Chapter 4 Pipeline processor (part 2)
Control Signal for Pipeline Processor

Outline

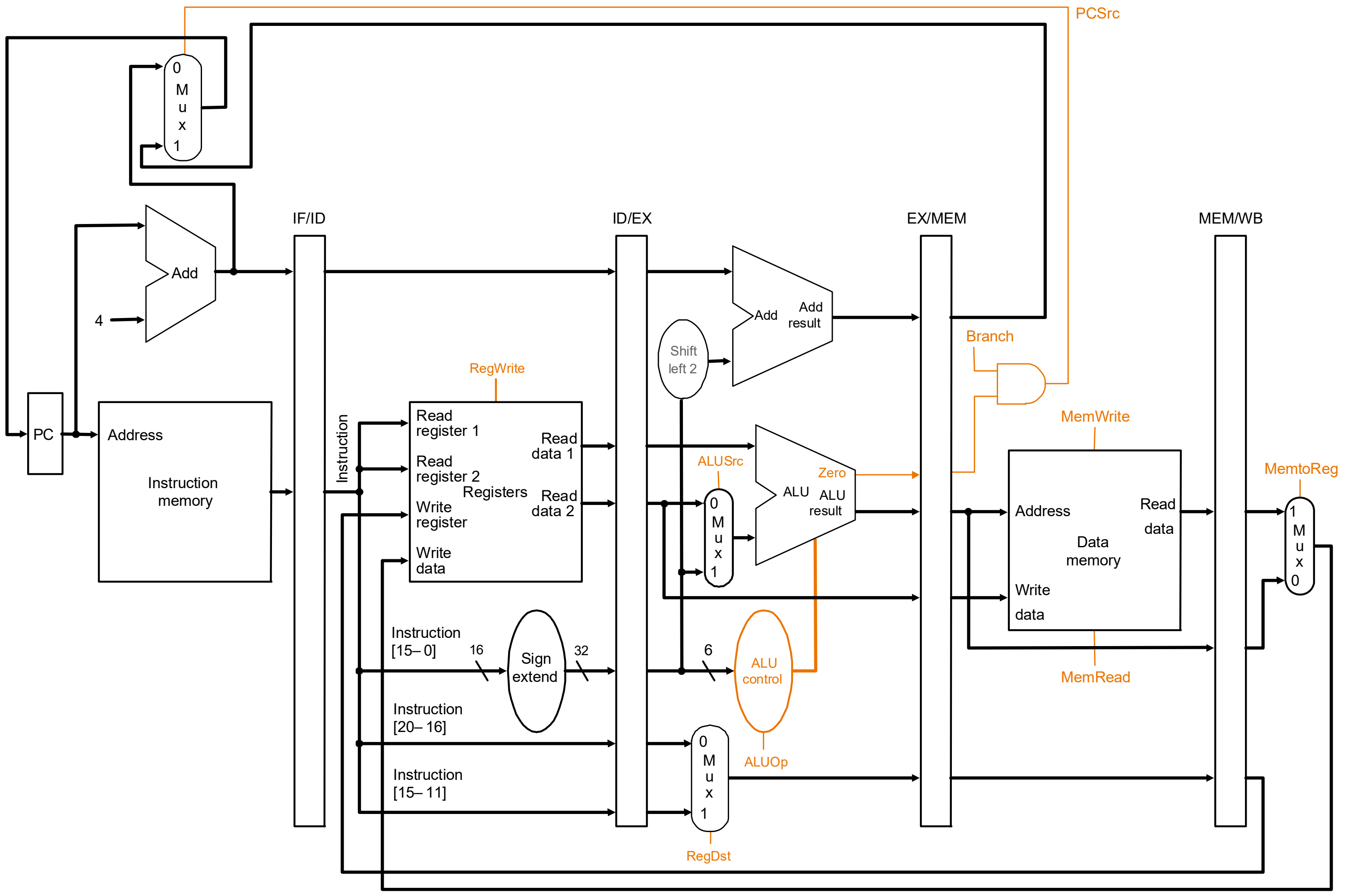
- A pipelined datapath
- Pipelined control
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards

Pipeline Control

- Three steps are needed
  - Step 1: Begin with the same control signal with single-cycle datapath control
  - Step 2: Group control lines into five groups according to pipeline stage
    - Since control signals are associated with components active during a single pipeline stage
  - Step 3: Set control signals during each pipeline stage

Pipelined Datapath with Control – Step 1

Start with Same control signals as the single-cycle datapath



Pipeline Control Signals- Step 2

- Group control lines into five groups according to pipeline stage
  - instruction fetch / PC increment (IF)
  - instruction decode / register fetch (ID)
  - execution / address calculation (EX)
  - memory access (M)
  - write back (WB)

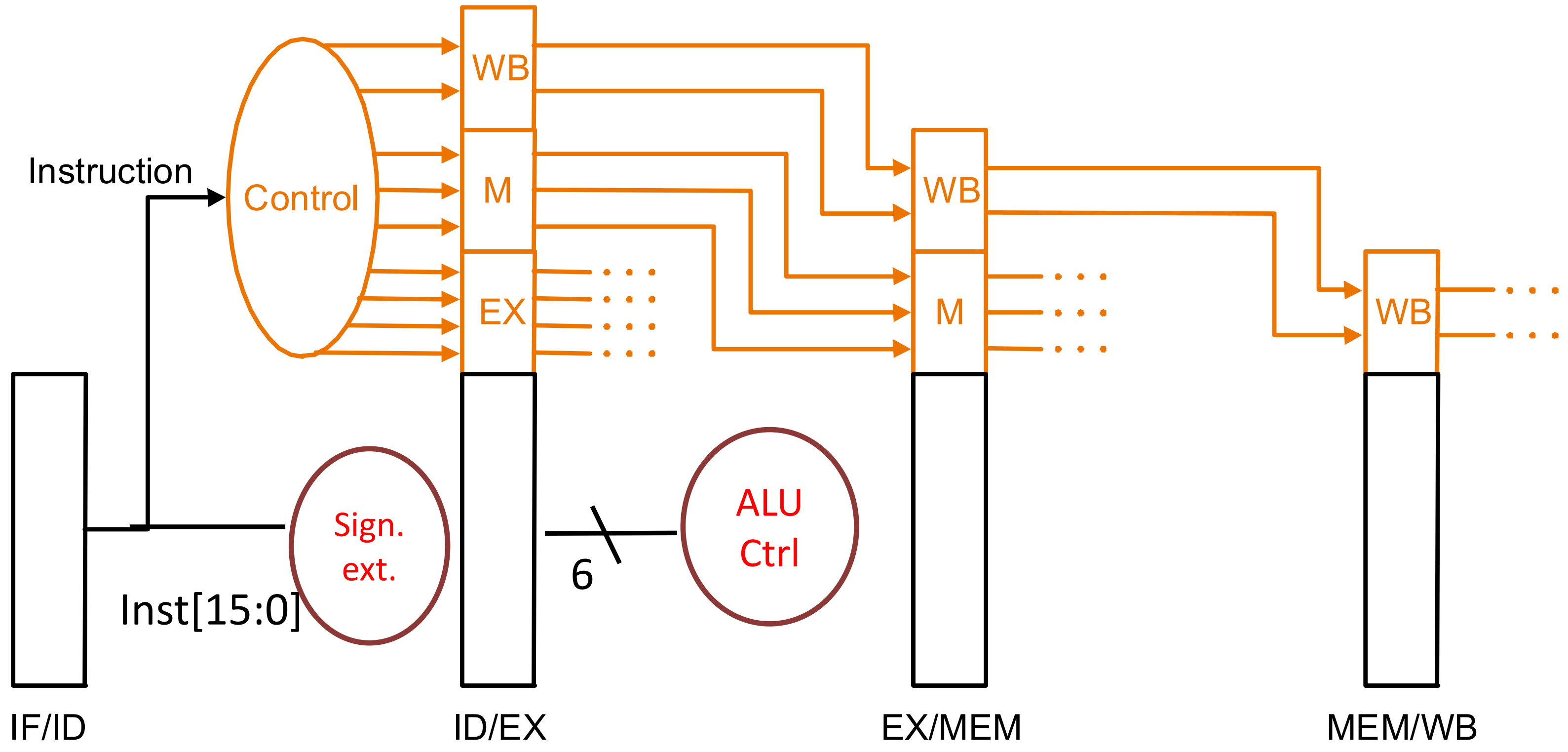
Nothing to control as instruction memory read and PC write are always enabled

(the following table)

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

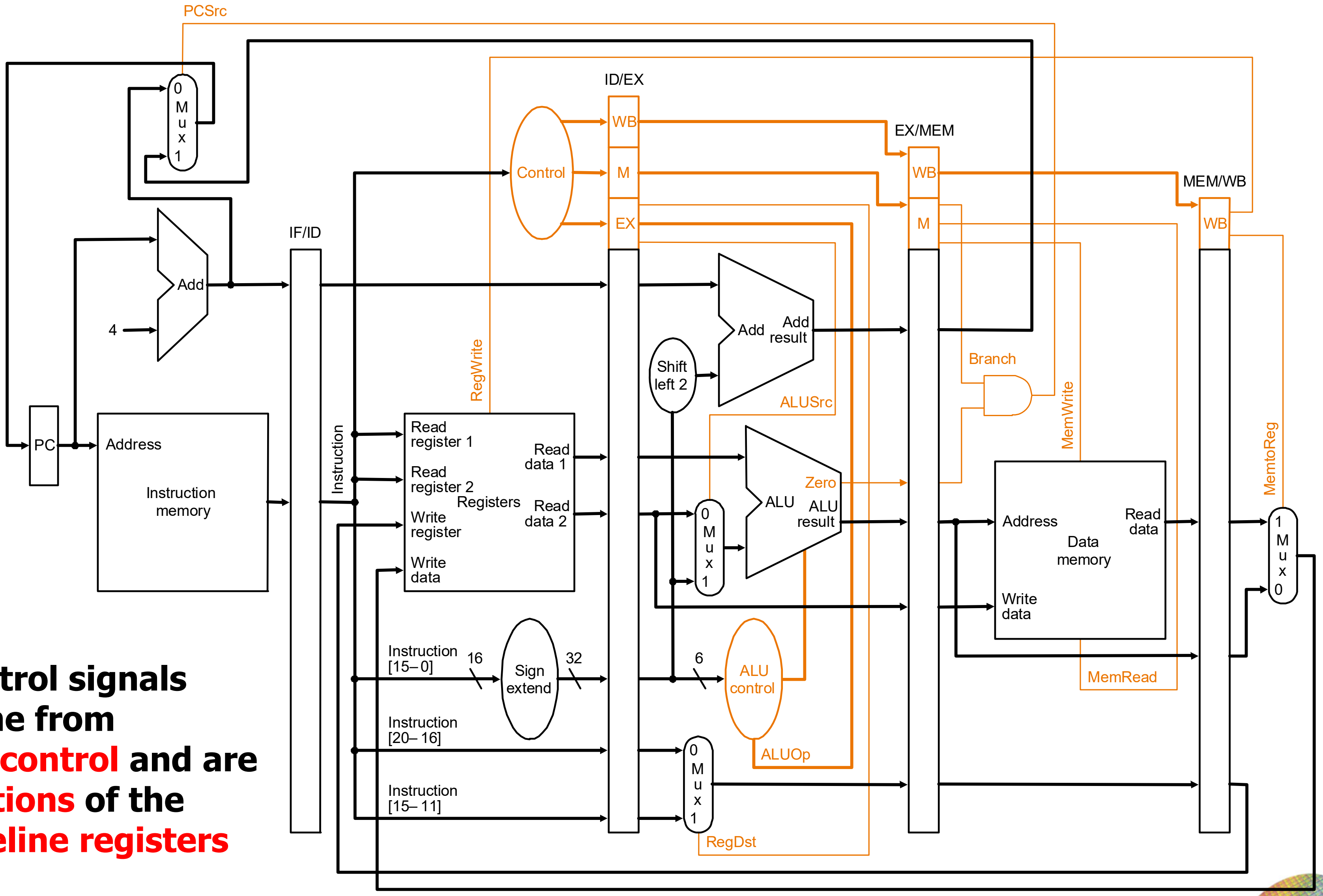
Pipeline Control Implementation

- *Pass control signals along just like the data* – extend each pipeline register to hold needed control bits for succeeding stages



- *Note*: The 6-bit *funct field* of the instruction required in the EX stage to generate ALU control can be retrieved as the 6 least significant bits of the immediate field which is sign-extended and passed from the IF/ID register to the ID/EX register

