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Pipeline Hazards

Hazards

- Situations that prevent starting the next instruction in the next cycle

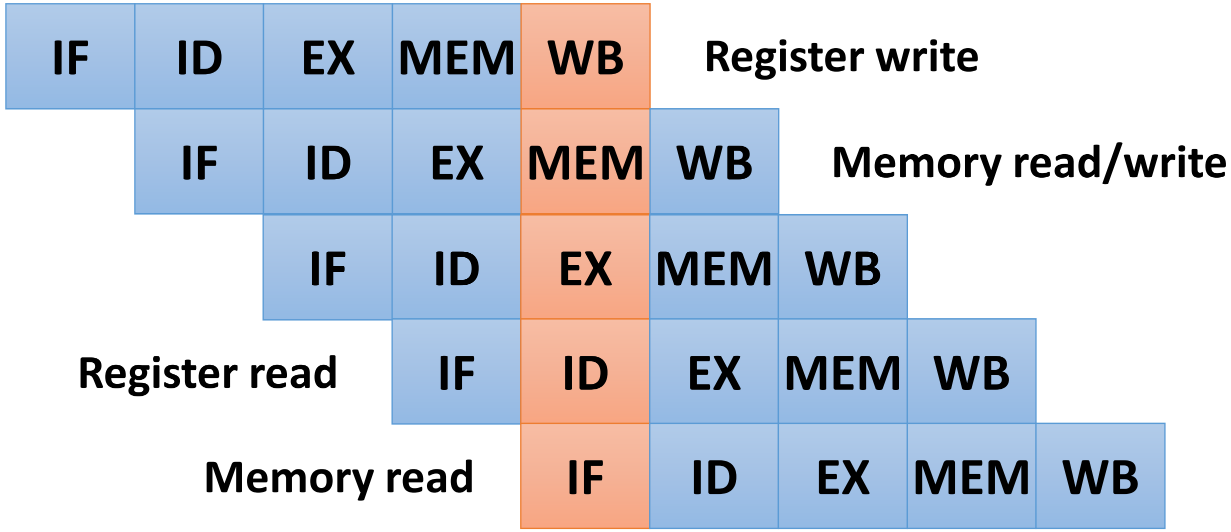
- Structural hazard
  - A required resource is busy

- Data hazard
  - Need to wait (or *stall*) for previous instruction to complete its data read/write

- Control hazard
  - Deciding on control action depends on previous instruction

Structural Hazard

- Conflict for use of a resource
- In RISC-V pipeline with a single memory
  - Load/store requires data access
  - Instruction fetch would have to *stall* for that cycle
    → Would cause a pipeline "bubble"
  - Pipelined datapaths require separate instruction/data memories (or separate instruction/data caches)
- Register file also requires multiple ports (for 2 reads and 1 write)



