Chapter 6: Pipelining

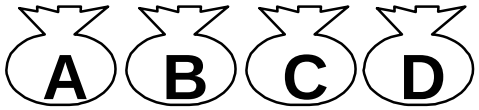
Outline

- An overview of pipelining
- A pipelined datapath
- Pipelined control
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards
- Exceptions
- Superscalar and dynamic pipelining

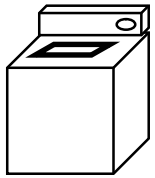
Pipelining Is Natural!

- Laundry example:

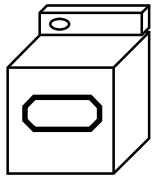
Ann, Brian, Cathy, Dave
each have one load of
clothes to wash, dry,
and fold



Washer takes 30 minutes

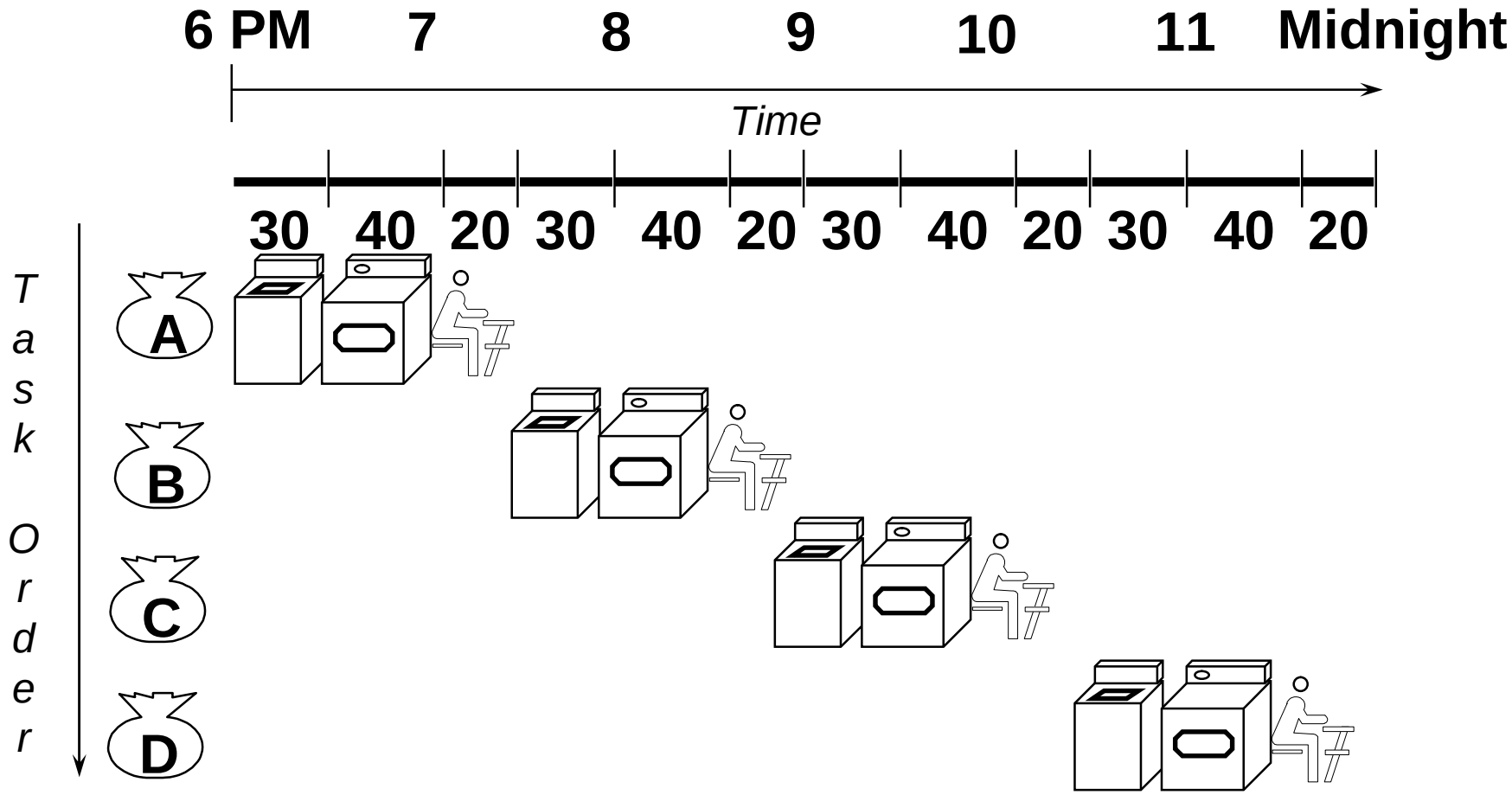


Dryer takes 40 minutes



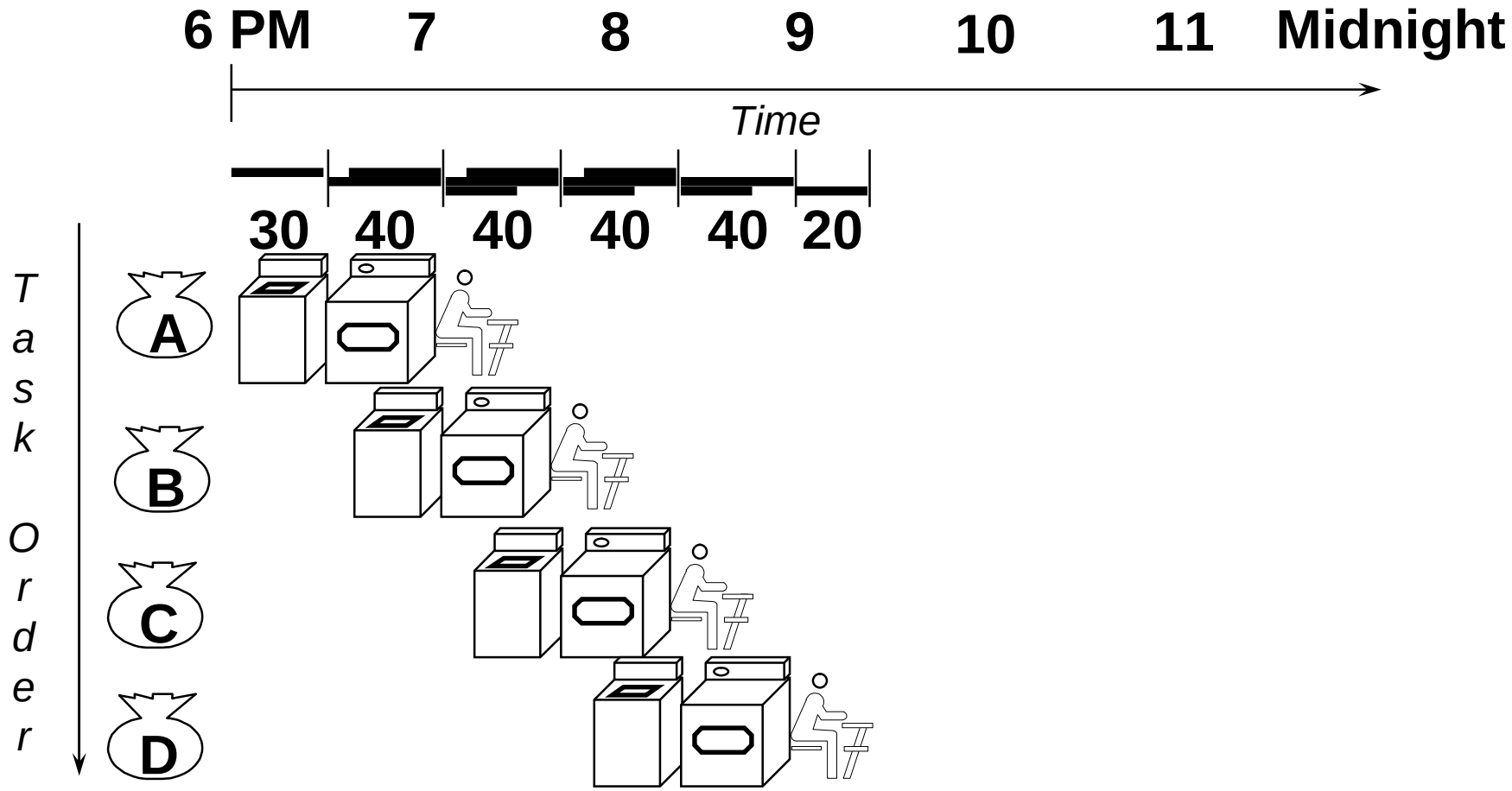
“Folder” takes 20 minutes

Sequential Laundry



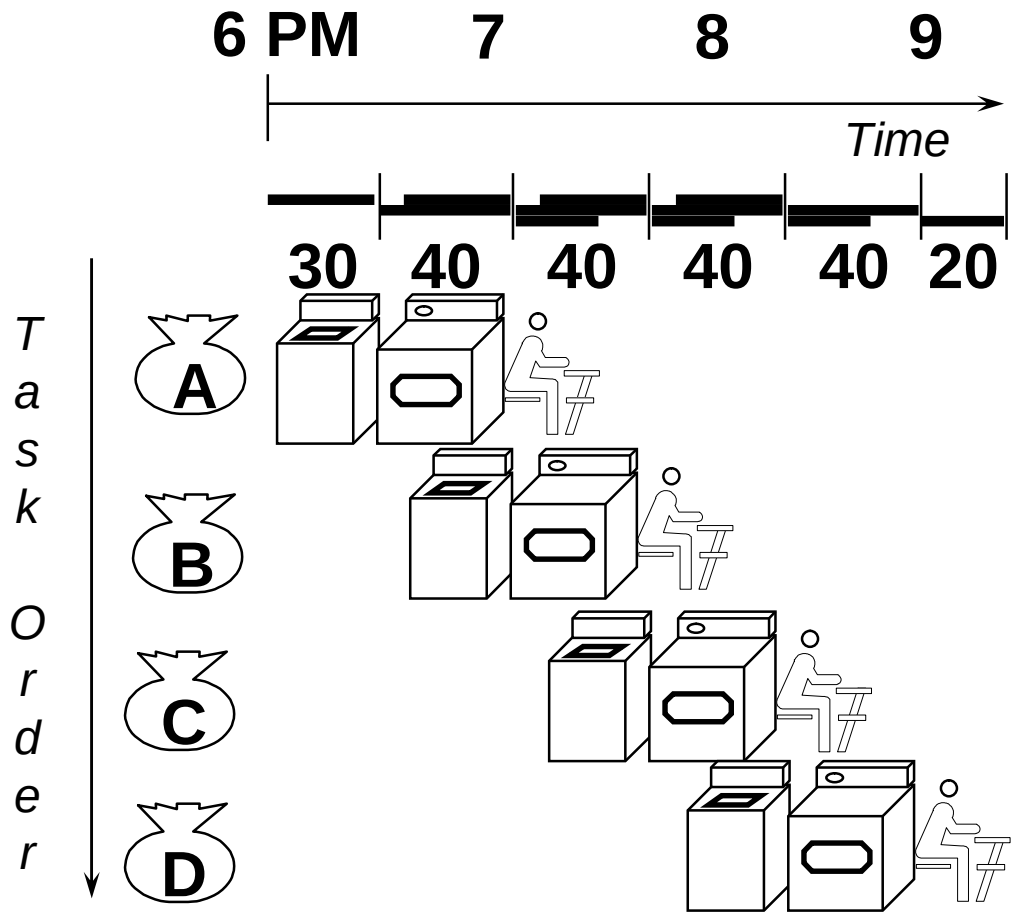
- Sequential laundry takes 6 hours for 4 loads
- If they learned pipelining, how long would it take?

Pipelined Laundry: Start ASAP



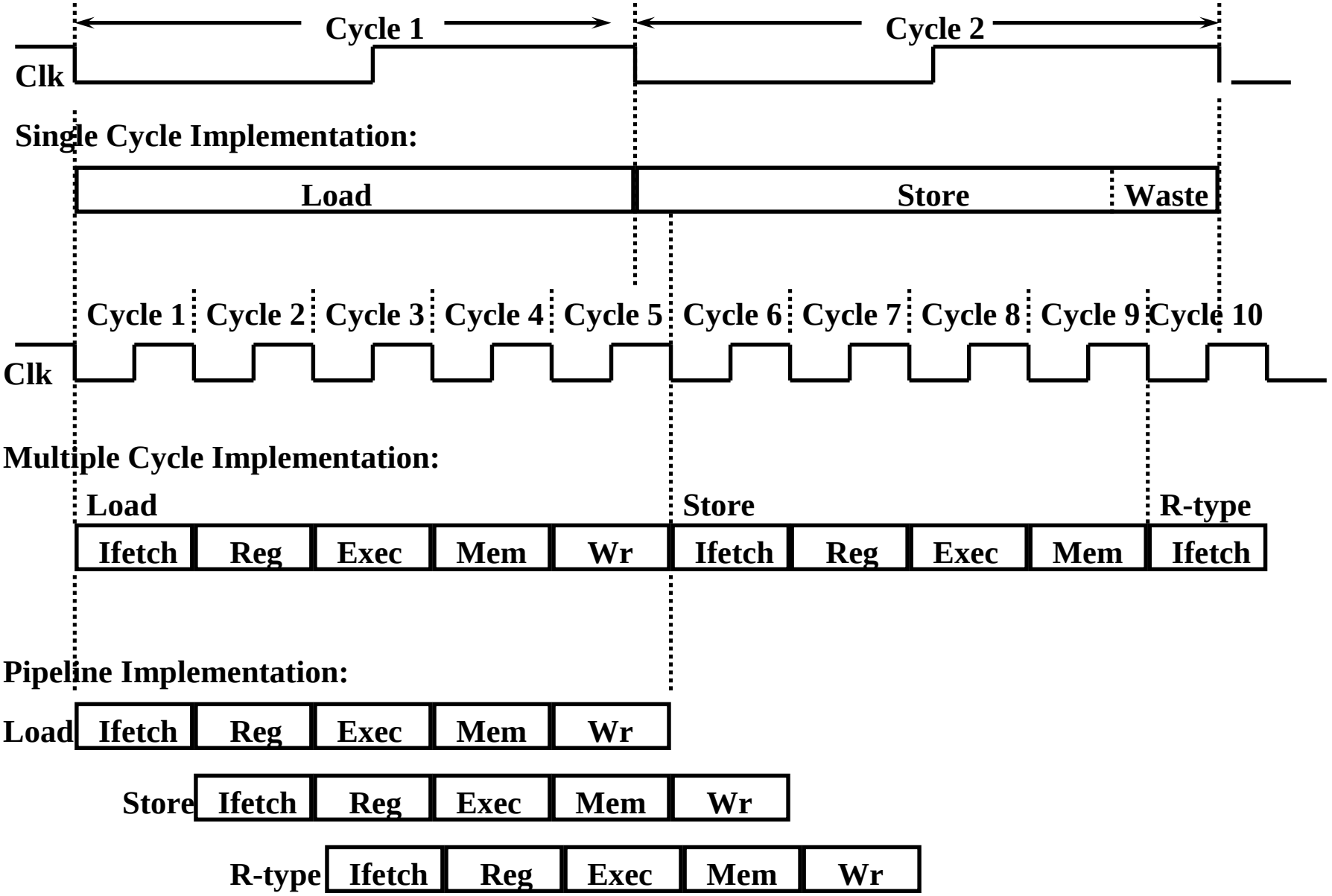
- Pipelined laundry takes 3.5 hours for 4 loads

Pipelining Lessons



- Doesn’t help latency of single task, but throughput of entire
- Pipeline rate limited by slowest stage
- Multiple tasks working at same time using different resources
- Potential speedup = Number of pipe stages
- Unbalanced stage length; time to “fill” & “drain” the pipeline reduce speedup
- Stall for dependences

Single-, Multi-Cycle, vs. Pipeline



Pipelining MIPS Execution

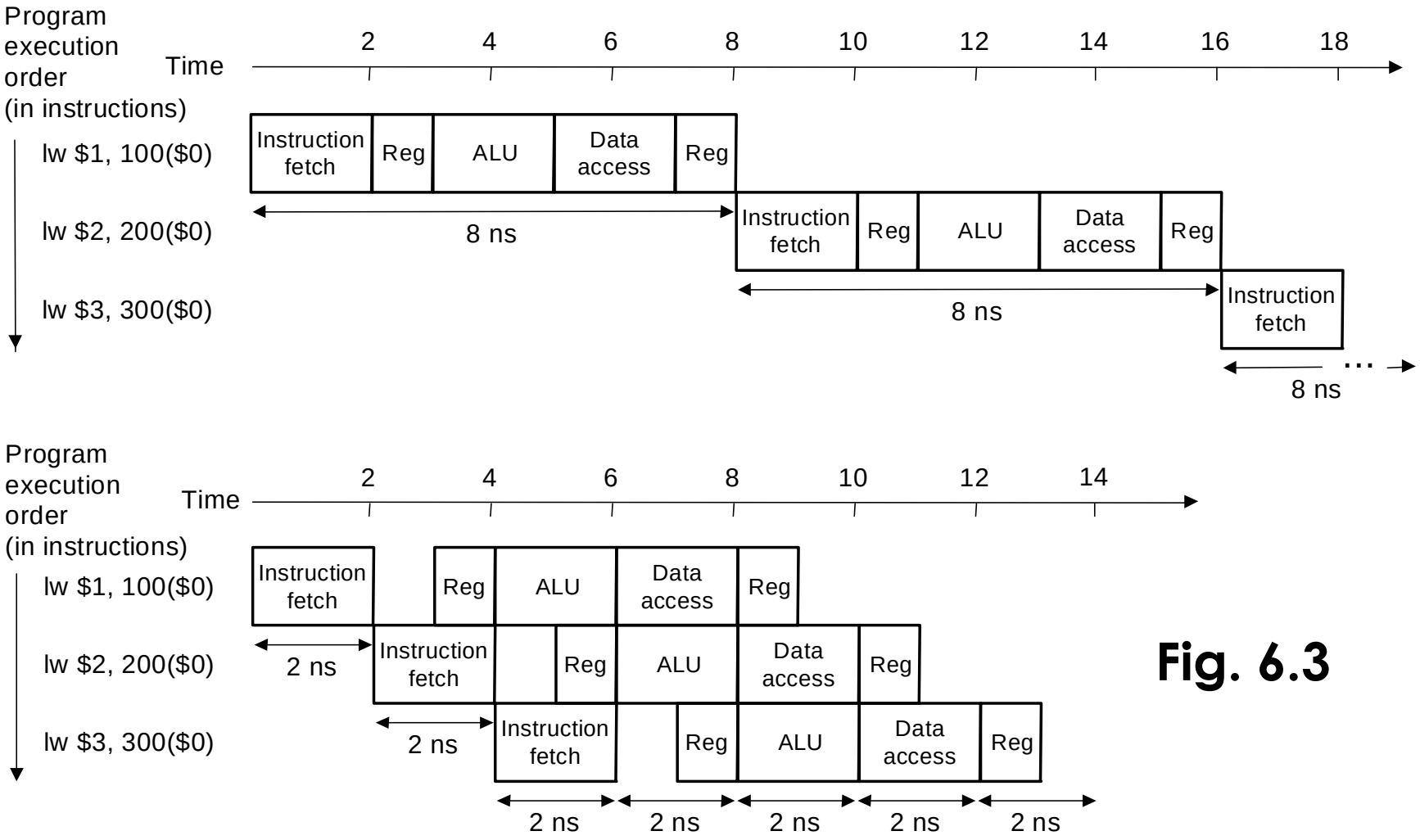
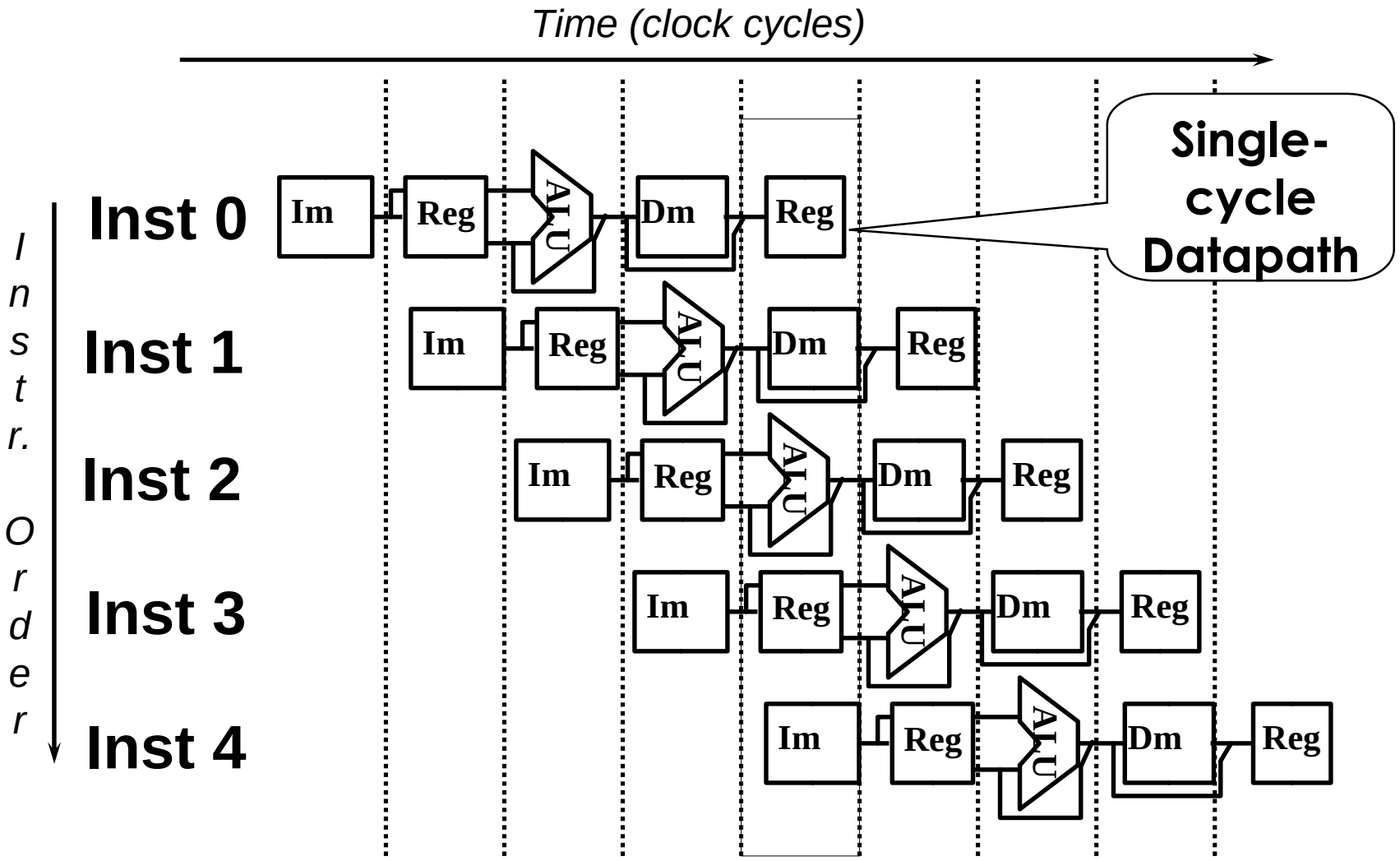


Fig. 6.3

Why Pipeline? Because the Resources Are There!



Hazard

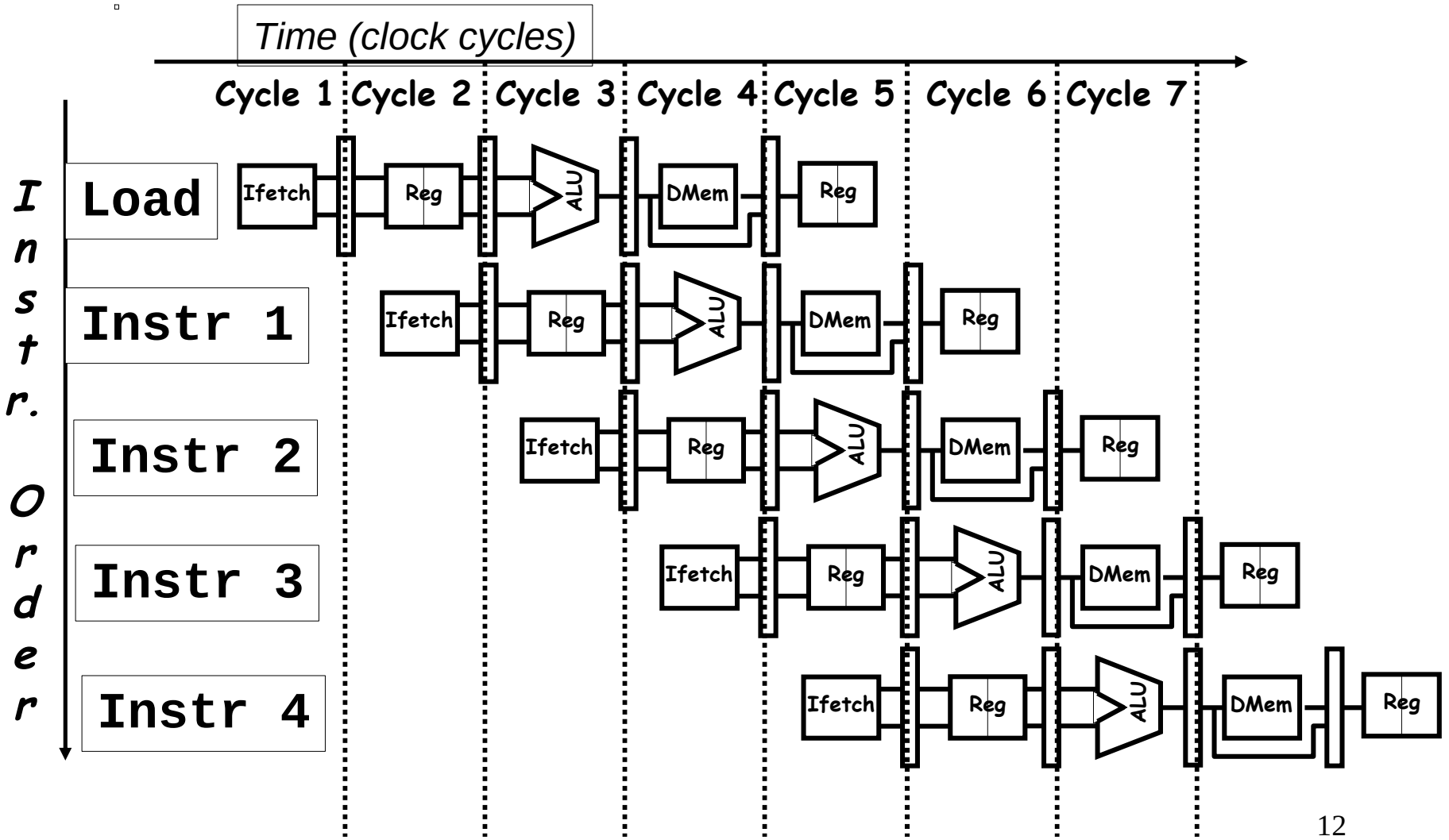
- Limits to pipelining: Hazards prevent next instruction from executing during its designated clock cycle
  - Structural hazards: Hardware cannot support this combination of instructions - two instructions need the same resource.
  - Data hazards: Instruction depends on result of prior instruction still in the pipeline
  - Control hazards: Pipelining of branches & other instructions that change the PC
- Common solution is to stall the pipeline until the hazard is resolved, inserting one or more “bubbles” in the pipeline
- To do this, hardware or software must detect that a hazard has occurred.

Structural Hazards

- Structural hazards occur when two or more instructions need the same resource.
- Common methods for eliminating structural hazards are:
  - Duplicate resources
  - Pipeline the resource
  - Reorder the instructions
- It may be too expensive too eliminate a structural hazard, in which case the pipeline should stall.
- When the pipeline stalls, no instructions are issued until the hazard has been resolved.
- What are some examples of structural hazards?

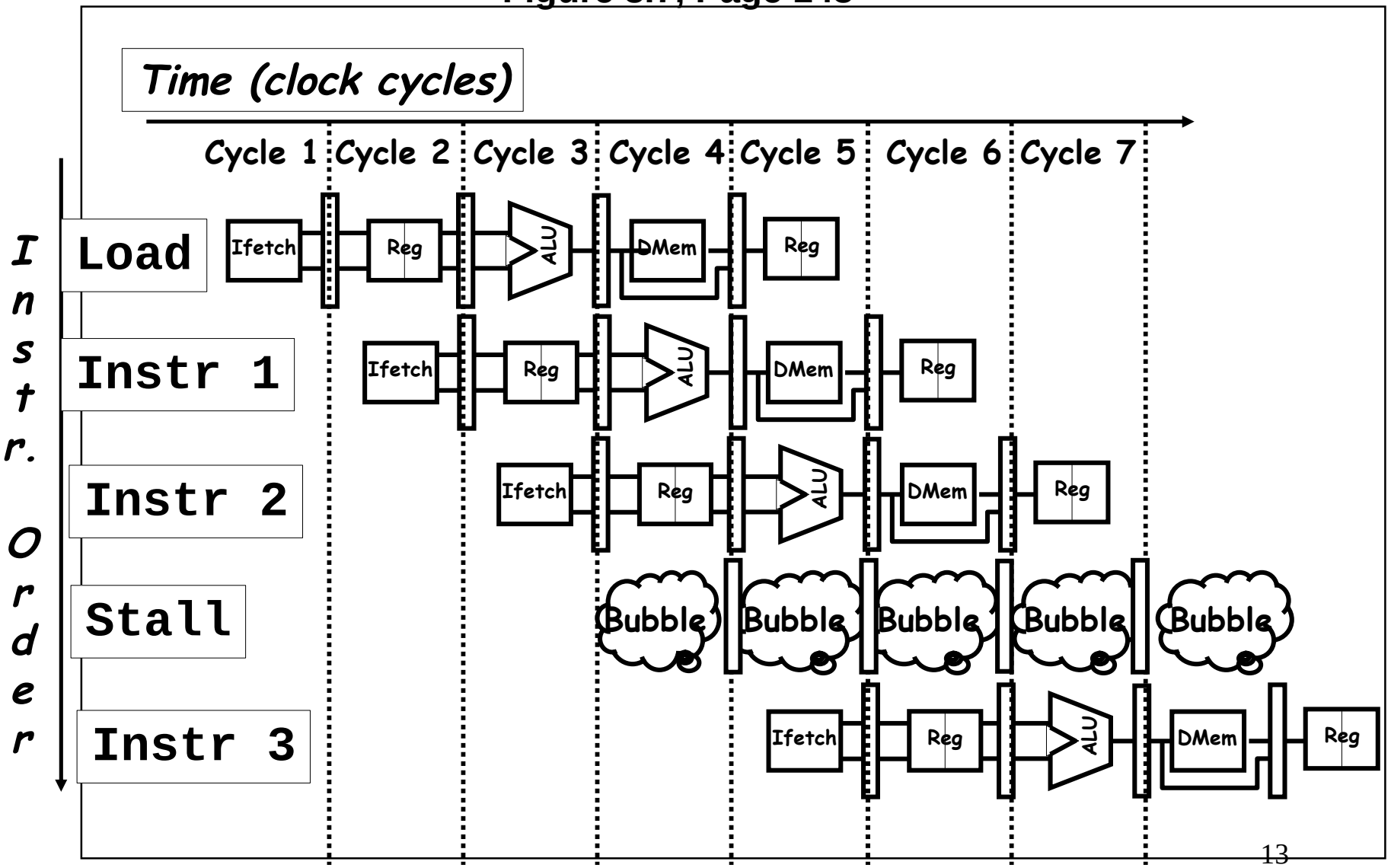
One Memory Port Structural Hazards

Figure 3.6, Page 142



One Memory Port Structural Hazards

Figure 3.7, Page 143



Outline

- An overview of pipelining
- A pipelined datapath (6.2)
- Pipelined control
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards
- Exceptions
- Superscalar and dynamic pipelining

Designing a Pipelined Processor

- Examine the datapath and control diagram
  - Starting with single- or multi-cycle datapath?
  - Single- or multi-cycle control?
- Partition datapath into stages:
  - IF (instruction fetch)
  - ID (instruction decode and register file read)
  - EX (execution or address calculation)
  - MEM (data memory access)
  - WB (write back)
- Associate resources with stages
- Ensure that flows do not conflict, or figure out how to resolve
- Assert control in appropriate stage

Use Multicycle Execution Steps

Step name	Action for R-type instructions	Action for memory-reference instructions	Action for branches	Action for jumps
Instruction fetch	IR = Memory[PC] PC = PC + 4			
Instruction decode/register fetch	A = Reg [IR[25-21]] B = Reg [IR[20-16]] ALUOut = PC + (sign-extend (IR[15-0]) << 2)			
Execution, address computation, branch/ jump completion	ALUOut = A op B	ALUOut = A + sign-extend (IR[15-0])	if (A ==B) then PC = ALUOut	PC = PC [31-28] II (IR[25-0]<<2)
Memory access or R-type completion	Reg [IR[15-11]] = ALUOut	Load: MDR = Memory[ALUOut] or Store: Memory [ALUOut] = B		
Memory read completion		Load: Reg[IR[20-16]] = MDR		

But, use single-cycle datapath ...