Pipelined Datapath with Control – Step 3



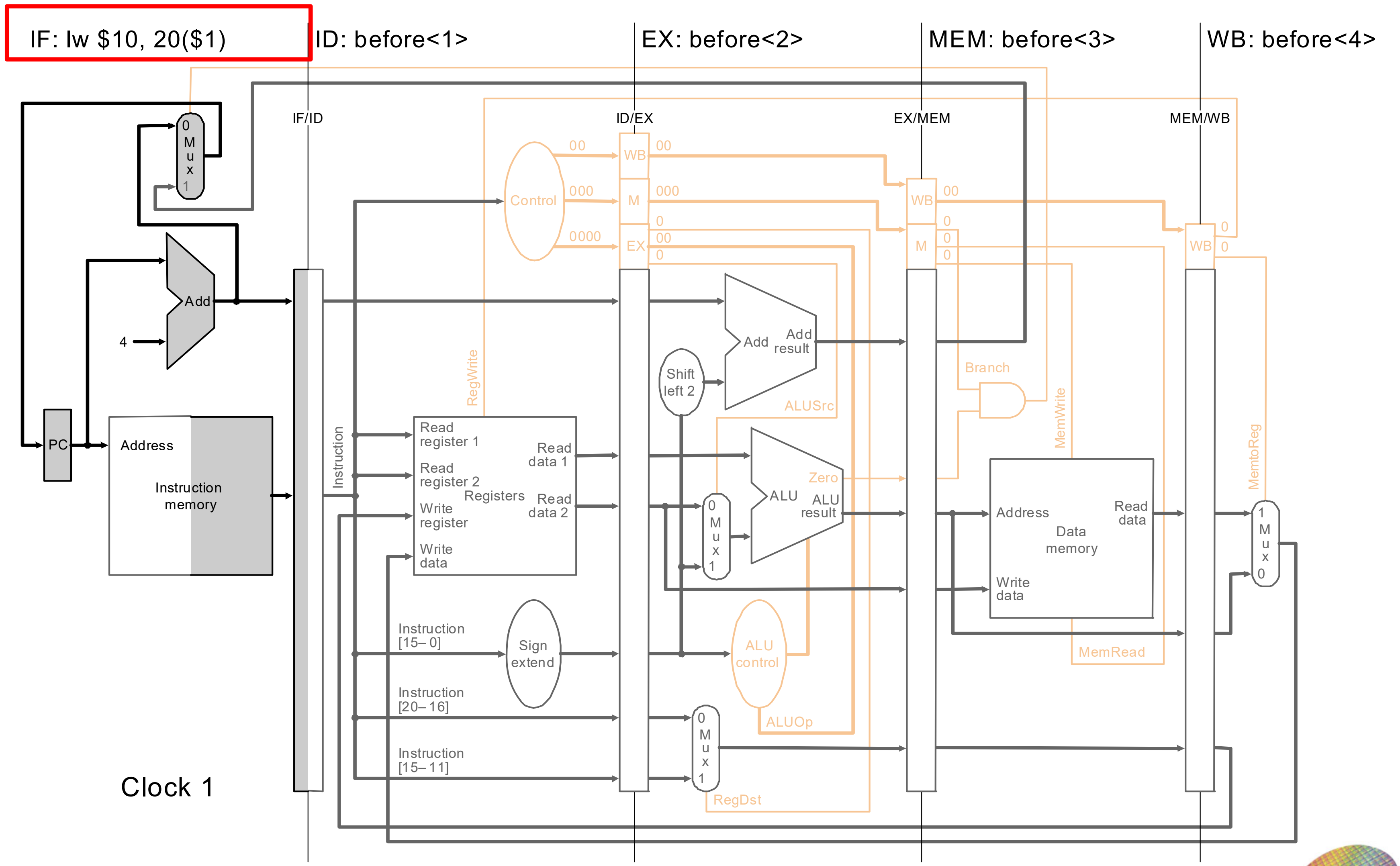
Control signals come from the control and are portions of the pipeline registers

An Example

```
lw    $10, 20($1)

sub   $11, $2, $3

and   $12, $4, $5

or    $13, $6, $7

add   $14, $8, $9
```

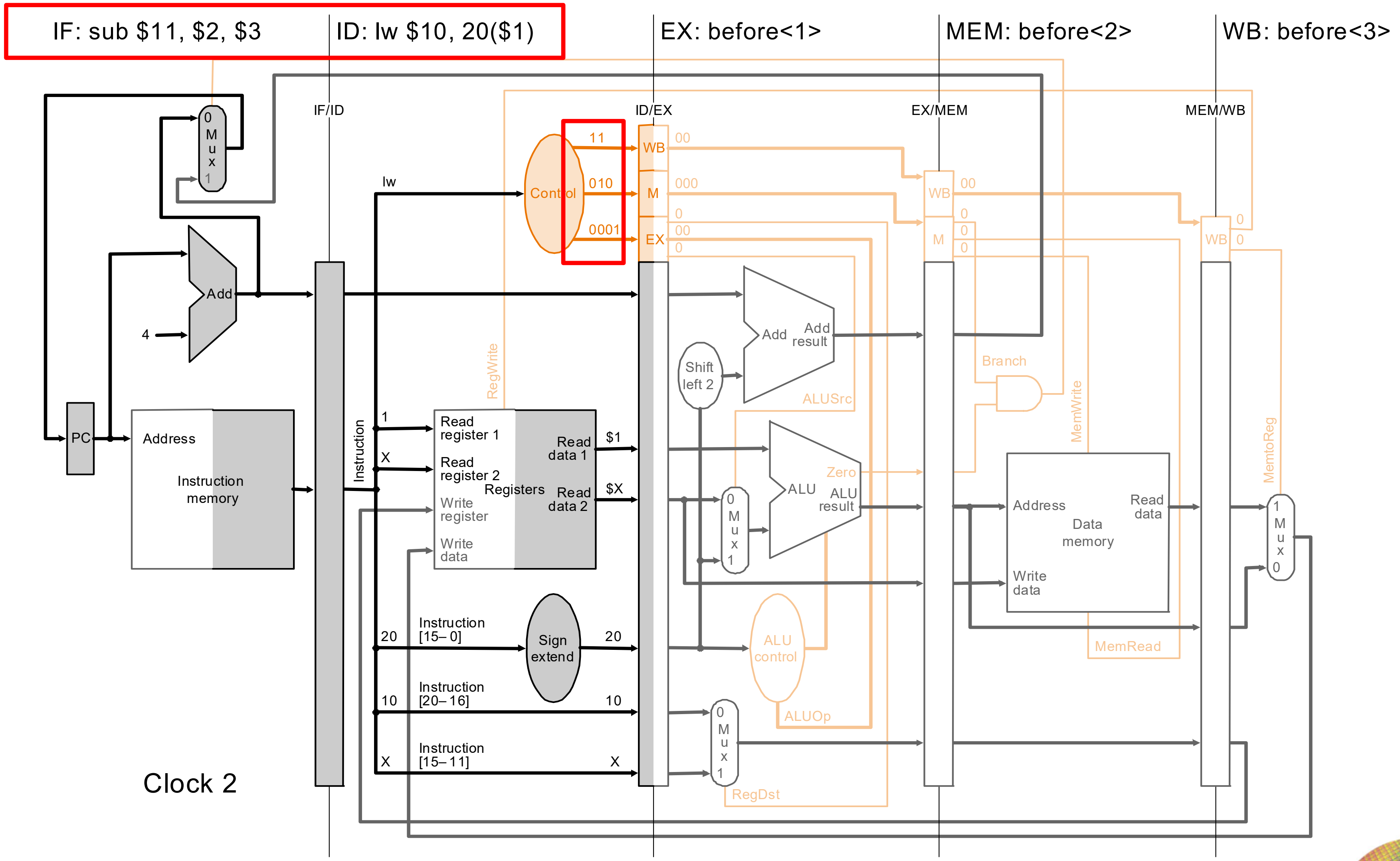
```
lw  $10, 20($1)
sub $11, $2, $3
and $12, $4, $5
or  $13, $6, $7
add $14, $8, $9
```