IF ID EX MEM **WB** Register write

IF ID EX **MEM** WB Memory read/write

IF ID **EX** MEM WB

Register read IF **ID** EX MEM WB

Memory read **IF** ID EX MEM WB

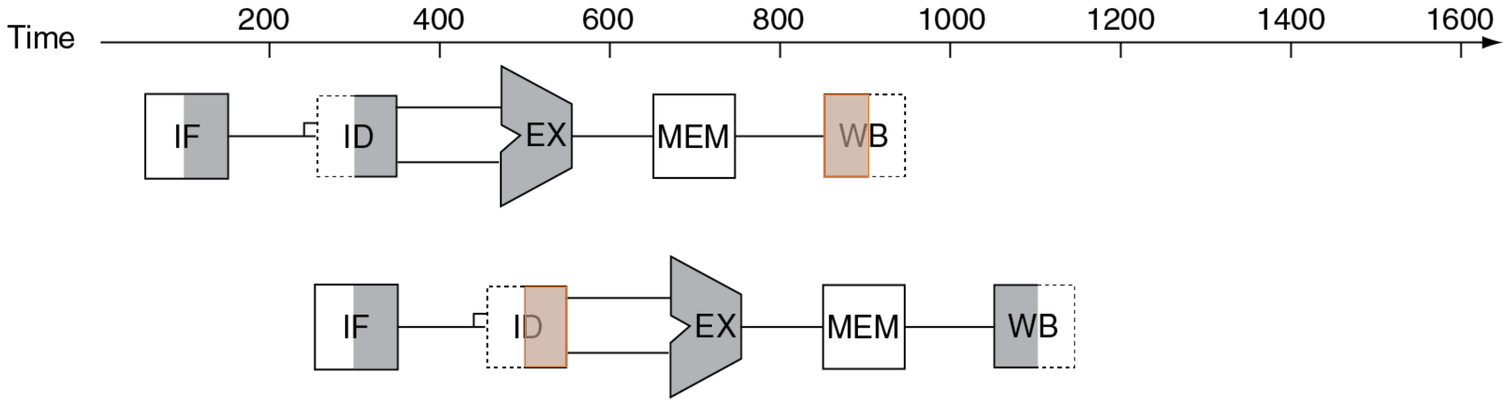
Data Hazards

Chap. 4.8

Data Hazard

- An instruction depends on completion of data access by a previous instruction
- Also called "Read-After-Write (RAW)" hazard
- This hazard results from an actual need for communication

```
add  x19, x0, x1

sub  x2, x19, x3
```

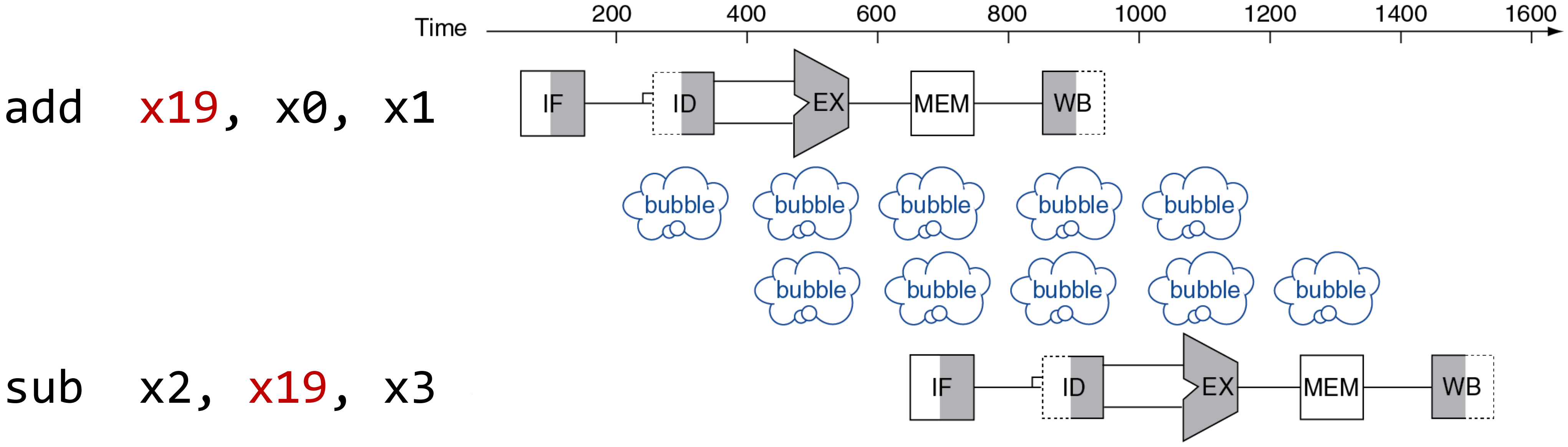


Solutions to Data Hazard

- Freezing (or stalling) the pipeline
- Forwarding
- Compiler scheduling
- Out-Of-Order execution (discussed later)

Freezing the Pipeline

- Stall the pipeline until dependences are resolved
- ALU result to next instruction (2 stalls)