Split Single-cycle Datapath

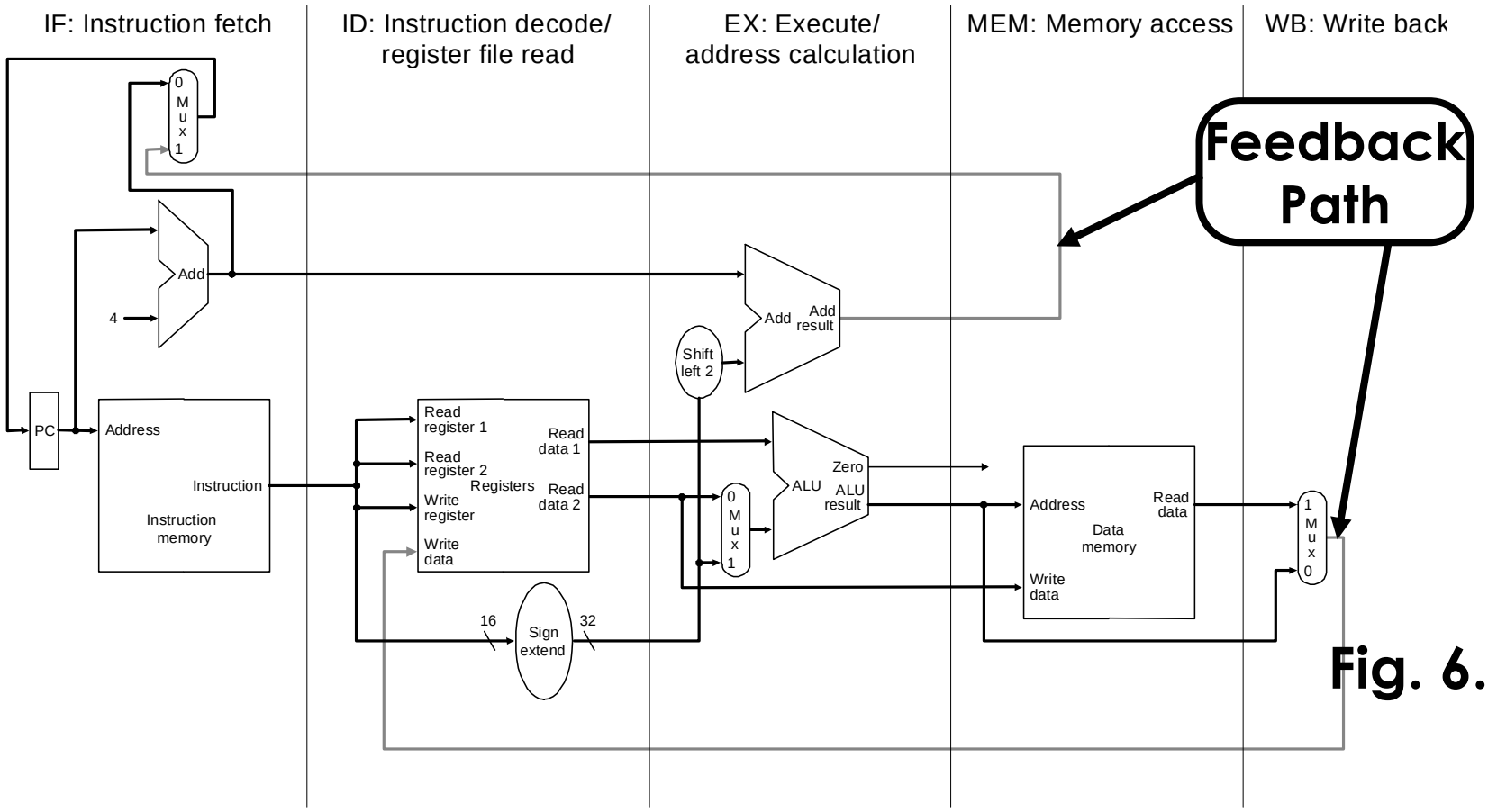


Fig. 6.9

Add Pipeline Registers

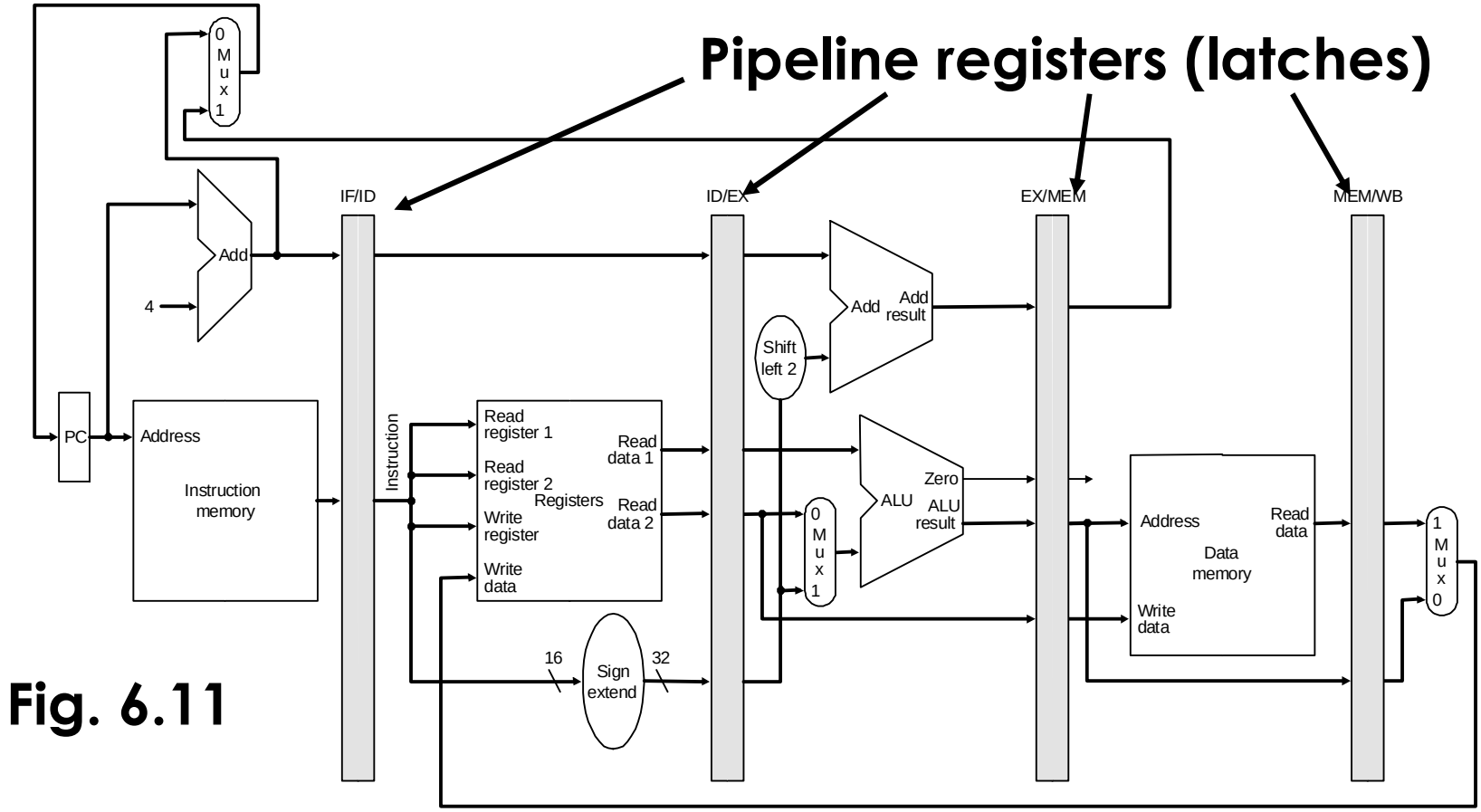
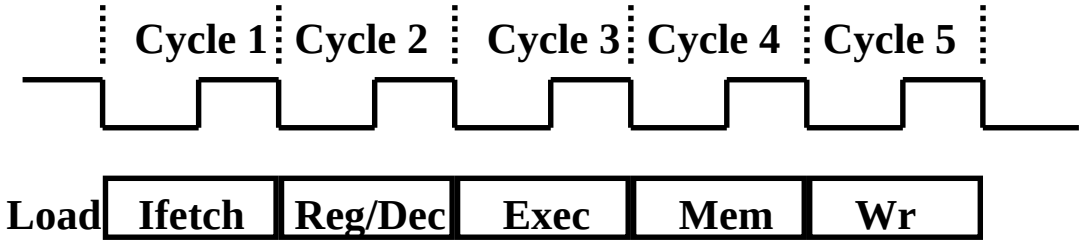


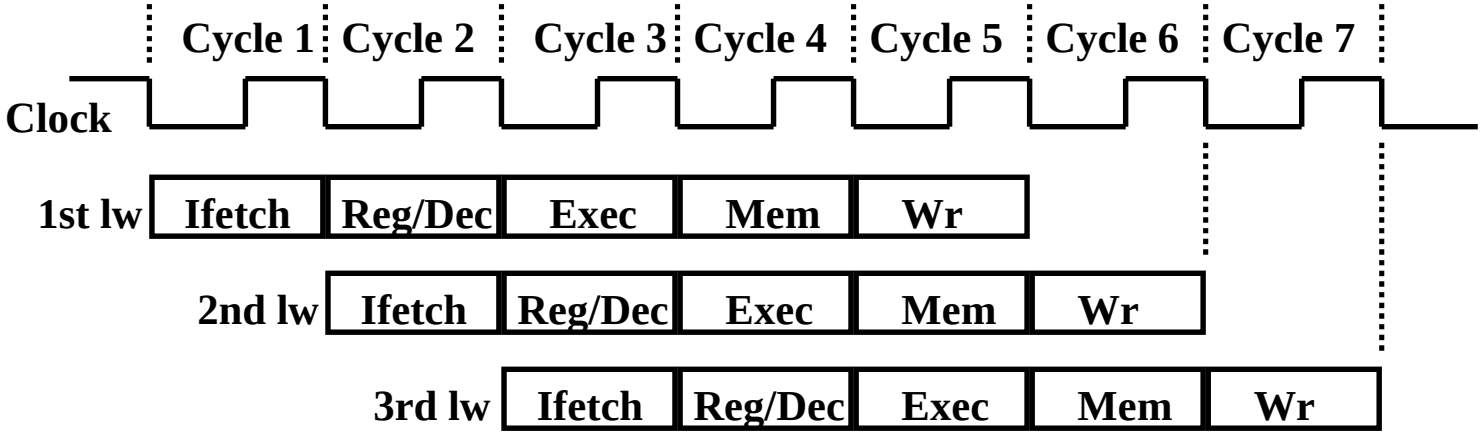
Fig. 6.11

Consider `load`



- IF: Instruction Fetch
  - Fetch the instruction from the Instruction Memory
- ID: Instruction Decode
  - Registers fetch and instruction decode
- EX: Calculate the memory address
- MEM: Read the data from the Data Memory
- WB: Write the data back to the register file

Pipelining `load`



- 5 functional units in the pipeline datapath are:
  - Instruction Memory for the Ifetch stage
  - Register File's Read ports (busA and busB) for the Reg/Dec stage
  - ALU for the Exec stage
  - Data Memory for the MEM stage
  - Register File's Write port (busW) for the WB stage

IF Stage of `load`

- IR = mem[PC]; PC = PC + 4

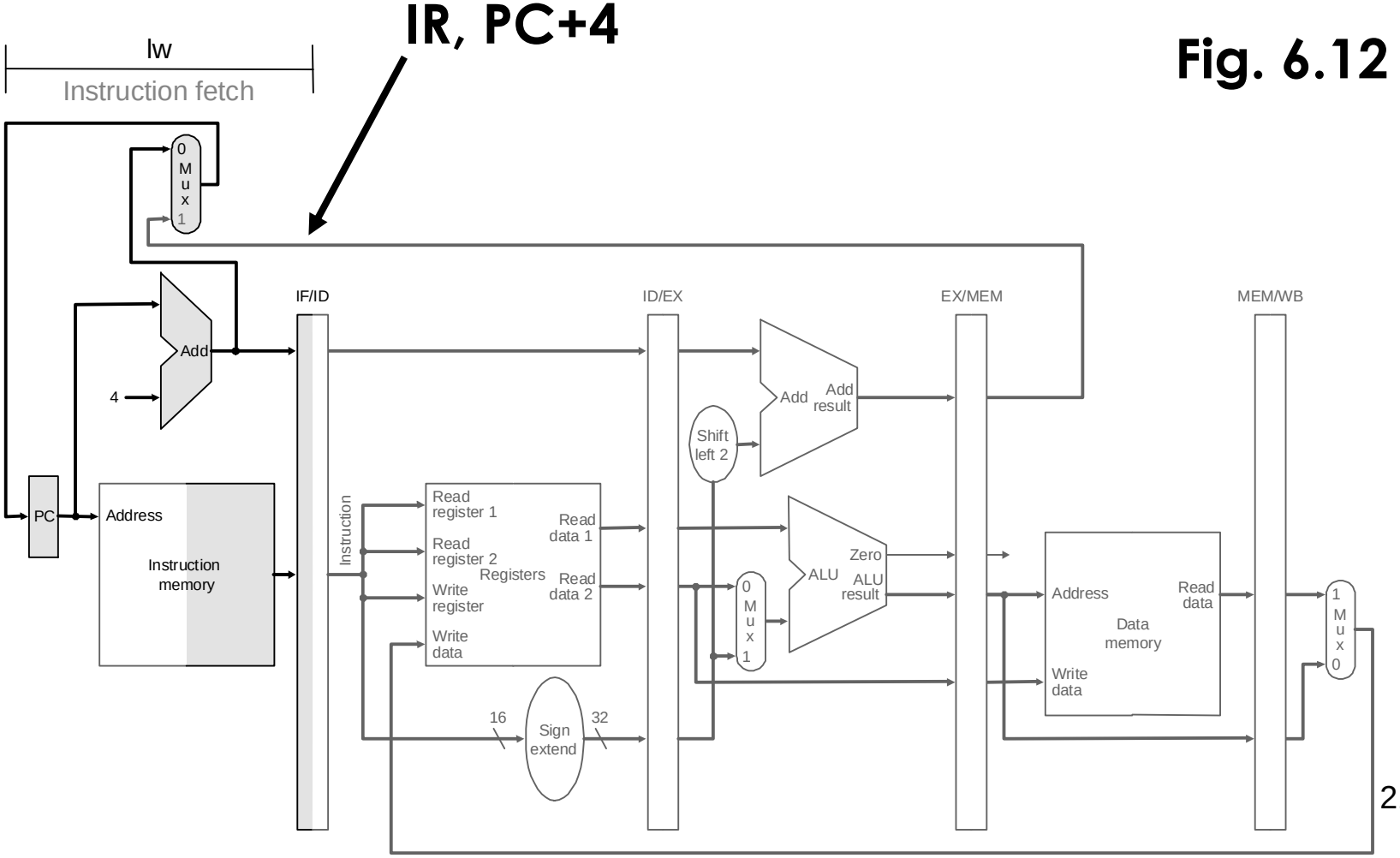


Fig. 6.12

ID Stage of `load`

- A = Reg[IR[25-21]]; B = Reg[IR[20-16]];
  ALUout = PC + (sign-ext(IR[15-0]) << 2) (some ops moved to the next stage)

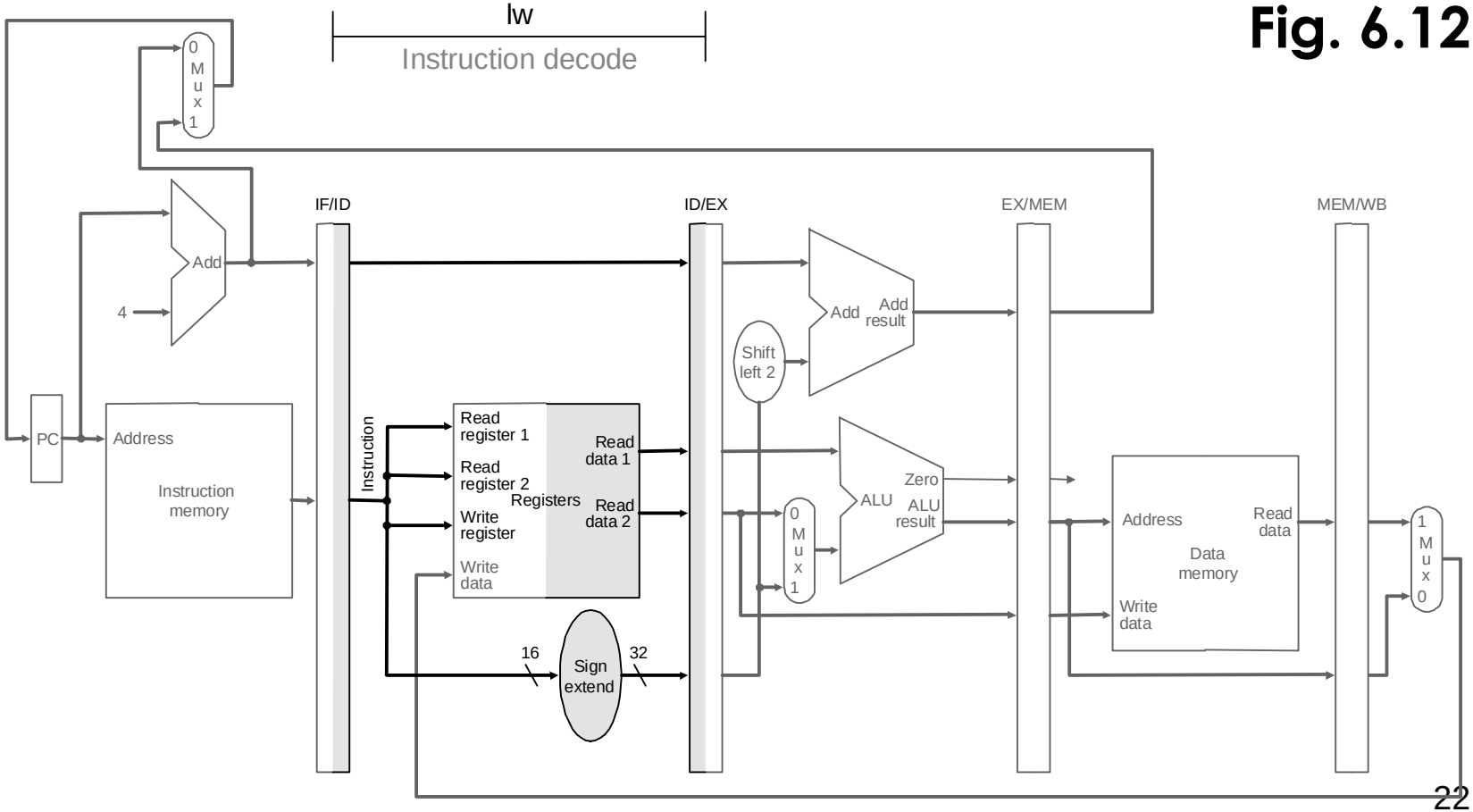
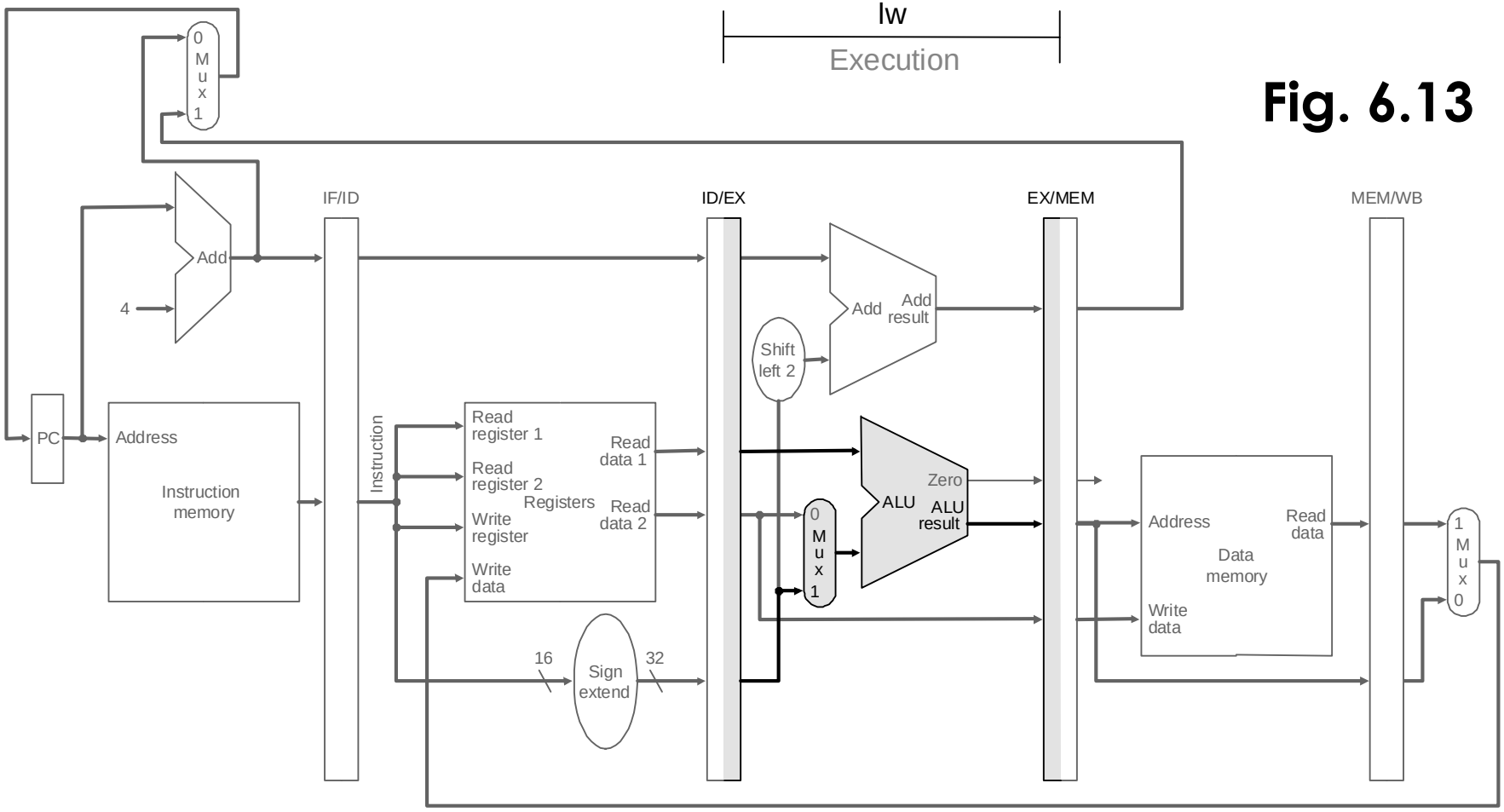


Fig. 6.12

EX Stage of `load`

- ALUout = A + sign-ext(IR[15-0])



MEM State of `load`

- MDR = mem[ALUout]

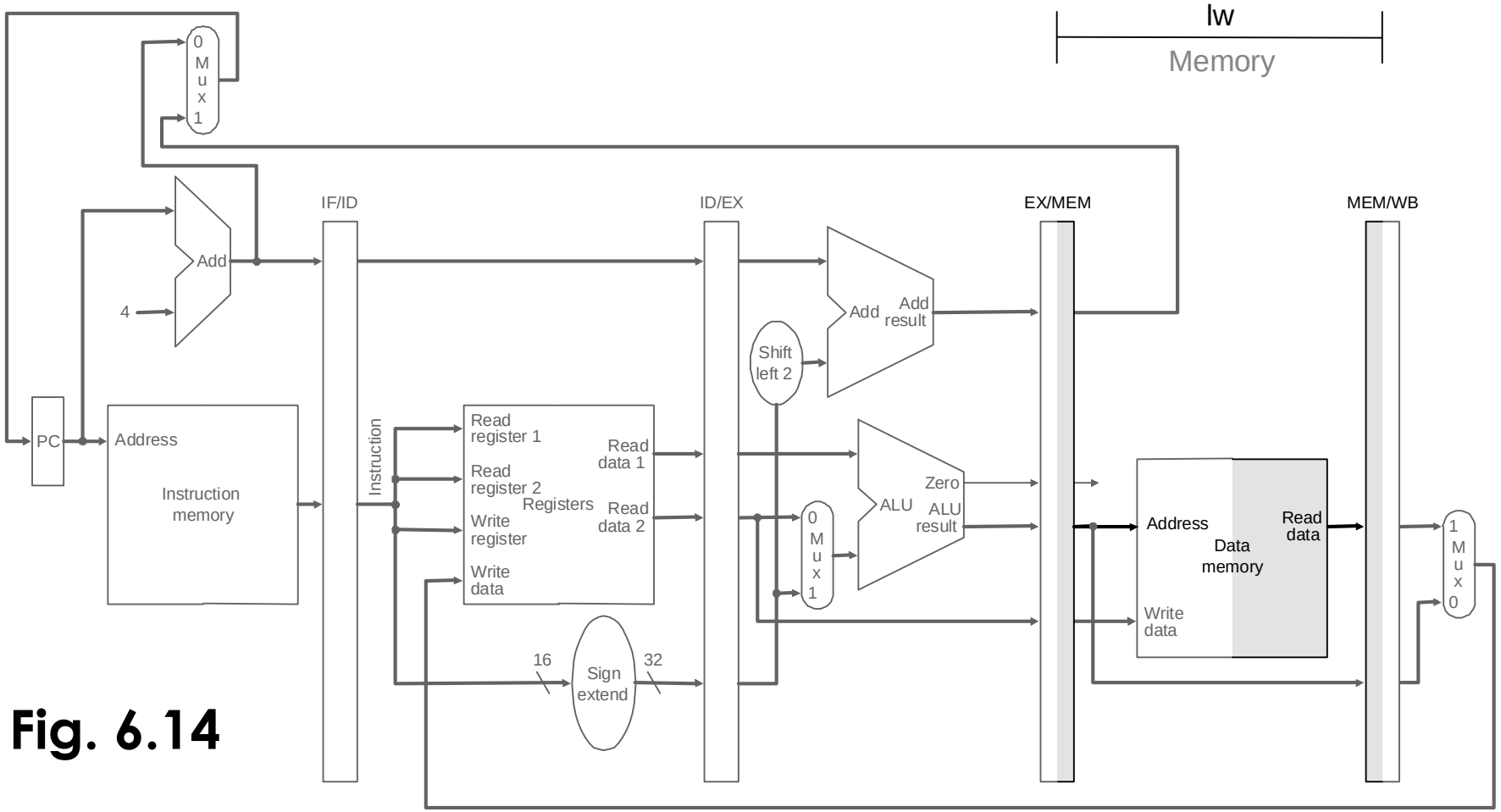


Fig. 6.14

WB Stage of `load`

- Reg[IR[20-16]] = MDR

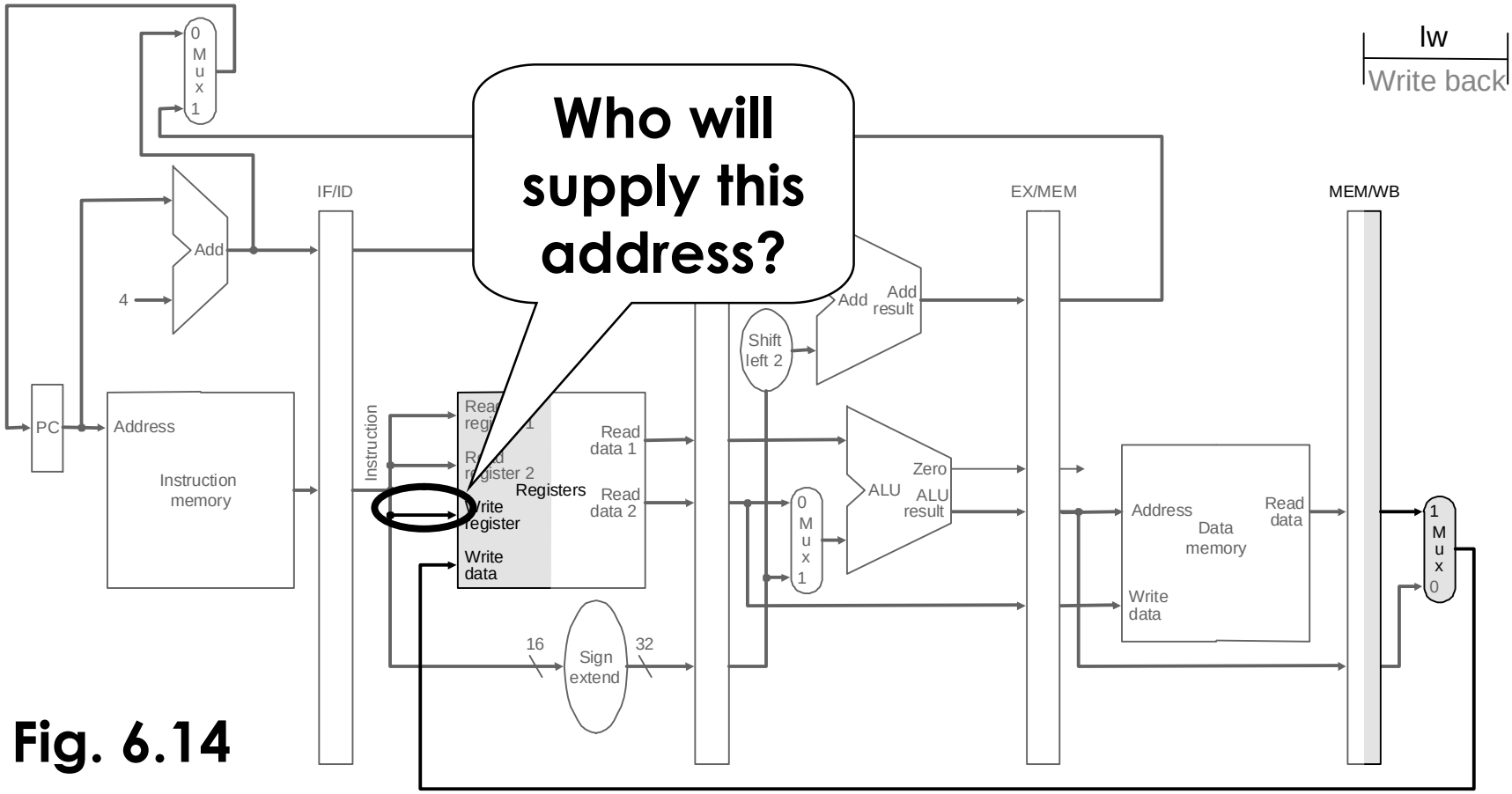
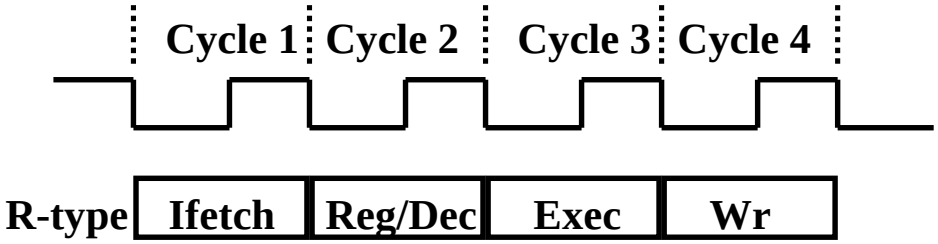


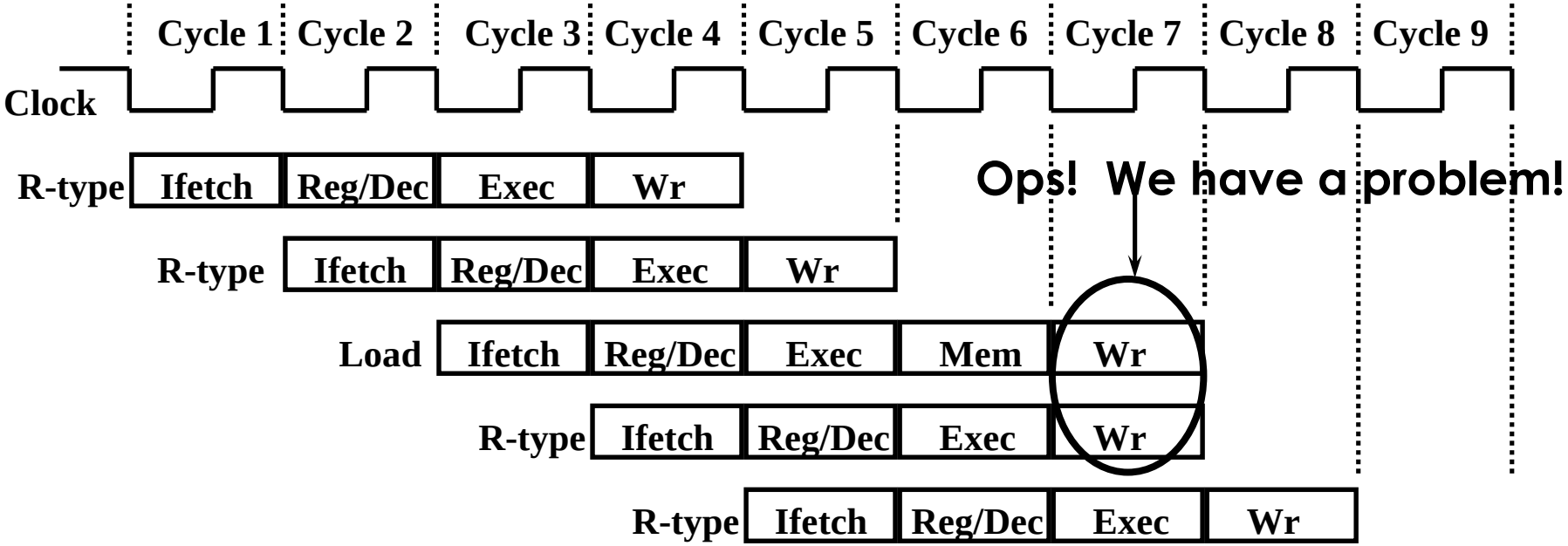
Fig. 6.14

The Four Stages of R-type



- IF: fetch the instruction from the Instruction Memory
- ID: registers fetch and instruction decode
- EX: ALU operates on the two register operands
- WB: write ALU output back to the register file

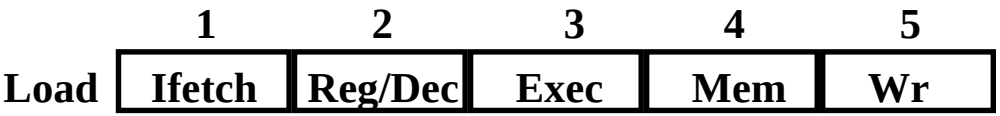
Pipelining R-type and `load`



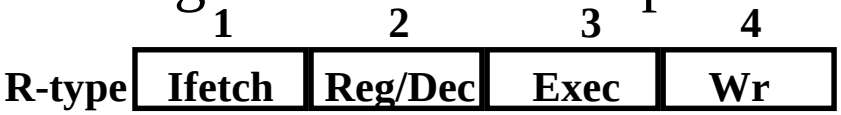
- We have a *structural hazard*:
  - Two instructions try to write to the register file at the same time!
  - Only one write port

Important Observation

- Each functional unit can only be used once per instruction
- Each functional unit must be used at the same stage for all instructions:
  - Load uses Register File's write port during its 5th stage



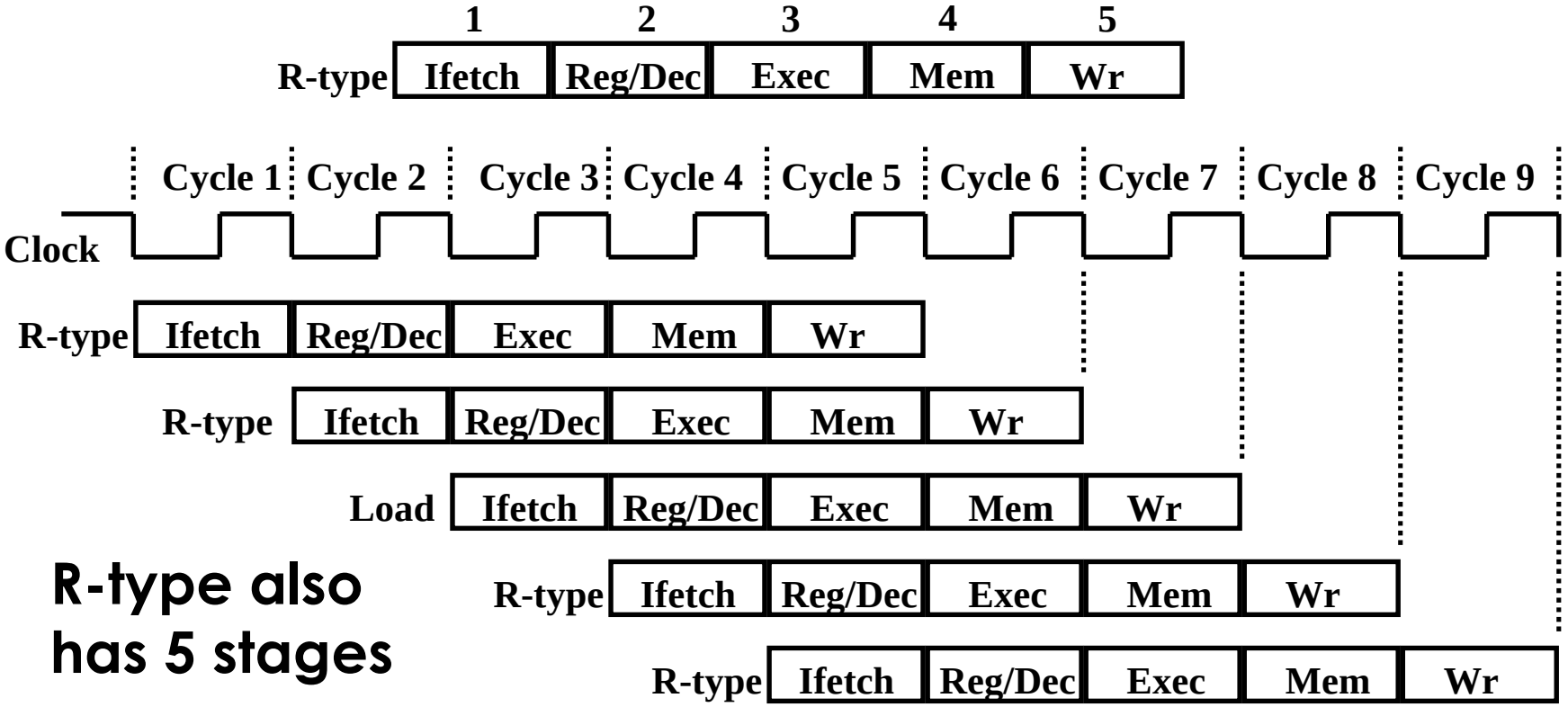
  - R-type uses Register File's write port during its 4th stage



Several ways to solve: forwarding, adding pipeline bubble, making instructions same length

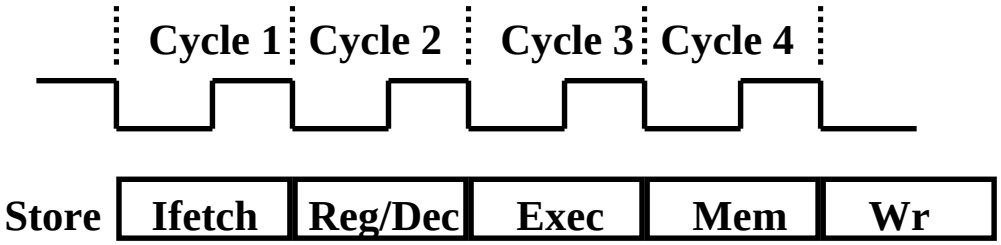
Solution: Delay R-type's Write

- Delay R-type's register write by one cycle:
  - R-type also use Reg File's write port at Stage 5
  - MEM is a NOP stage: nothing is being done.