Cycle 1



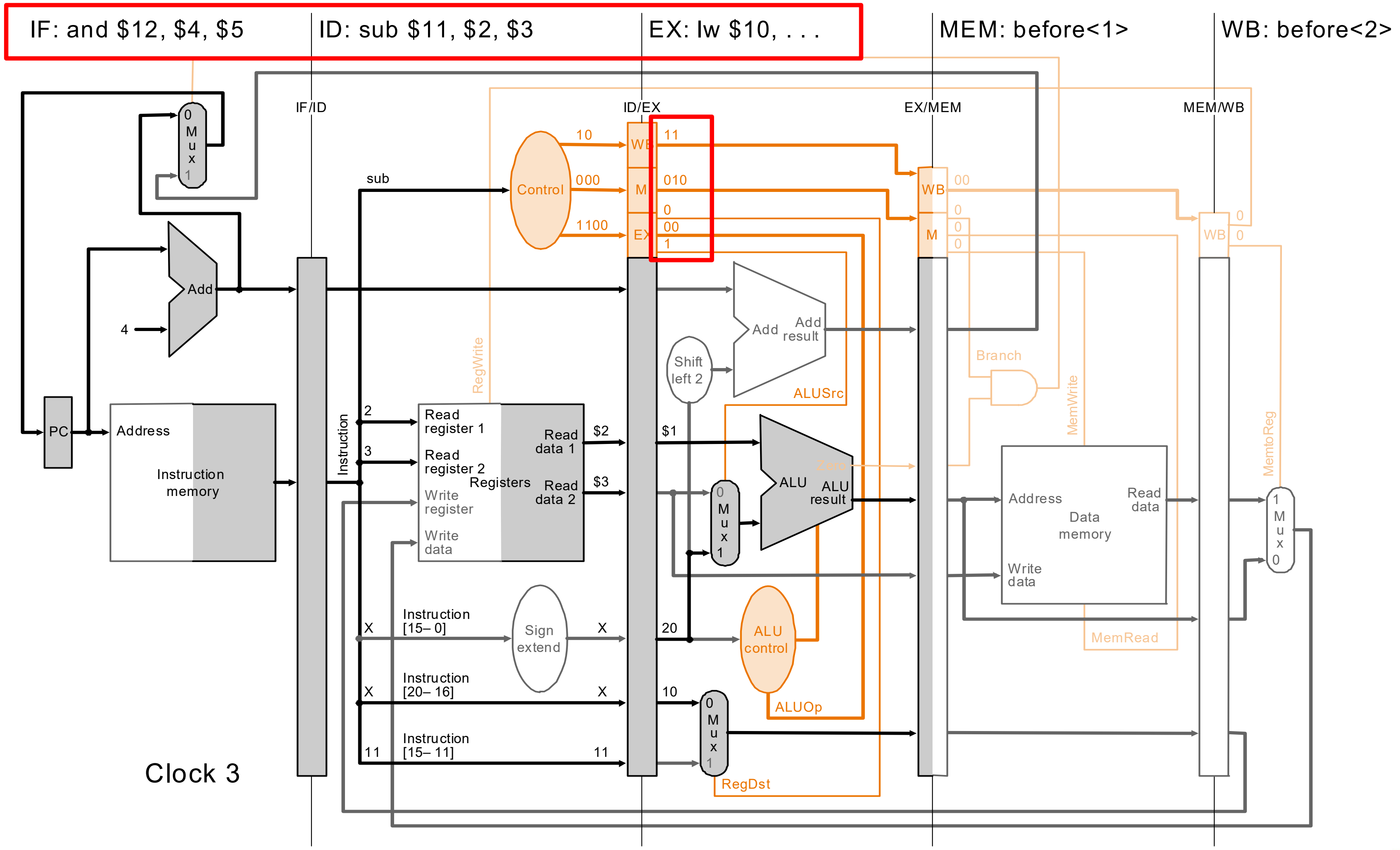
Cycle 2

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



Cycle 3

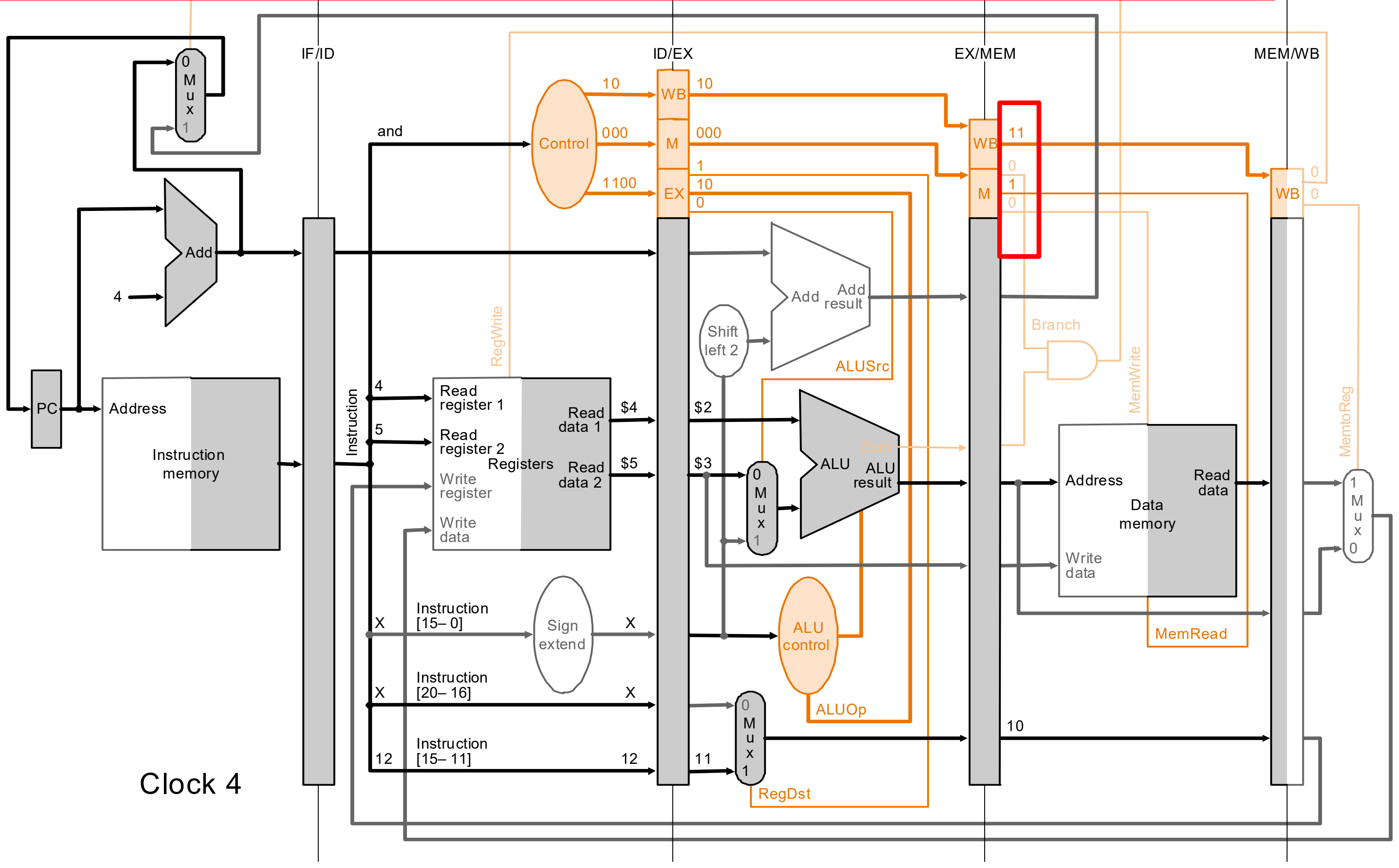
```
lw  $10, 20($1)
sub $11, $2, $3
and $12, $4, $5
or  $13, $6, $7
add $14, $8, $9
```



Cycle 4

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

IF: or $13, $6, $7 | ID: and $12, $2, $3 | EX: sub $11, . . . | MEM: lw $10, . . . | WB: before<1>

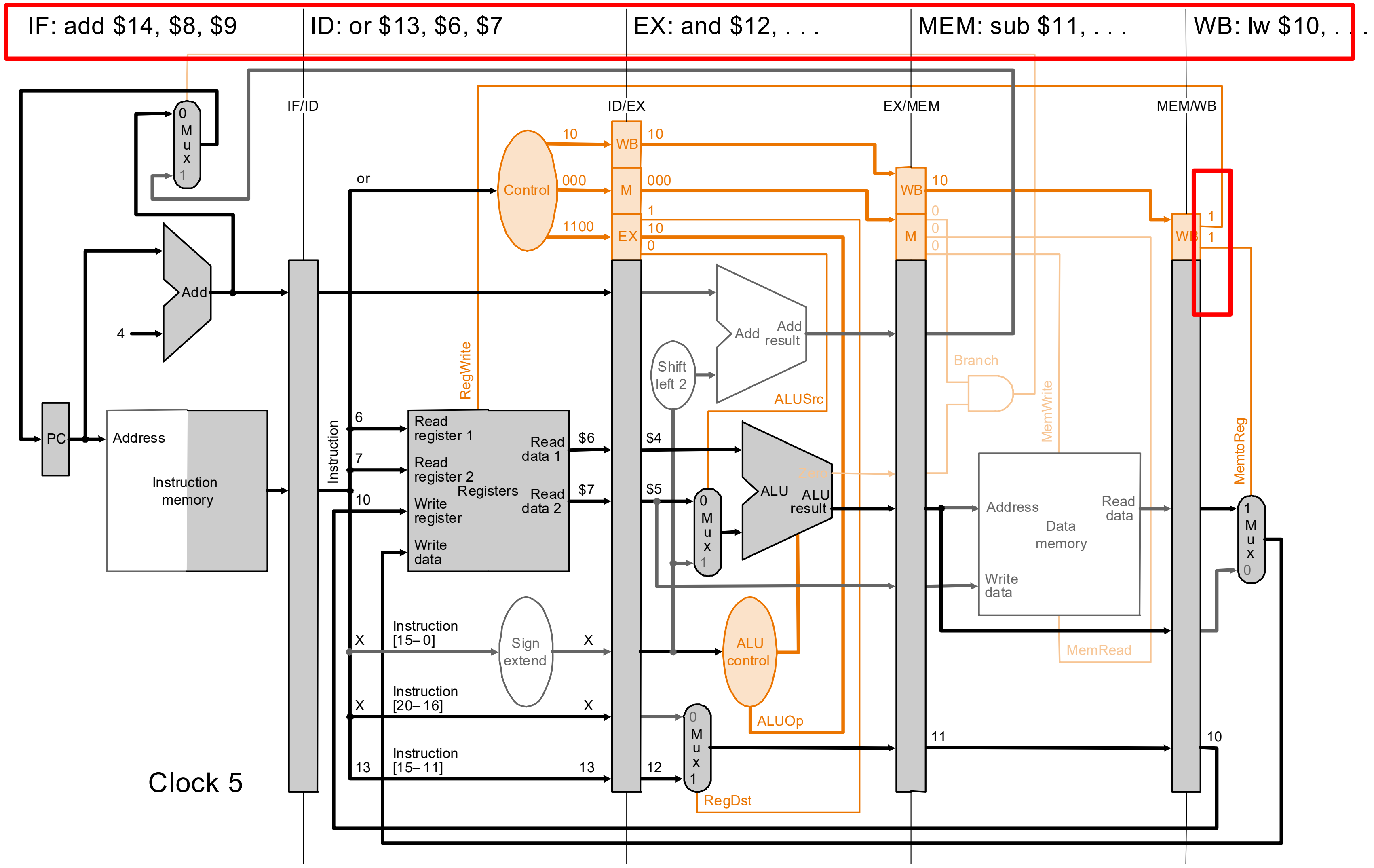


Clock 4

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

Cycle 5

IF: add $14, $8, $9 | ID: or $13, $6, $7 | EX: and $12, . . . | MEM: sub $11, . . . | WB: lw $10, . . .

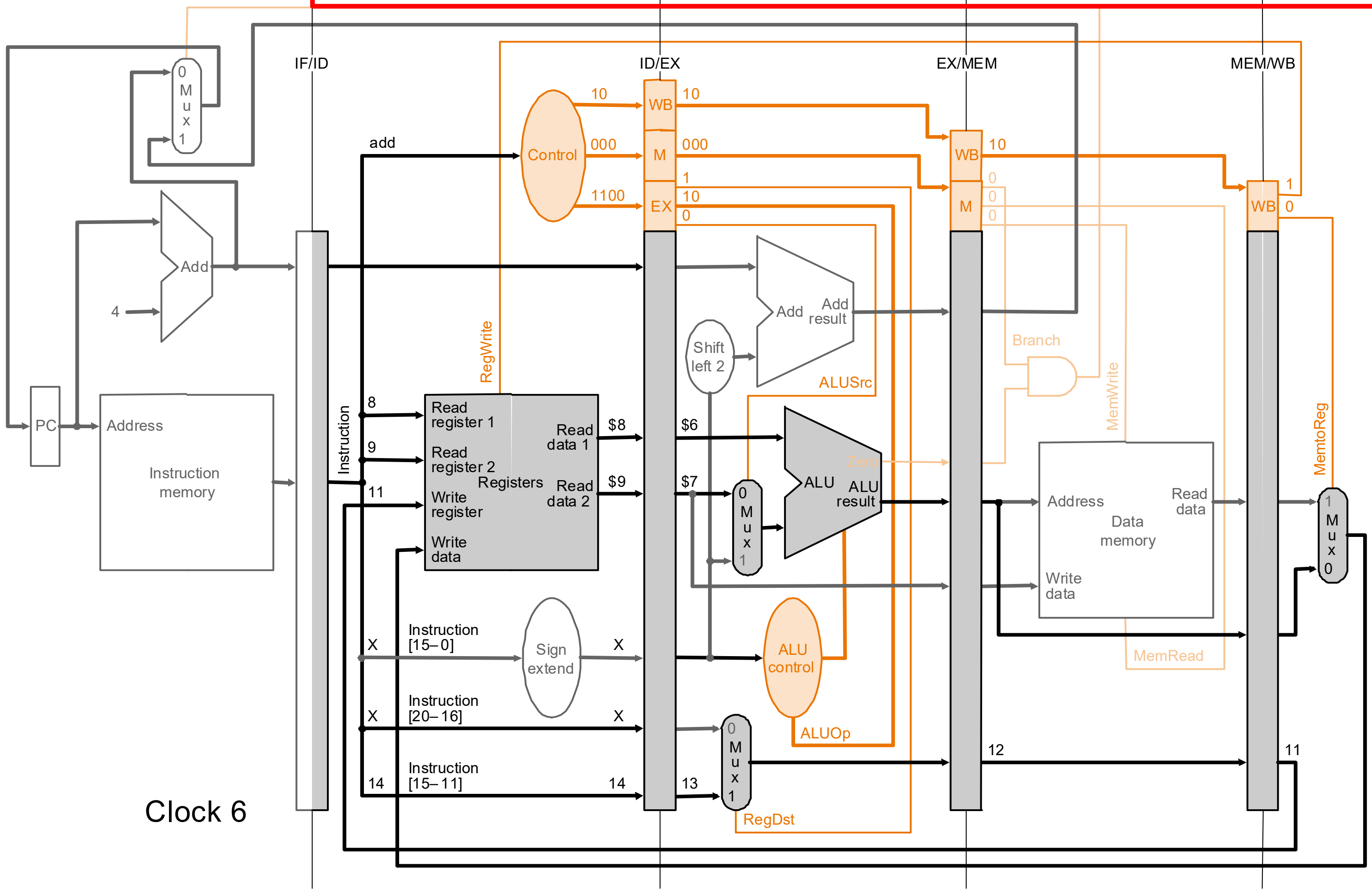


```
lw  $10, 20($1)
sub $11, $2, $3
and $12, $4, $5
or  $13, $6, $7
add $14, $8, $9
```

Cycle 6

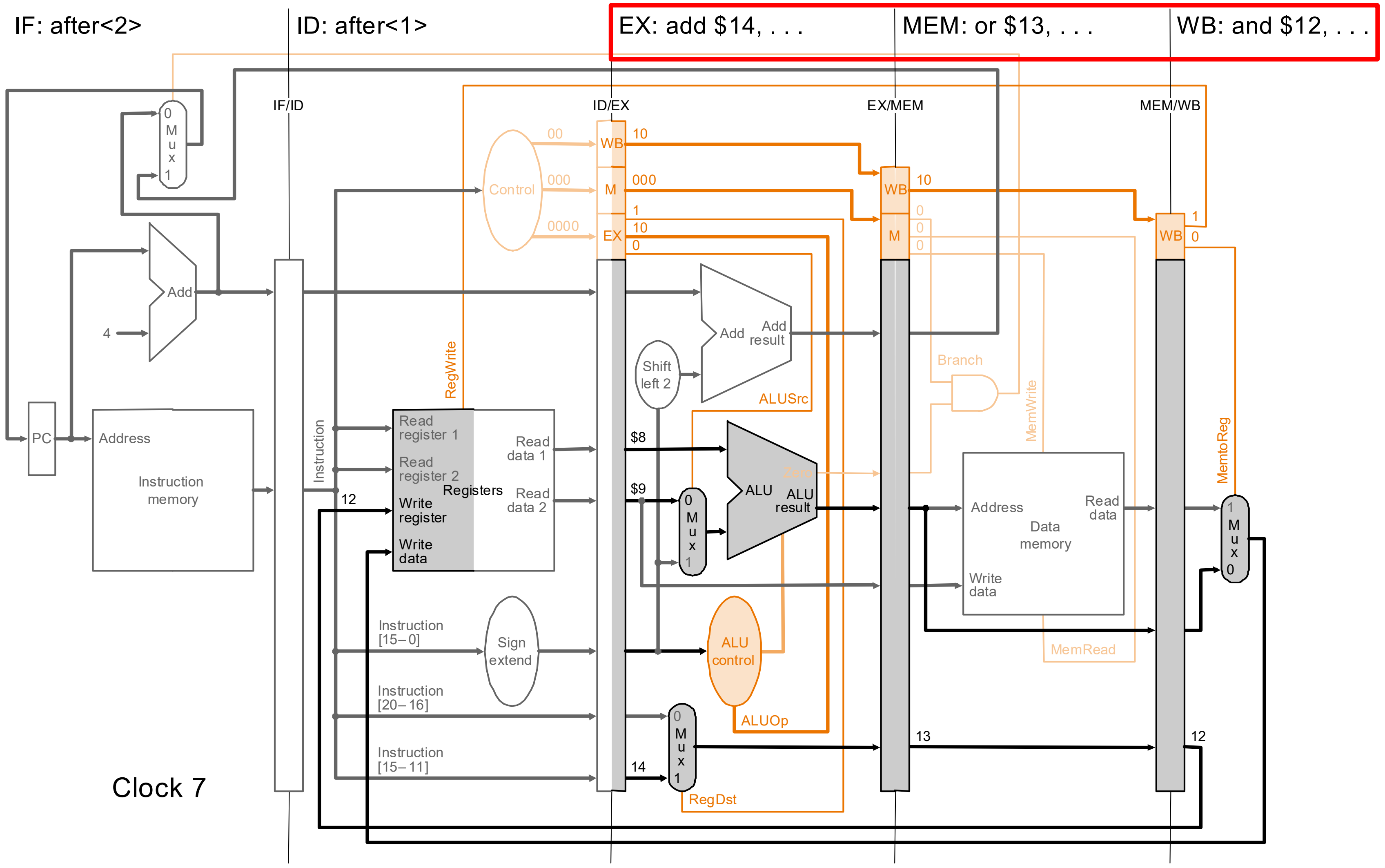
IF: after<1>

ID: add $14, $8, $9 | EX: or $13, . . . | MEM: and $12, . . . | WB: sub $11, . . .