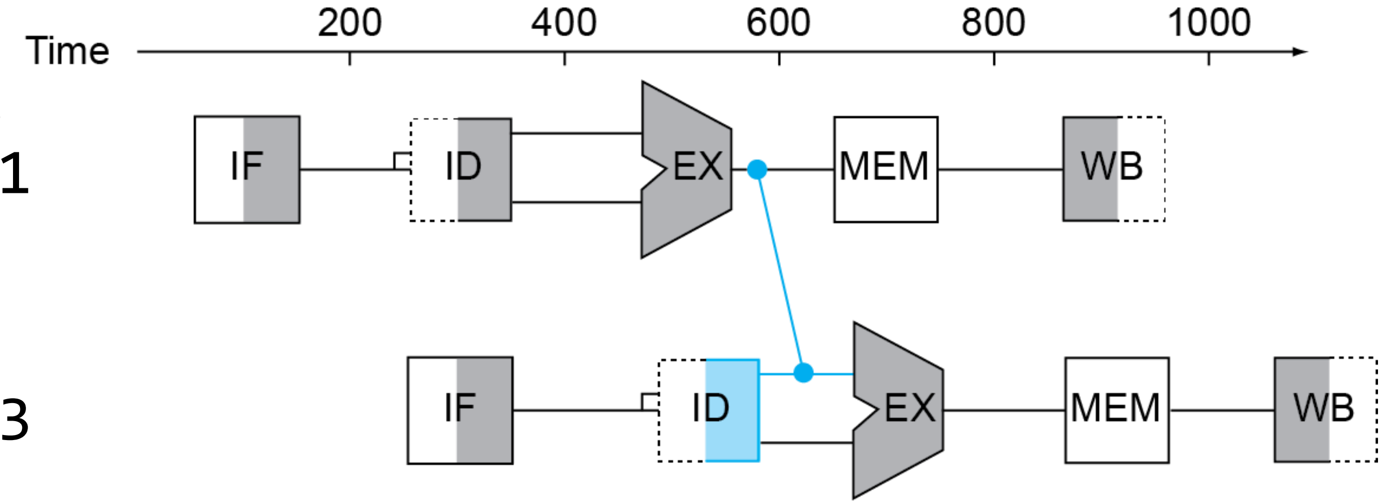


Forwarding (or Bypassing)

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

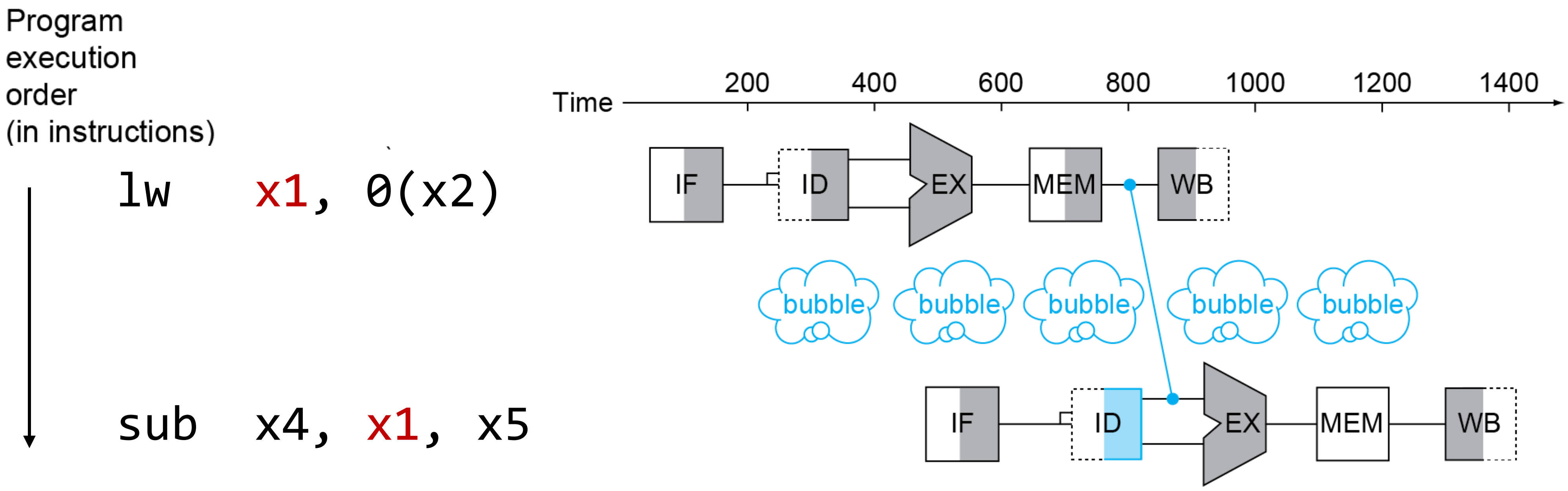
Program execution order (in instructions)

```
add  x19, x0, x1

sub  x2, x19, x3
```