R-type also has 5 stages

The Four Stages of `store`

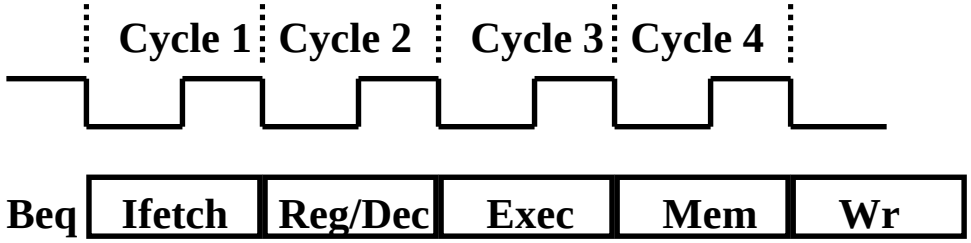


- IF: fetch the instruction from the Instruction Memory
- ID: registers fetch and instruction decode
- EX: calculate the memory address
- MEM: write the data into the Data Memory

Add an extra stage:

- WB: NOP

The Three Stages of beq

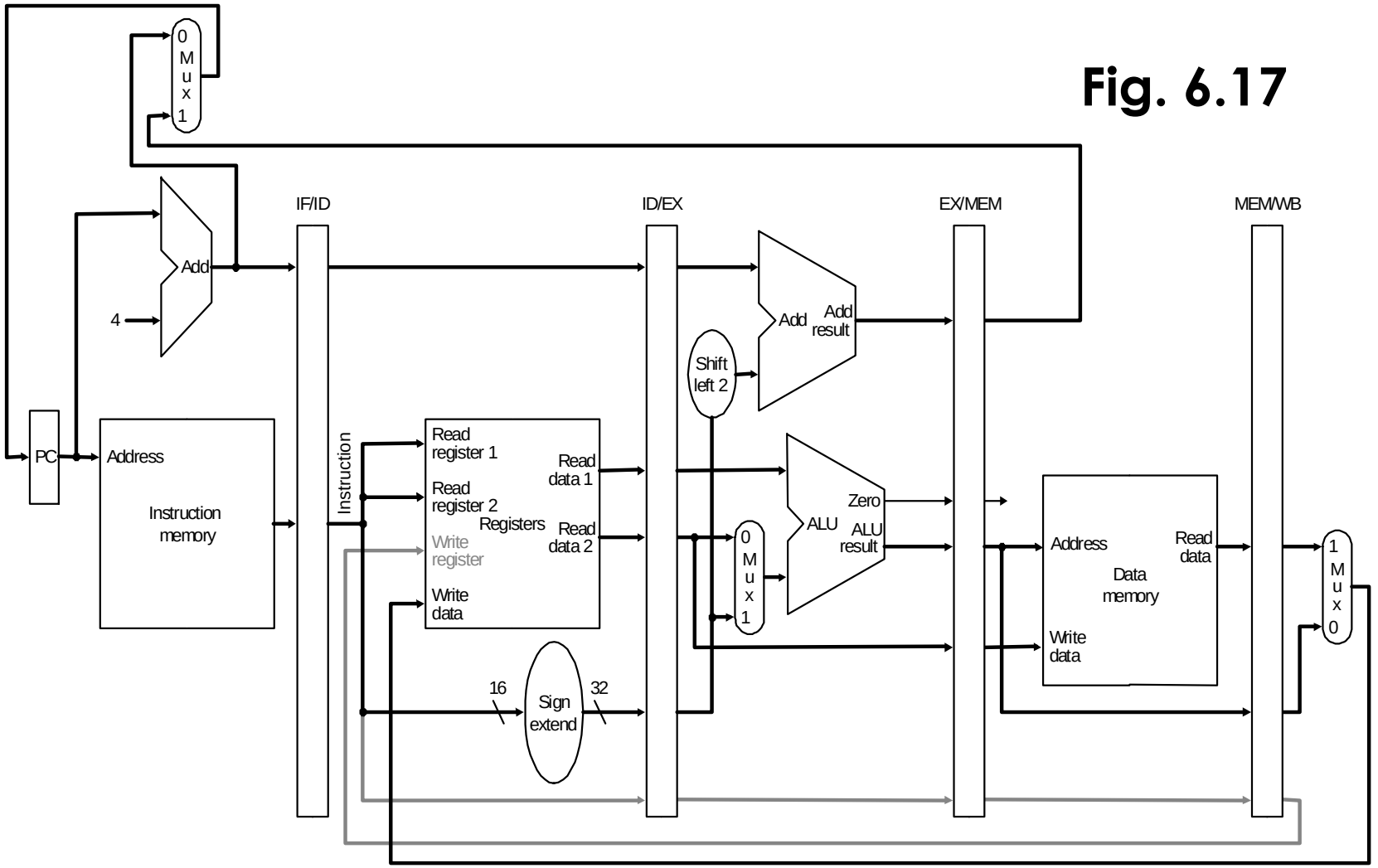


- IF: fetch the instruction from the Instruction Memory
- ID: registers fetch and instruction decode
- EX:
  - compares the two register operand
  - select correct branch target address
  - latch into PC

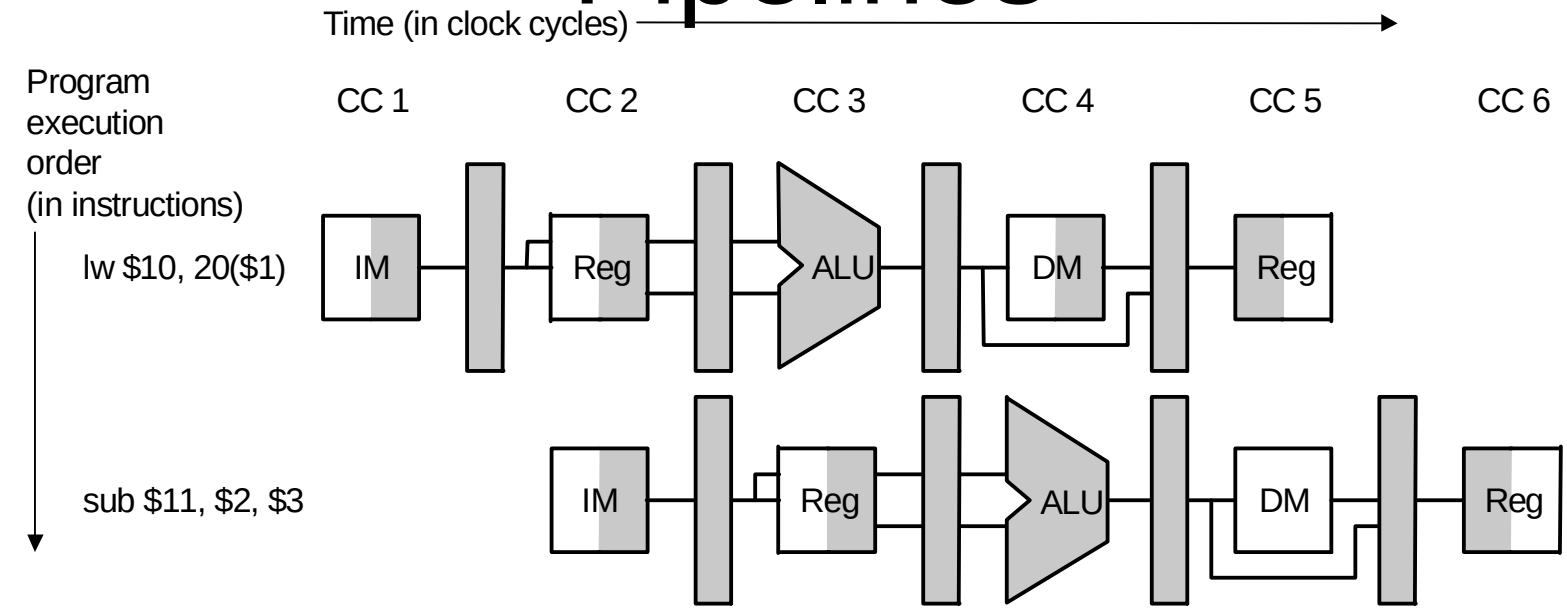
Add two extra stages:

- MEM: NOP
- WB: NOP

Pipelined Datapath



Graphically Representing Pipelines



- Can help with answering questions like:
  - How many cycles to execute this code?
  - What is the ALU doing during cycle 4?
  - Help understand datapaths

Example 1: Cycle 1

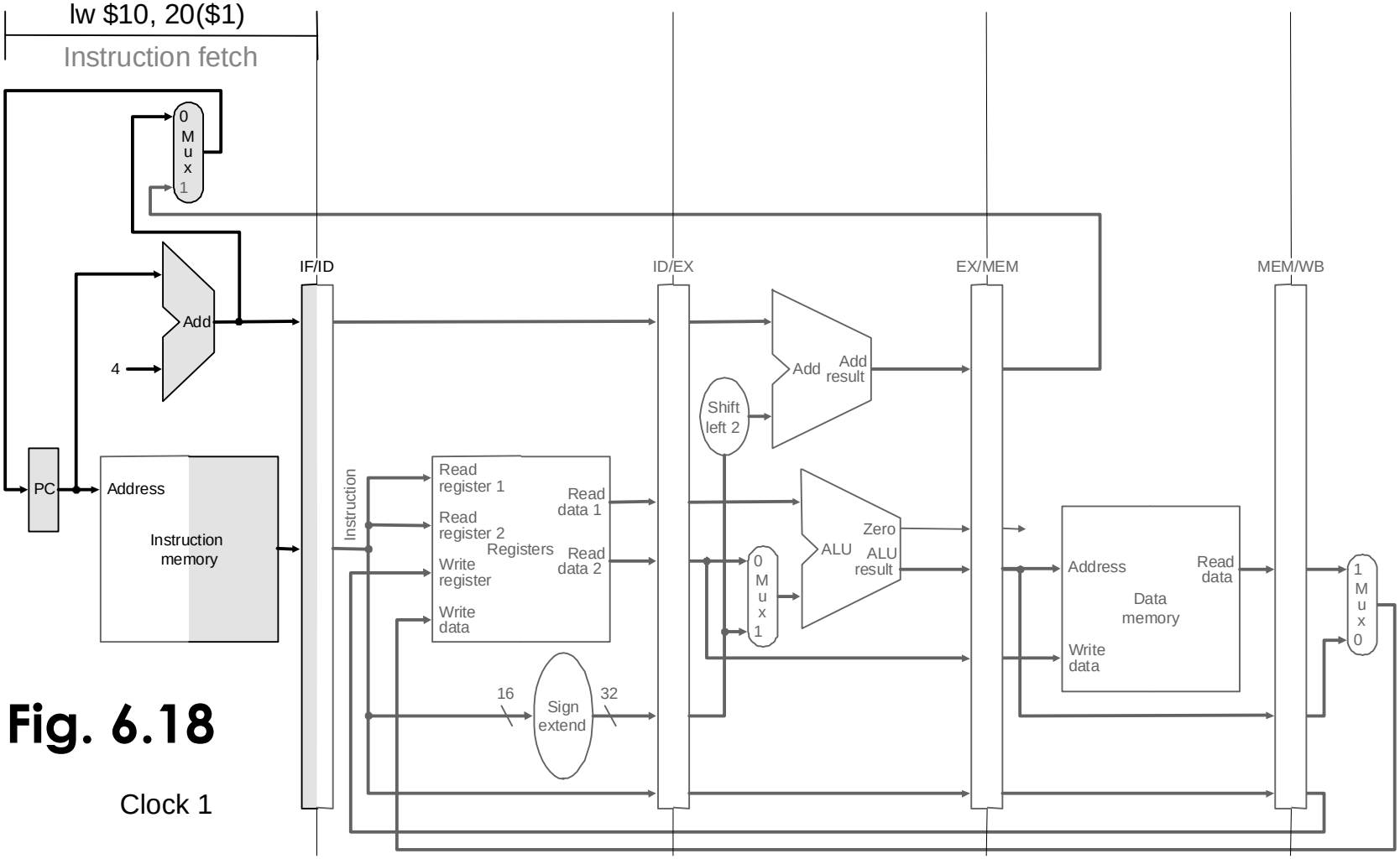


Fig. 6.18

Clock 1

Example 1: Cycle 2

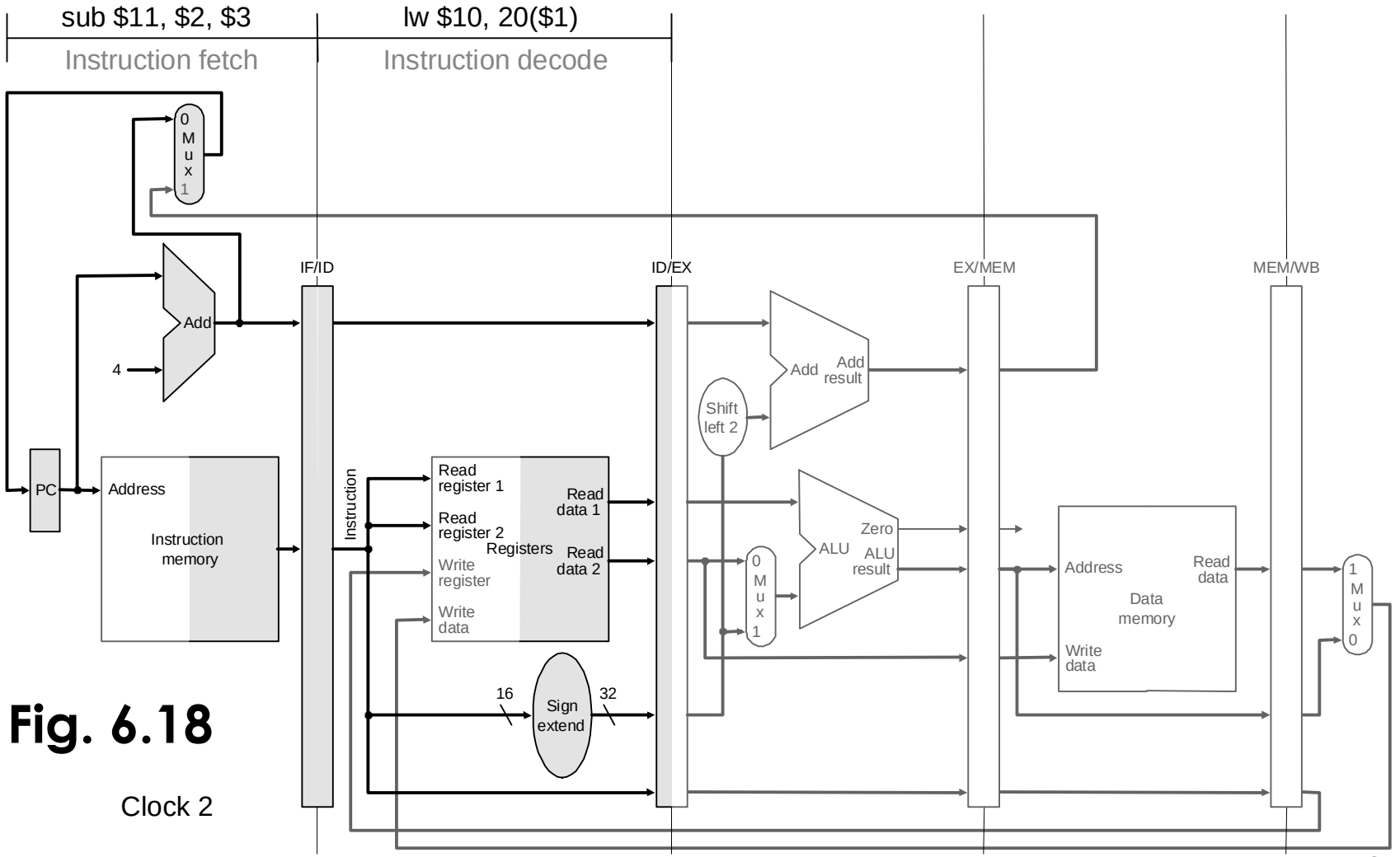


Fig. 6.18

Clock 2

Example 1: Cycle 3

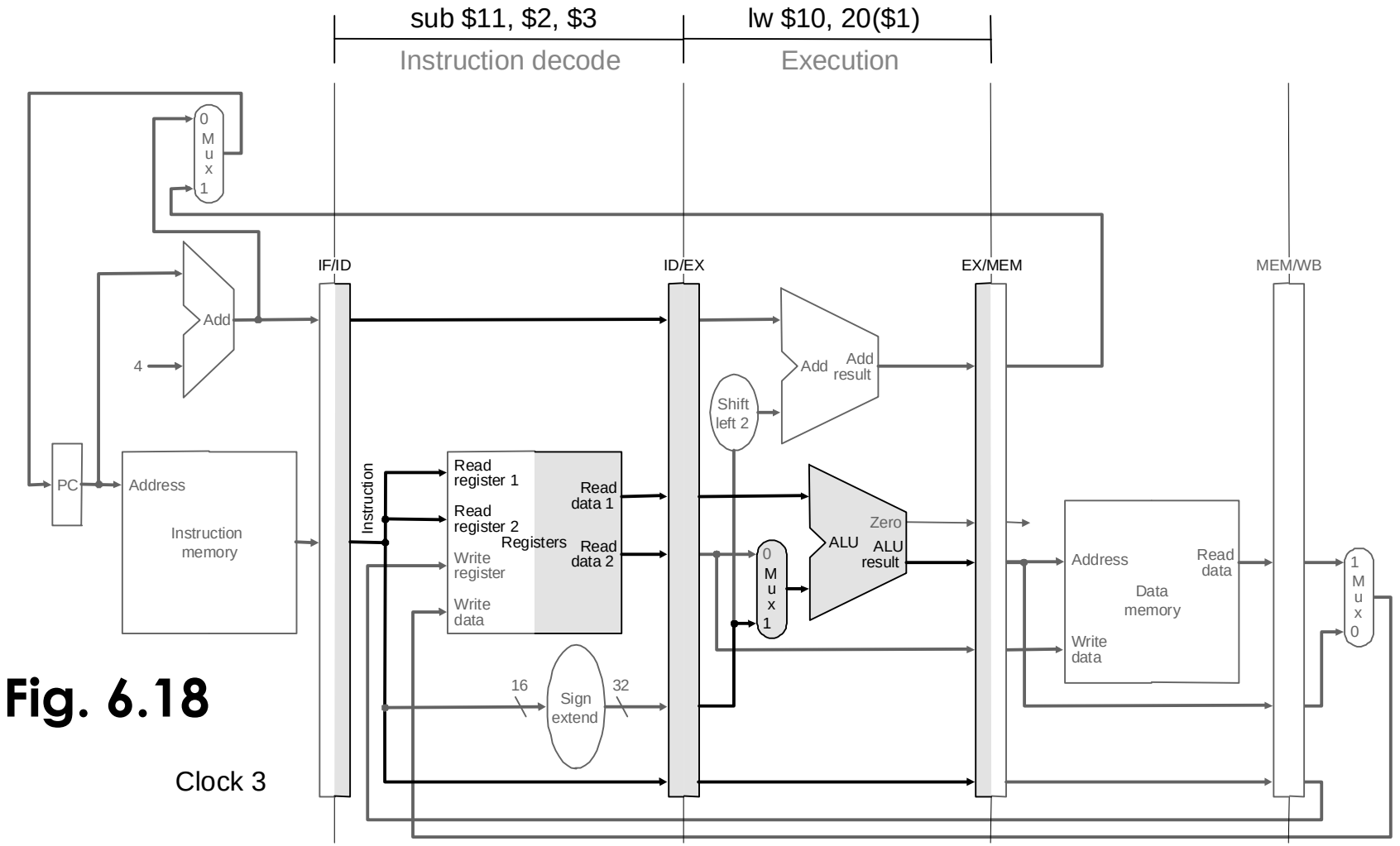


Fig. 6.18

Clock 3

Example 1: Cycle 4

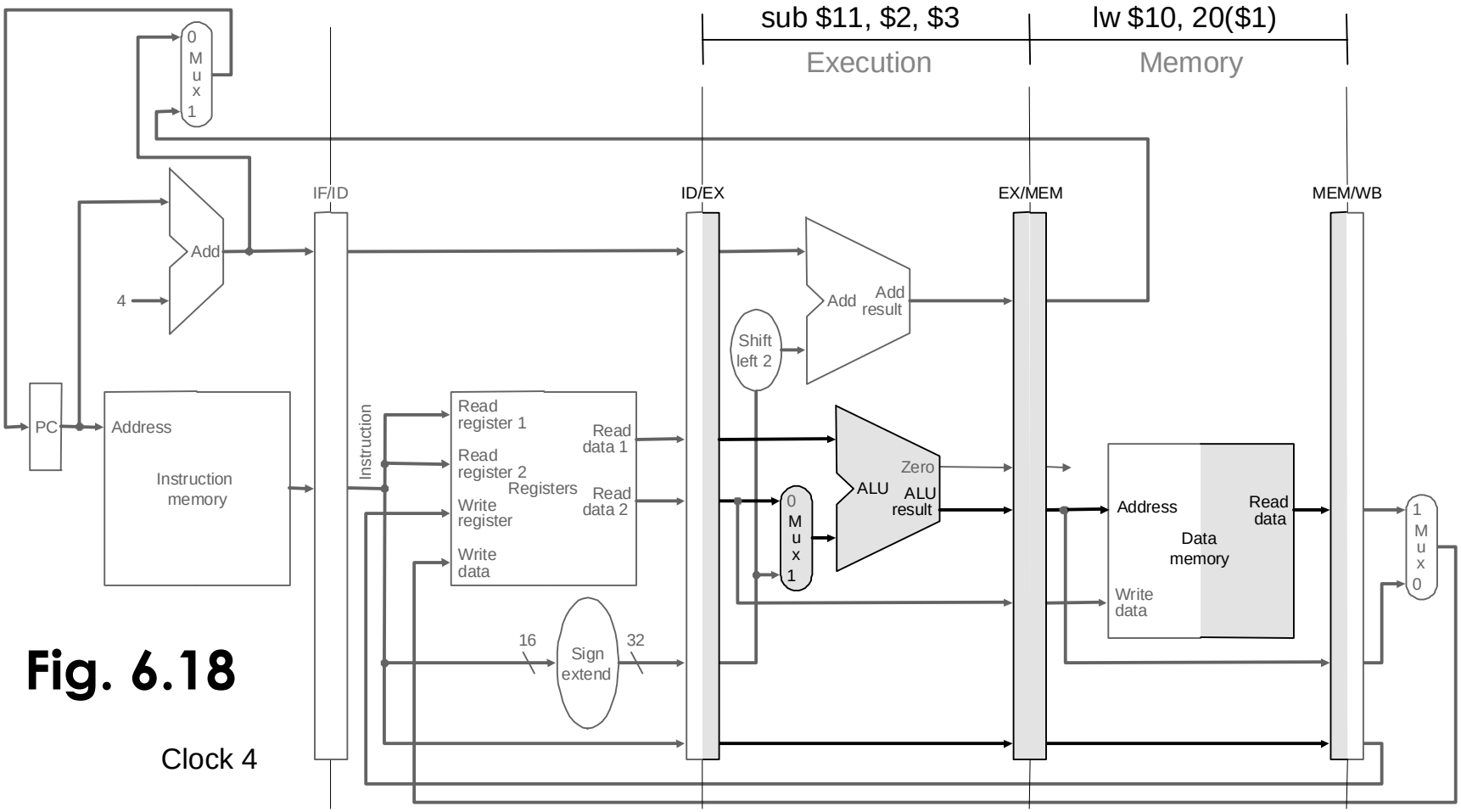


Fig. 6.18

Clock 4

Example 1: Cycle 5

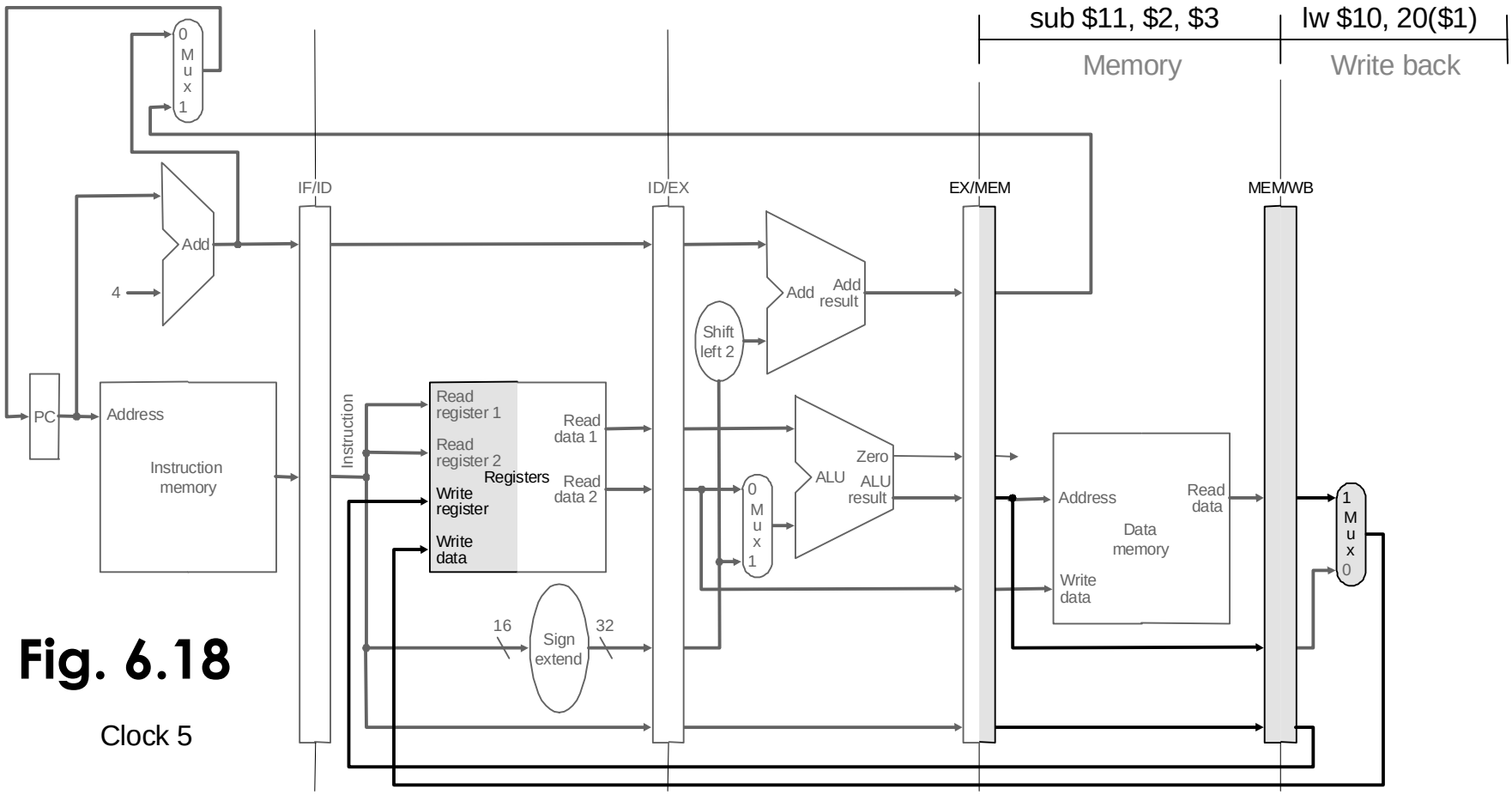


Fig. 6.18

Clock 5

Example 1: Cycle 6

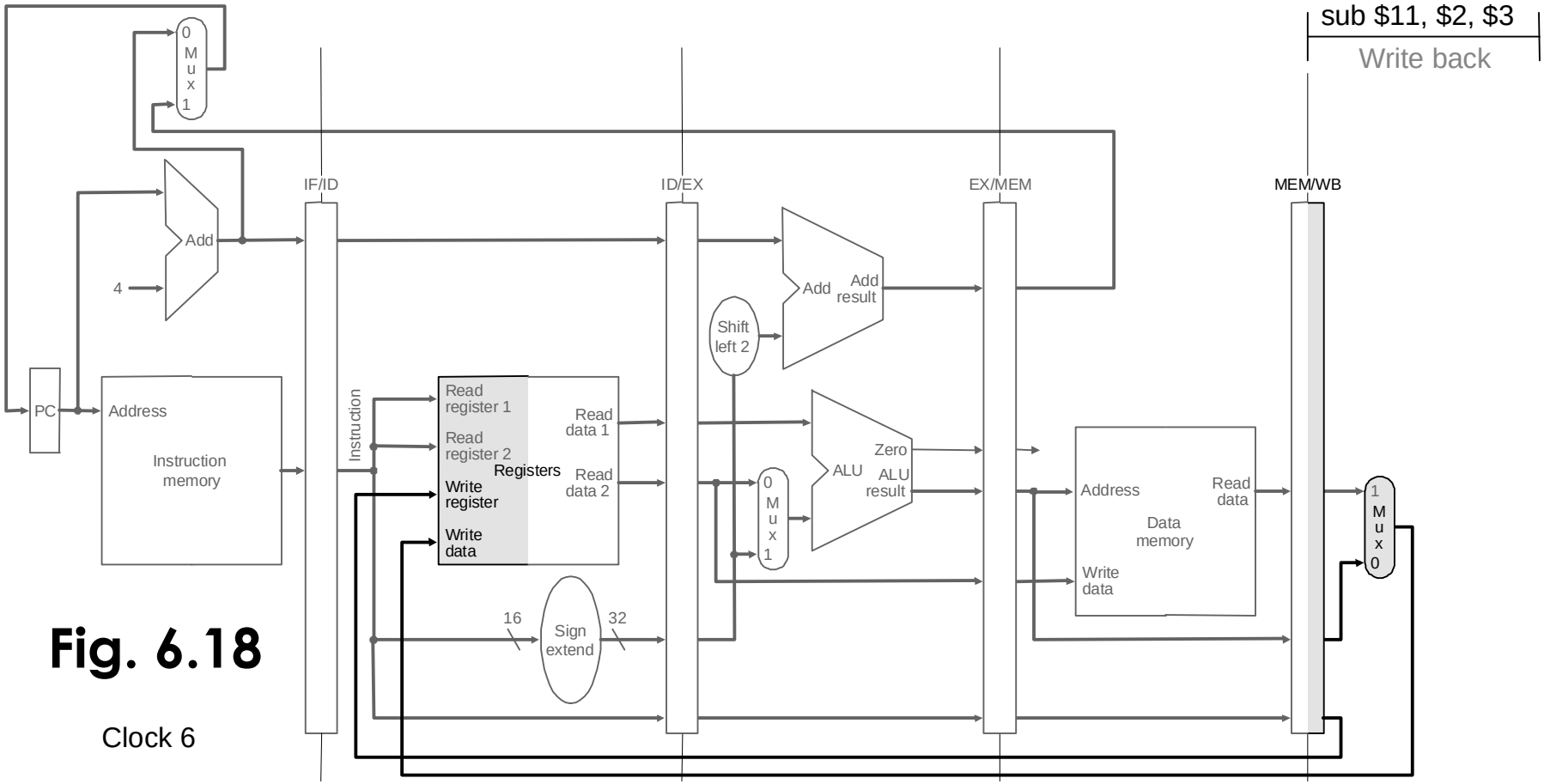


Fig. 6.18

Clock 6

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- Pipelined control (6.3)
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards
- Exceptions
- Superscalar and dynamic pipelining

Pipeline Control: Control Signals

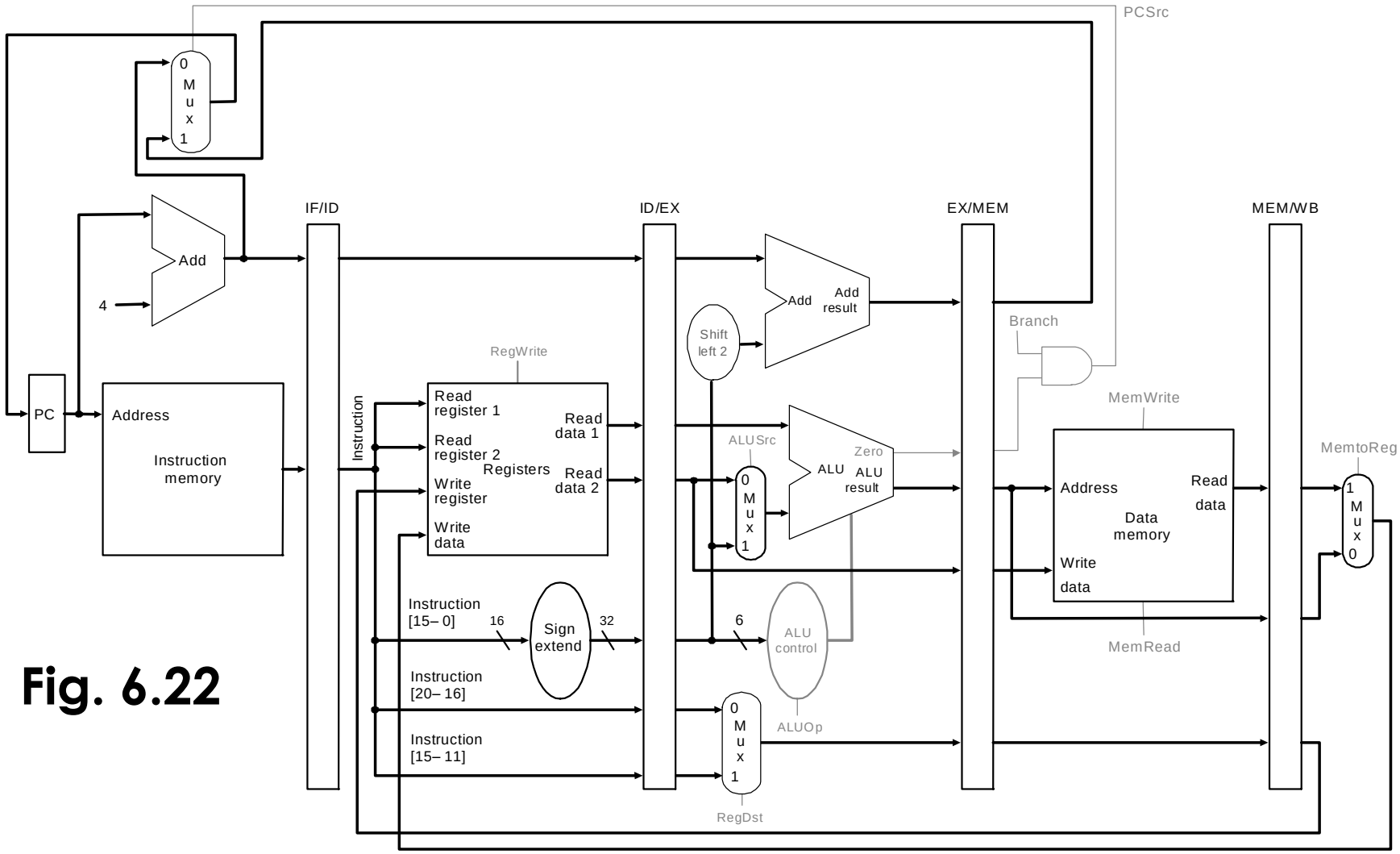


Fig. 6.22

Group Signals According to Stages

- Can use control signals of single-cycle CPU (Fig. 6.23, 6.24 <==> 5.12, 5.16)

	Execution/Address Calculation stage control lines				Memory access stage control lines			Write-back stage control lines	
	Reg Dst	ALU Op1	ALU Op0	ALU Src	Branch	Mem Read	Mem Write	Reg write	Mem to Reg
R-type	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

Fig. 6.25

Data Stationary Control

- Pass control signals along just like the data
  - Main control generates control signals during ID

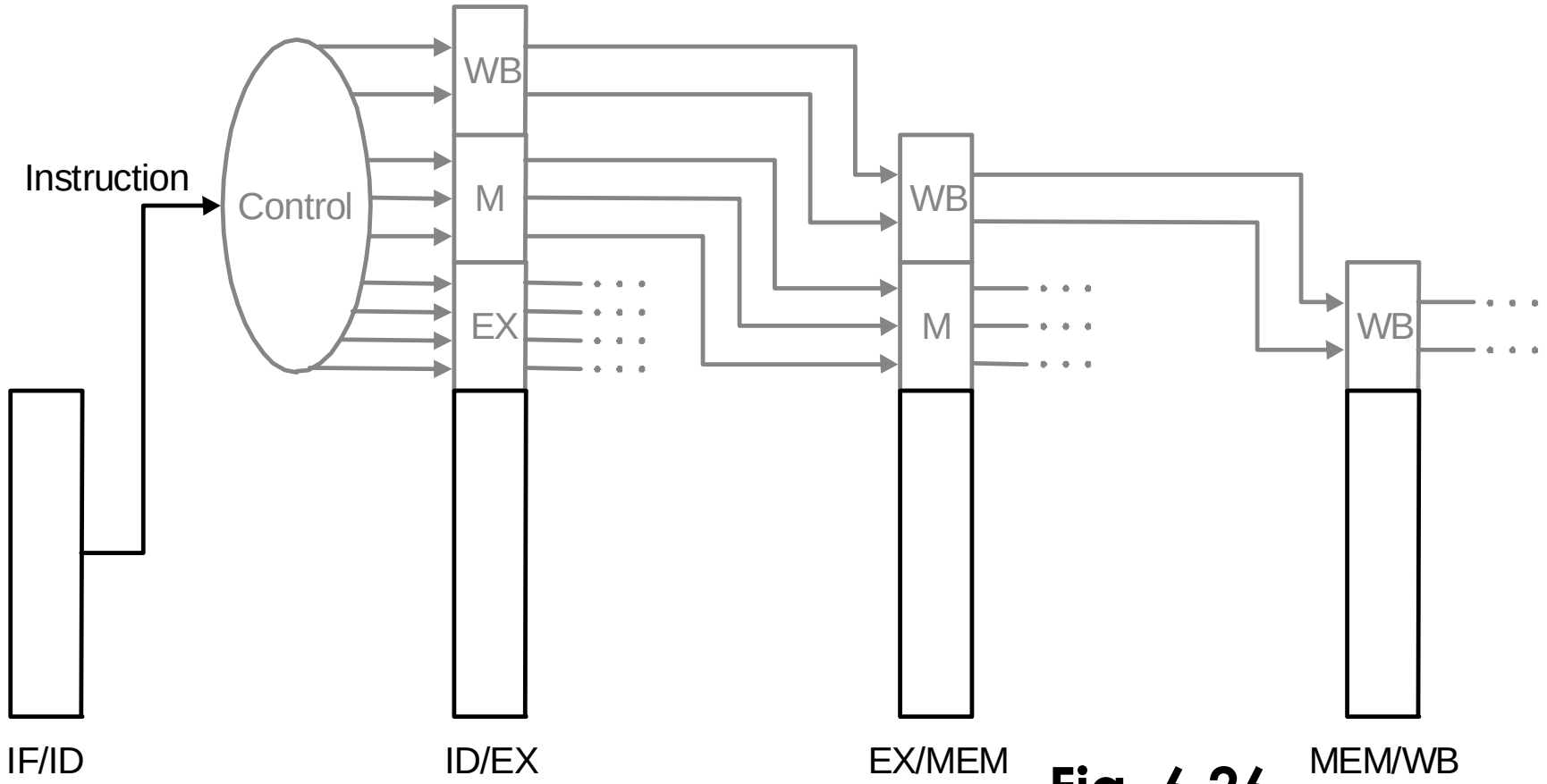
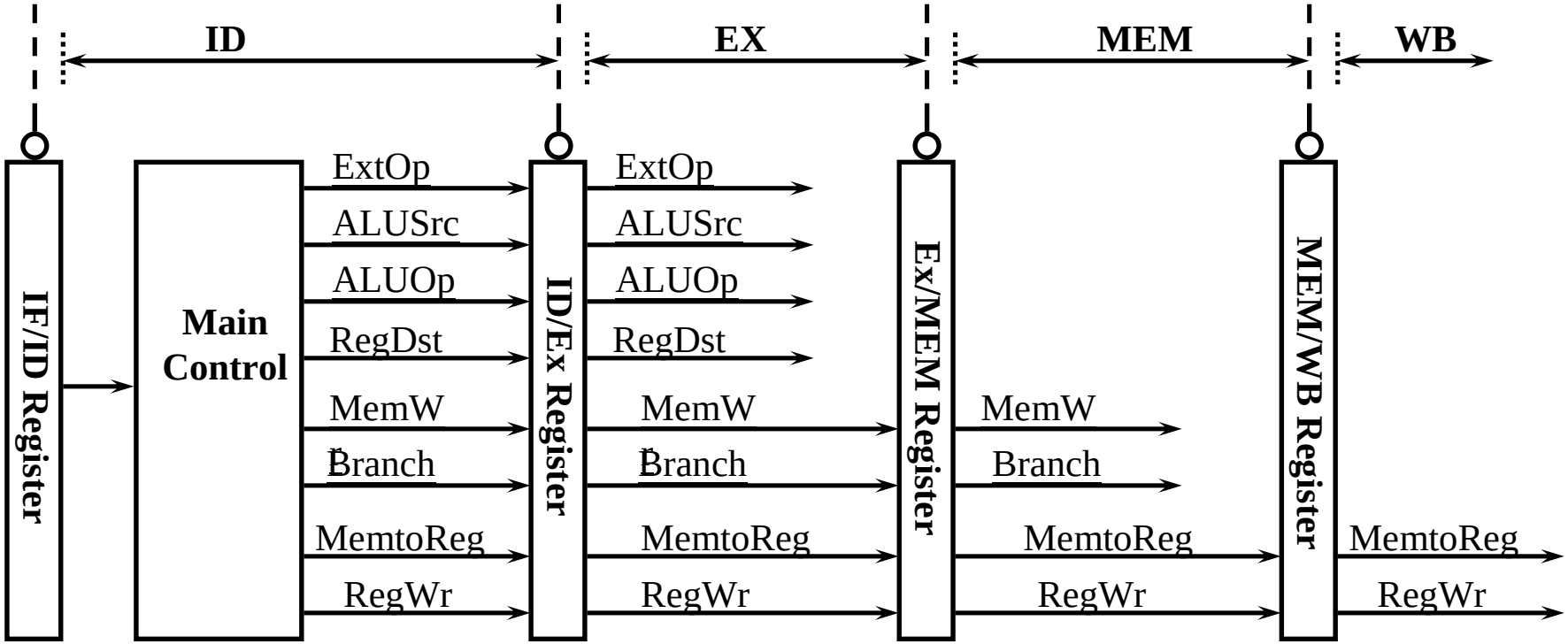


Fig. 6.26

Data Stationary Control (cont.)