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

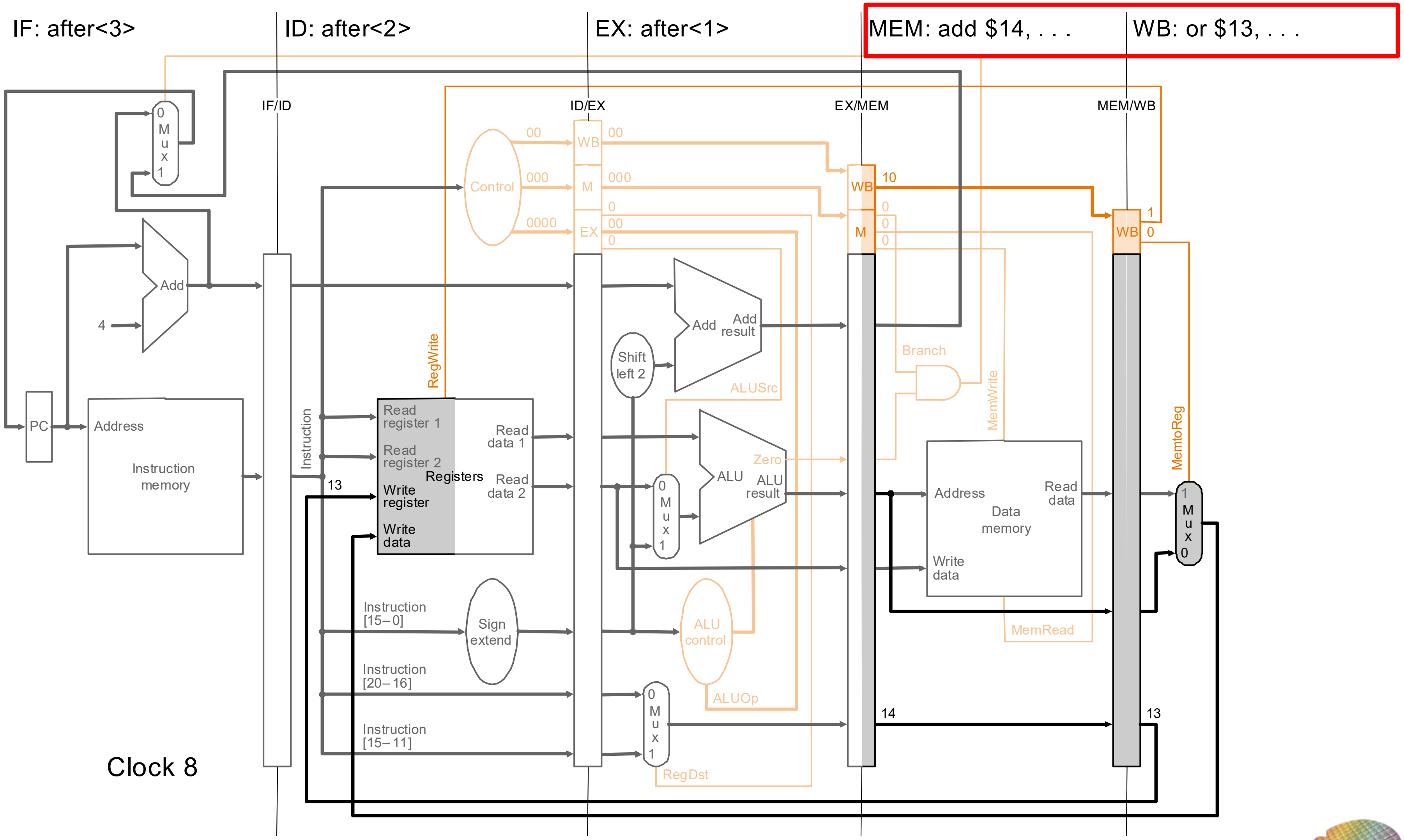
Cycle 7



Cycle 8

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

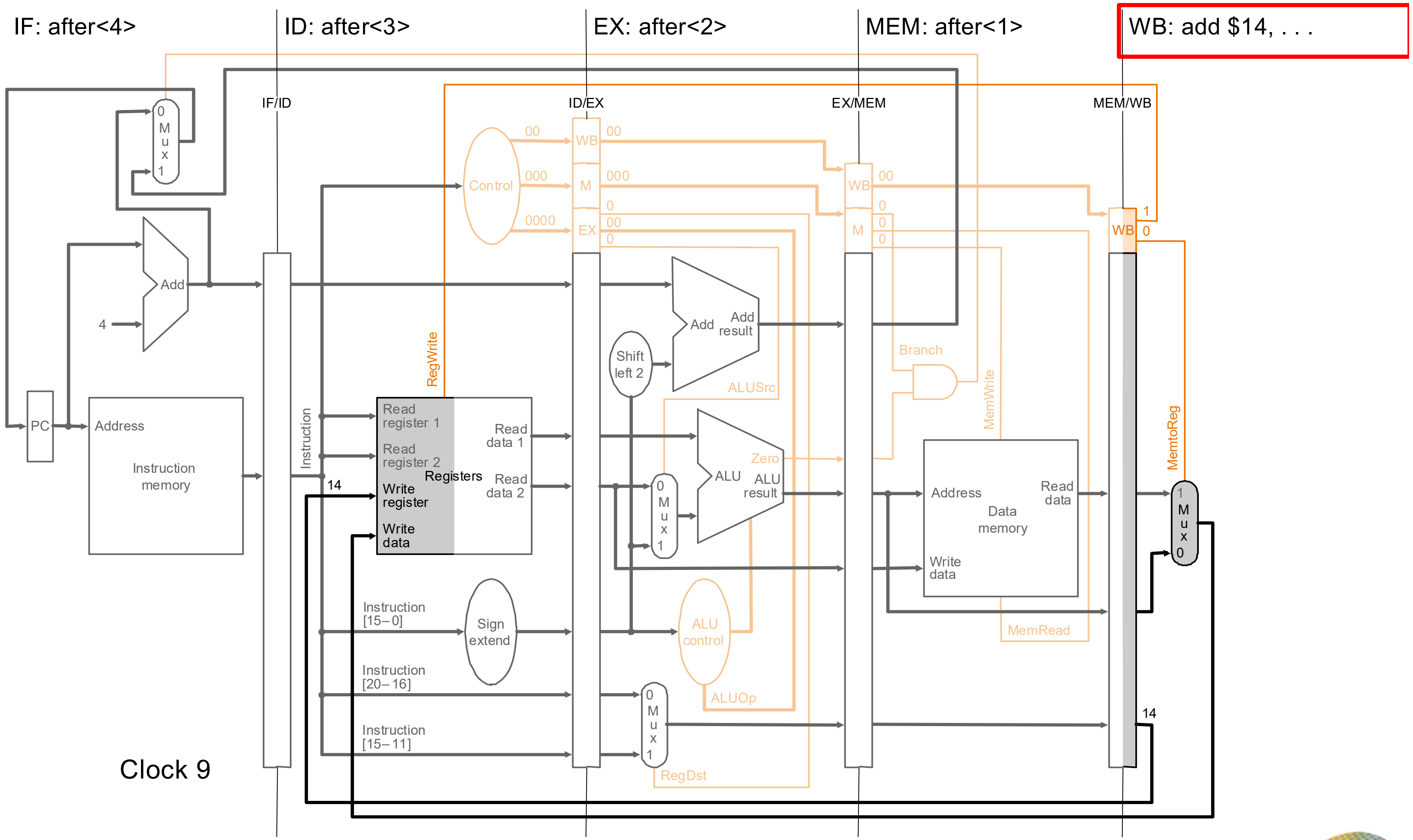
IF: after<3> | ID: after<2> | EX: after<1> | MEM: add $14, . . . | WB: or $13, . . .



Clock 8

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

Cycle 9



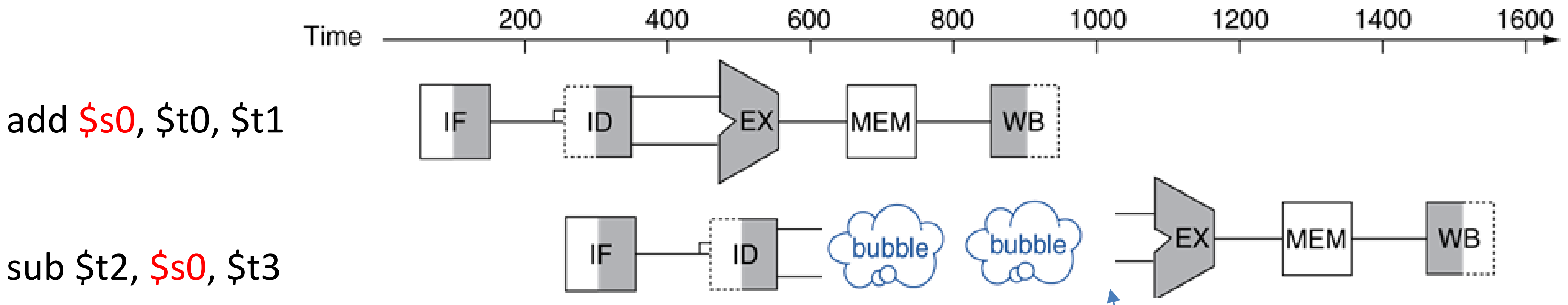
Clock 9

Outline

- A pipelined datapath
- Pipelined control
- Data hazards and forwarding
- Data hazards and stalls
- Branch hazards

Pipeline Hazards

- Pipeline Hazards:
  - Structural hazards, Data hazards, Control hazards
- Hazards can be resolved by waiting (add stalls/bubble)
  - pipeline control must detect the hazard
  - take action (or delay action) to resolve hazards



Wait until the data are ready

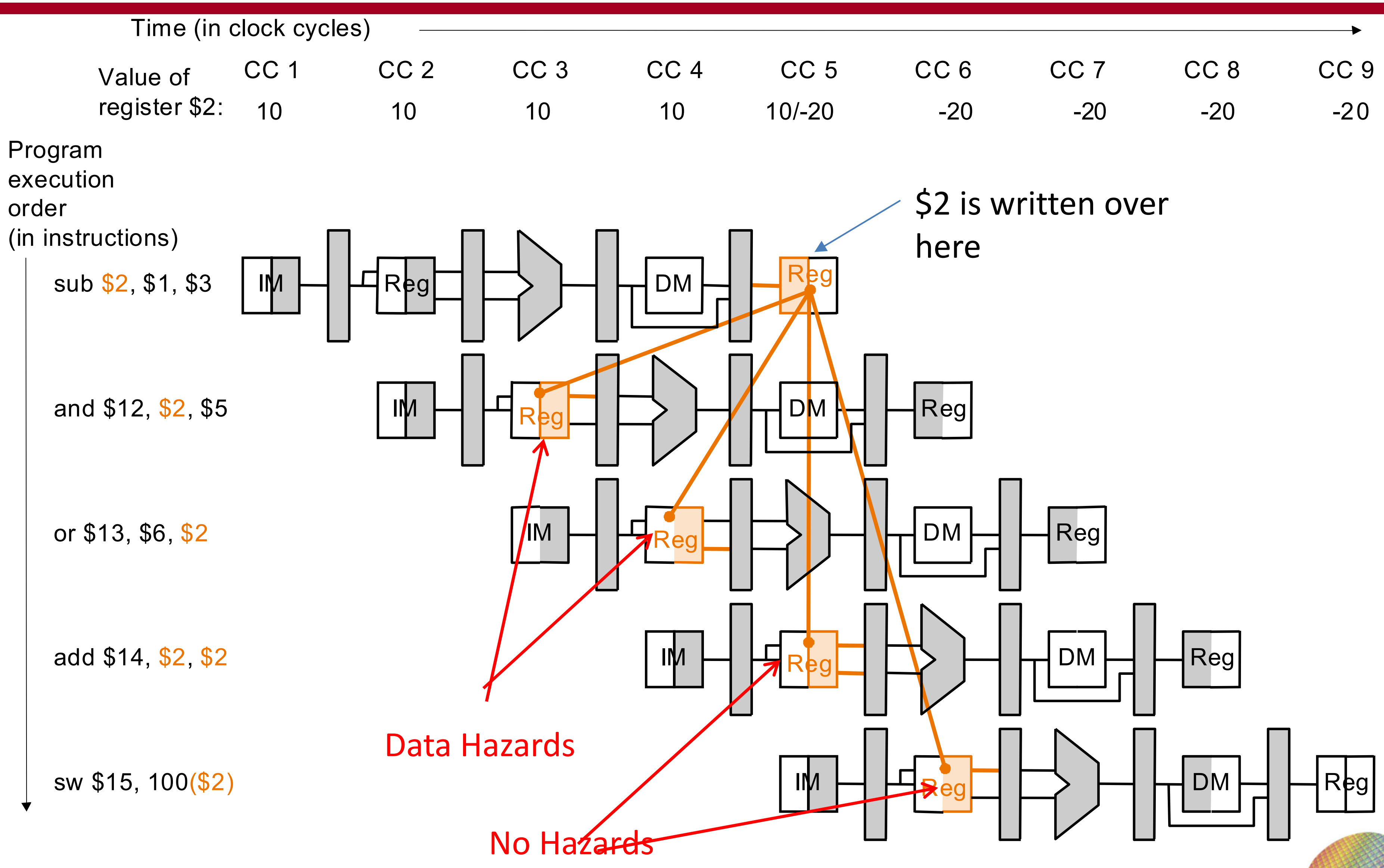
Data Hazards in ALU Instructions

- 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?