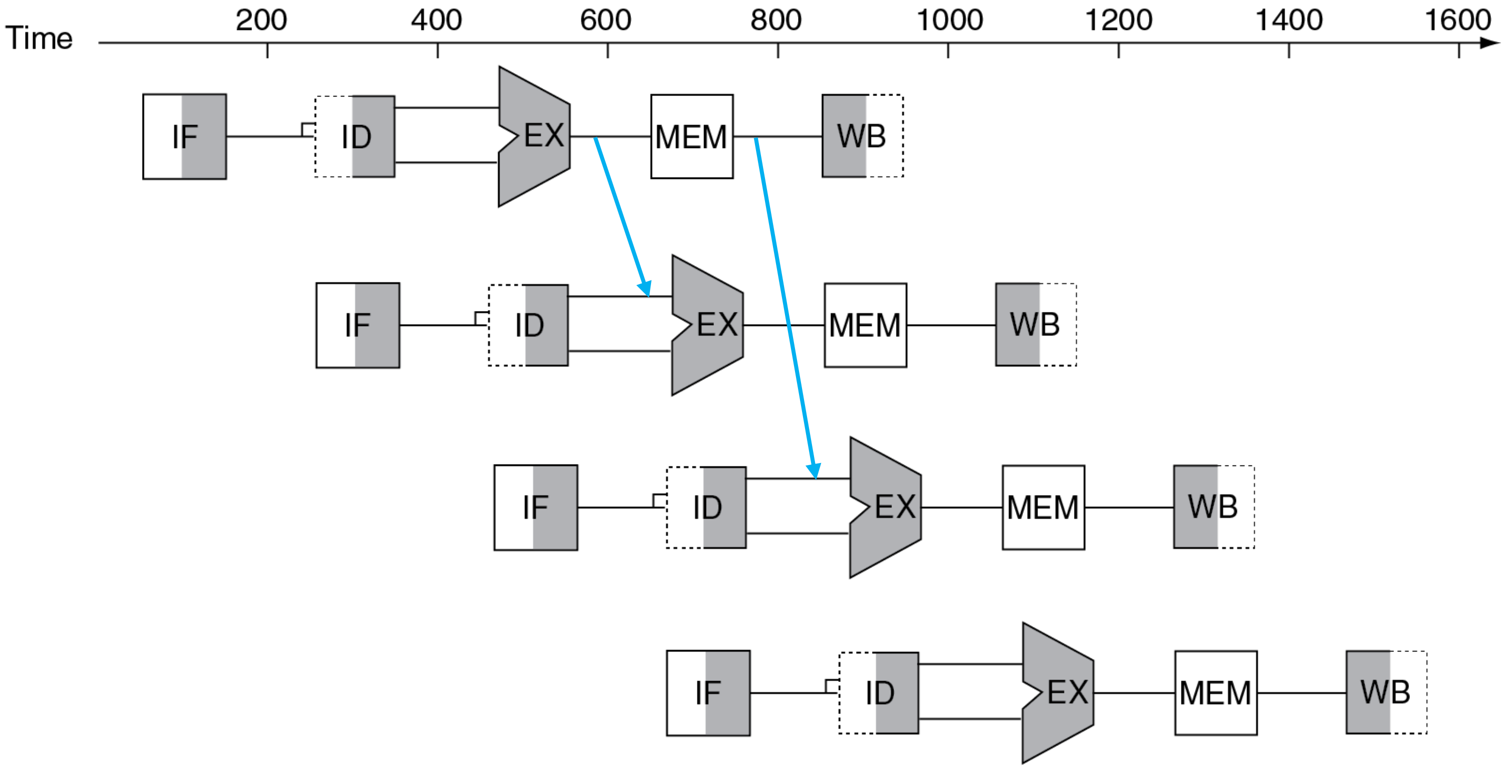
Forwarding: Load-Use Data Hazard

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