- Signals for EX (ExtOp, ALUSrc, ...) are used 1 cycle later
- Signals for MEM (MemWr, Branch) are used 2 cycles later
- Signals for WB (MemtoReg, MemWr) are used 3 cycles later



WB Stage of `load`

- Reg[IR[20-16]] = MDR

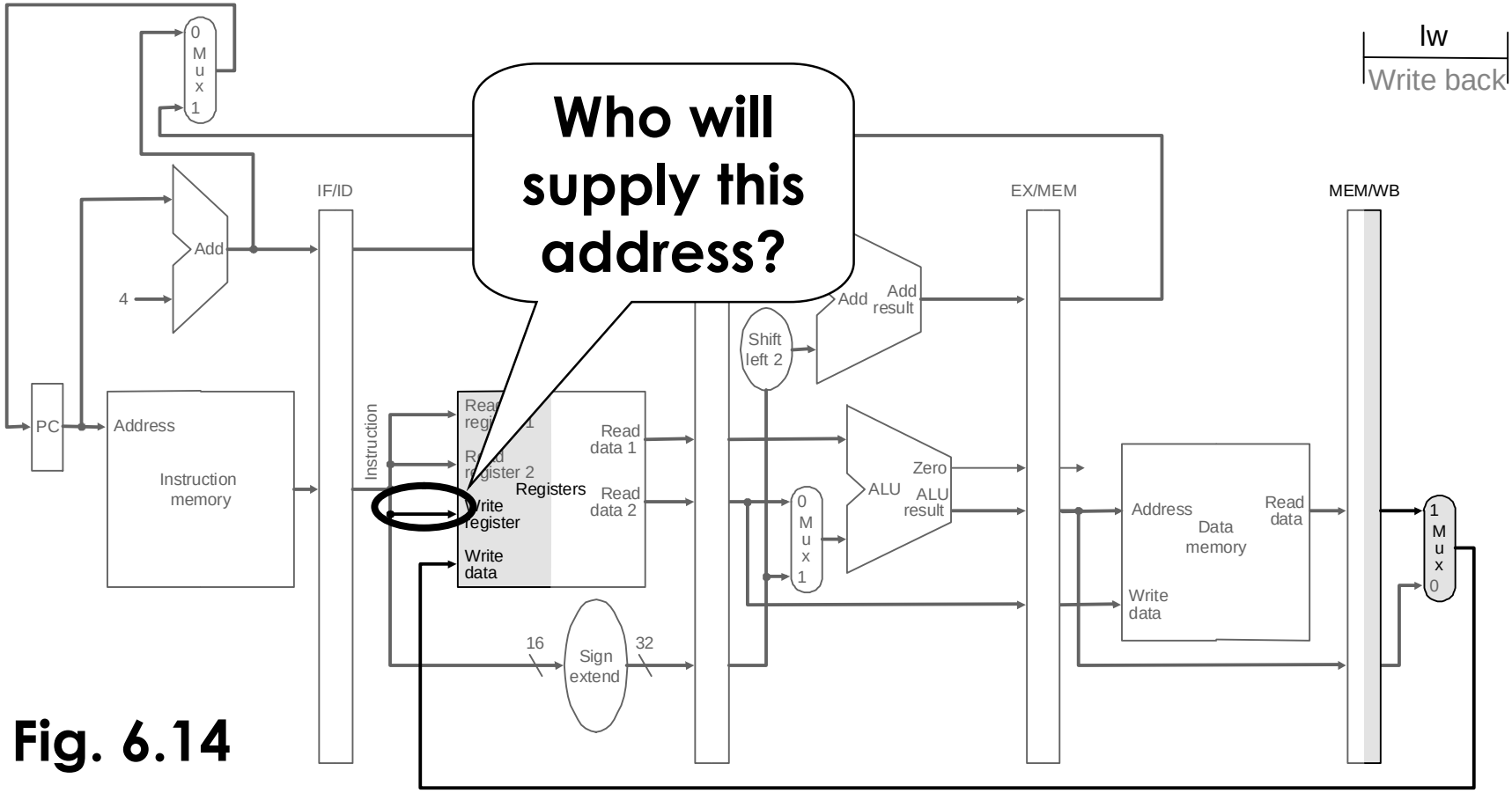


Fig. 6.14

Datapath with Control

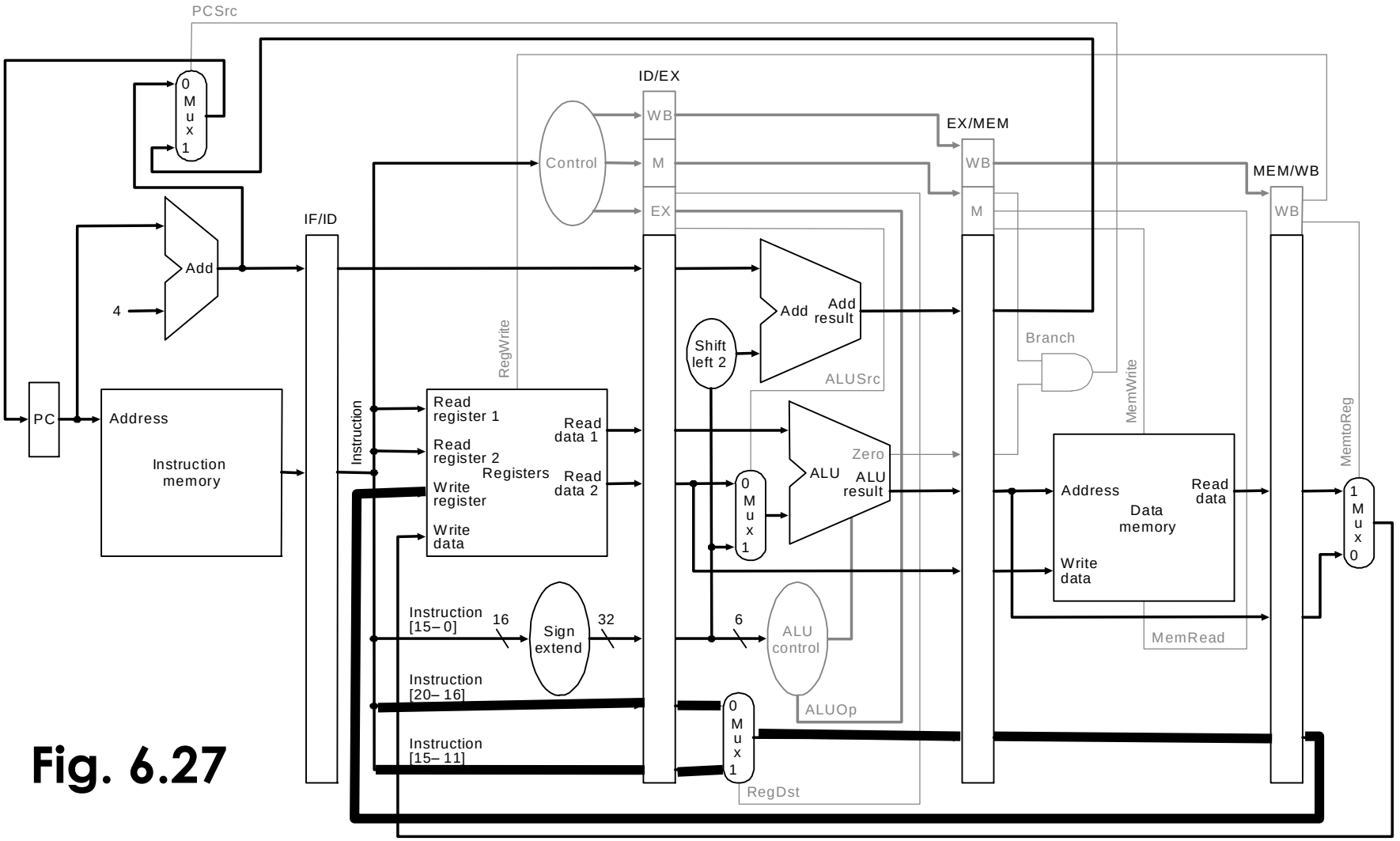
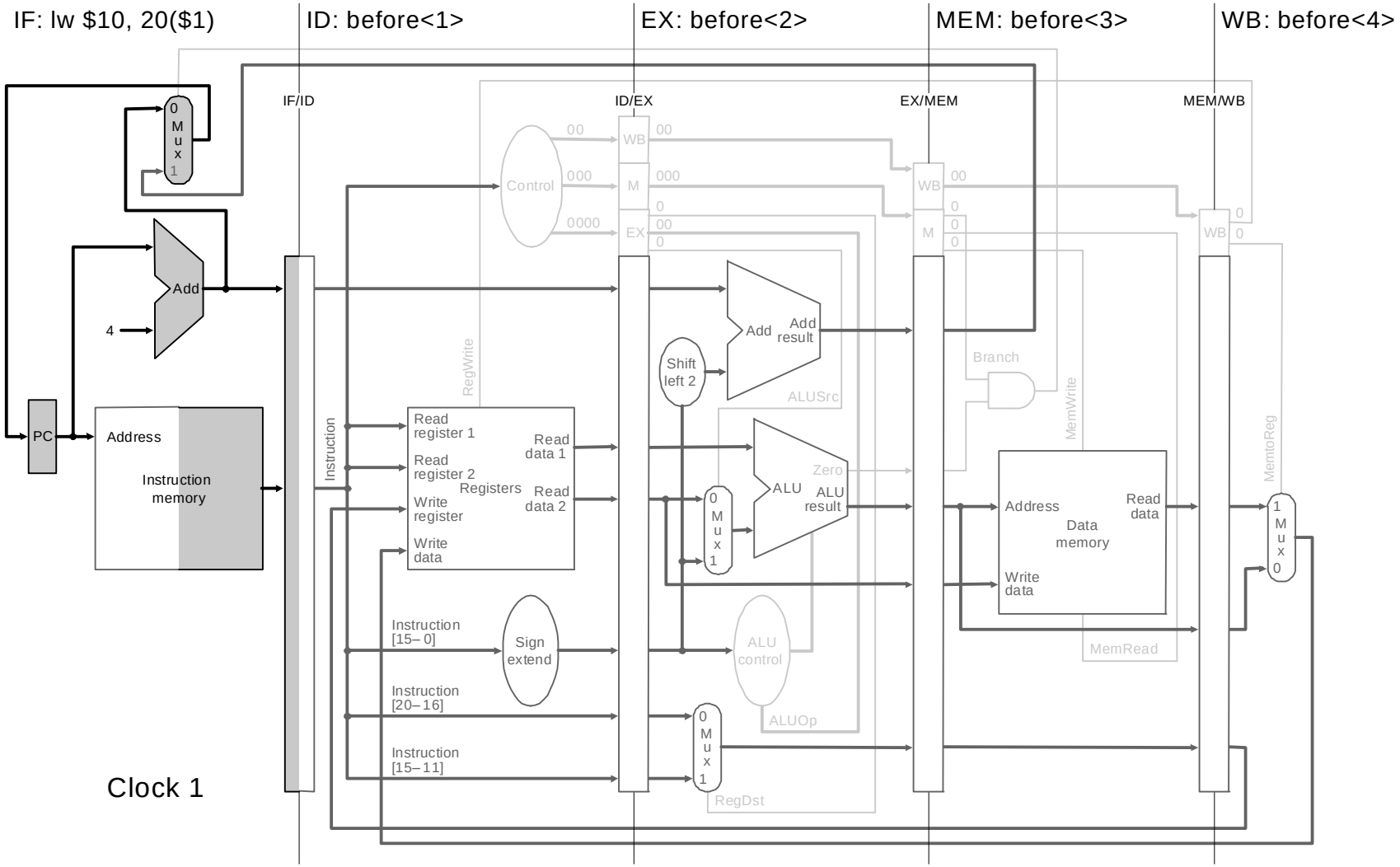


Fig. 6.27

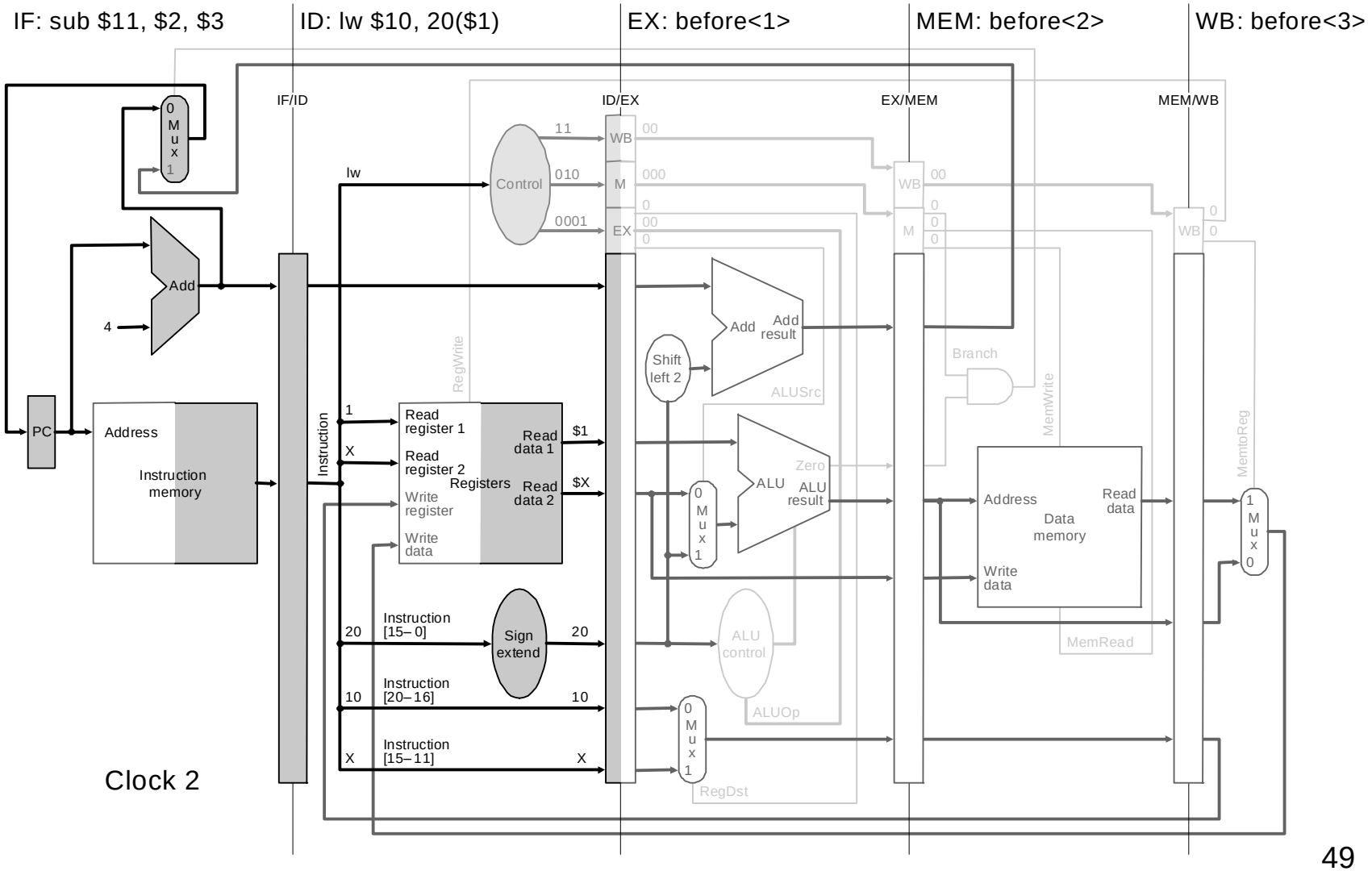
Let’s Try it Out

```
lw  $10, 20($1)
sub $11, $2, $3
and $12, $4, $5
or  $13, $6, $7
add $14, $8, $9
```