Data Hazards



Three Types of Data Dependency (RAW, WAR, WAW)

- RAW (read after write): also called true dependence
  i2 tries to read operand before i1 writes it

```
    W  R  R
sub $2 $1 $3
add $4 $3 $2
    W  R  R
```

- WAR (write after read): also called antidependence
  i2 tries to write operand before i1 reads it

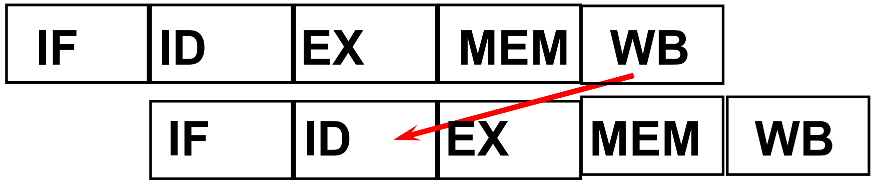
```
       R
add $4 $2 $3
sub $2 $1 $3
    W
```

- WAW (write after write): also called output dependence
  i2 tries to write operand before i1 writes it

```
       R  R
sub $2 $1 $3
sub $2 $1 $3
    W  R  R
```

Data Dependency that causes hazard in MIPS

- RAW (read after write):

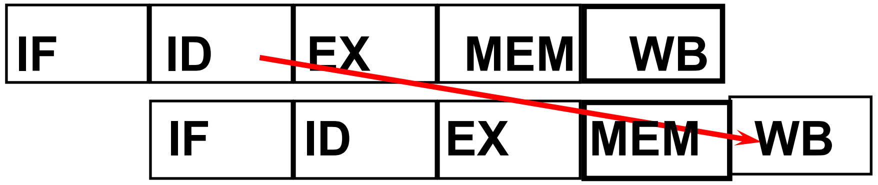


RAW can cause data hazard

```
          W  R   R
      sub $2 $1 $3
      add $4 $3 $2
          W  R   R
```

```
                R
      add $4 $2 $3
      sub $2 $1 $3
             W
```

- WAR (write after read):
  - WAR is not a issue 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, the following instruction never corrupt the previous instruction



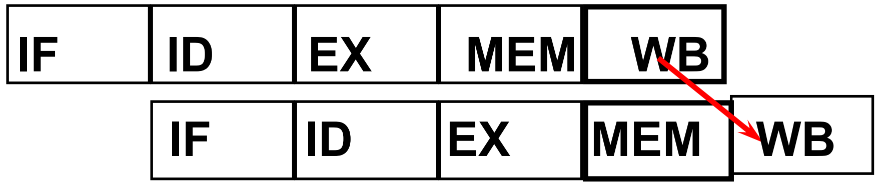
Do not cause stall !!!
WAR is not data hazard

Data Dependency that causes hazard in MIPS-2

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

```
      W  R   R
sub $2 $1 $3
sub $2 $1 $3
      W  R   R
```

- WAW (write after write):
  - WAW is not an issue in MIPS 5-stage pipeline because all instructions take 5 stages, and writes are always in stage 5



Do not cause stall !!!
WAW is not data hazard

Quick summary:
Three data dependency: RAW, WAR, WAW
only RAW may cause data hazard in MIPS

Exercise

- Identify the data dependency (RAW, WAW, WAR) in the following instruction

lw \$1,40(\$6)
add \$6, \$2, \$2
sw \$6, 50(\$1)

Ans:

lw \$1,40(\$6)

W R

add \$6, \$2, \$2

W R R

sw \$6, 50(\$1)

R R

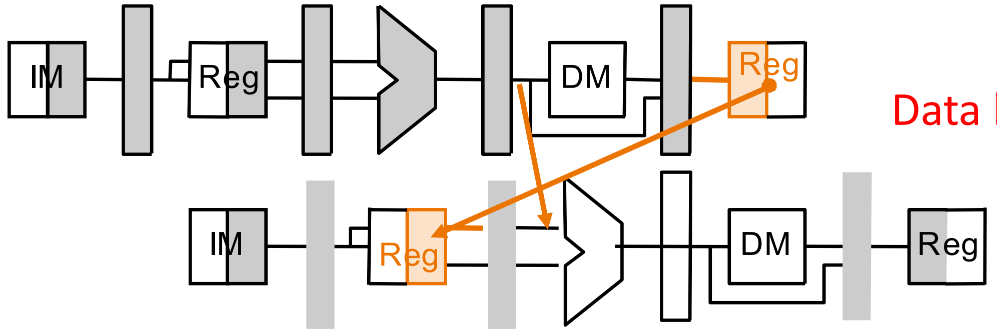
I1 to I2: WAR on \$6
I1 to I3: RAW on \$1
I2 to I3: RAW on \$6

Hardware Method to Avoid Hazard: Forwarding

- Idea: fetch "fresh" data as early as possible

sub $2 $1 $3
add $4 $2 $3

Fetch $2 when
$2 is Ready



Data hazard

Forwarding to remove hazard

- Two steps:

Step 1: Detect data hazard:

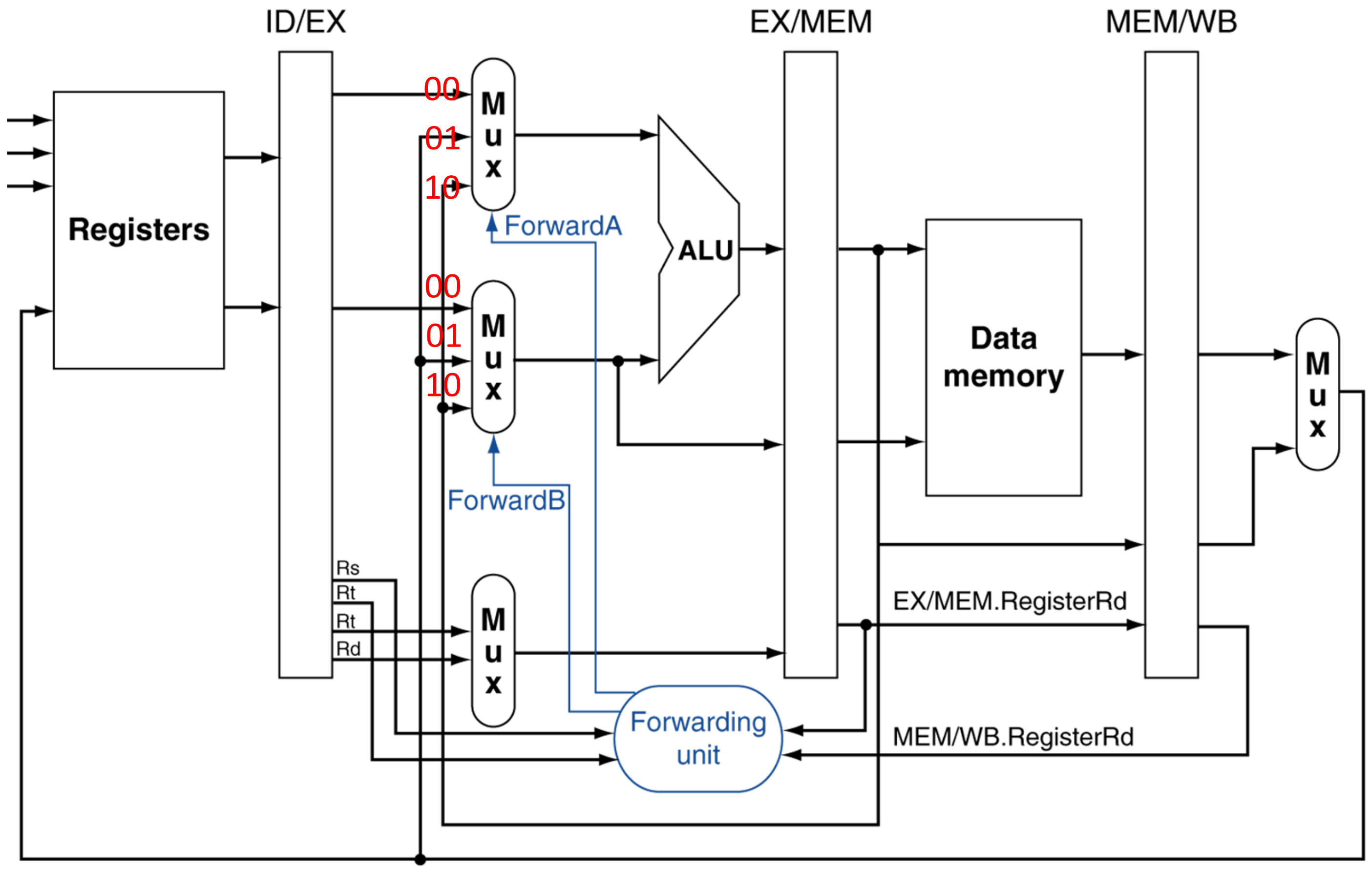
Is the datum just produced required by the following inst.?

Step 2: Forward intermediate data to resolve hazard

If yes, then forward the requested datum to the requesting inst. immediately.

Forwarding Hardware: Multiplexor Control

- Add Forwarding unit and ForwardA and ForwardB control signal to control mux (See next slides)



Forwarding Hardware: Multiplexor Control

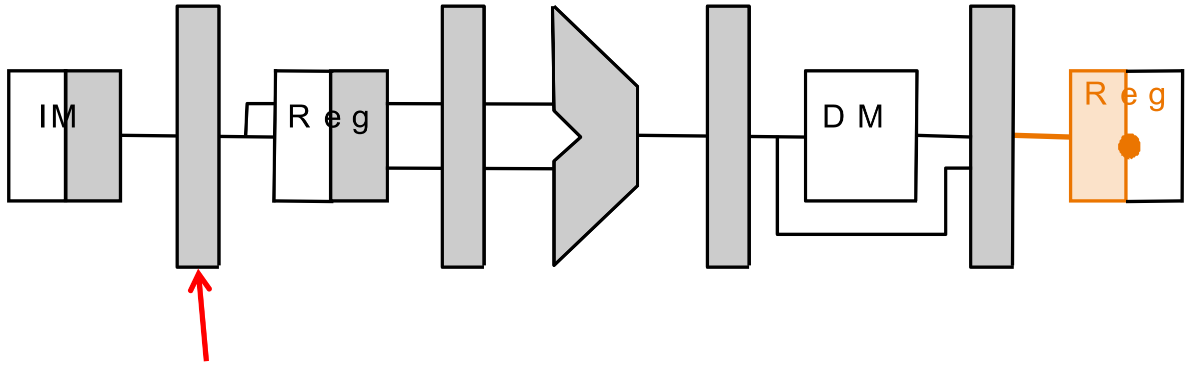
Mux control	Source	Explanation
ForwardA = 00	ID/EX	The first ALU operand (Rs) comes from the register file
ForwardA = 10	EX/MEM	The first ALU operand is forwarded from prior ALU result
ForwardA = 01	MEM/WB	*The first ALU operand is forwarded from data memory or an earlier ALU result

ForwardB = 00	ID/EX	The second ALU operand (Rt) comes from the register file
ForwardB = 10	EX/MEM	The second ALU operand is forwarded from prior ALU result
ForwardB = 01	MEM/WB	*The second ALU operand is forwarded from data memory or an earlier ALU result