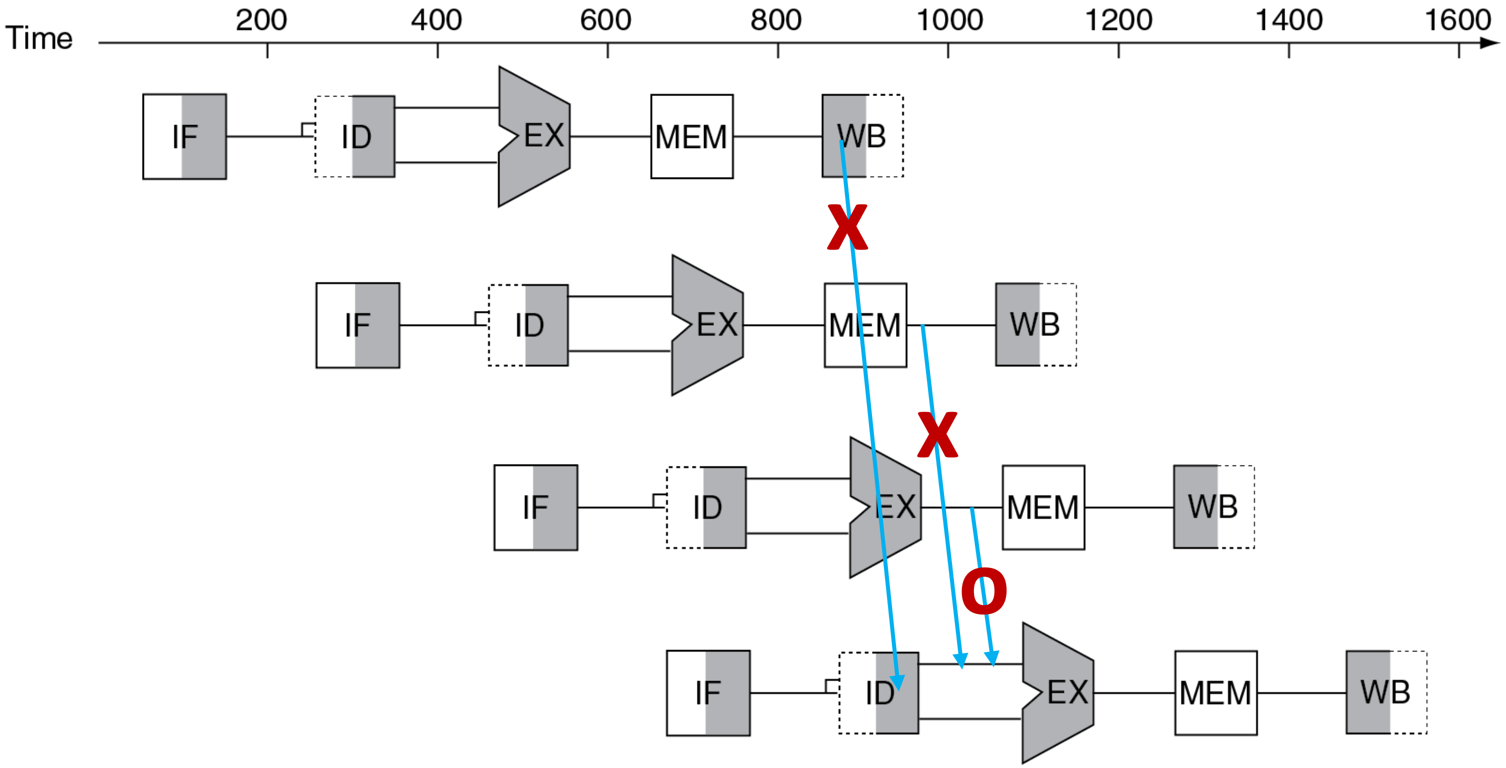
Forwarding: Multiple Readers

```
add  x10, x4, x5

sub  x6, x10, x4

and  x7, x10, x0

xor  x8, x10, x3
```



