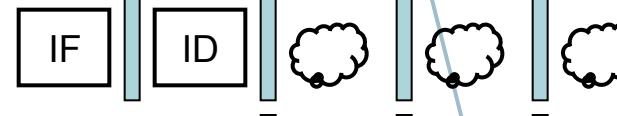
# Data Hazards for Branches

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

lw \$1, addr

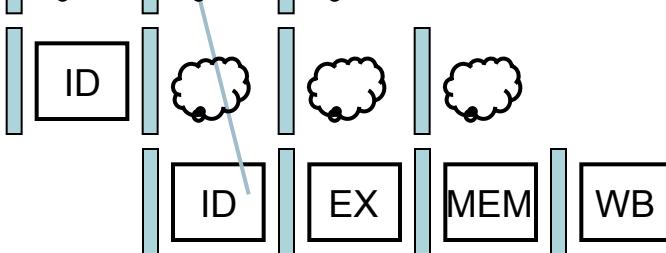


beq stalled



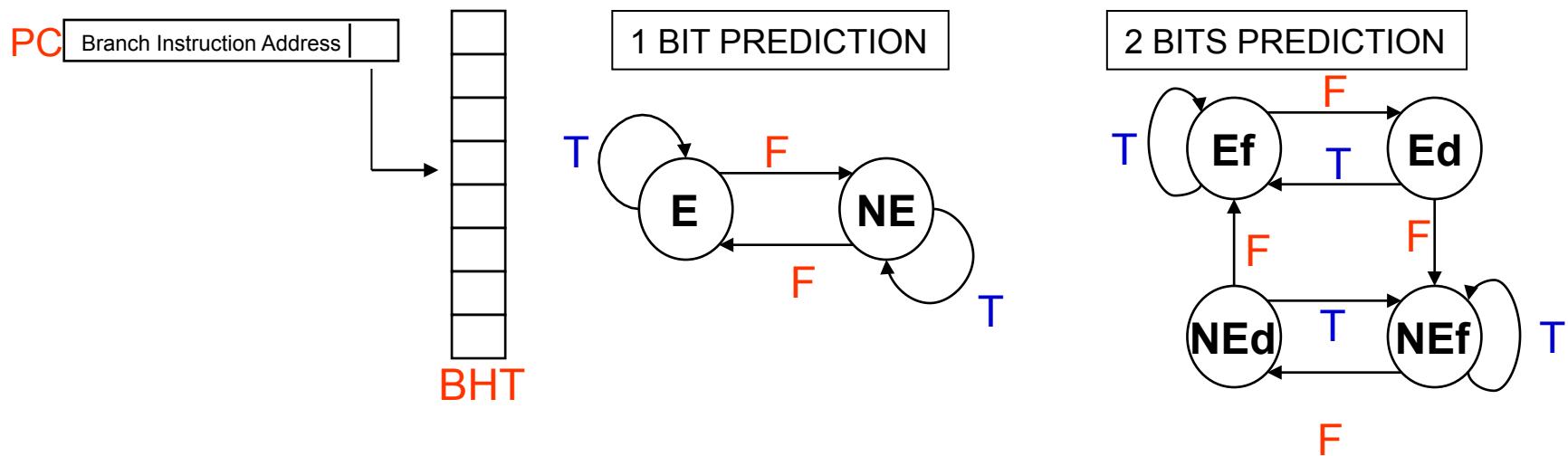
beq stalled

beq \$1, \$0, target



# Branch Hazard and Prediction

- Static prediction: always predict the same: Speculative running until condition is solved. If error, remove speculative results:
  - Effective Prediction (E): branch occurs.
  - No Effective prediction (NE): branch does NOT occur.
  - Prediction NE if the branch is forward and E if it is back.
- Dynamic Prediction: change the prediction according the branch history. Use a small memory for each branch address (BHT, *Branch History Table*)