* Depending on the selection in the rightmost multiplexor (see datapath with control diagram)

Detecting the Need to Forward

- Register numbers are passed along pipeline
  - e.g., ID/EX.RegisterRs = register number for Rs sitting in ID/EX pipeline register
- E.g.: ALU operand register numbers in EX stage are given by
  - ID/EX.RegisterRs, ID/EX.RegisterRt



sub $2 $1 $3

At the first cycle,
IF/ID.RegisterRs=$1
IF/ID.RegisterRt=$3
IF/ID.RegisterRd=$2

Detecting hazard- EX and MEM hazard

- Data hazards when

  1a. EX/MEM.RegisterRd = ID/EX.RegisterRs

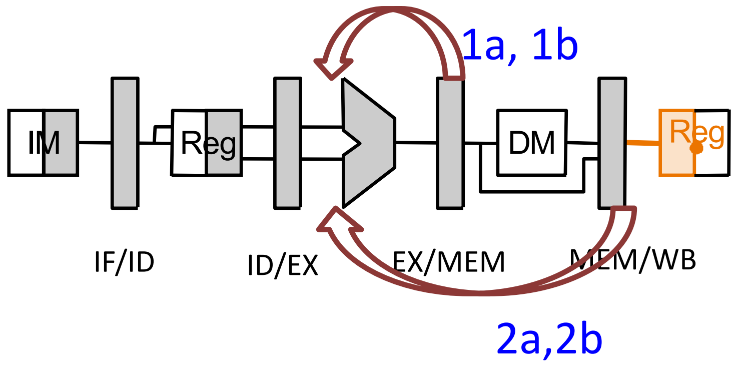
  1b. EX/MEM.RegisterRd = ID/EX.RegisterRt

  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



```
sub $2, $1, $3
and $12, $2, $5
```

Hazard is detected when AND is in EX stage and SUB is in MEM stage because

EX/MEM.RegisterRd = ID/EX.RegisterRs = $2 (1a)

Detecting EX hazard and forward

- Forwarding is needed if earlier instruction write to a register!
  - Check if EX/MEM.RegWrite, MEM/WB.RegWrite is 1

```
Inst1 sub $2, $1, $3
Inst2 and $12, $2, $5
```

- Forwarding is needed if Rd is not $zero

  If Rd=$zero, result is always 0

  Check if EX/MEM.RegisterRd ≠ 0,MEM/WB.RegisterRd ≠ 0

```
Inst1 sub $2, $1, $3
Inst2 and $0, $2, $5
```

Inst 1 does not need to forward to inst2 because inst2 always produce 0 ($zero)

Summary for 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

Detecting MEM hazard and forward (1)

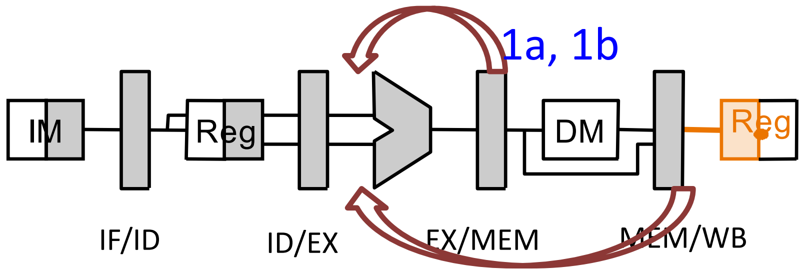
- MEM hazards when

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



Version 1 (similar to EX 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

Forwarding is not needed if the later instruction is going to write the same register, even if there is register number match as in conditions above

```
Inst1   add $7, $8, $9
Inst2   add $9, $10, $11
Inst3   add $7, $7, $11
```

Does Inst1 need to forward to Inst3?

Yes

```
Inst1   add $7, $8, $9
Inst2   add $7, $10, $11
Inst3   add $7, $7, $11
```

Does Inst1 need to forward to Inst3?

No. Inst2 has newer data.
Inst2 forward to Inst3

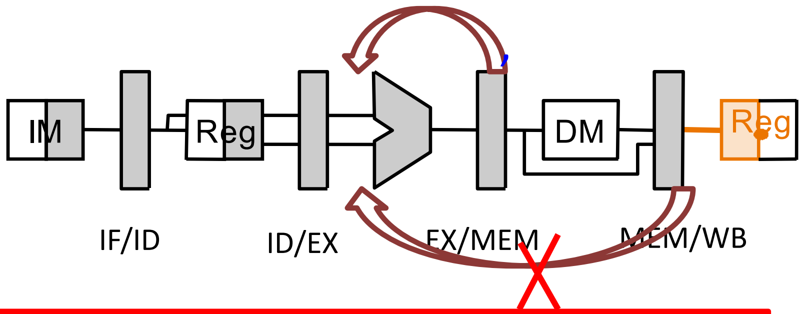
Both MEM Hazard and EX Hazard exist, only

Double Data Hazard

- Consider the sequence

Inst1	**add $7, $8, $9**
Inst2	**add $7, $10, $11**
Inst3	**add $7, $7, $11**

Inst 1 does not need to forward to inst 3 because inst2 has more recent data => Forward when EX hazard does not exist



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

Typo in the book(should be ==, not !=)

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

Outline

- A pipelined datapath
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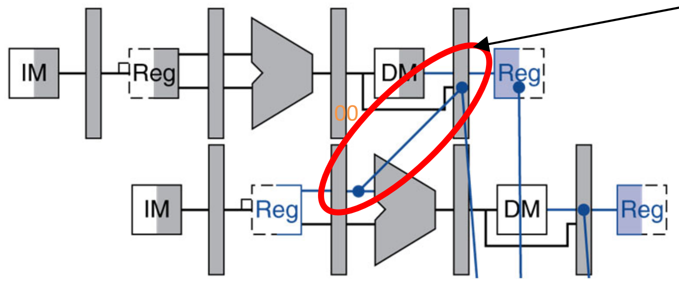
Load-Use Data Hazard

- One stall is needed for load-use data hazard

=> similar to add a nop (no operation) instruction

```
lw  $2, 20($1)

and $4, $2, $5
```

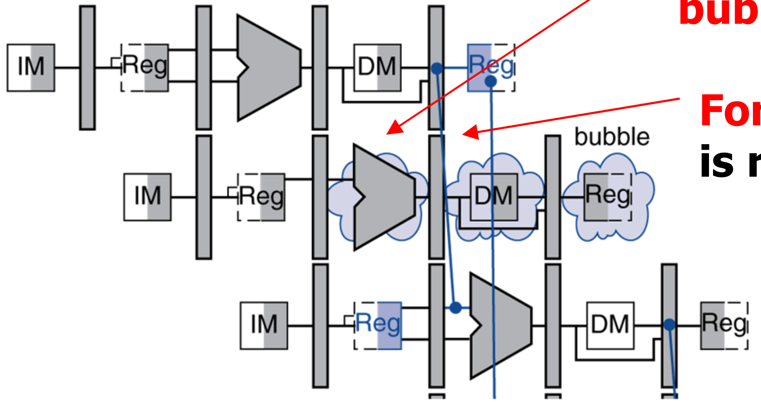


Need to stall one cycle

```
lw  $2, 20($1)


nop

and $4, $2, $5
```



Hazard detection unit inserts a 1-cycle bubble in the pipeline

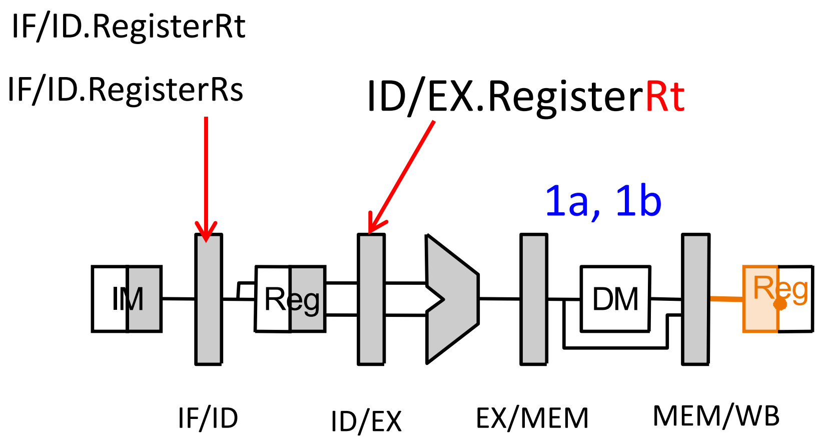
Forward data when it is ready

Hazard Detection Logic to Stall

- Recall: lw instruction format: `lw  Rt, offset(Rs)`
- Hardware to check if stall is needed

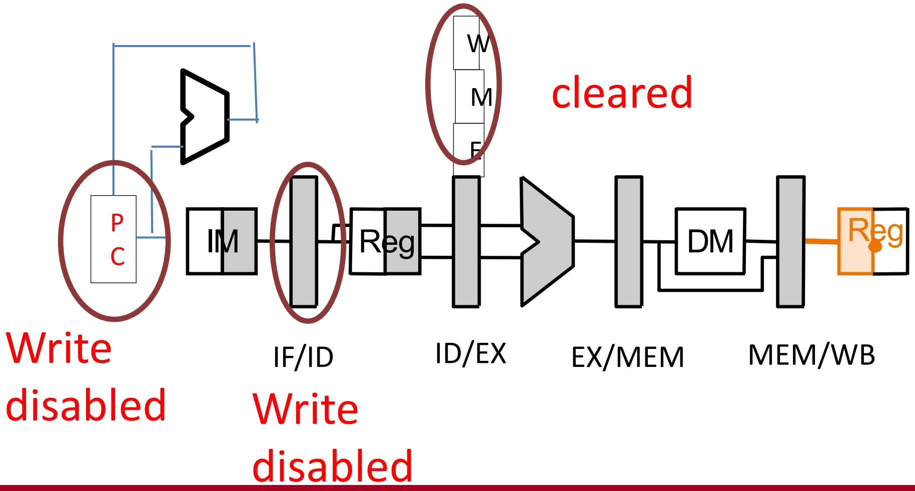
Destination Register in lw instruction is Rt

```
if ( ID/EX.MemRead                              // if the instruction in the EX stage is a load...
  and ( ( ID/EX.RegisterRt = IF/ID.RegisterRs )       // and the destination register
    or  ( ID/EX.RegisterRt = IF/ID.RegisterRt ) ) )  // matches either source register
      stall the pipeline                              // of the instruction in the ID stage
```

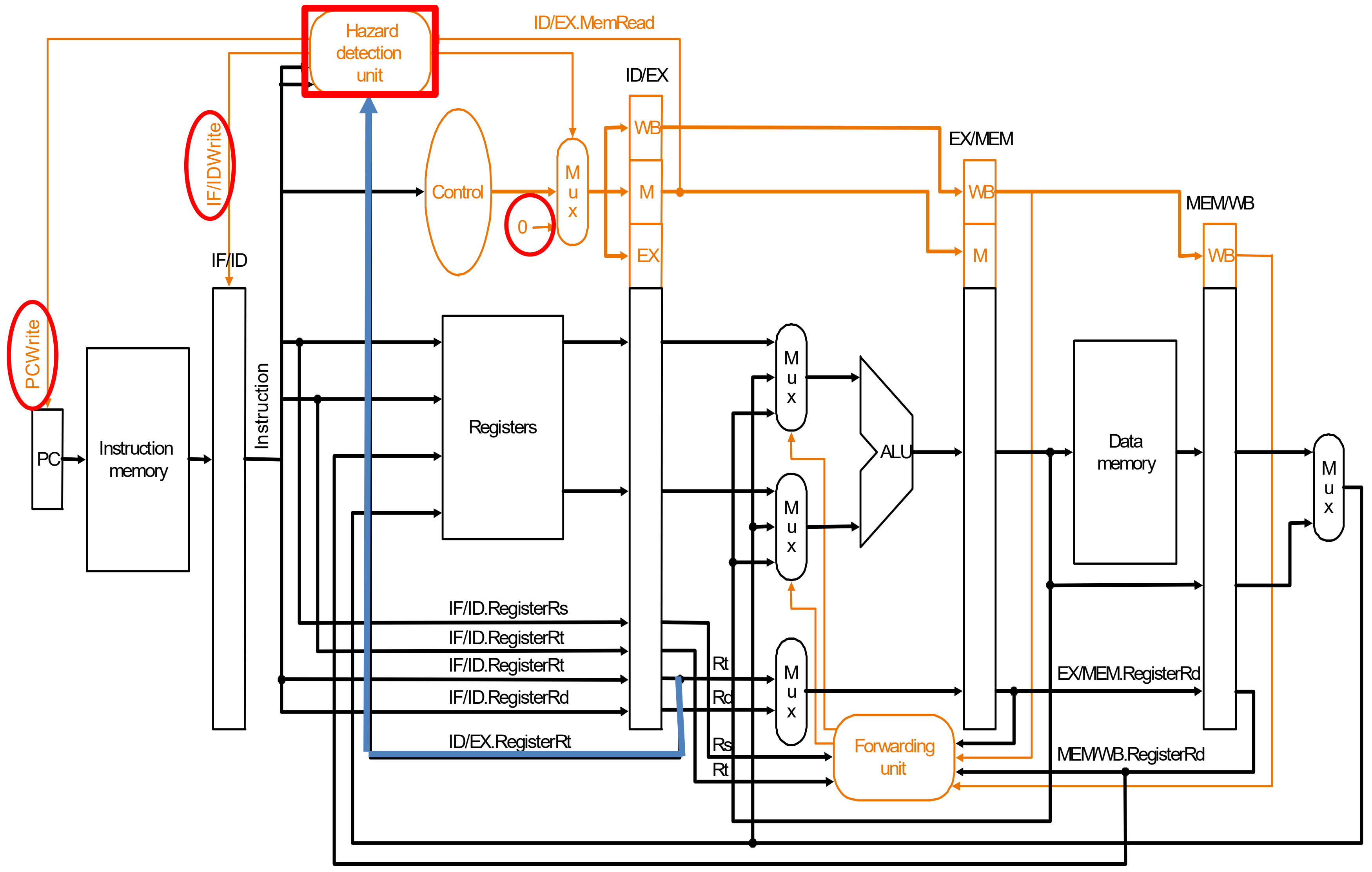


How to stall the Pipeline

- *Only Stall 1 clock cycle* after the load
  - the forwarding unit can resolve the dependency
- How hardware stalls the pipeline 1 cycle:
  - Disable write on PC => this will cause the instruction in the IF stage to repeat, i.e., *stall*
  - Disable write on IF/ID register => this will cause the instruction in the ID stage to repeat, i.e., *stall*
  - Changes all the EX, MEM and WB control fields in the ID/EX pipeline register to 0 => , so the instruction just behind the load becomes a nop – a bubble is said to have been inserted into the pipeline