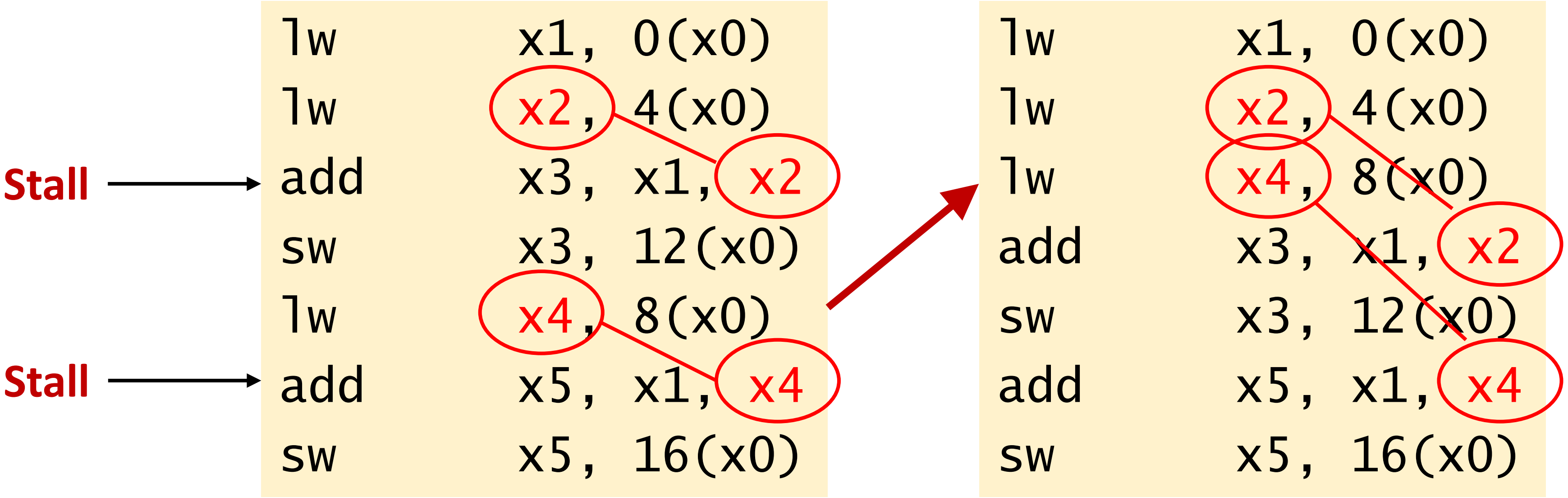
Forwarding: Multiple Writers

```
add  x10, x4, x5

sub  x10, x5, x6

addi x10, x2, 1

xor  x8, x10, x7
```



Compiler Scheduling

- Reorder code to avoid use of load result in the next instruction
- C code for `v[3] = v[0] + v[1];  v[4] = v[0] + v[2];`



```
lw      x1, 0(x0)
lw      x2, 4(x0)
add     x3, x1, x2
sw      x3, 12(x0)
lw      x4, 8(x0)
add     x5, x1, x4
sw      x5, 16(x0)
```

13 cycles

```
lw      x1, 0(x0)
lw      x2, 4(x0)
lw      x4, 8(x0)
add     x3, x1, x2
sw      x3, 12(x0)
add     x5, x1, x4
sw      x5, 16(x0)
```