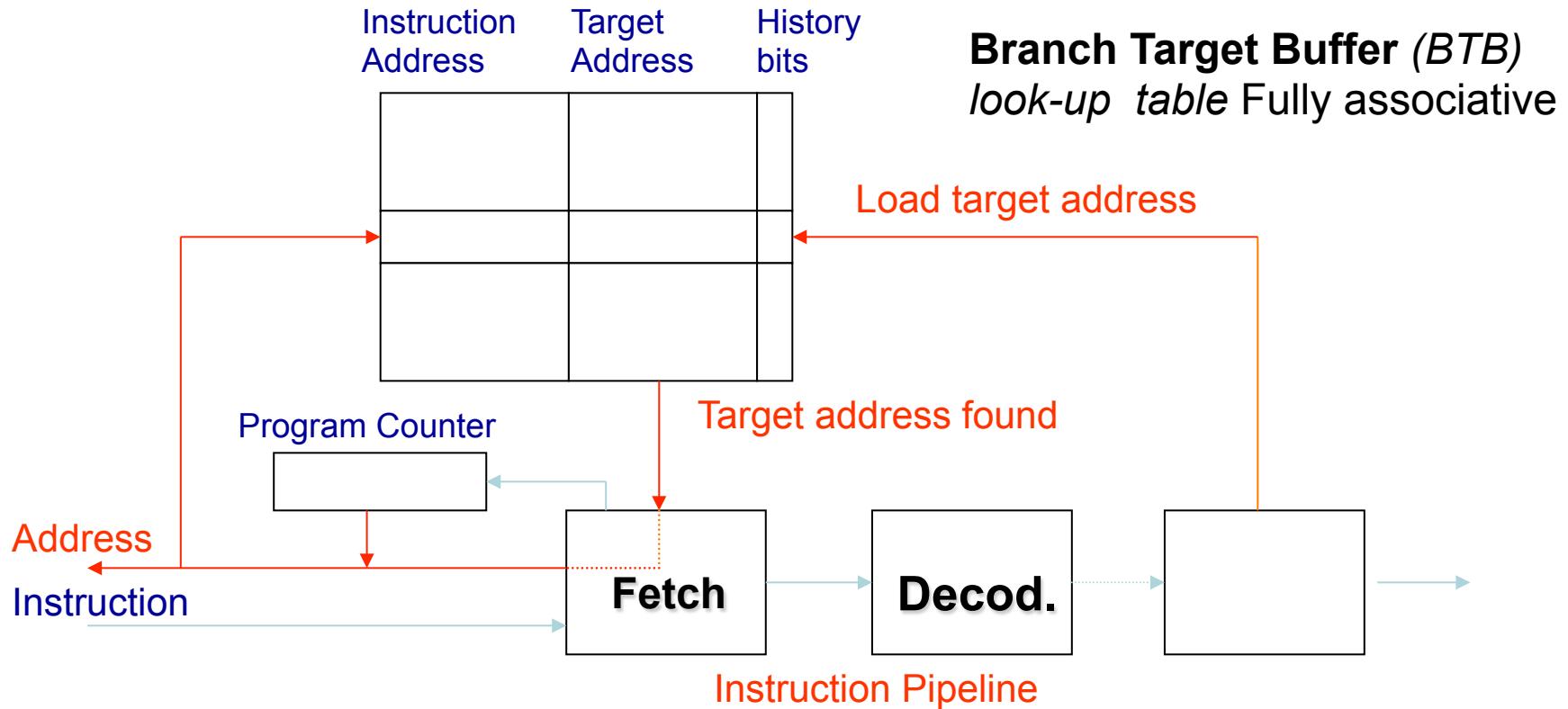
# Dynamic Branch Prediction

- 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

# 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

# Branch Target Buffer (BTB)



# 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

# 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

# Información Adicional

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- Información adicional para los problemas del capítulo 2

# Tipos de riesgos por dependencia de datos

- ❑ Dependencias que se presentan para 2 instrucciones i y j, con i ejecutándose antes que j.
  - ❑ RAW (Read After Write): la instrucción posterior j intenta leer una fuente antes de que la instrucción anterior i la haya modificado.
  - ❑ WAR (Write After Read): la instrucción j intenta modificar un destino antes de que la instrucción i lo haya leído como fuente.
  - ❑ WAW (Write After Write): la instrucción j intenta modificar un destino antes de que la instrucción i lo haya hecho (se modifica el orden normal de escritura).

✓ Ejemplos:    **RAW**

**ADD r1, r2, r3**  
**SUB r5, r1, r6**  
**AND r6, r5, r1**  
**ADD r4, r1, r3**  
**SW r10, 100(r1)**

**WAR**

**ADD r1, r2, r3**  
**OR r3,r4, r5**

**WAW**

**DIV r1, r2, r3**  
**AND r1,r4, r5**

En procesadores segmentados con ejecución en orden SÓLO hay que gestionar los RAW