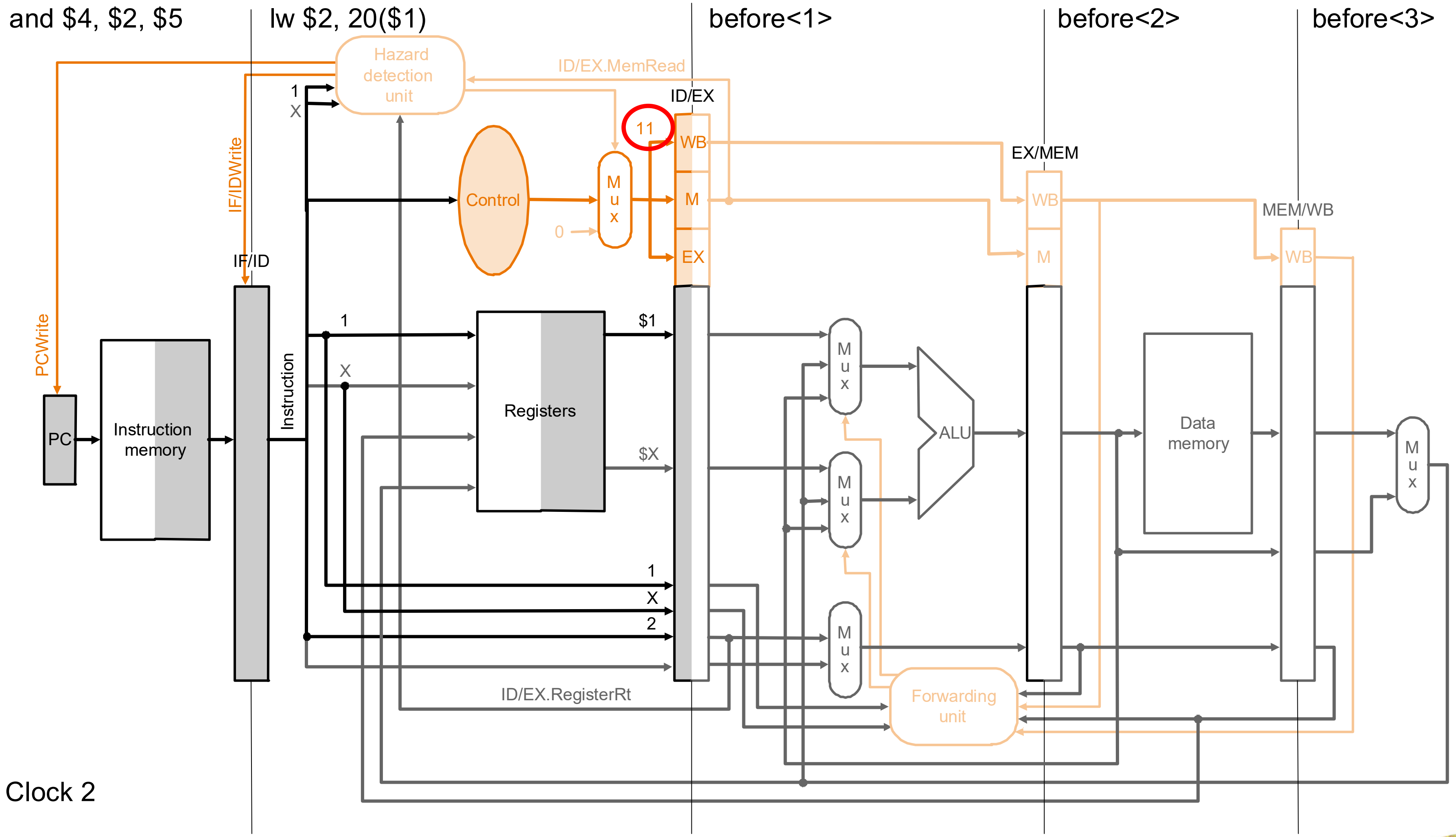
Adding Hazard Detection Unit



Datapath with forwarding hardware, the hazard detection unit and controls wires – certain details, e.g., branching hardware are omitted to simplify the drawing

```
lw  $2, 20($1)
and $4, $2, $5
or  $4, $4, $2
add $9, $4, $2
```

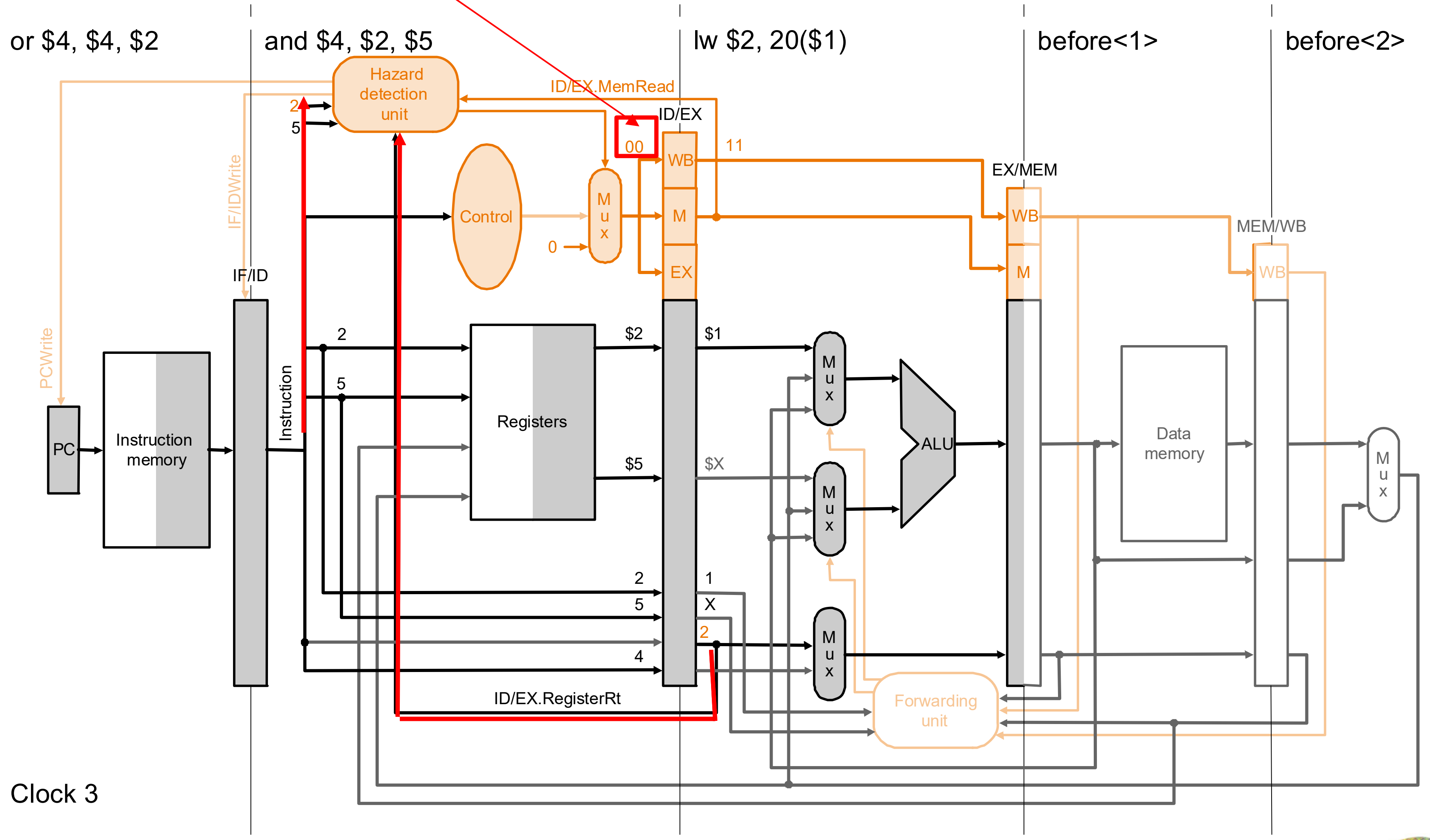
Cycle 2



Cycle 3

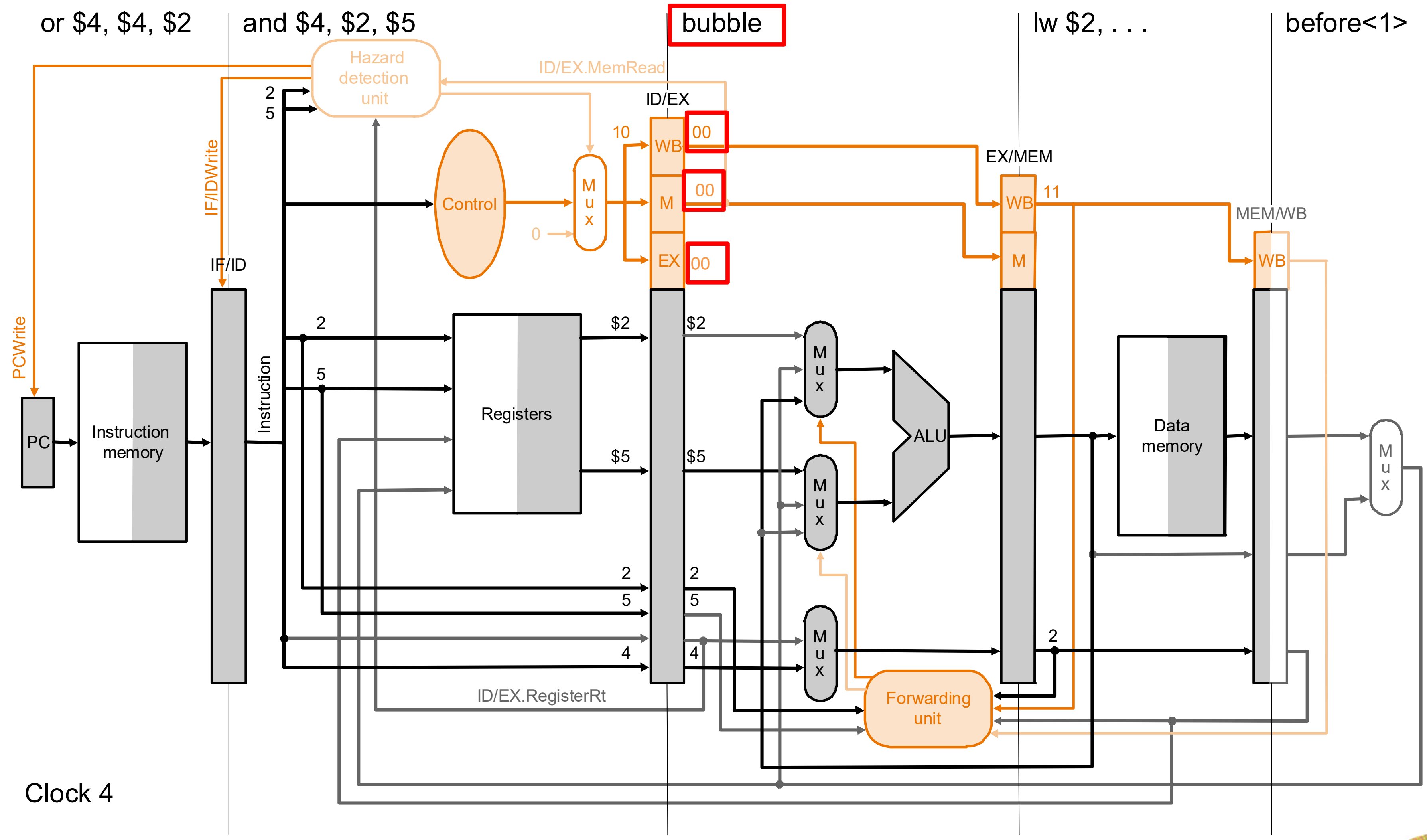
```
lw  $2, 20($1)
and $4, $2, $5
or  $4, $4, $2
add $9, $4, $2
```