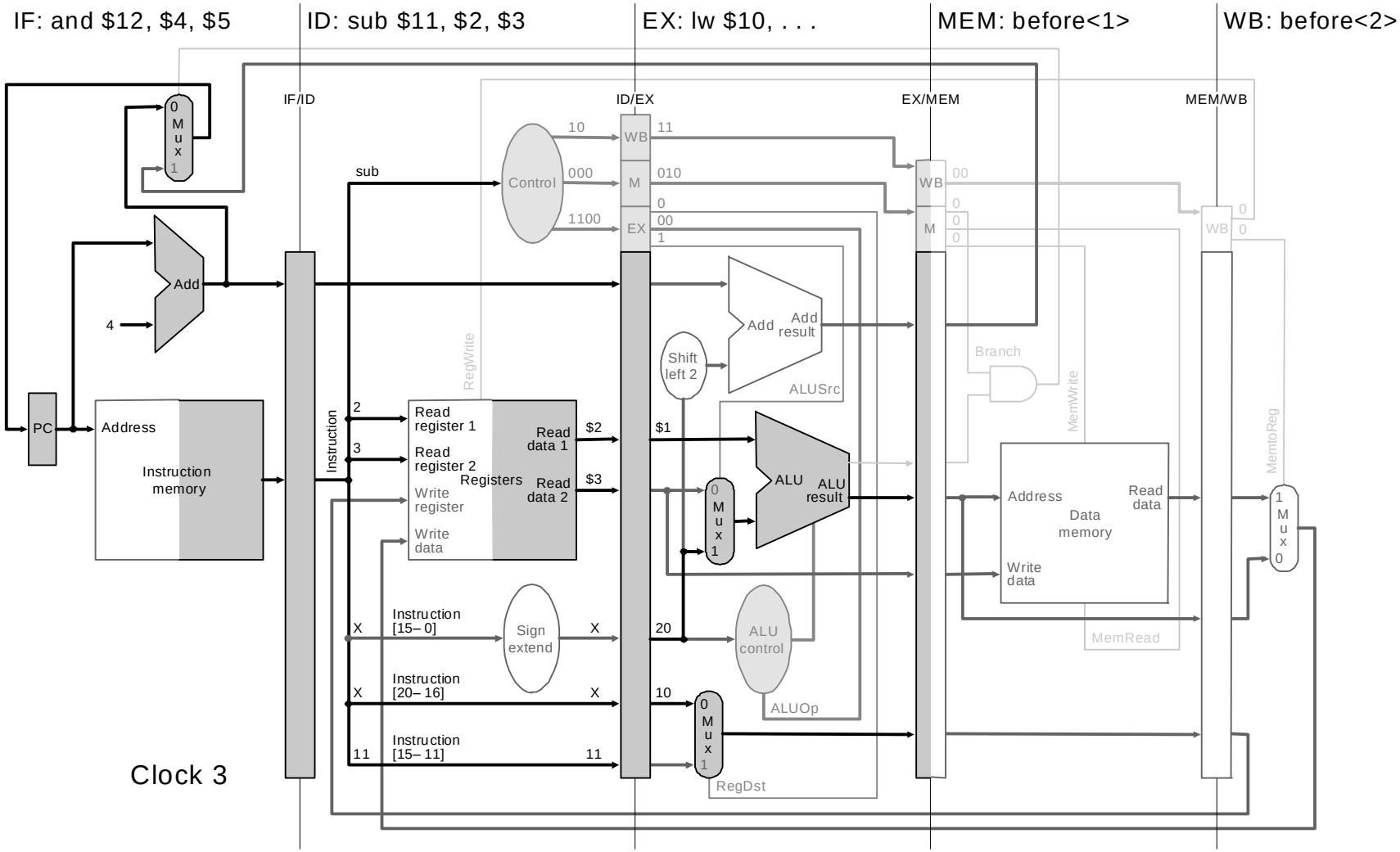
Example 2: Cycle 1



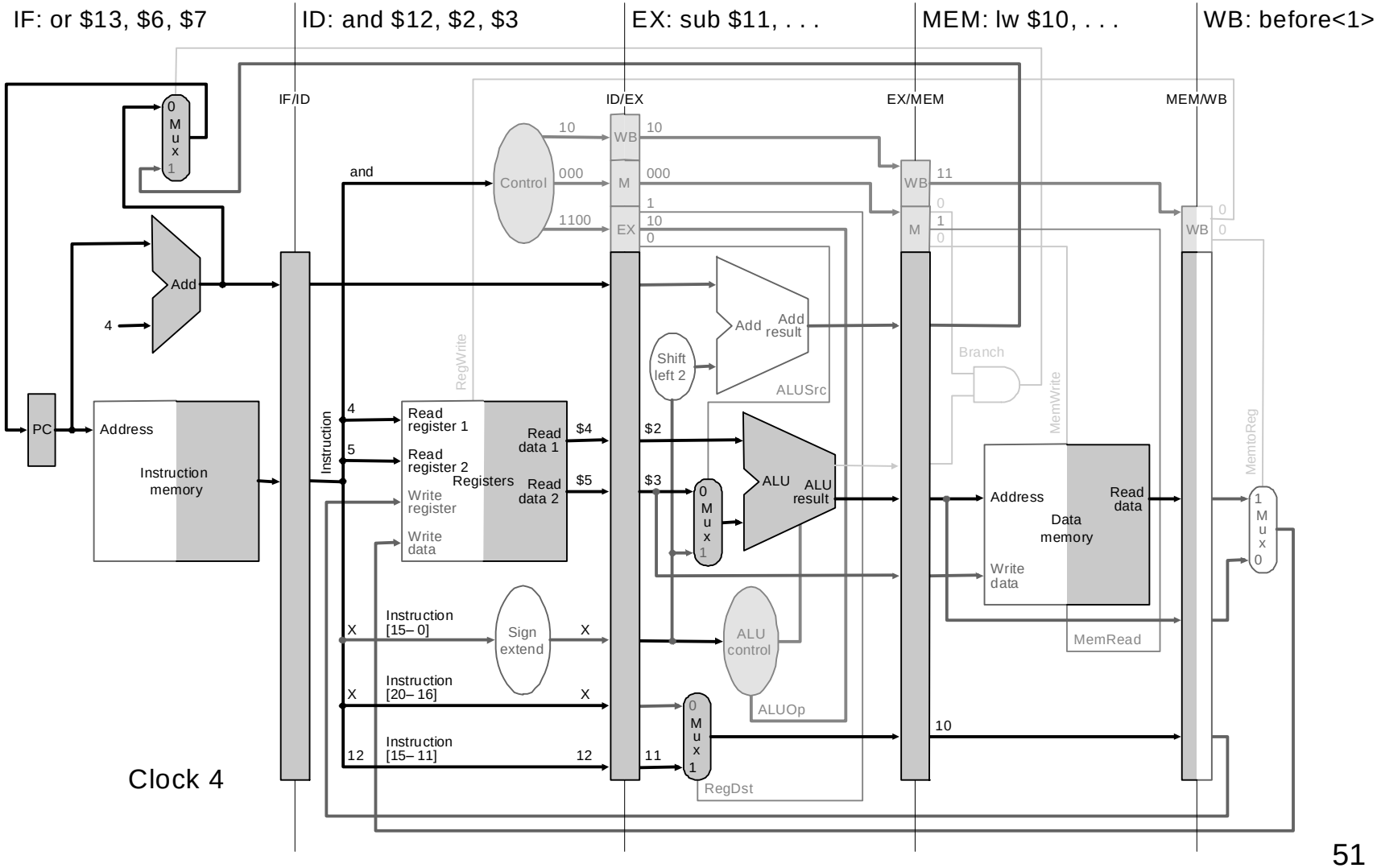
Example 2: Cycle 2



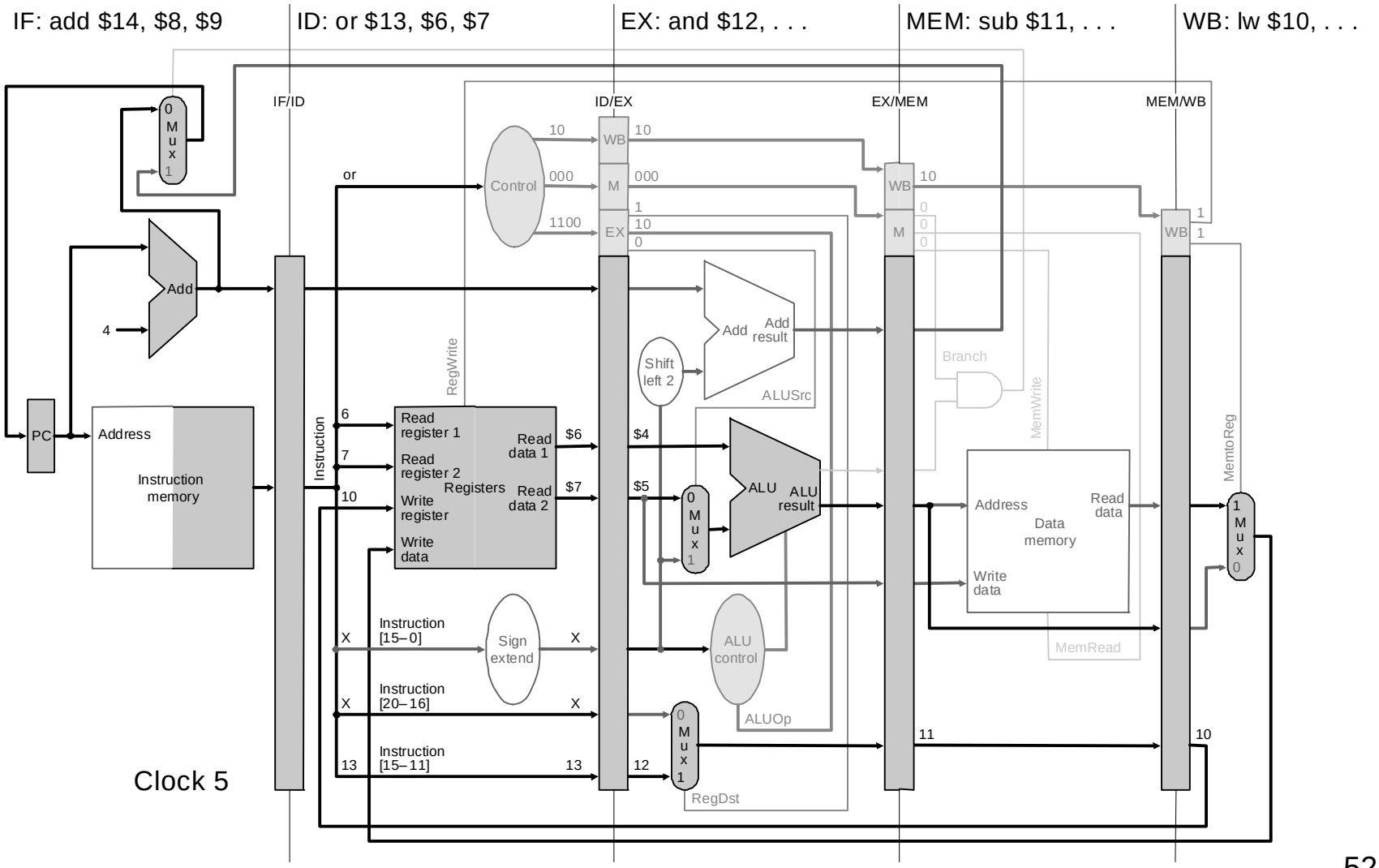
Example 2: Cycle 3



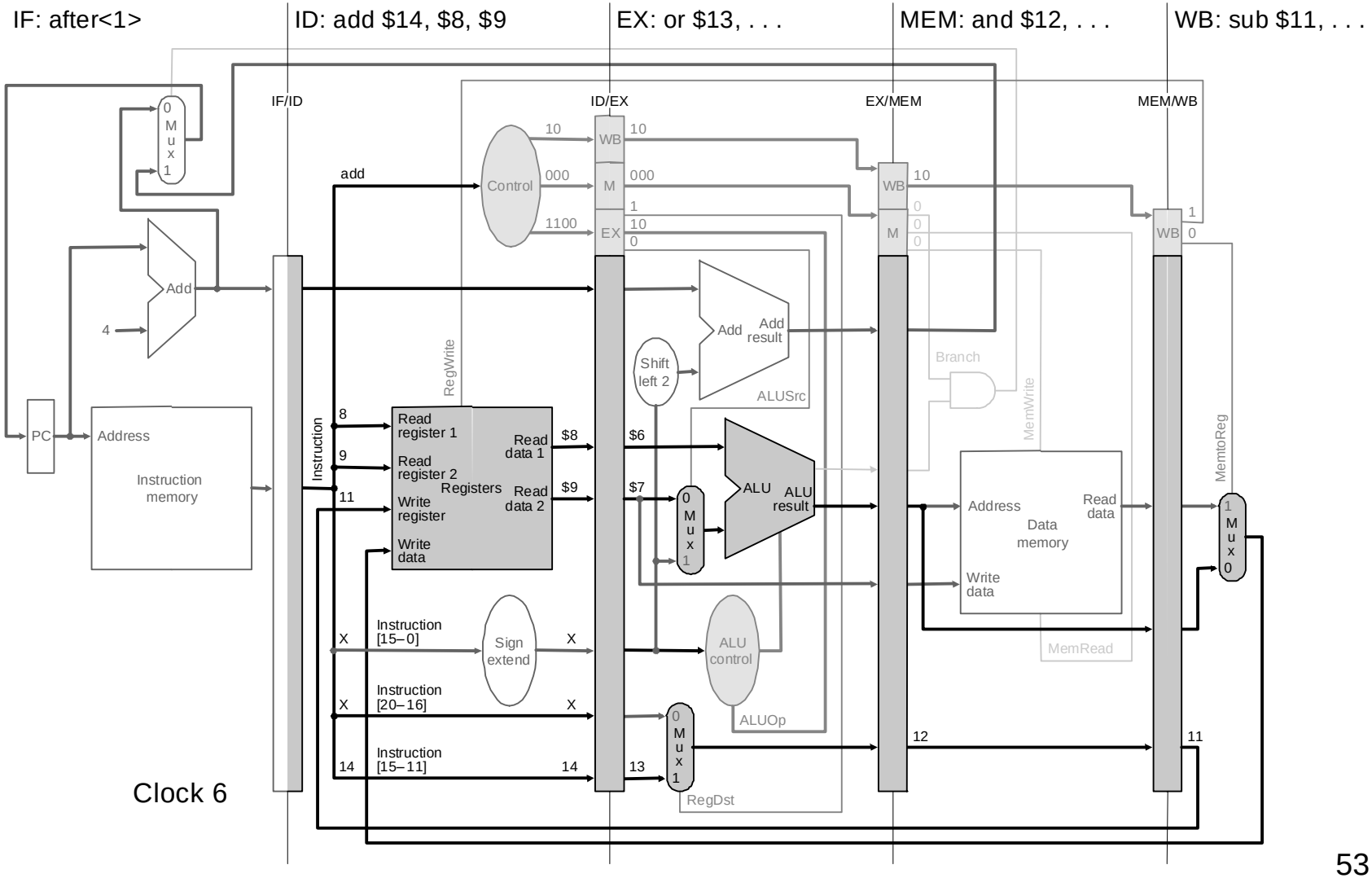
Example 2: Cycle 4



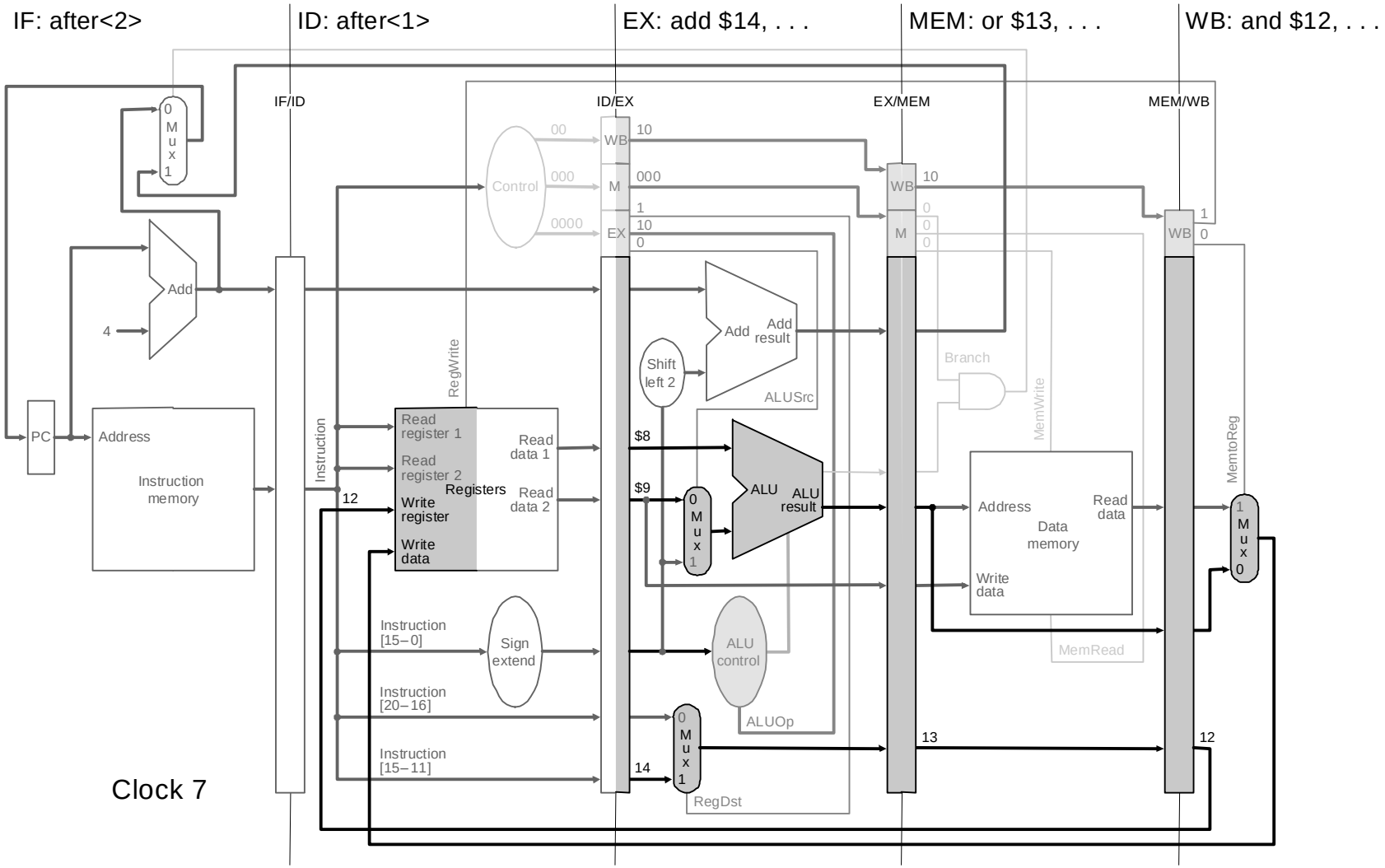
Example 2: Cycle 5



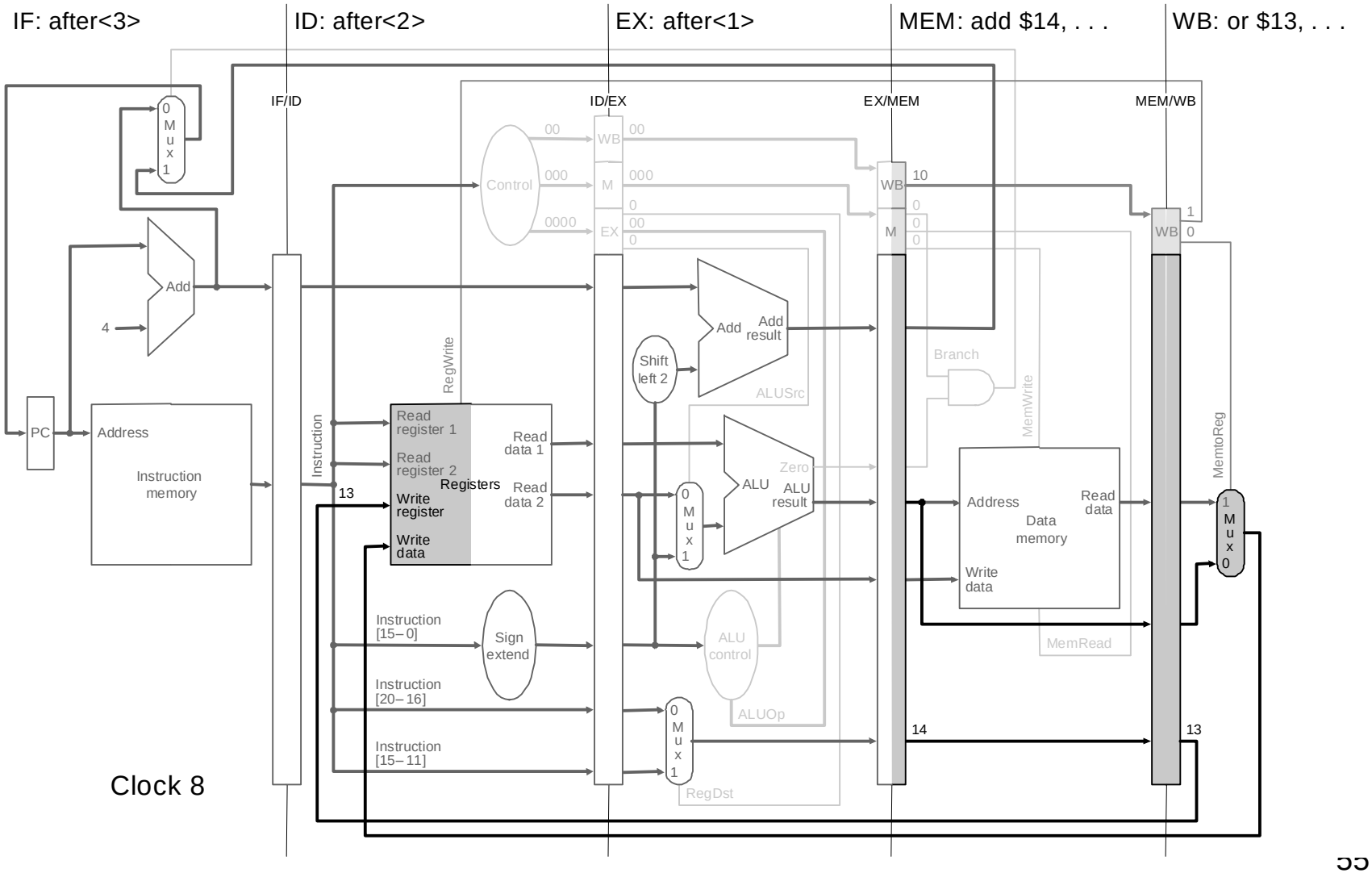
Example 2: Cycle 6



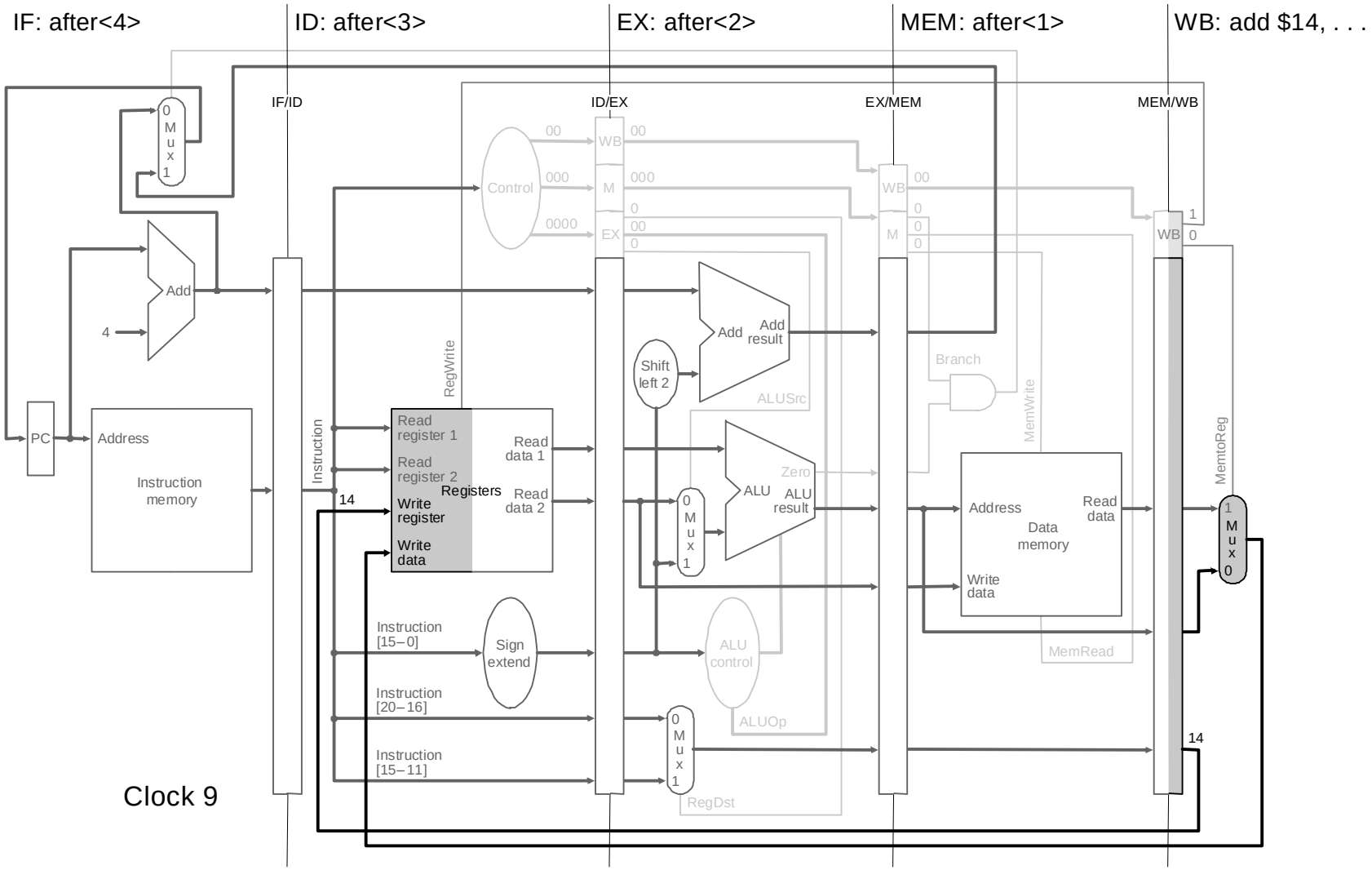
Example 2: Cycle 7



Example 2: Cycle 8



Example 2: Cycle 9



Summary of Pipeline Basics

- Pipelining is a fundamental concept
  - Multiple steps using distinct resources
  - Utilize capabilities of datapath by pipelined instruction processing
    - Start next instrunction while working on the current one
    - Limited by length of longest stage (plus fill/flush)
    - Need to detect and resolve hazards
- What makes it easy in MIPS?
  - All instructions are of the same length
  - Just a few instruction formats
  - Memory operands only in loads and stores
- What makes pipelining hard? hazards

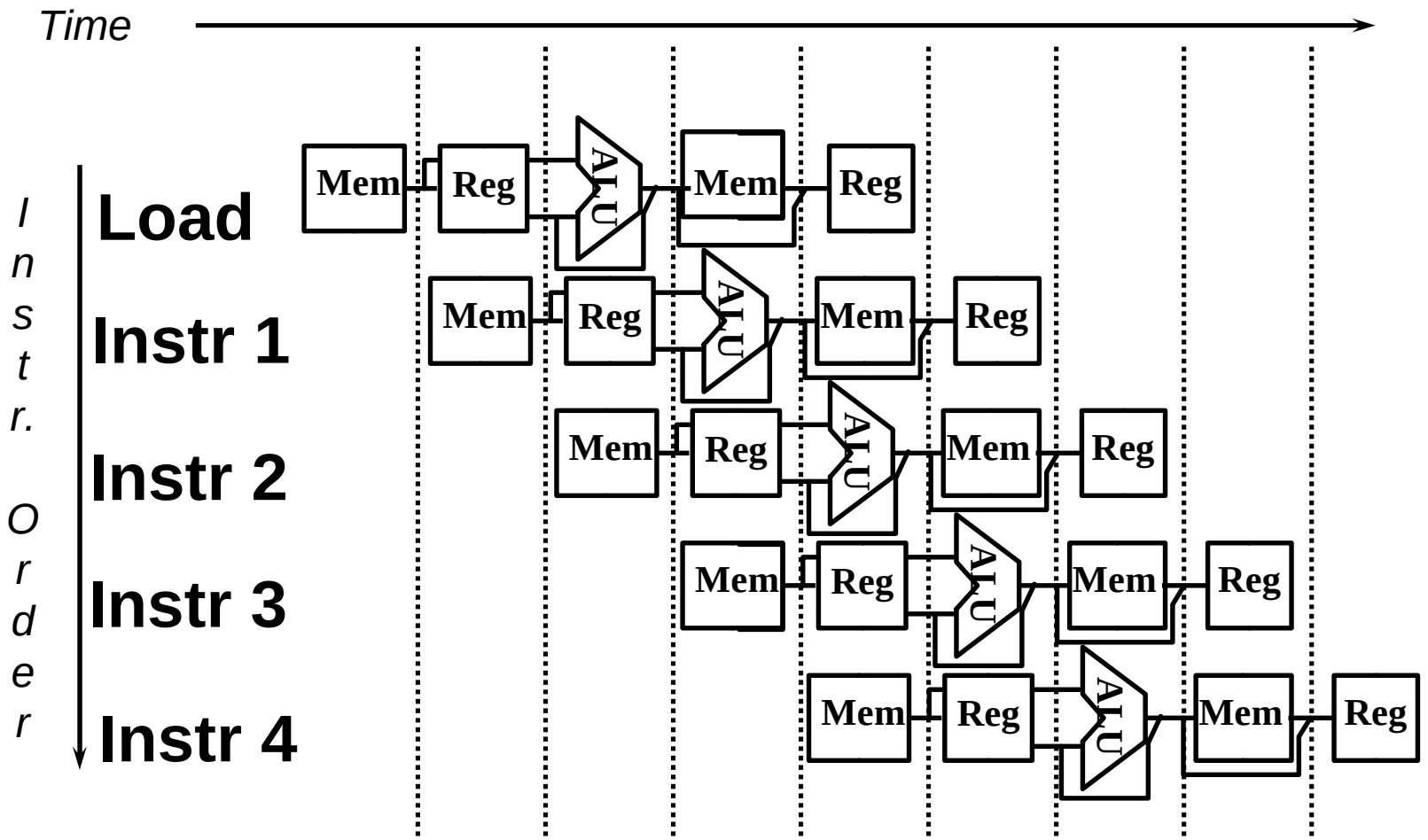
Outline

- An overview of pipelining
- A pipelined datapath
- Pipelined control
- Data hazards and forwarding (6.4)
- Data hazards and stalls (6.5)
- Branch hazards
- Exceptions
- Superscalar and dynamic pipelining

Pipeline Hazards

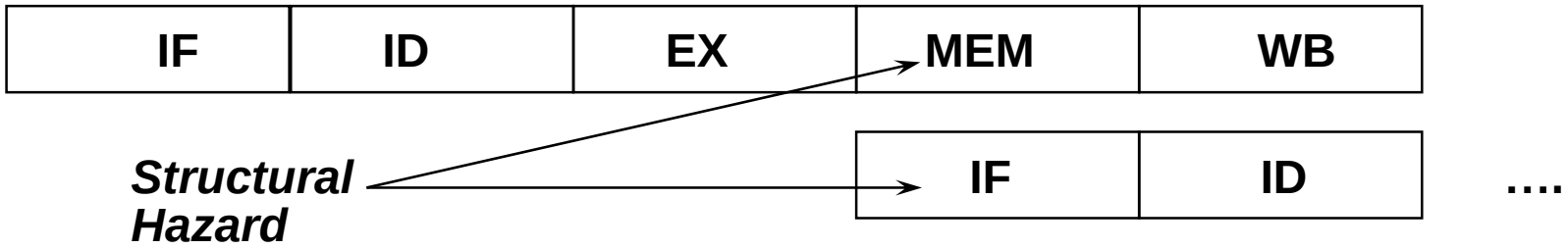
- Pipeline Hazards:
  - Structural hazards: attempt to use the same resource in two different ways at the same time
    - Ex.: combined washer/dryer or folder busy doing something else (watching TV)
  - Data hazards: attempt to use item before ready
    - Instruction depends on result of prior instruction still in the pipeline
  - Control hazards: attempt to make decision before condition is evaluated
    - Ex.: wash football uniforms and need to see result of previous load to get proper detergent level
    - Branch instructions
- Can always resolve hazards by waiting
  - pipeline control must detect the hazard
  - take action (or delay action) to resolve hazards

Structural Hazard: Single Memory



Use 2 memory: data memory and instruction memory

Pipeline Hazards Illustrated



Data Hazards

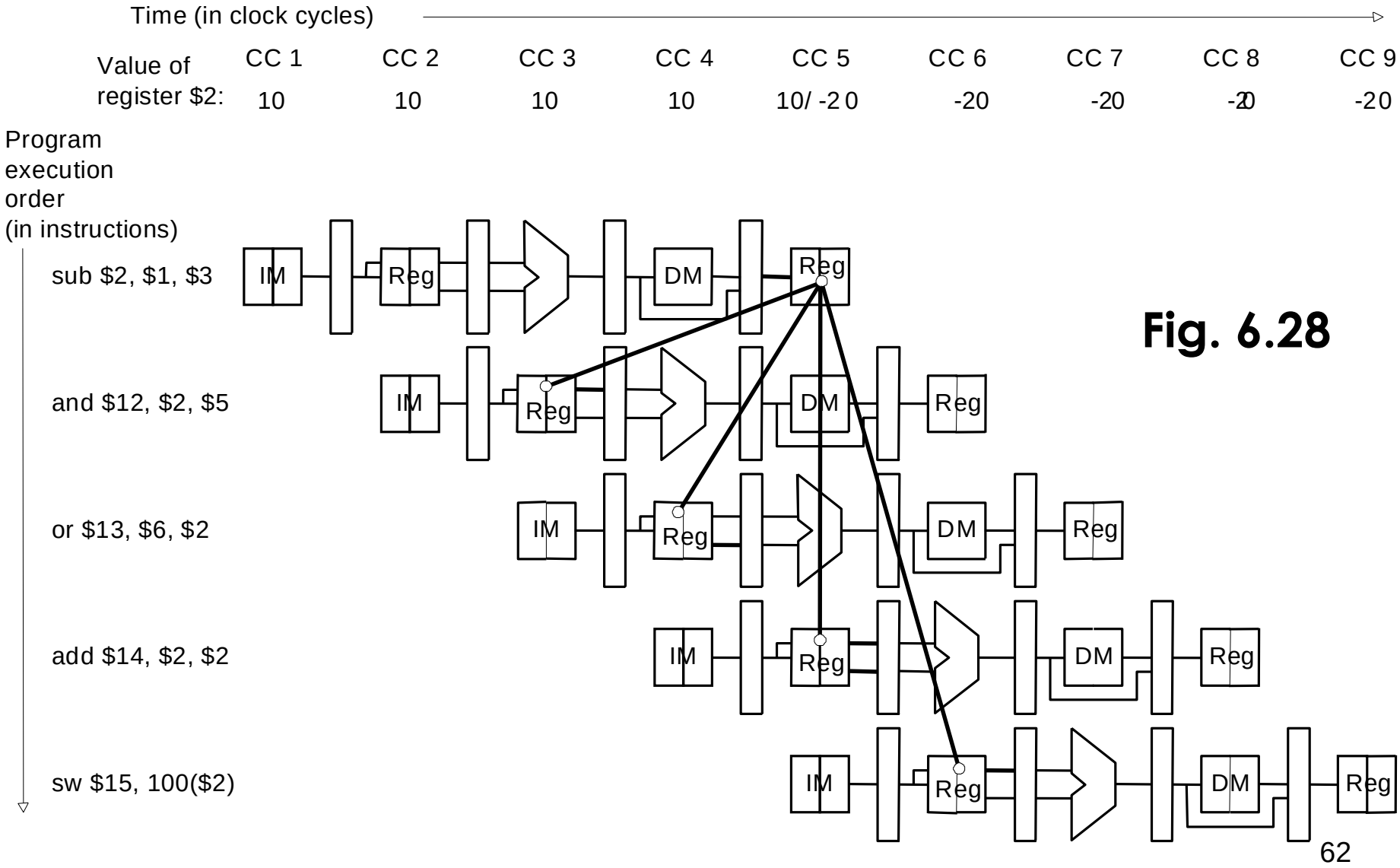


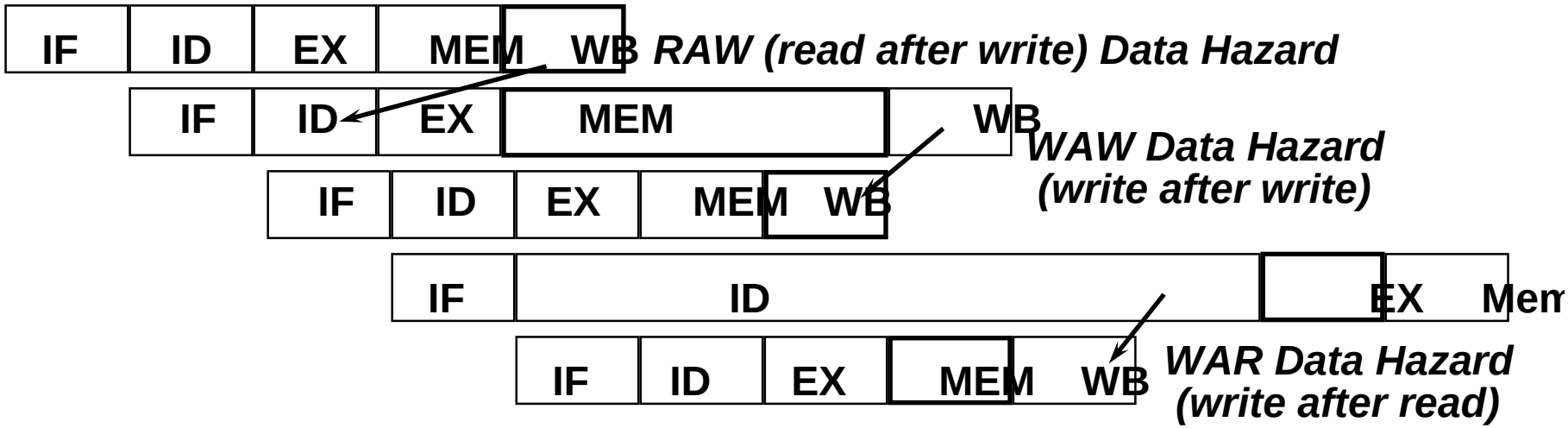
Fig. 6.28

Types of Data Hazards

Three types: (inst. i1 followed by inst. i2)

- RAW (read after write):
  i2 tries to read operand before i1 writes it
- WAR (write after read):
  i2 tries to write operand before i1 reads it
  - Gets wrong operand, e.g., autoincrement addr.
  - Can't happen in MIPS 5-stage pipeline because:
    - All instructions take 5 stages, and reads are always in stage 2, and writes are always in stage 5
- WAW (write after write):
  i2 tries to write operand before i1 writes it
  - Leaves wrong result (i1's not i2's); occur only in pipelines that write in more than one stage
  - Can't happen in MIPS 5-stage pipeline because:
    - All instructions take 5 stages, and writes are always in stage 5

Pipeline Hazards Illustrated



Handling Data Hazards

- Use simple, fixed designs
  - Eliminate WAR by always fetching operands early (ID) in pipeline
  - Eliminate WAW by doing all write backs in order (last stage, static)
  - These features have a lot to do with ISA design
- Internal forwarding in register file:
  - Write in first half of clock and read in second half
  - Read delivers what is written, resolve hazard between sub and add
- Detect and resolve remaining ones
  - Compiler inserts NOP
  - Forward
  - Stall

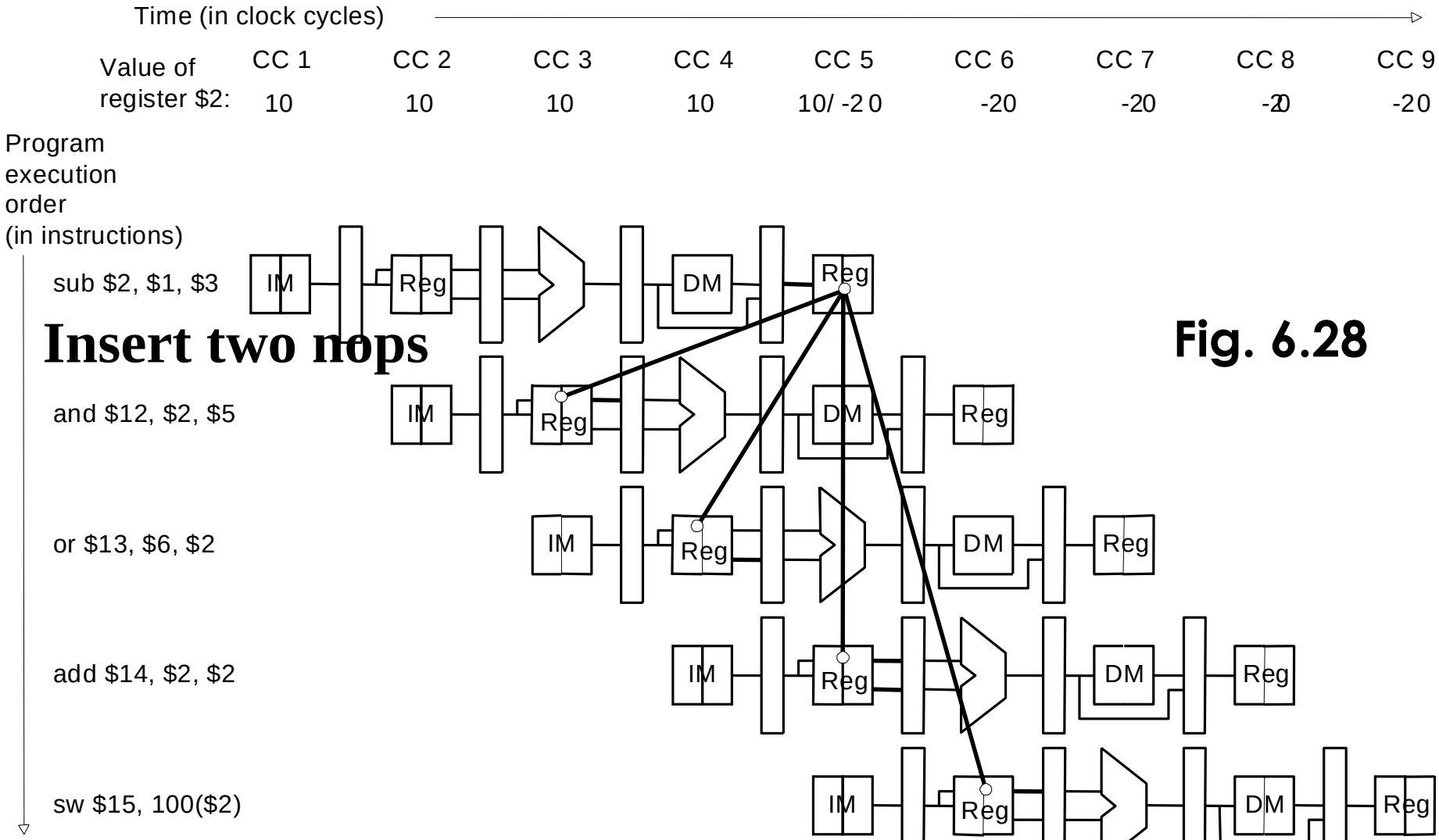
Software Solution

- Have compiler guarantee no hazards
- Where do we insert the NOPs?

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

- Problem: this really slows us down!

Data Hazards



Insert two nops

Fig. 6.28

Data Hazards : Forwarding

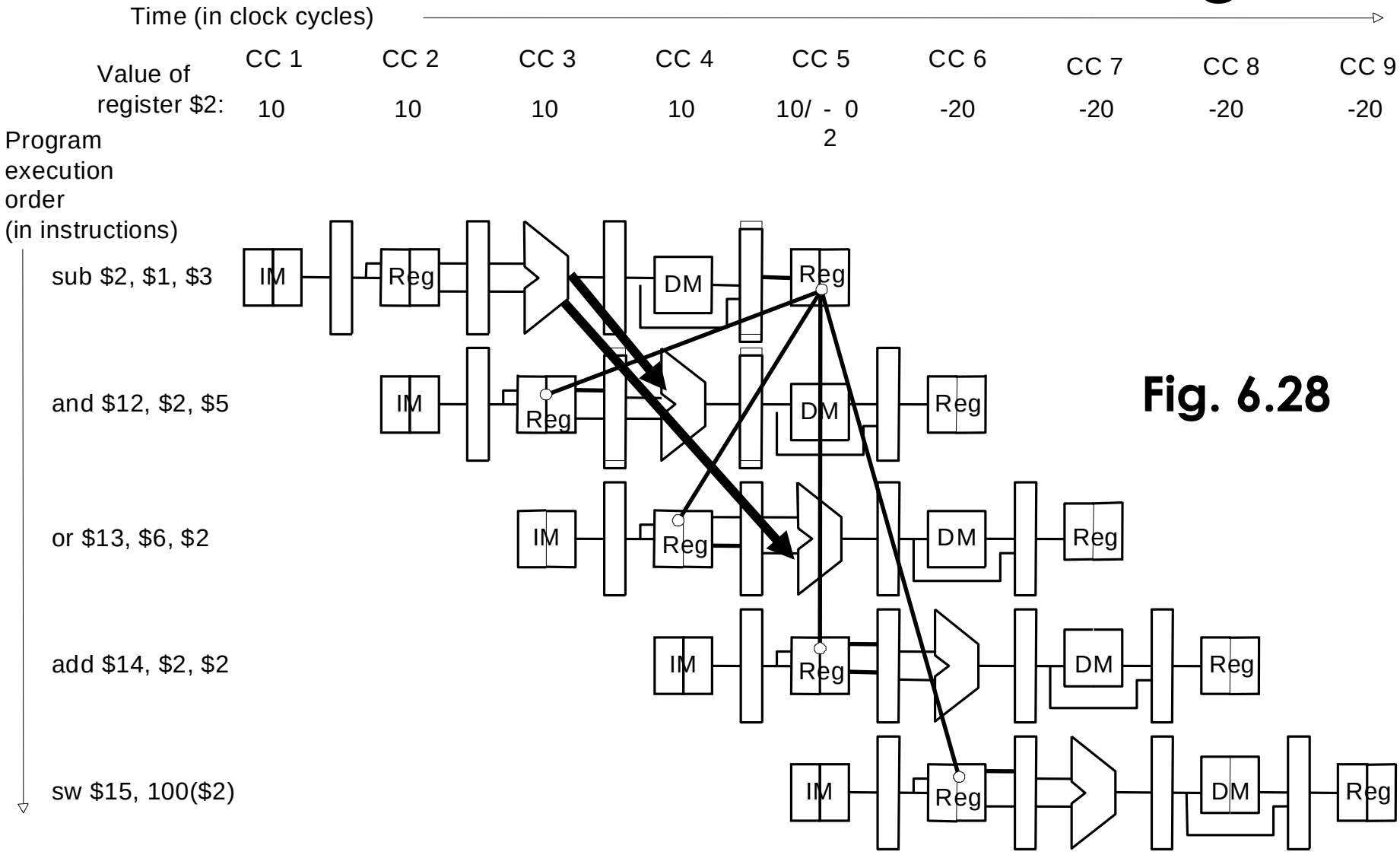
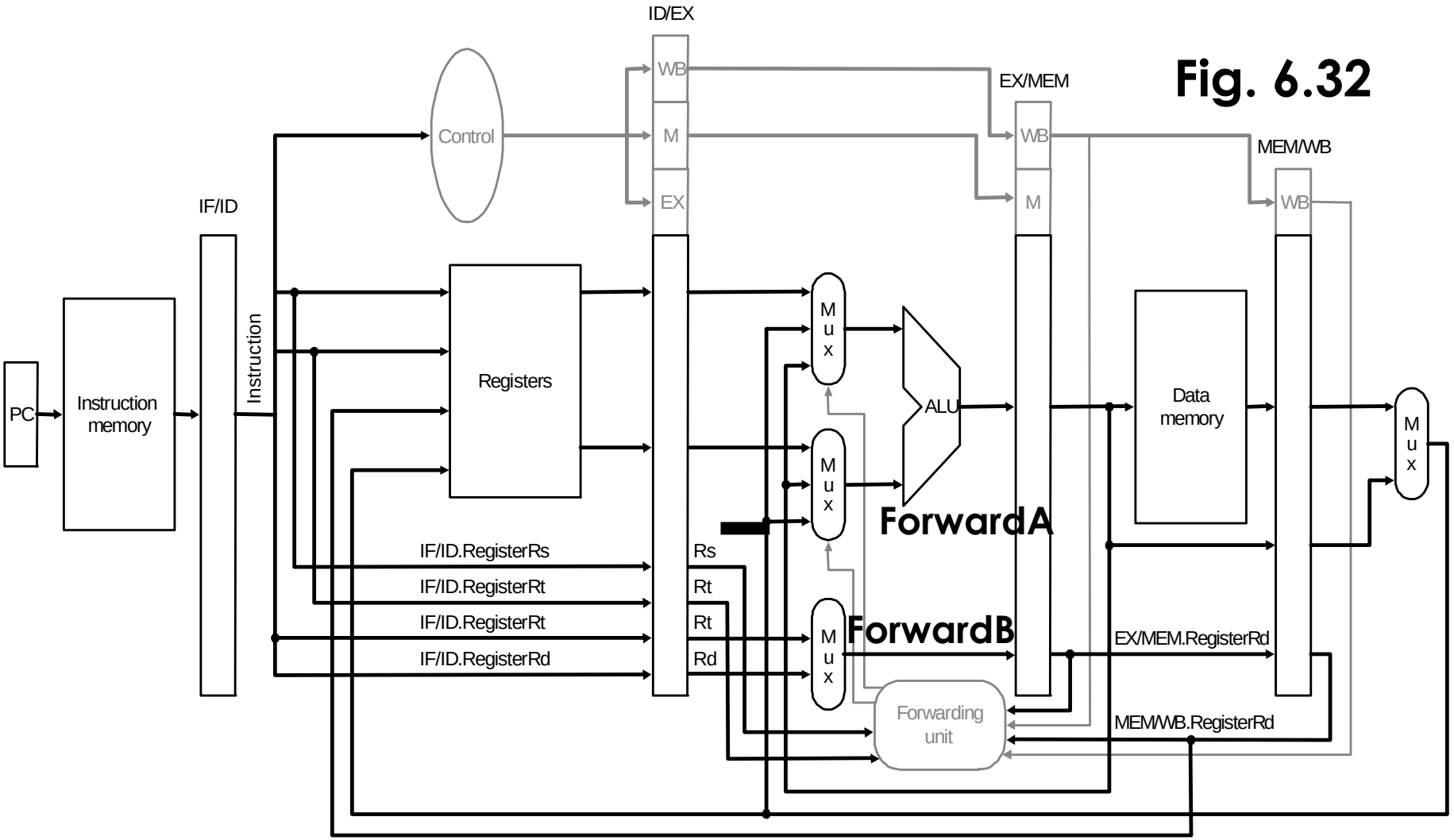


Fig. 6.28

Pipeline with Forwarding



Detecting Data Hazards

- Hazard conditions:
  - 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
- Two optimizations:
  - Don’t forward if instruction does not write register
    => check if RegWrite is asserted
  - Don’t forward if destination register is $0
    => check if RegisterRd = 0

Detecting Data Hazards (cont.)