Detect a hazard and insert a stall



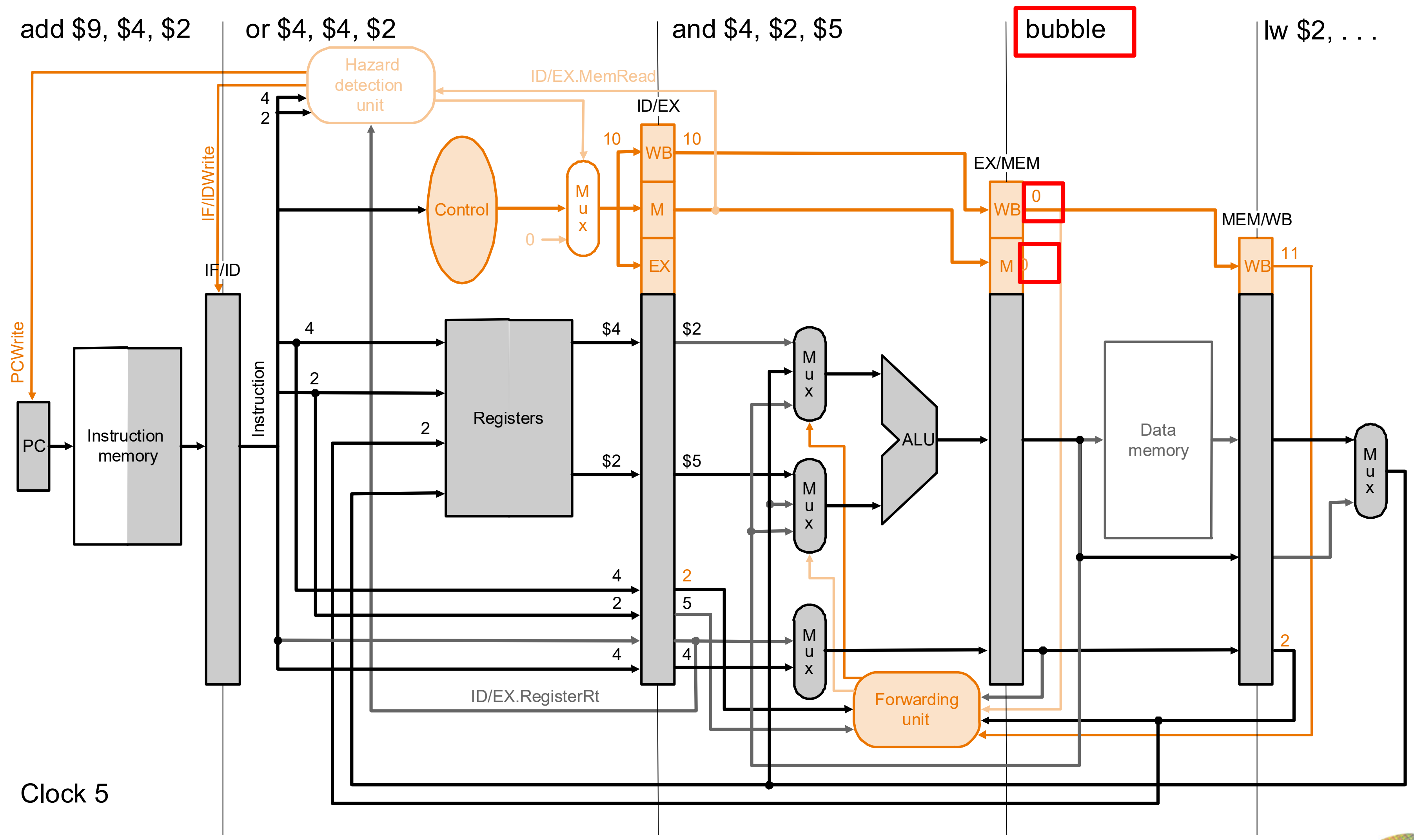
```
lw  $2, 20($1)
and $4, $2, $5
or  $4, $4, $2
add $9, $4, $2
```

Cycle 4



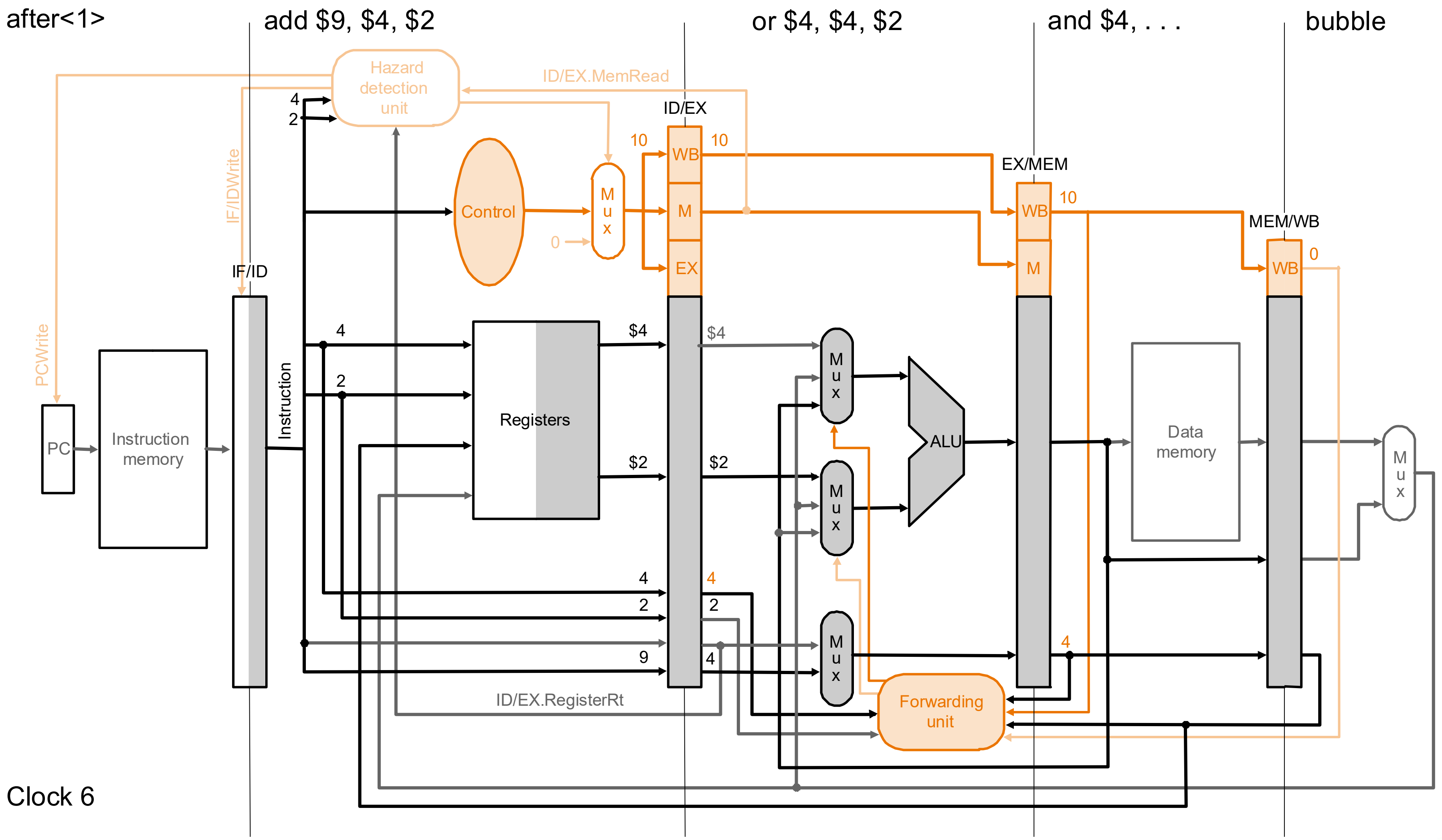
Cycle 5

```
lw  $2, 20($1)
and $4, $2, $5
or  $4, $4, $2
add $9, $4, $2
```



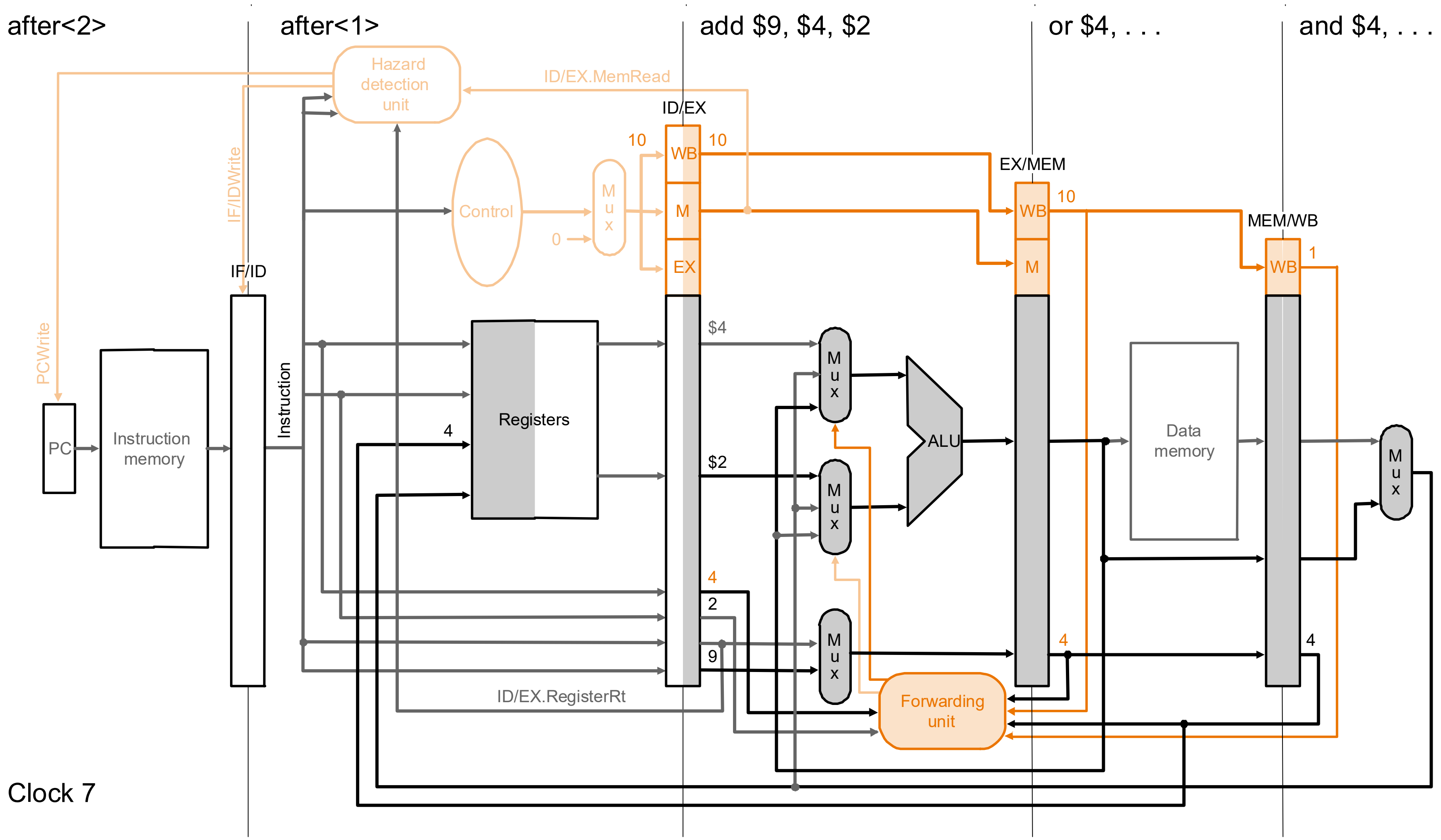
Cycle 6

```
lw  $2, 20($1)
and $4, $2, $5
or  $4, $4, $2
add $9, $4, $2
```



Cycle 7

```
lw  $2, 20($1)
and $4, $2, $5
or  $4, $4, $2
add $9, $4, $2
```



Hidden

Special case: load store pair

- Are there any stalls in the following instructions if forwarding is used? If yes, how many?

```
lw  $2, 20($1)
and $4, $2, $5
```

- Are there any stalls in the following instructions if forwarding is used? If yes, how many?

```
lw $2, 20($1)
sw $2, 4($3)
```

Backup Slides