- Hazard conditions using control signals:
  - At EX stage:
    EX/MEM.RegWrite and (EX/MEM.RegRd≠0)
    and (EX/MEM.RegRd=ID/EX.RegRs)
  - At MEM stage:
    MEM/WB.RegWrite and (MEM/WB.RegRd≠0)
    and (MEM/WB.RegRd=ID/EX.RegRs)
  - (replace ID/EX.RegRt for ID/EX.RegRs for the other two conditions)

Resolving Hazards: Forwarding

- Use temporary results, e.g., those in pipeline registers, don't wait for them to be written

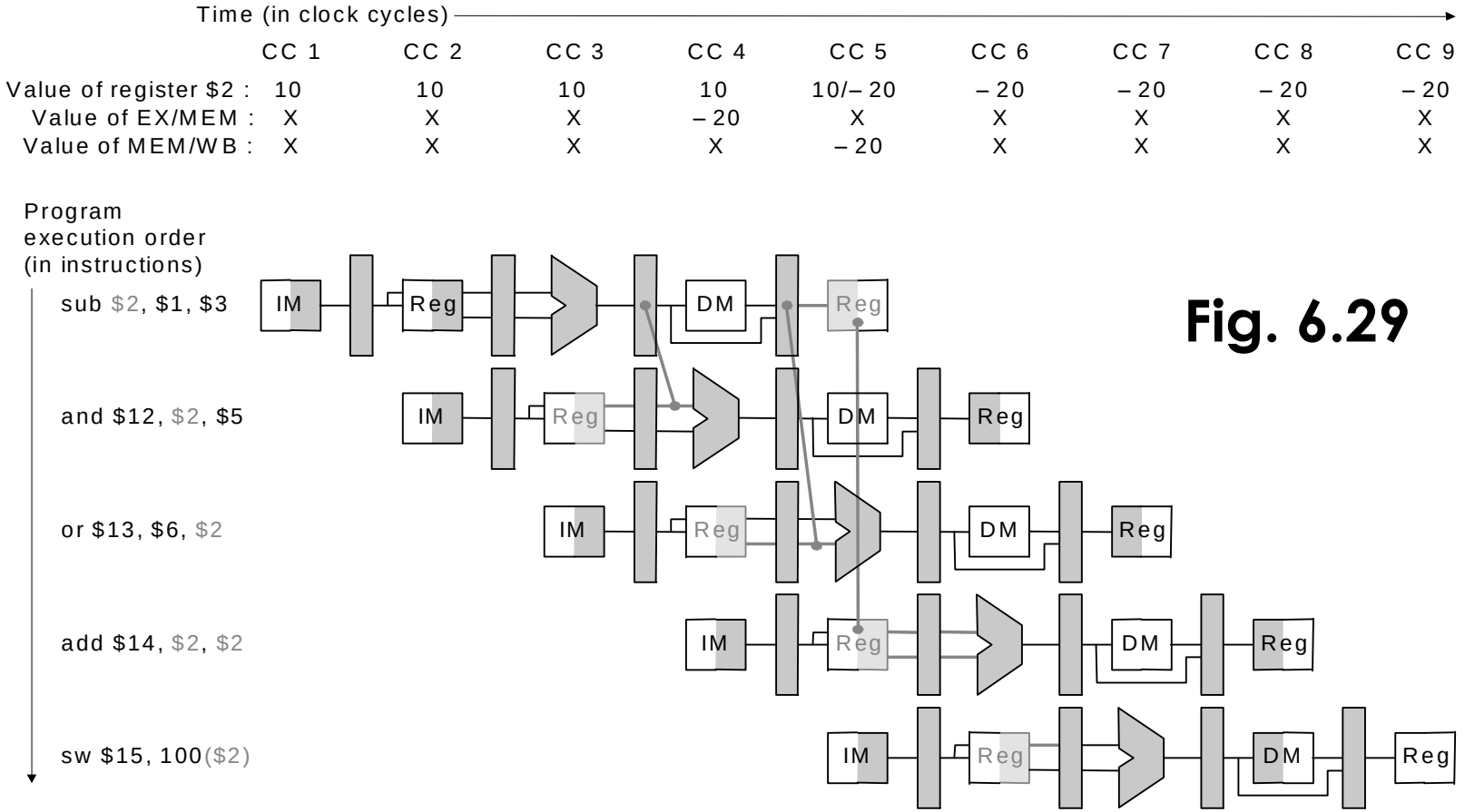


Fig. 6.29

Pipeline with Forwarding

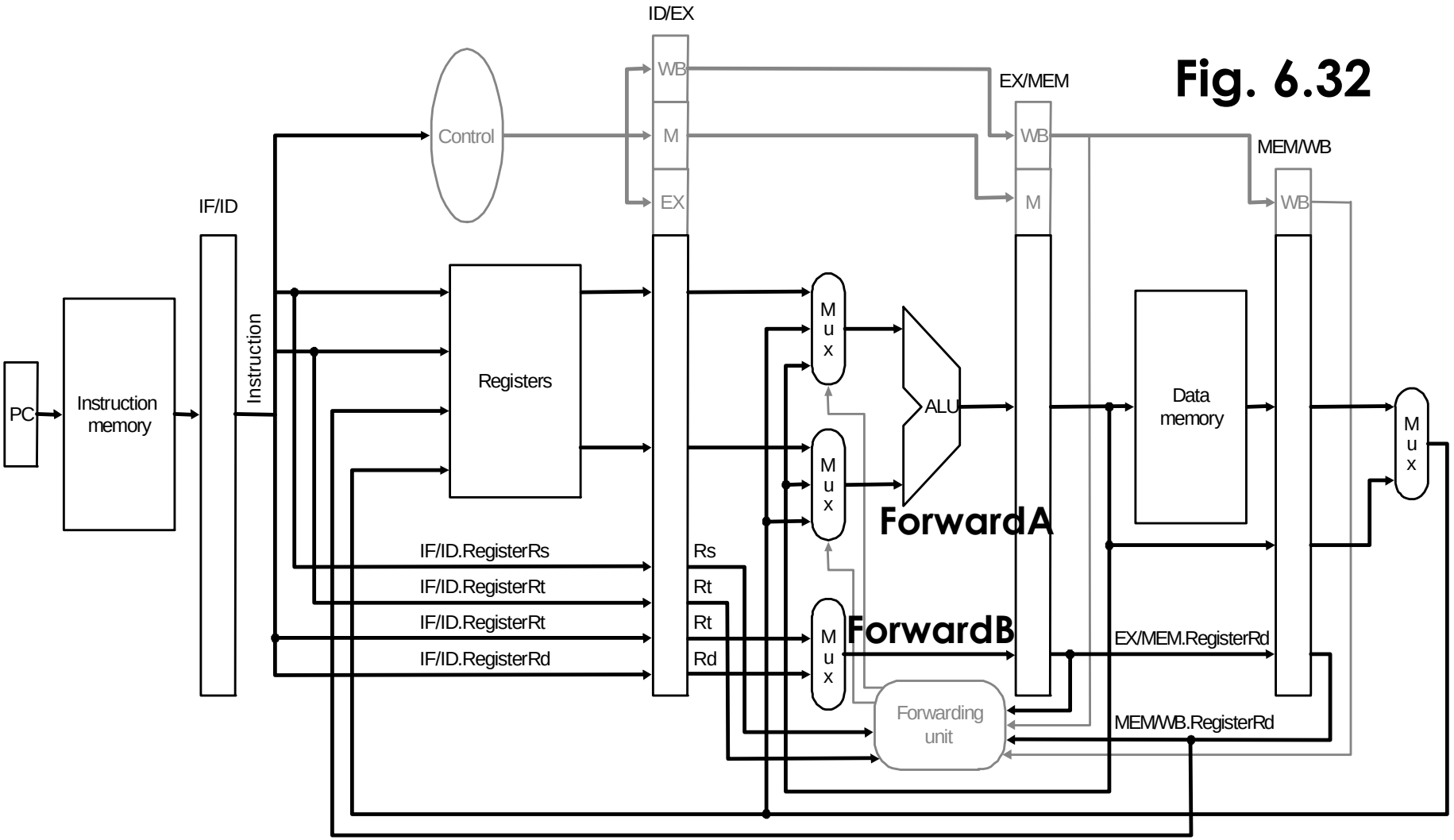
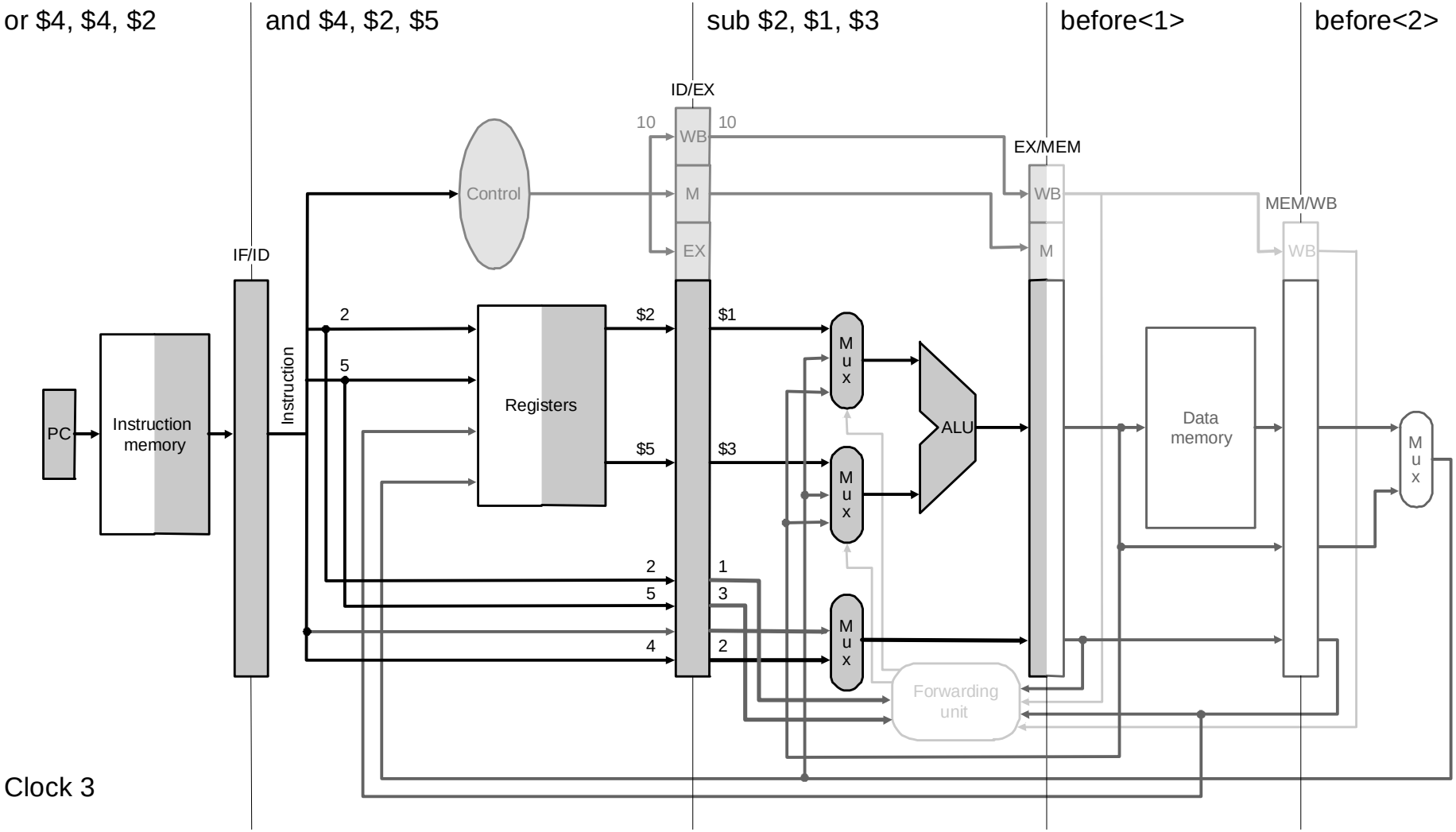


Fig. 6.32

Forwarding Logic

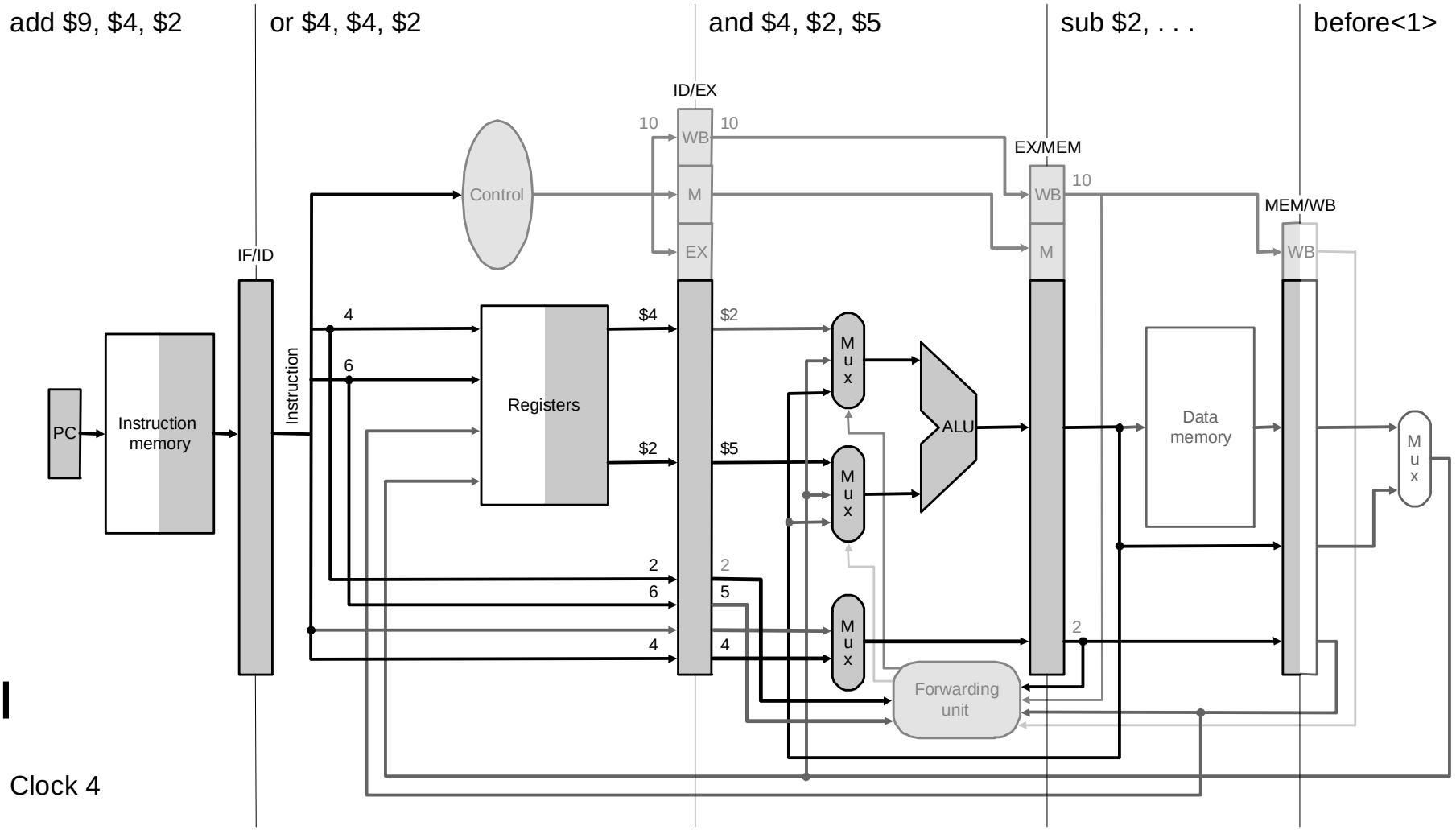
- Forwarding: input to ALU from any pipe reg.
  - Add multiplexors to ALU input 
  - Control forwarding in EX => carry Rs in ID/EX
- Control signals for forwarding:
  - If both WB and MEM forward, e.g., `add $1,$1,$2; add $1,$1,$3; add $1,$1,$4;` => let MEM forward
  - EX hazard:
    - `if (EX/MEM.RegWrite and (EX/MEM.RegRd≠0) and (EX/MEM.RegRd=ID/EX.RegRs)) ForwardA=10`
  - MEM hazard:
    - `if (MEM/WB.RegWrite and (MEM/WB.RegRd≠0) and (EX/MEM.RegRd ≠ ID/EX.Reg.Rs) and (MEM/WB.RegRd=ID/EX.RegRs)) ForwardA=01`

Example 3: Cycle 3

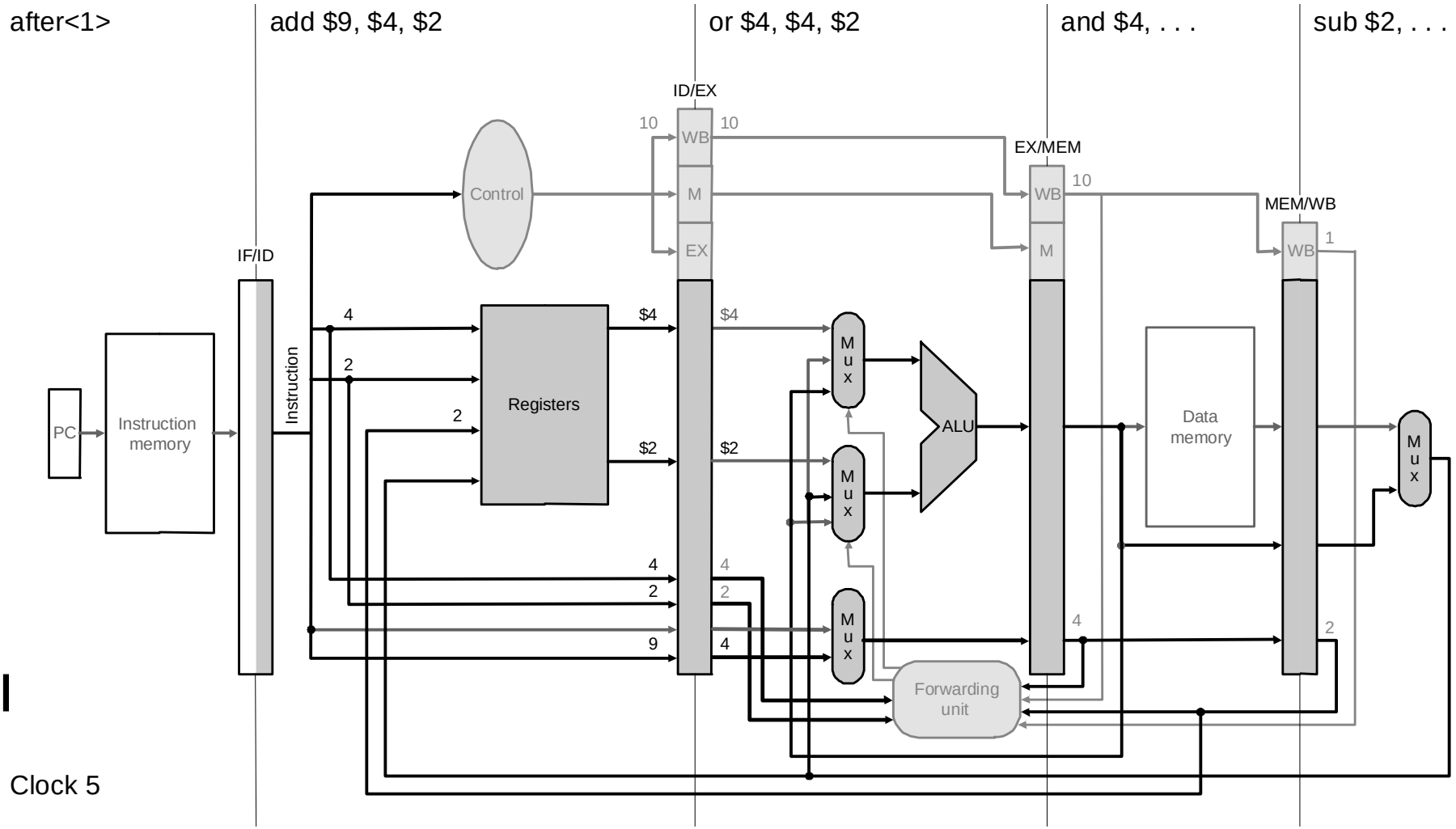


Clock 3

Example 3: Cycle 4

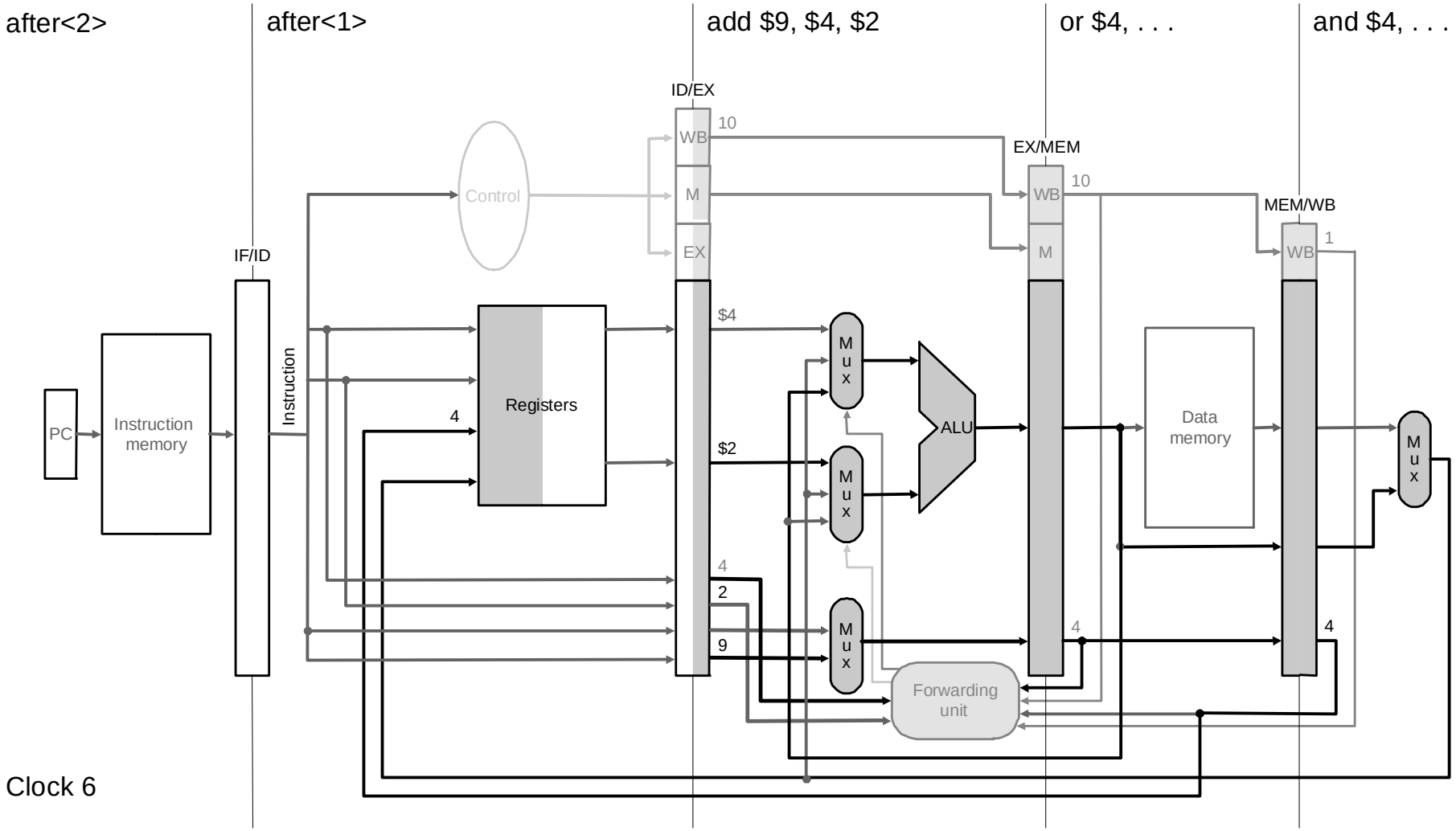


Example 3: Cycle 5



Clock 5

Example 3: Cycle 6



Can't Always Forward

- `lw` can still cause a hazard:
  - if is followed by an instruction to read the loaded reg.

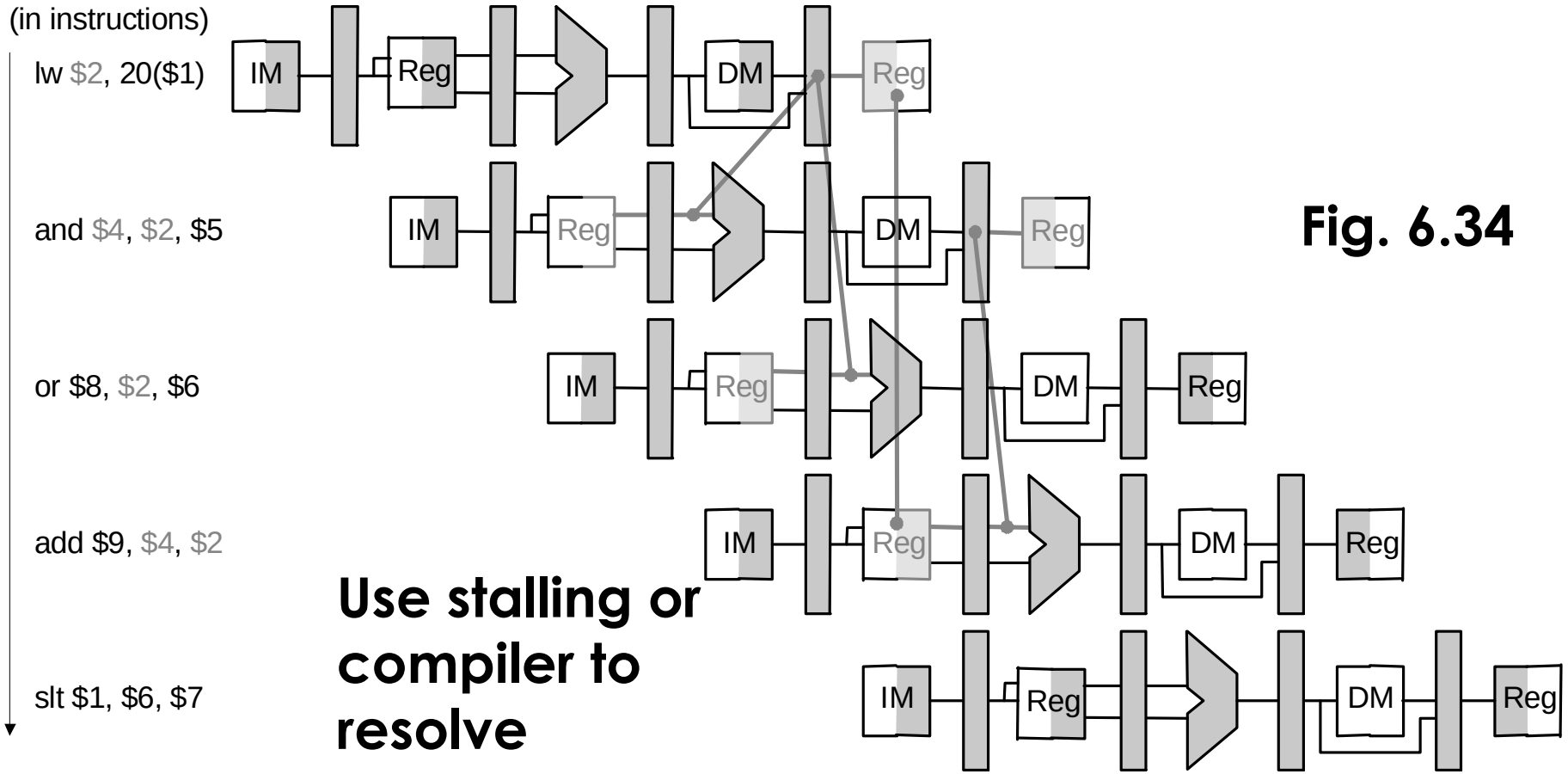


Fig. 6.34

Use stalling or compiler to resolve

Stalling

- Stall pipeline by keeping instructions in same stage and inserting an NOP instead

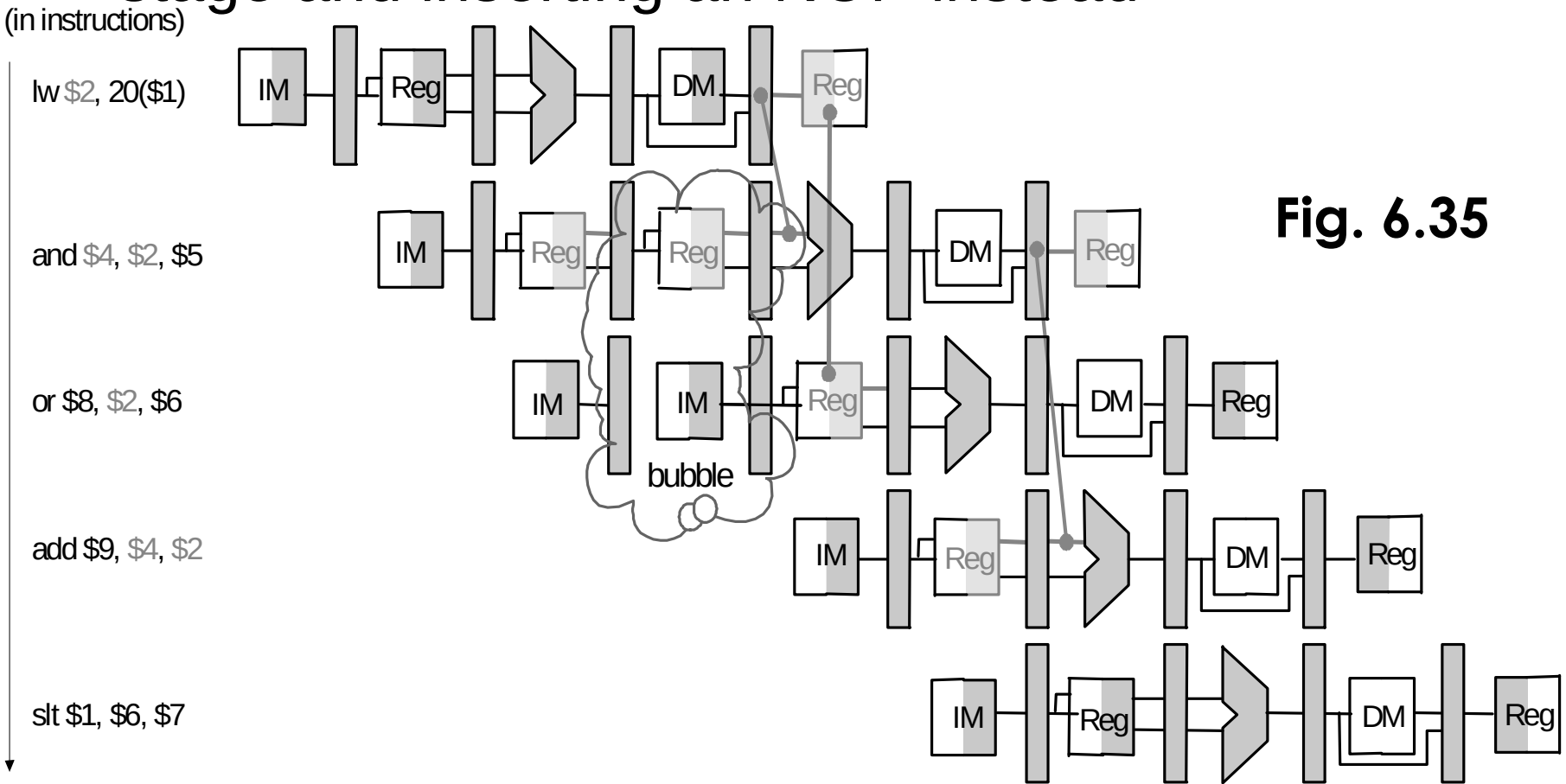


Fig. 6.35

Pipeline with Stalling Unit

- Forwarding controls ALU inputs, hazard detection controls PC, IF/ID, control signals

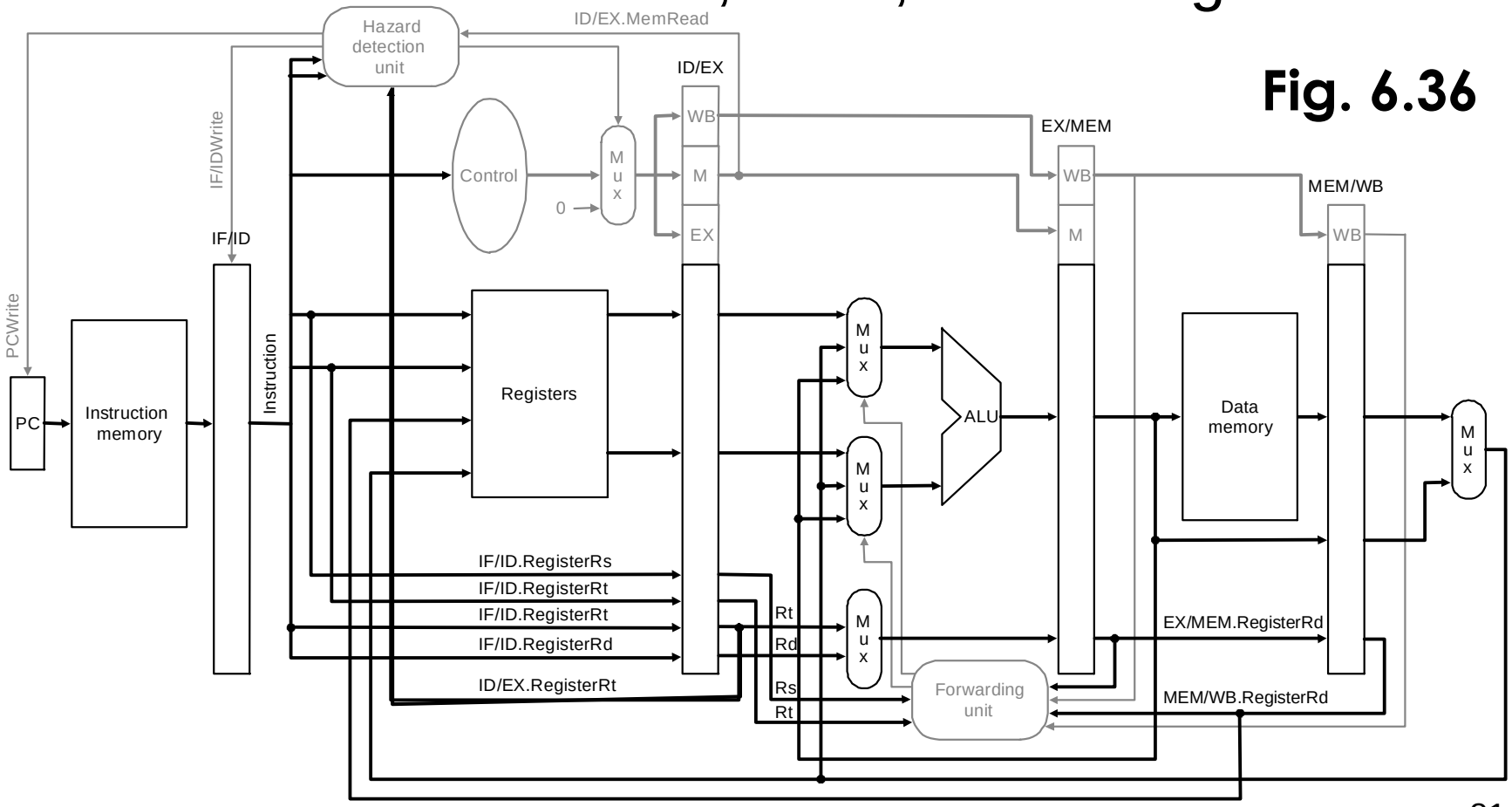


Fig. 6.36

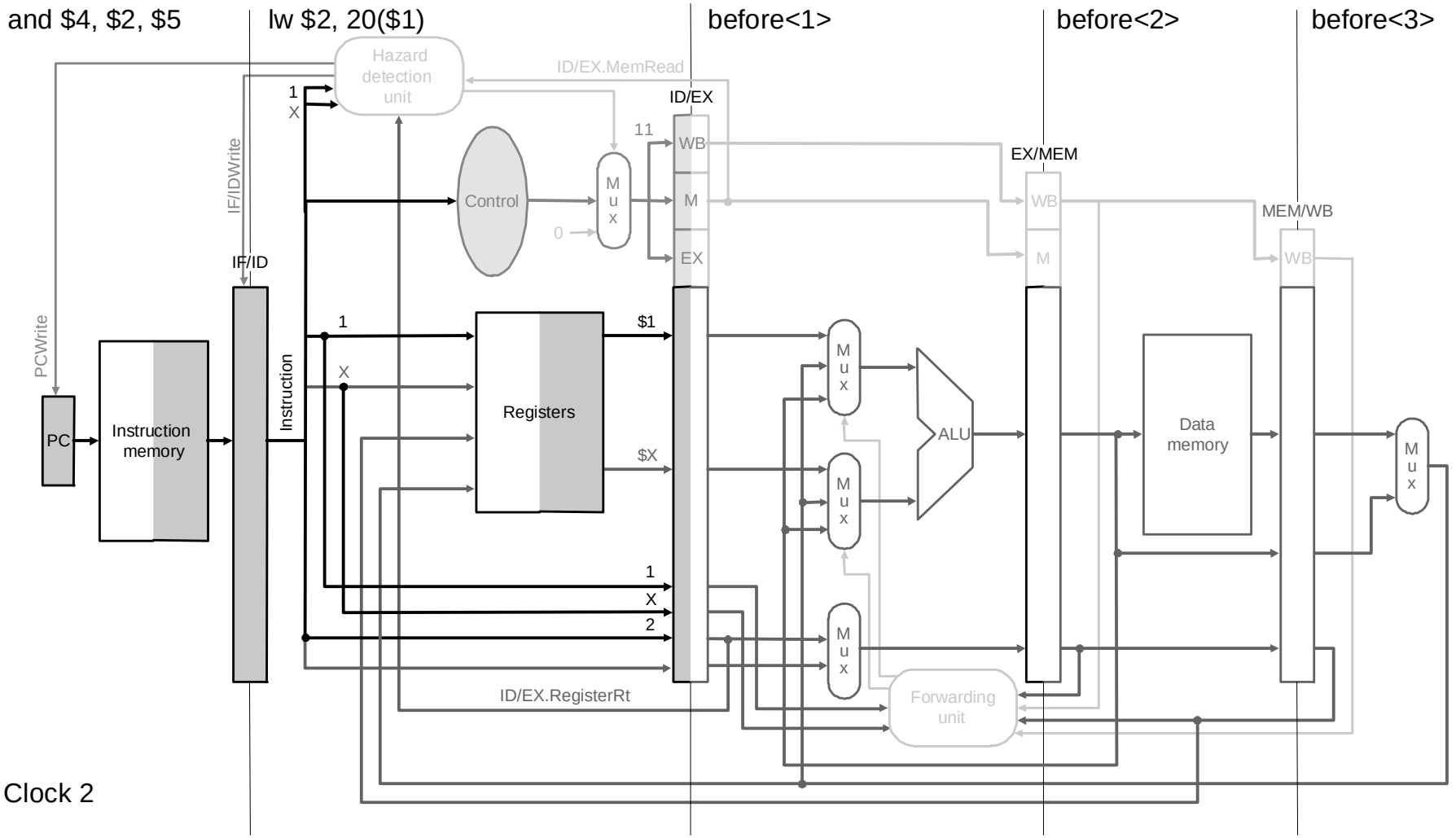
Handling Stalls

- Hazard detection unit in ID to insert stall between a load instruction and its use:

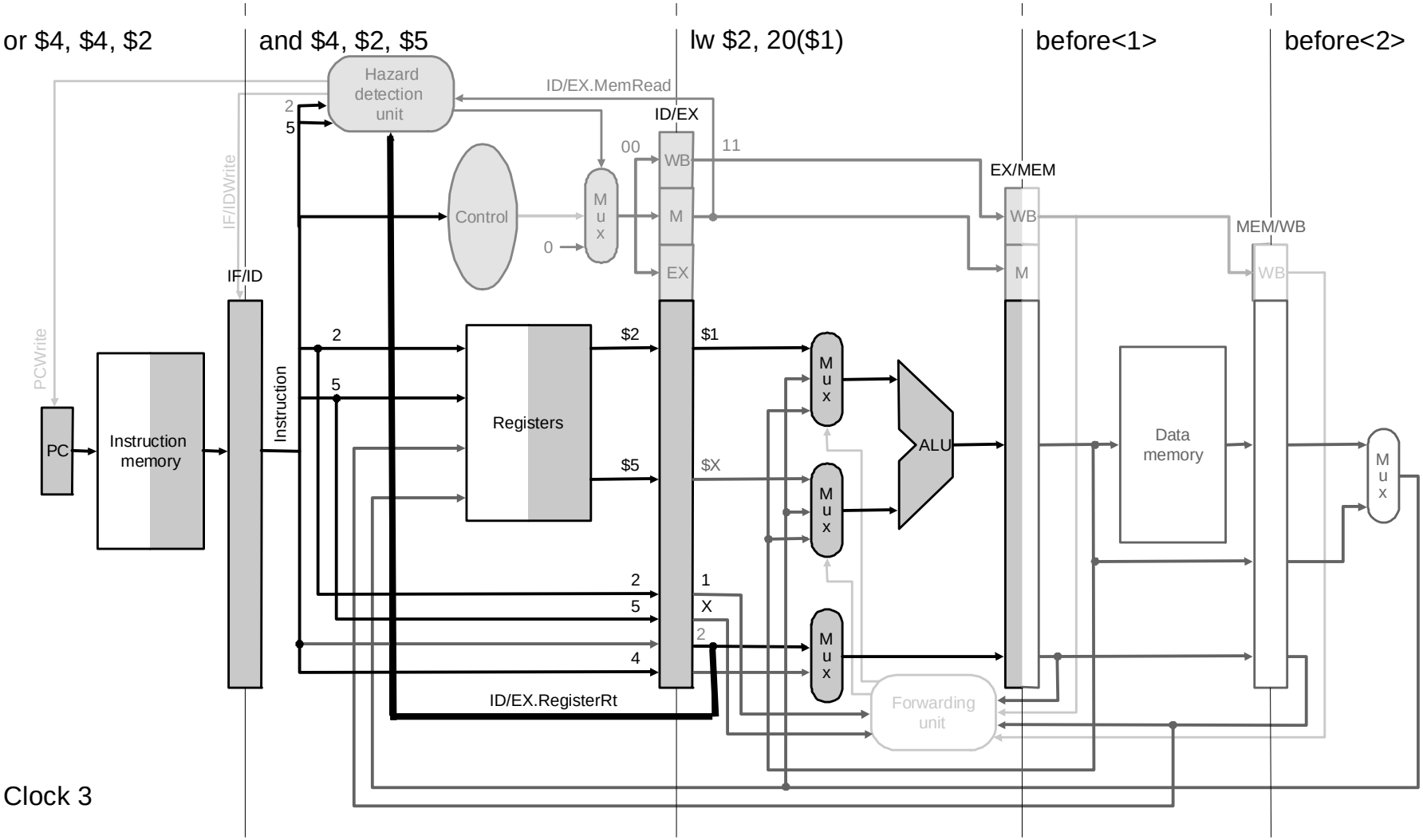
```
if (ID/EX.MemRead and
    ((ID/EX.RegisterRt = IF/ID.RegisterRs) or
     (ID/EX.RegisterRt = IF/ID.registerRt))
    stall the pipeline for one cycle
(ID/EX.MemRead=1 indicates a load instruction)
```

- How to stall?
  - Stall instruction in IF and ID: not change PC and IF/ID
    => the stages re-execute the instructions
  - What to move into EX: insert an NOP by changing EX, MEM, WB control fields of ID/EX pipeline register to 0
    - as control signals propagate, all control signals to EX, MEM, WB are deasserted and no registers or memories are written

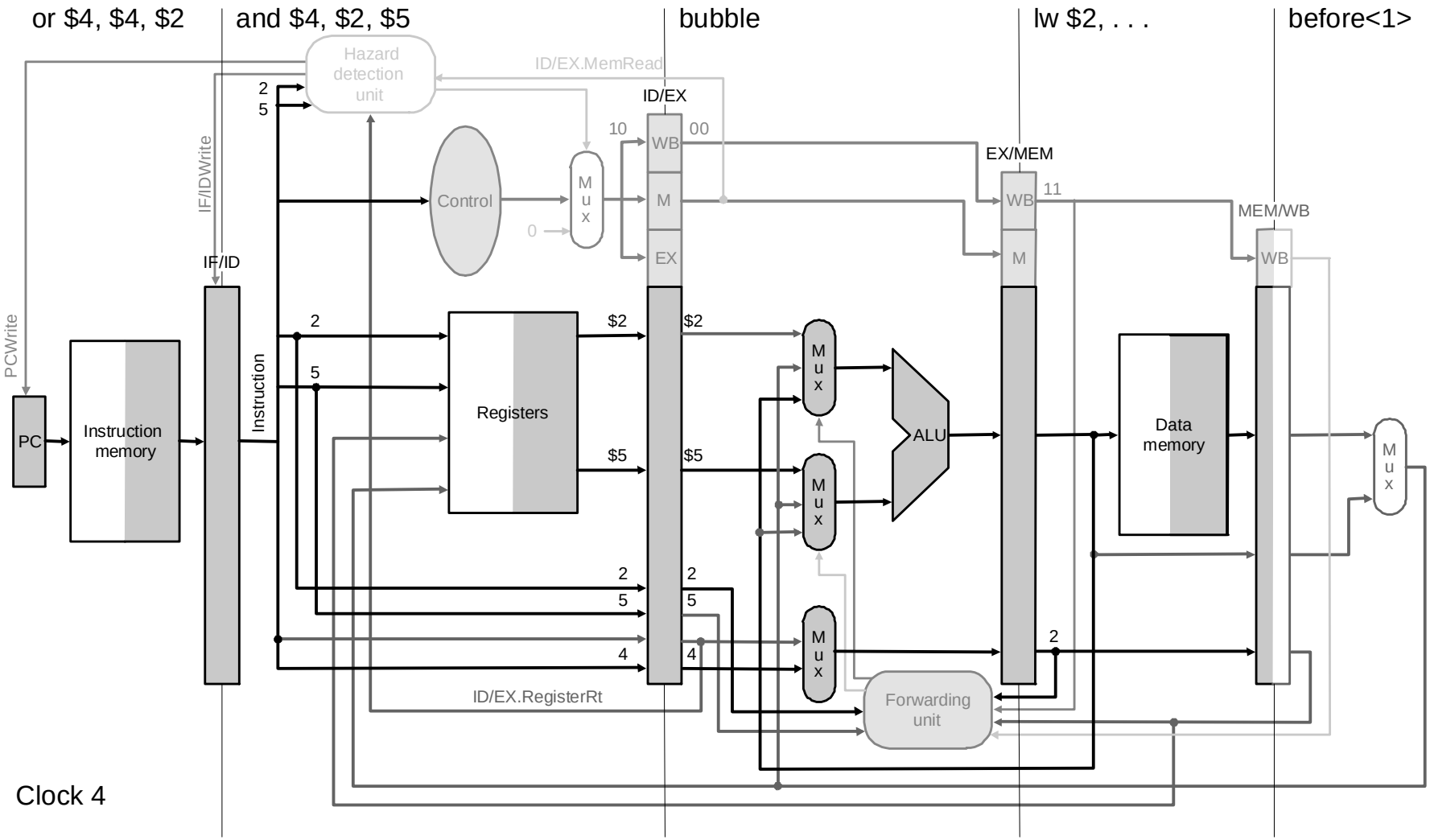
Example 4: Cycle 2



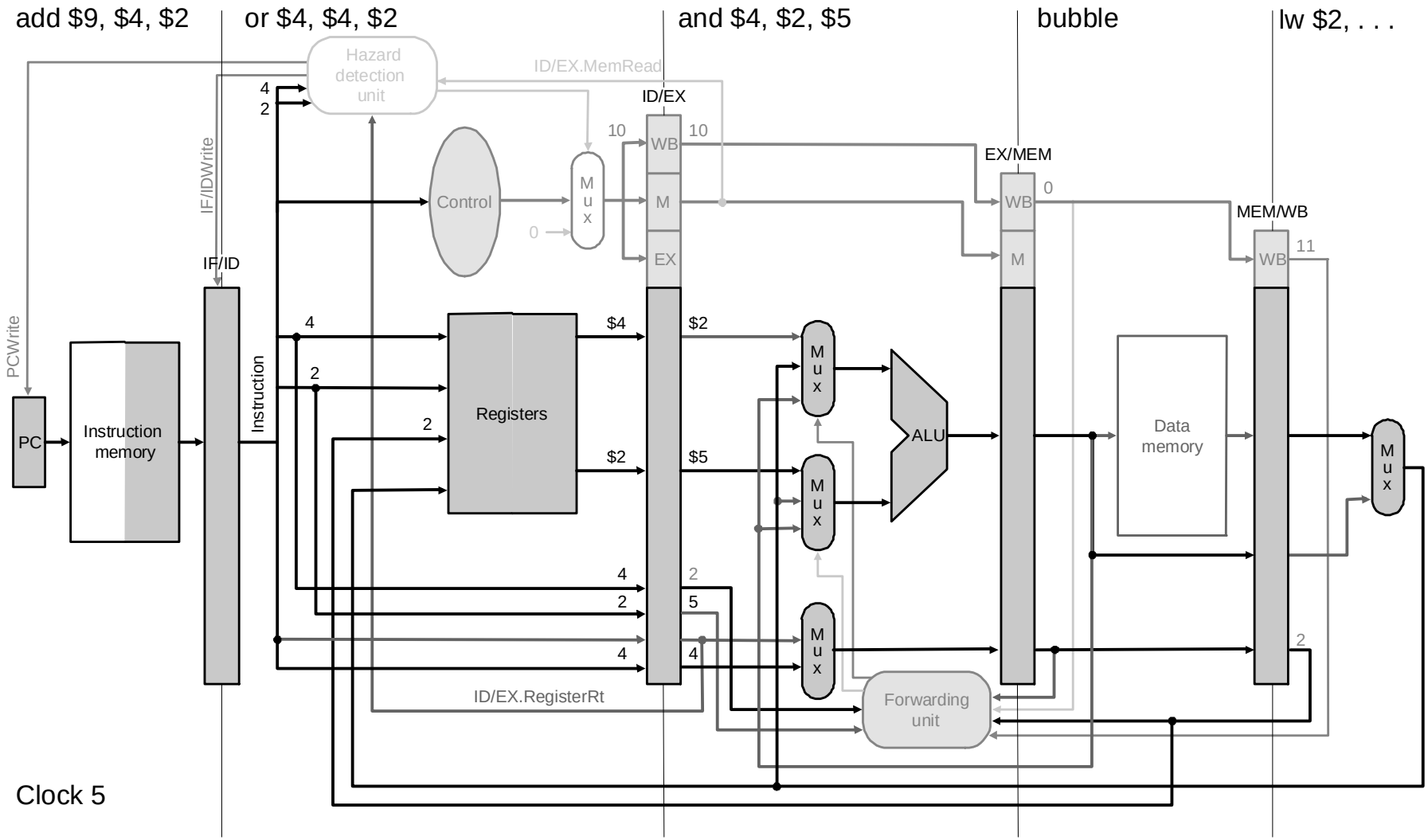
Example 4: Cycle 3



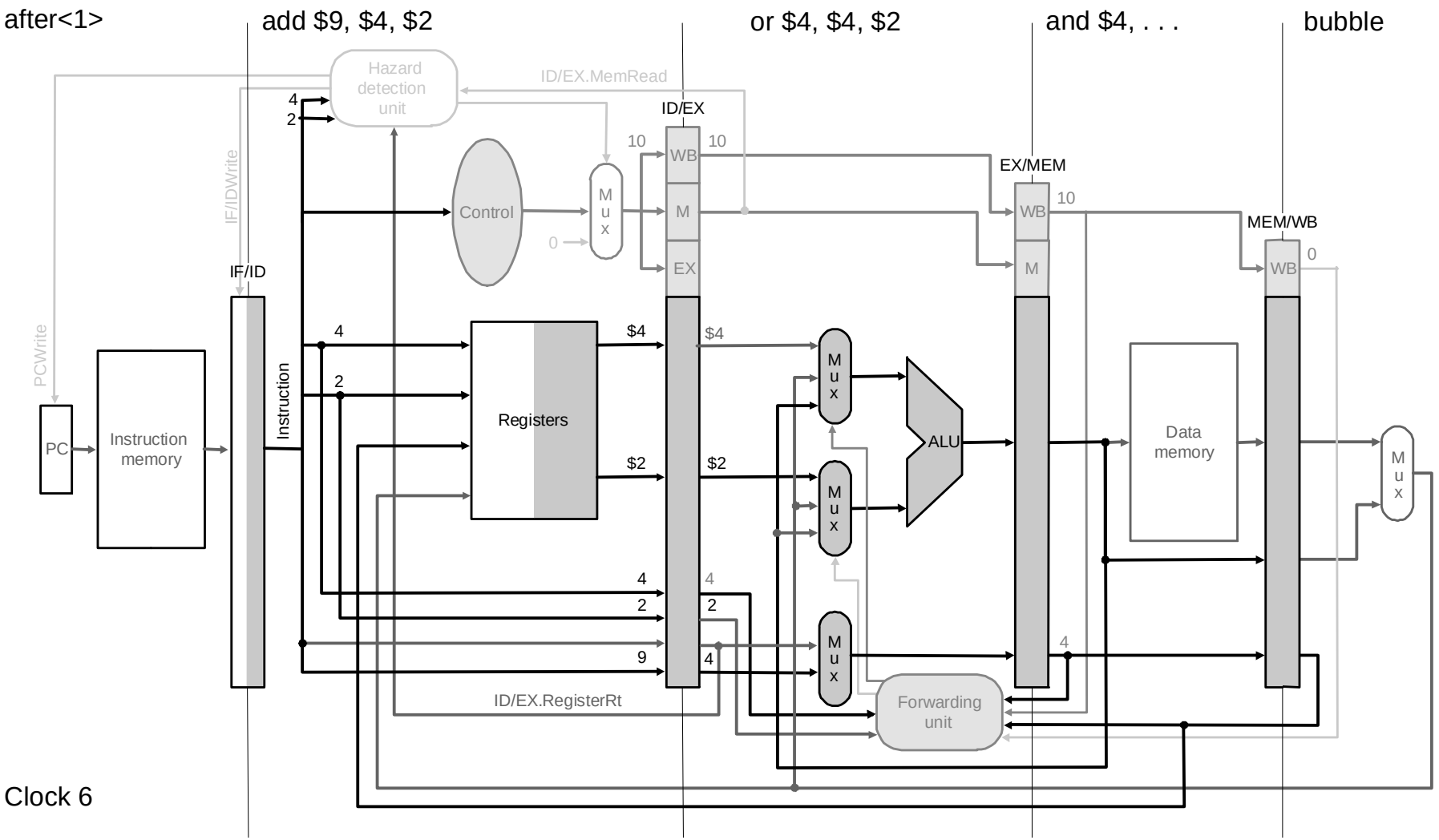
Example 4: Cycle 4



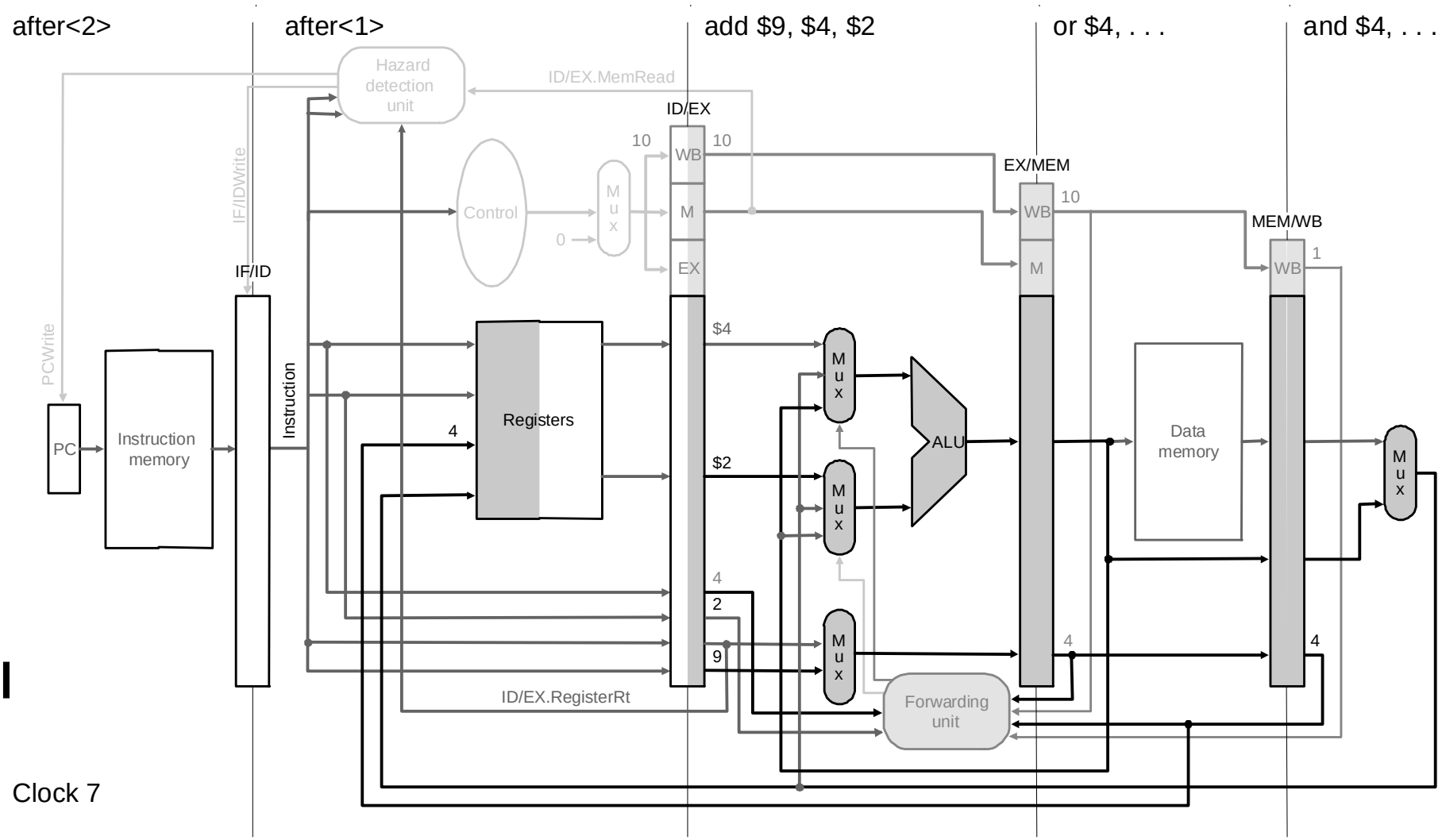
Example 4: Cycle 5



Example 4: Cycle 6



Example 4: Cycle 7



Outline

- An overview of pipelining
- A pipelined datapath
- Pipelined control
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards (6.6)
- Exceptions
- Superscalar and dynamic pipelining

Feedback Path

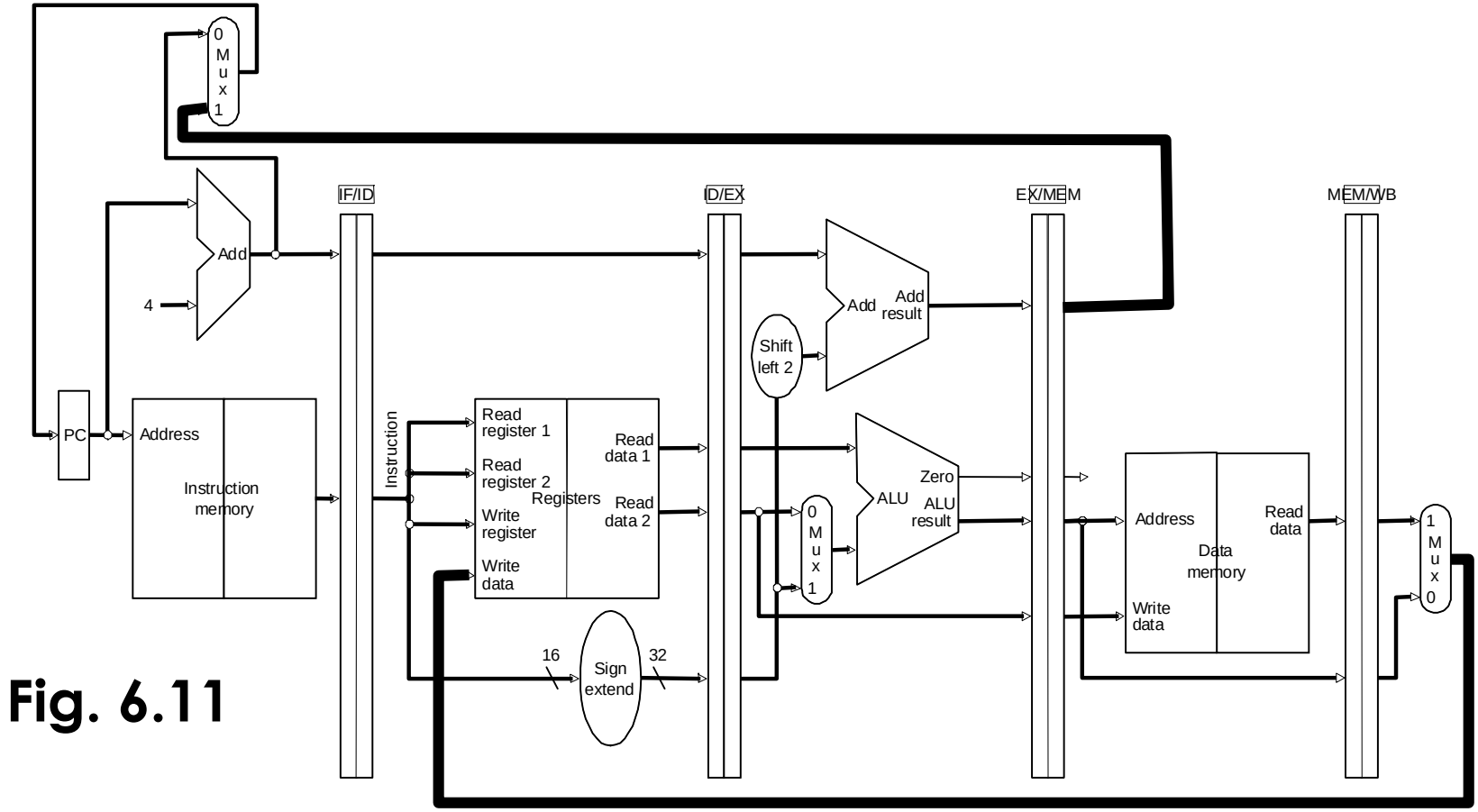


Fig. 6.11

Pipeline Datapath with Control Signals

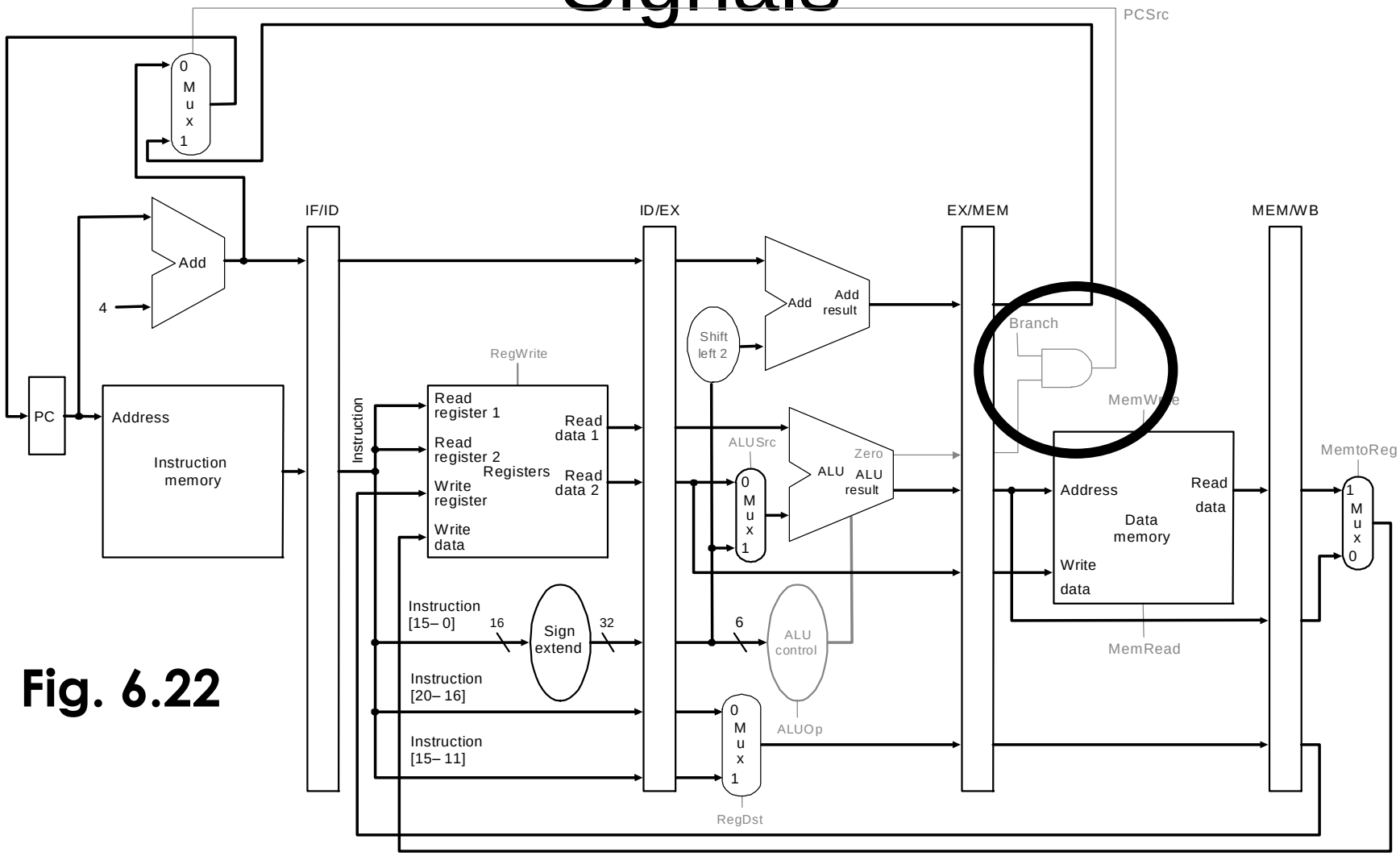
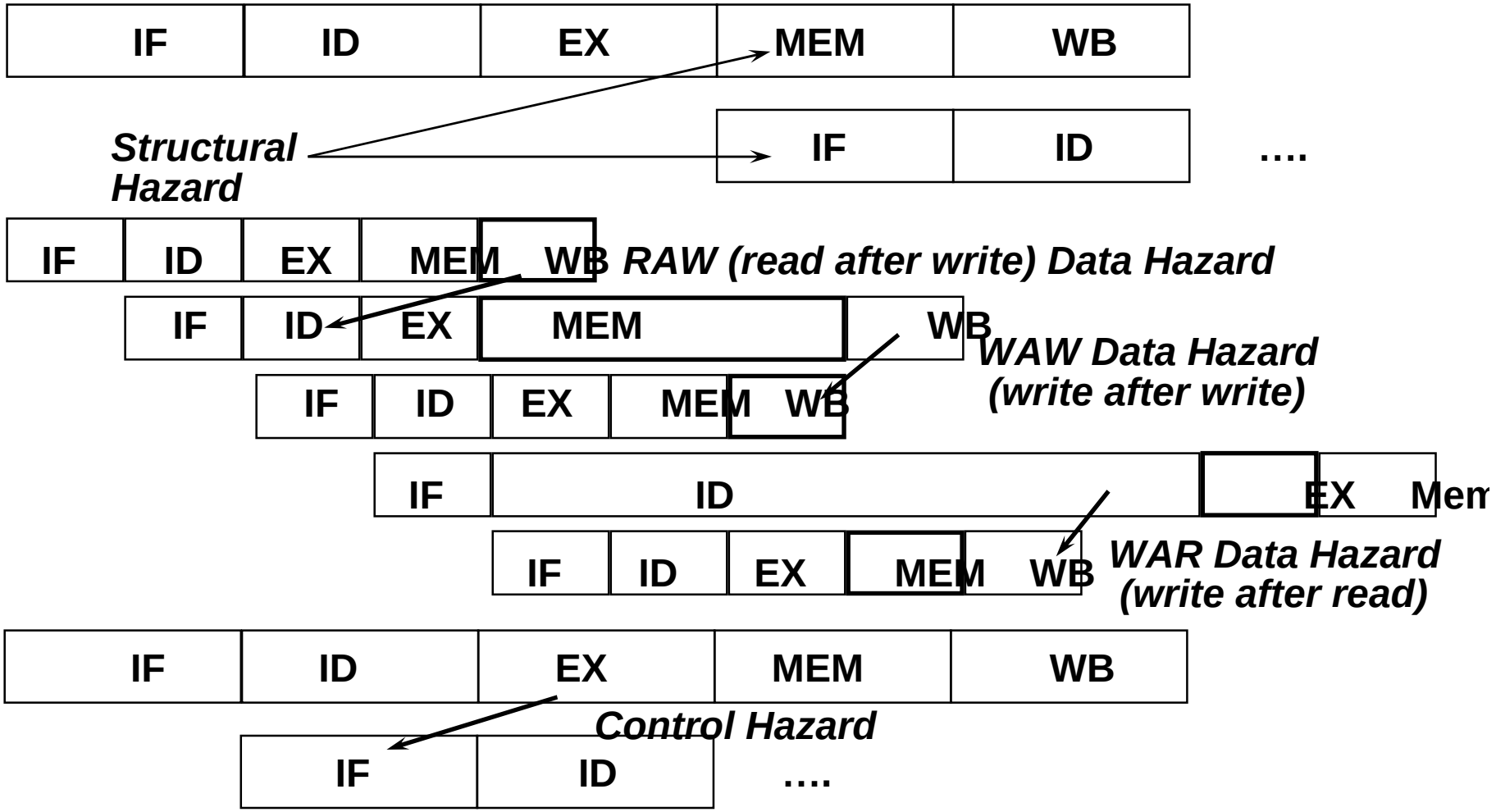


Fig. 6.22

Pipeline Hazards Illustrated



Branch Hazards

- When decide to branch, other inst. are in pipeline!

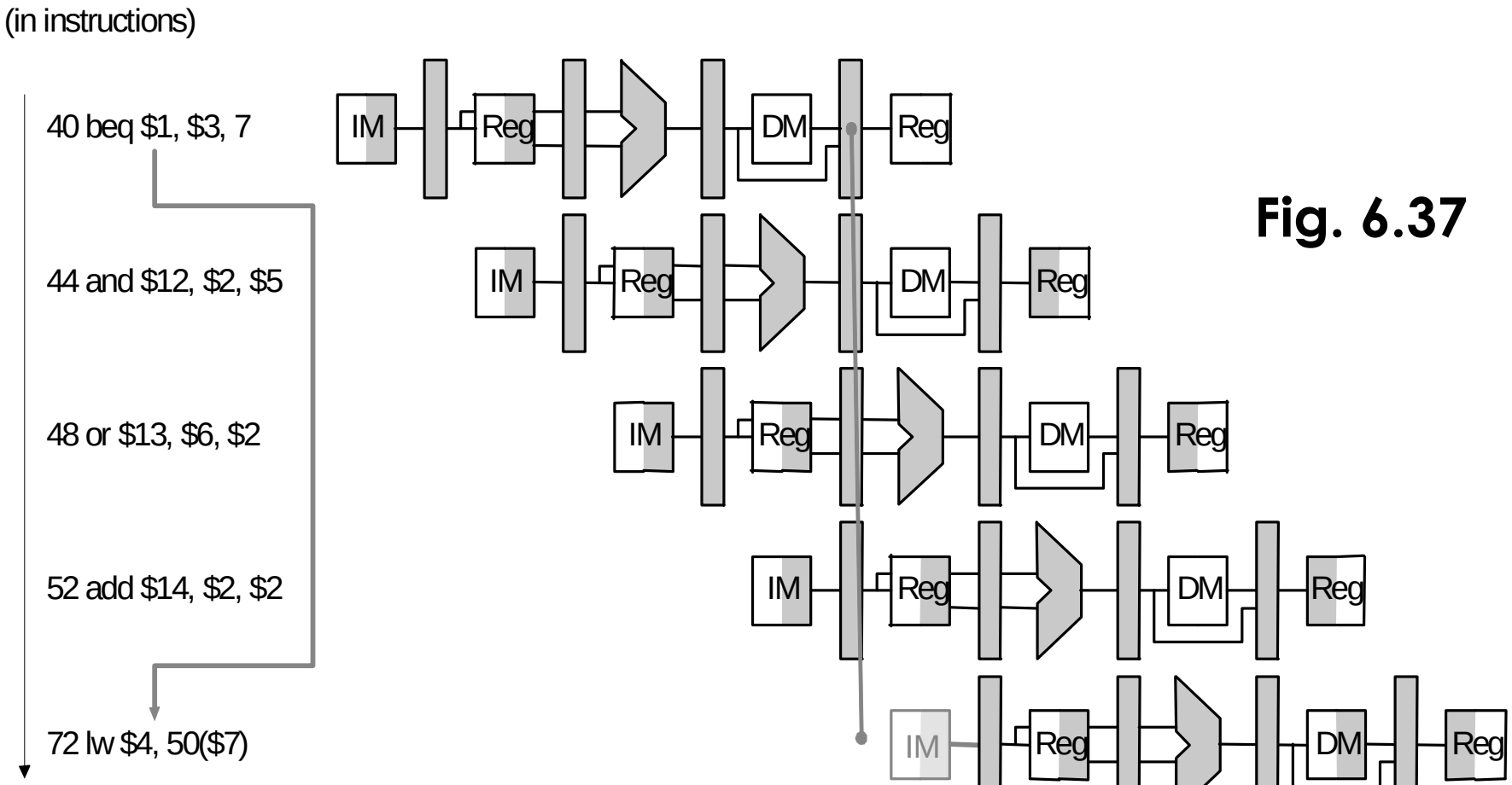


Fig. 6.37

Handling Branch Hazard

- Predict branch always not taken
  - Need to add hardware for flushing inst. if wrong
  - Branch decision made at MEM => need to flush instruction in IF/ID, ID/MEM by changing control values to 0
- Reduce delay of taken branch by moving branch execution earlier in the pipeline
  - Move up branch address calculation to ID
  - Check branch equality at ID (using XOR) by comparing the two registers read during ID
  - Branch decision made at ID => one instruction to flush
  - Add a control signal, IF.Flush, to zero instruction field of IF/ID => making the instruction an NOP
- Dynamic branch prediction
- Compiler rescheduling, delay branch

Pipeline with Flushing

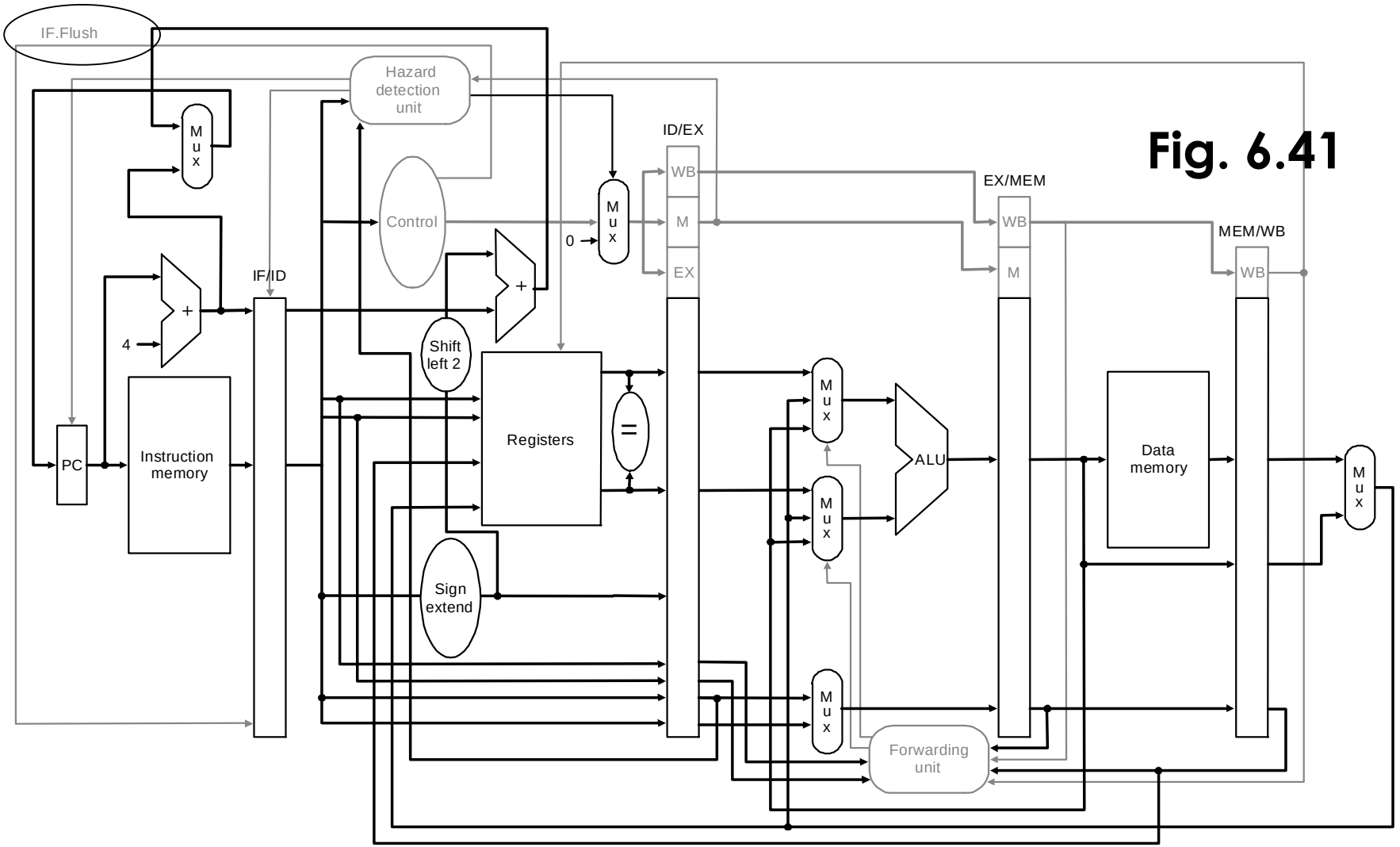


Fig. 6.41

Example 5: Cycle 3

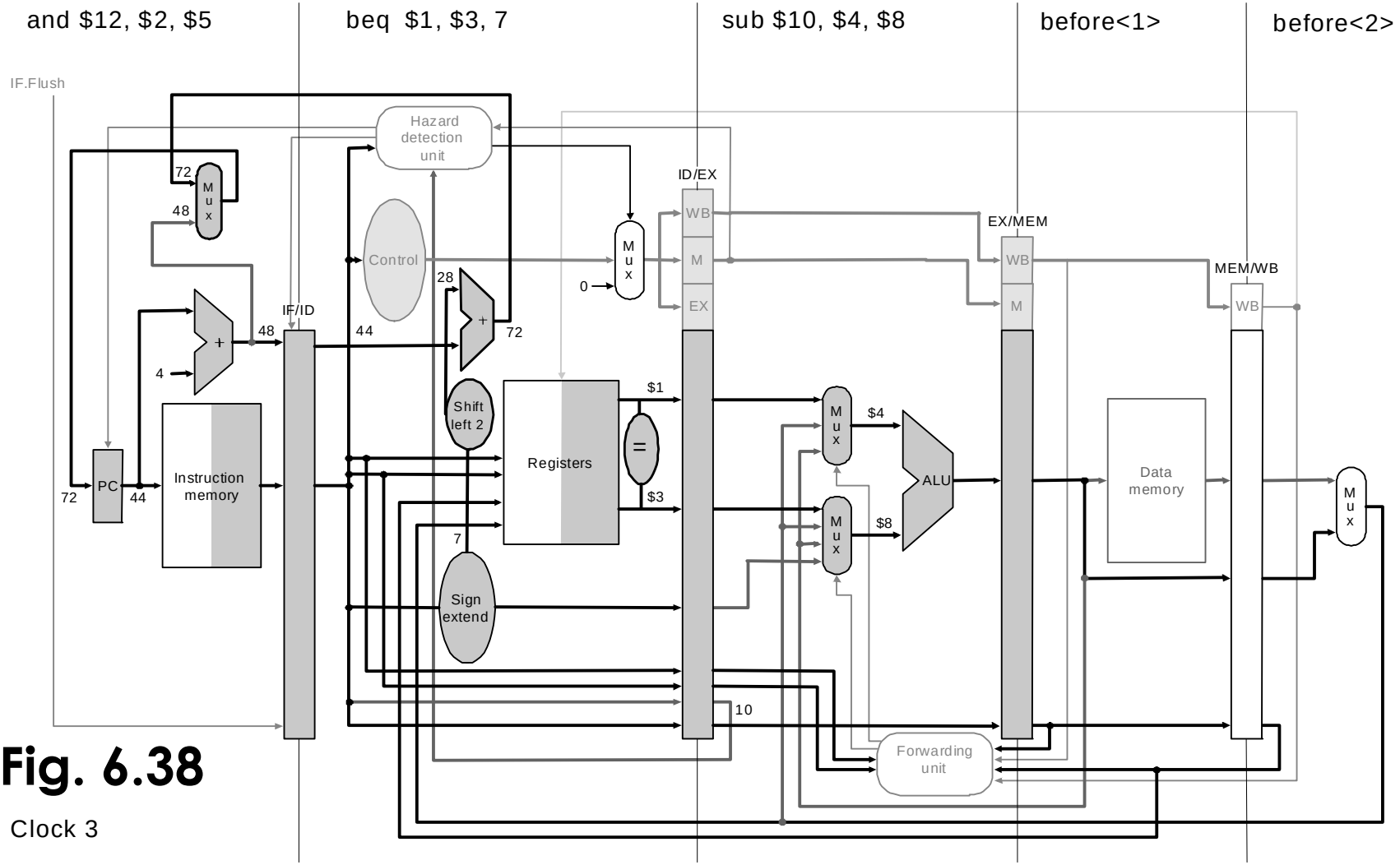


Fig. 6.38

Clock 3

Example 5: Cycle 4

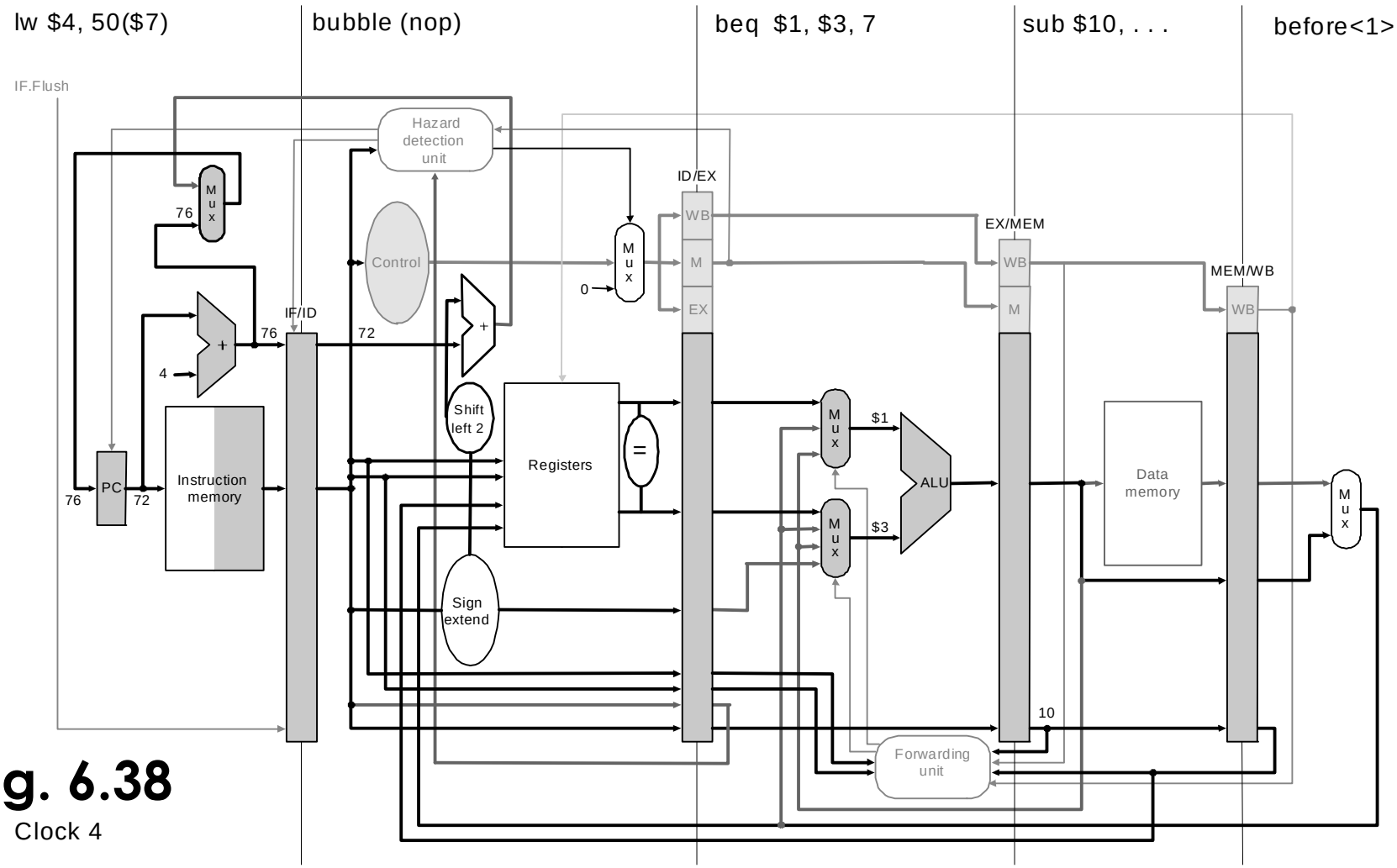
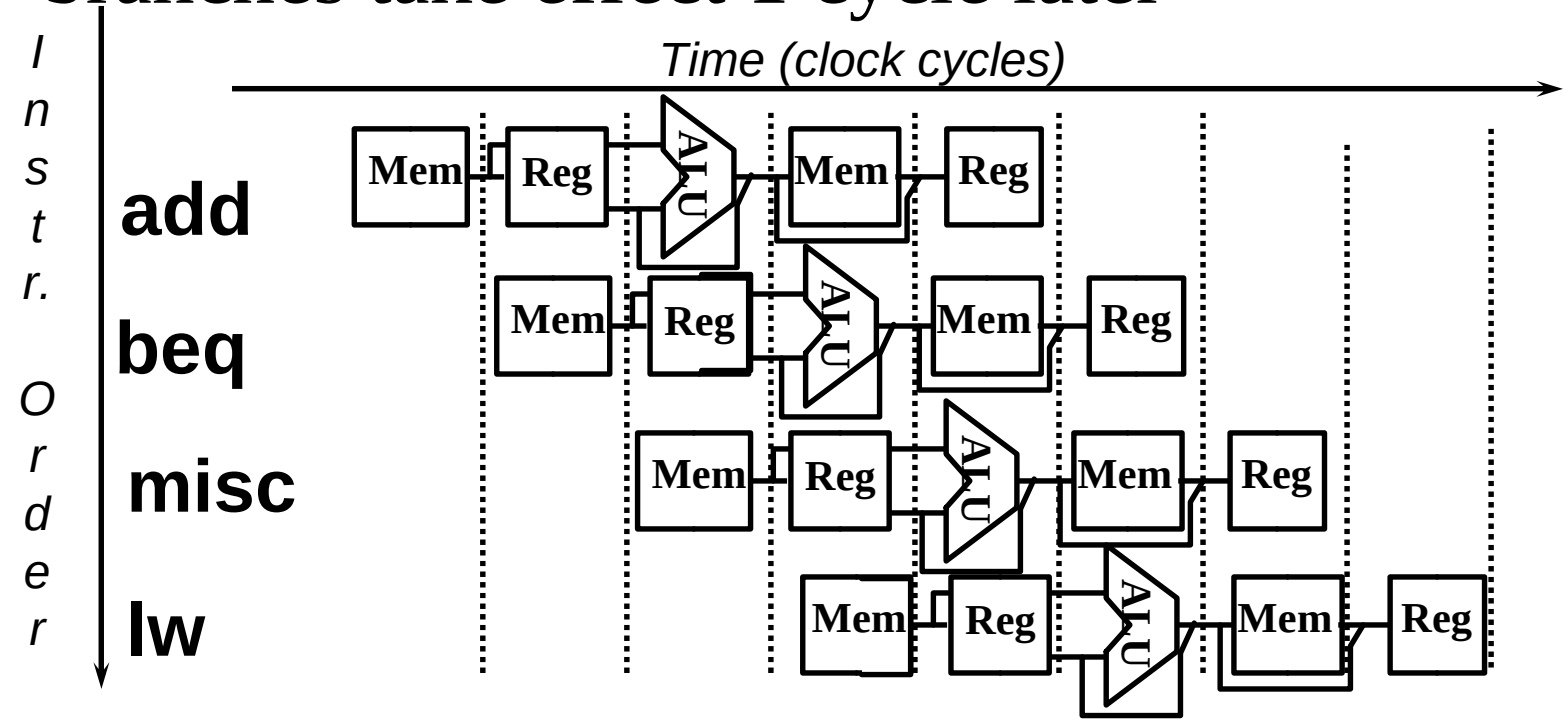


Fig. 6.38
Clock 4

Delayed Branch

- Predict-not-taken + branch decision at ID
  => the following instruction is always executed
  => branches take effect 1 cycle later



Dynamic Branch Prediction

- Performance = *ƒ*(accuracy, cost of misprediction)
- Branch History Table: Lower bits of PC address index table of 1-bit values
  - Says whether or not branch taken last time
  - No address check
- Problem: in a loop, 1-bit BHT will cause two mispredictions (avg is 9 iterations before exit):
  - End of loop case, when it exits instead of looping as before
  - First time through loop on *next* time through code, when it predicts exit instead of looping

1-Bit Prediction

- For each branch, keep track of what happened last time and use that outcome as the prediction
- What are prediction accuracies for branches 1 and 2 below:

```
while (1) {
   for (i=0;i<10;i++) {  branch-1
     …
   }
   for (j=0;j<20;j++) {  branch-2
     …
   }
}
```

2-Bit Prediction

- For each branch, maintain a 2-bit saturating counter:

  if the branch is taken: counter = min(3,counter+1)

  if the branch is not taken: counter = max(0,counter-1)
- If (counter >= 2), predict taken, else predict not taken
- Advantage: a few atypical branches will not influence the prediction (a better measure of “the common case”)
- Especially useful when multiple branches share the same counter (some bits of the branch PC are used to index into the branch predictor)
- Can be easily extended to N-bits (in most processors, N=2)

N-bit Branch Prediction Buffers

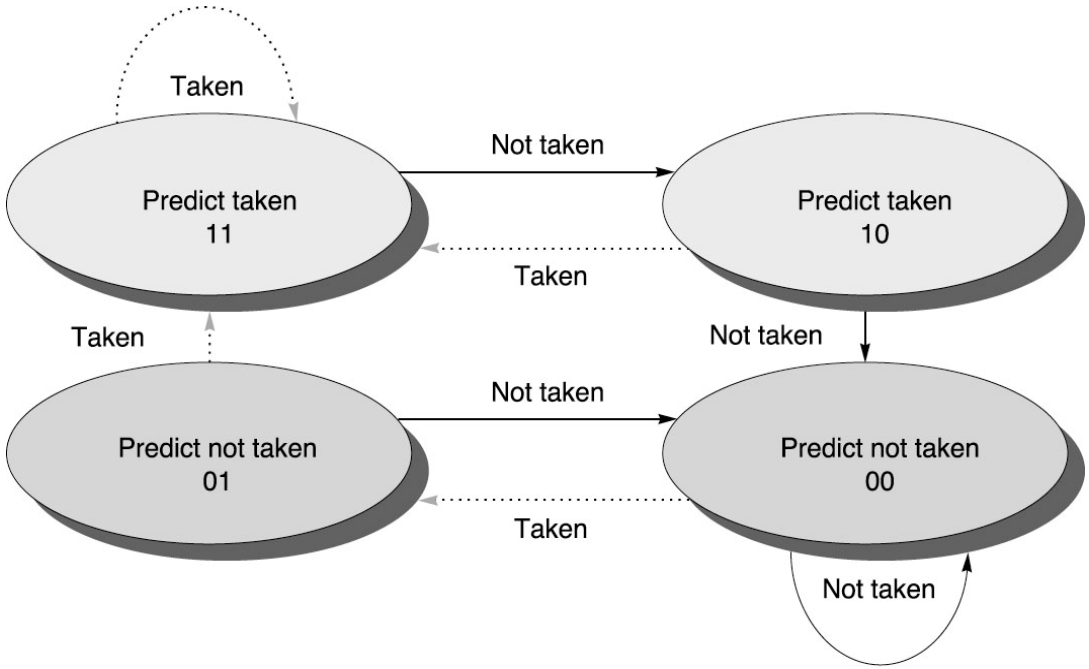
- When the counter is greater than or equal to one-half of its maximum value (2^n-1), the branch is predicted as taken.
- The counter is increased on a taken branch and decremented on an untaken branch.
- A branch buffer can be implemented as a small cache accessed during the IF stage.

N-bit Branch Prediction Buffers

Use an n-bit saturating counter

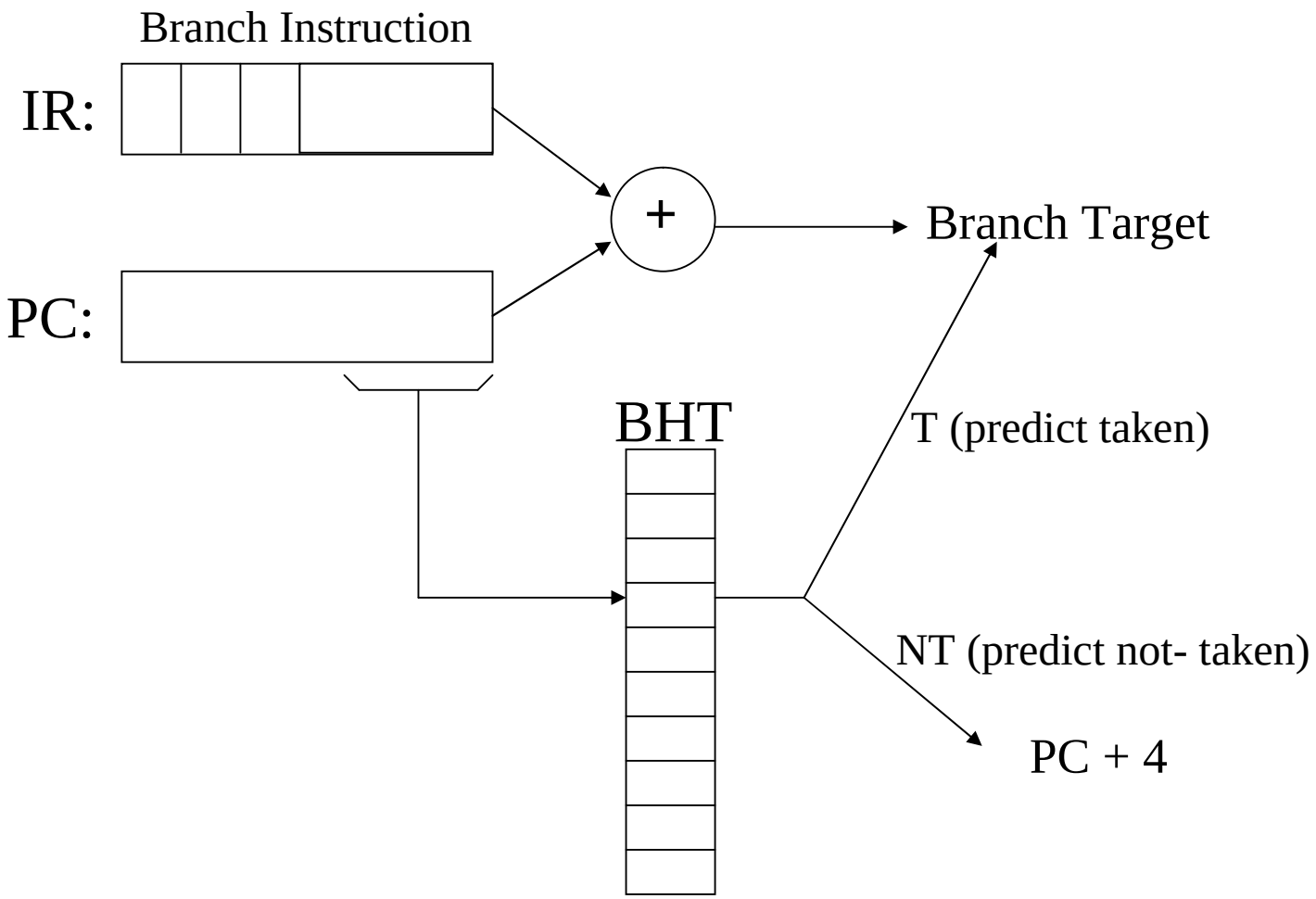
Only the loop exit causes a misprediction

2-bit predictor almost as good as any general n-bit predictor



Basic Branch Prediction Buffers

a.k.a. Branch History Table (BHT) - Small direct-mapped cache of T/NT bits



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What about Exceptions?

- Another form of branch hazard
  - How to stop the pipeline? restart?
  - Who caused the interrupt?
  - Who to serve first, if multiple interrupts at the same time?

Handling Exceptions

How to stop the pipeline? restart?

- Suppose overflow occur at `add $1,$2,$1`
  - Disable writes of instructions till trap hits WB, e.g., flush following instructions using IF.Flush, ID.Flush, EX.Flush to cause multiplexers to zero control signals (overflow exception detected at EX => flush offending instruction)
  - Force trap instruction into IF, e.g., fetch from 4000 0040hex by adding 4000 0040hex to PC input MUX
  - Save address of offending instruction in EPC

Pipeline with Exception

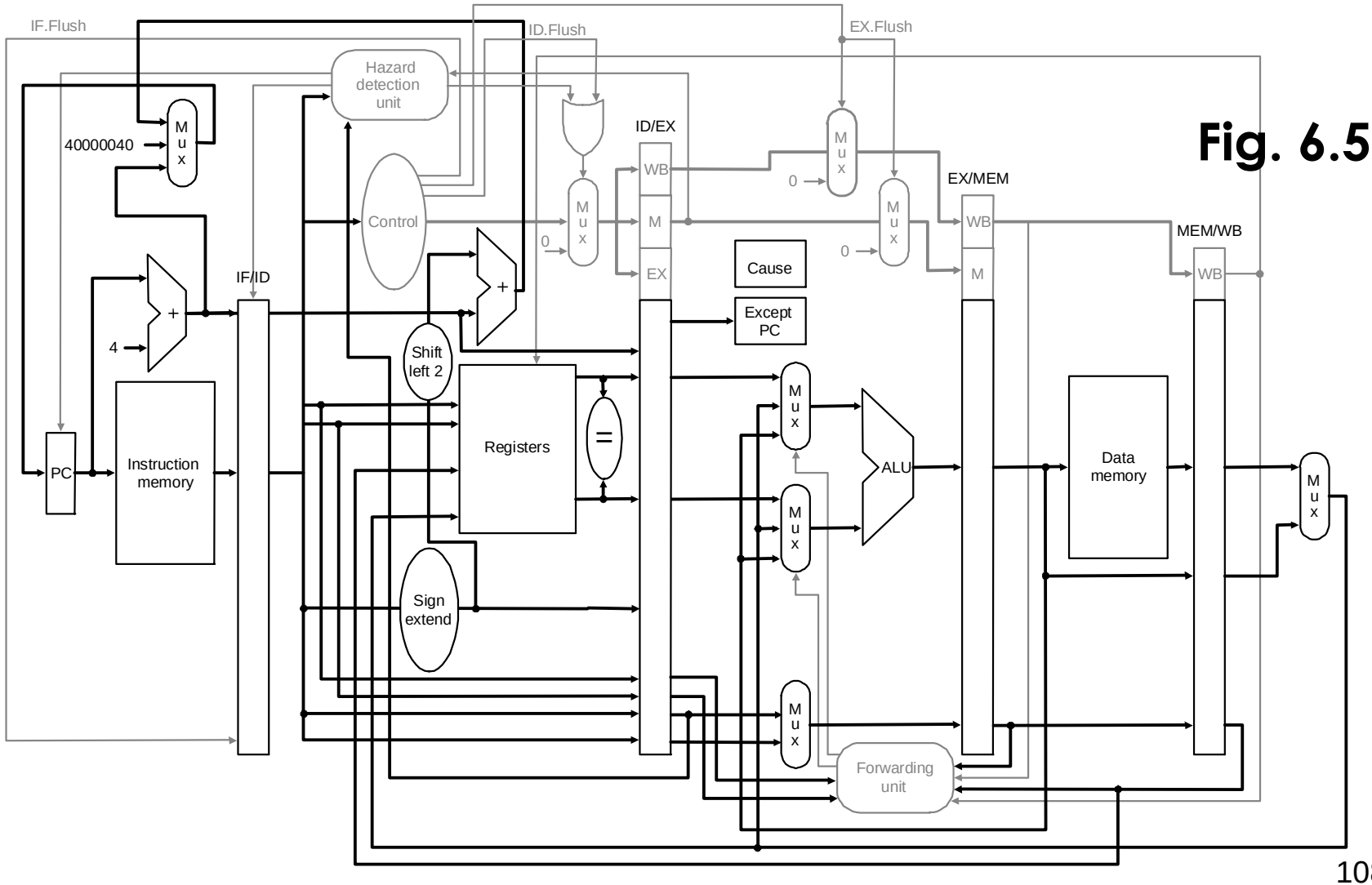


Fig. 6.55

Who caused the exception ?

- 5 instructions executing in 5 stage pipeline
- Who caused the exception? Need to know in which stage an exception can occur => help determine cause

Stage	*Problem interrupts occurring*
IF	Page fault; misaligned memory access; memory-protection violation
ID	Undefined or illegal opcode
EX	Arithmetic exception
MEM	Page fault; misaligned memory access; memory error; mem-protection violation;

When to Serve?

- Who to serve first, if multiple interrupts at the same time?
  - Multiple interrupts: use priority hardware to choose the earliest instruction to interrupt
  - External interrupts: flexible in when to interrupt

Outline

- An overview of pipelining
- A pipelined datapath
- Pipelined control
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards
- Exceptions
- Superscalar and dynamic pipelining

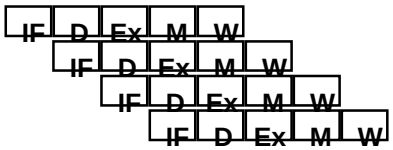
Instruction Level Parallelism

How to increase the potential amount of ILP:

- Increase the depth of the pipeline to overlap more instructions
  - super-pipeline
- Launch multiple instructions
  - Static multiple issue (decision made by compiler before execution)
  - Dynamic multiple issue (decision made during execution by the processor)

Different Pipelined Designs

☐**Pipelining**

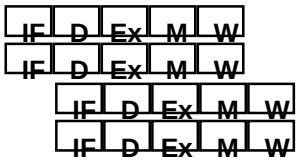


Limitation

Issue rate, FU stalls, FU depth

☐**Super-scalar**

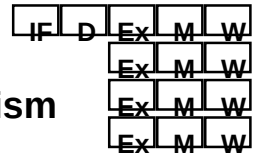
- Issue multiple scalar instructions per cycle



Hazard resolution

☐**VLIW (EPIC)**

- Each instruction specifies multiple scalar operations
- Compiler determines parallelism



Packing

Static Multiple Issue

- Use compiler to assist with packing instructions and handling hazard
- Very Long Instruction Word (VLIW)
- Explicitly Parallel Instruction Computer (EPIC) (Intel IA-64)

A Static Two-issue Datapath

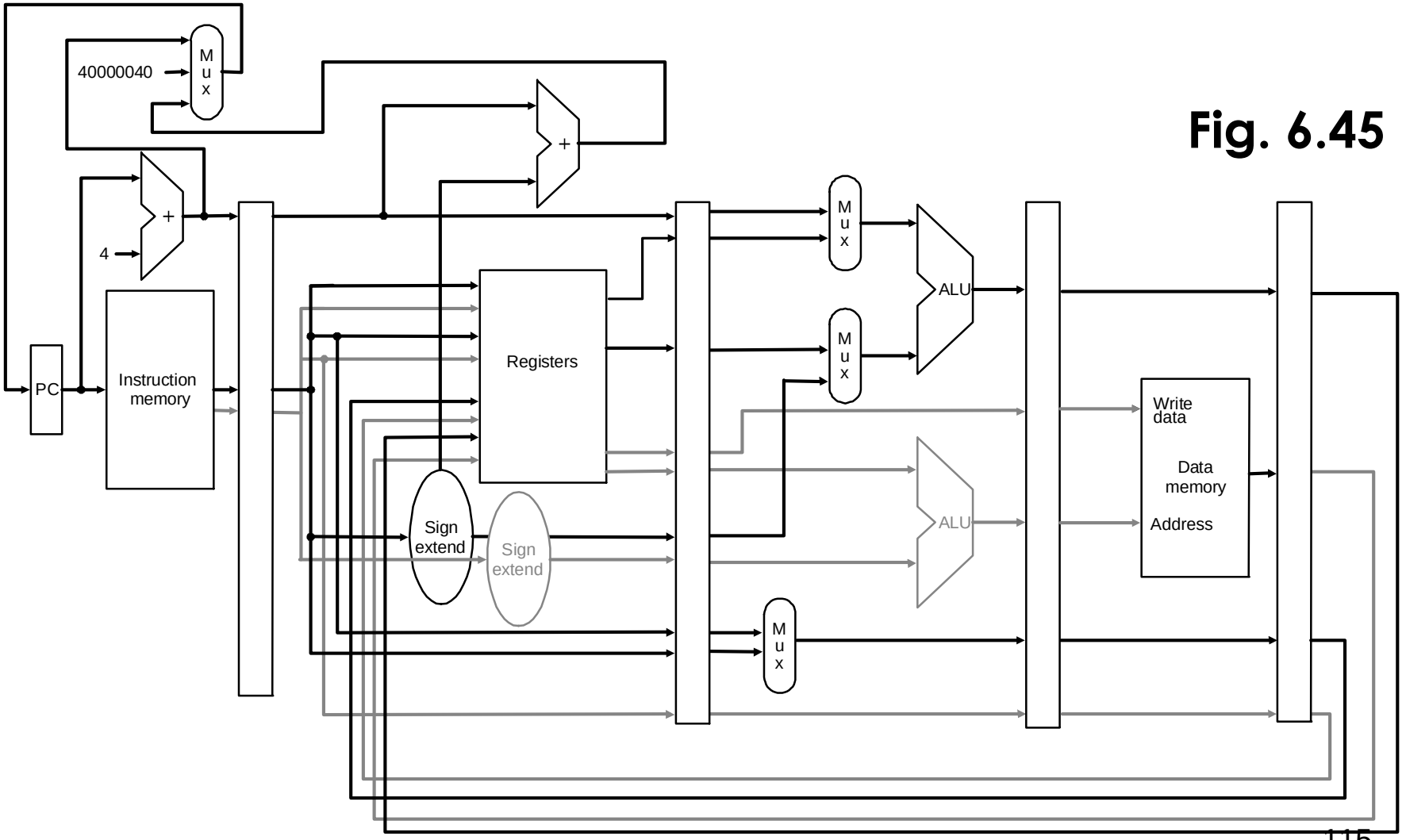


Fig. 6.45

Dynamic Multiple Issue

- The hardware performs the scheduling?
  - hardware tries to find instructions to execute
  - out of order execution is possible
  - speculative execution and dynamic branch prediction
- Superscalar

Superscalar: Three Primary Units

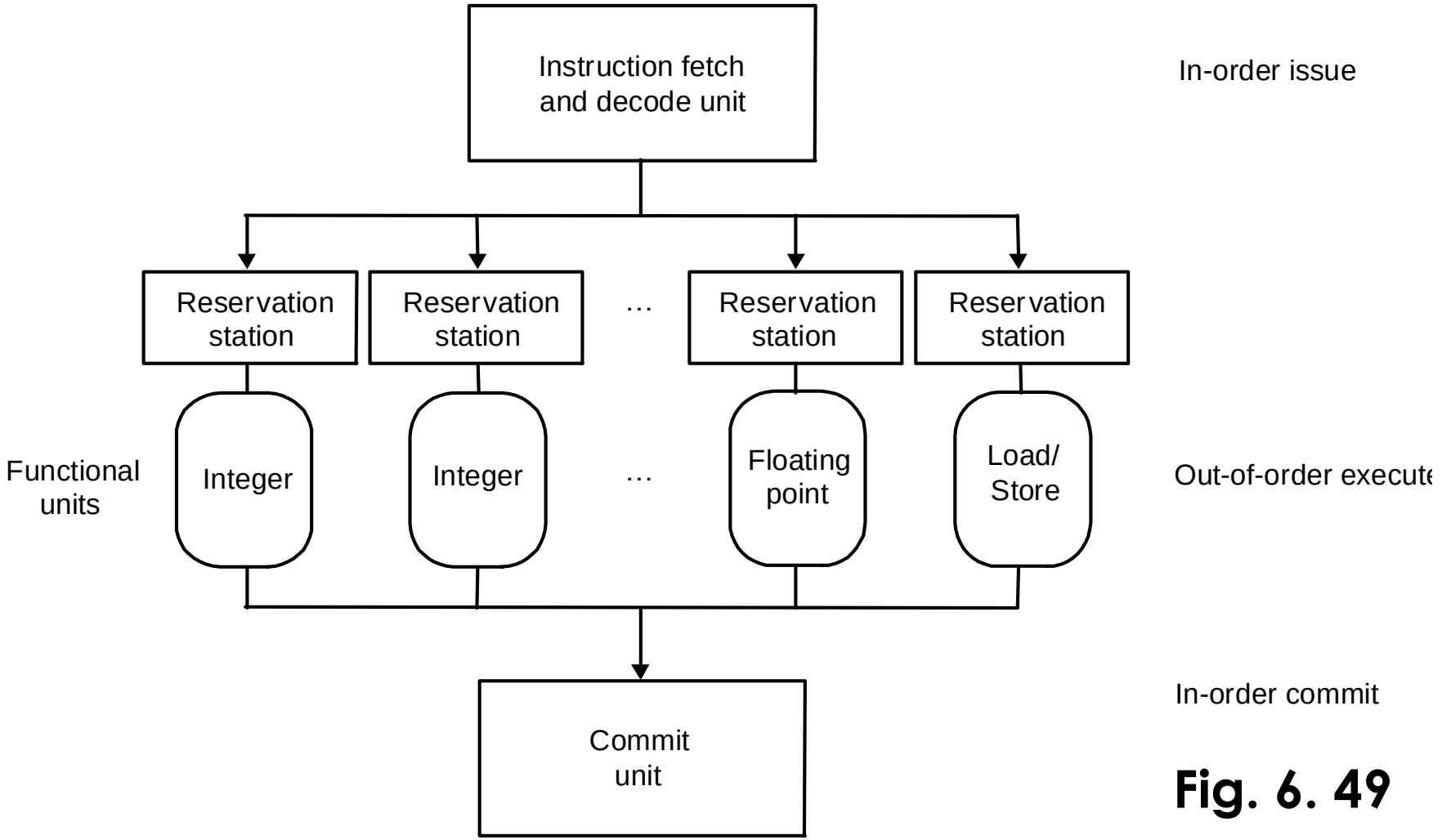
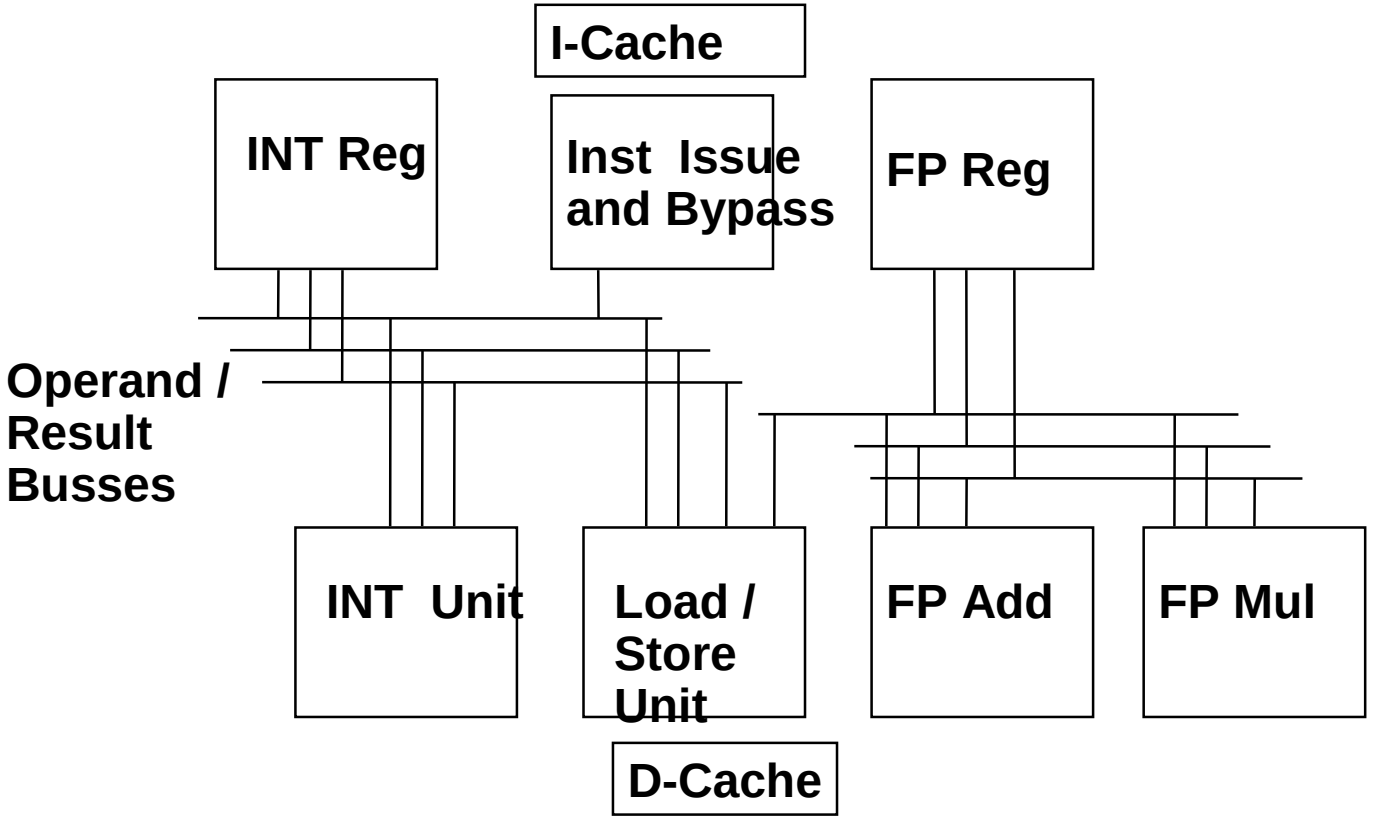


Fig. 6. 49

Simple Superscalar

- Independent INT and FP issue to separate pipelines



Dynamic Scheduling

- All modern processors are very complicated
  - DEC Alpha 21264: 9 stage pipeline, 6 instruction issue
  - PowerPC and Pentium: branch history table
  - Compiler technology important

Summary

- Pipelines pass control information down the pipe just as data moves down pipe
- Forwarding/stalls handled by local control
- Exceptions stop the pipeline
- MIPS instruction set architecture made pipeline visible (delayed branch, delayed load)
- More performance from deeper pipelines, parallelism