11 cycles

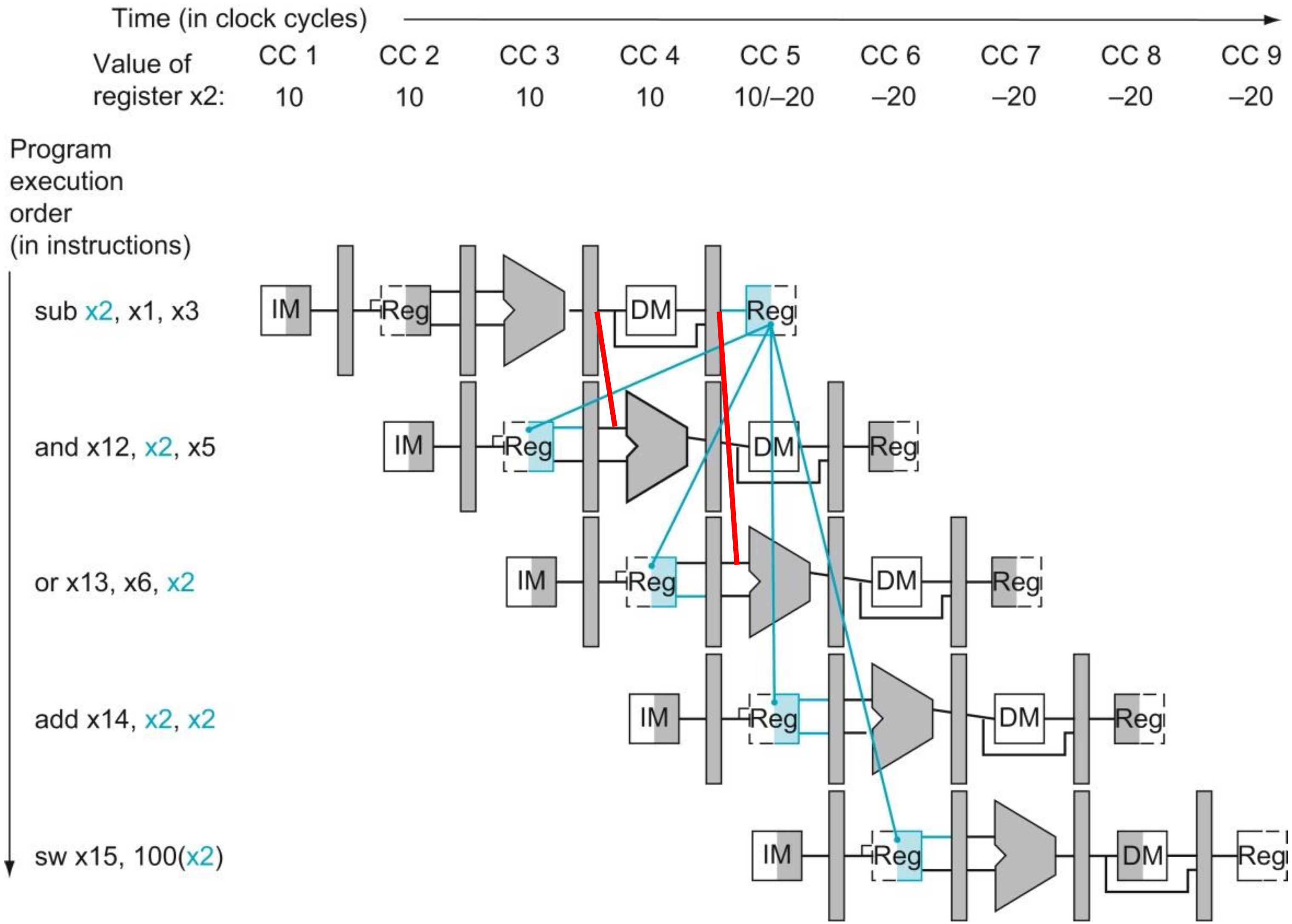
Data Hazards in RISC-V

- Consider this sequence:

```
sub   x2, x1, x3
and   x12, x2, x5
or    x13, x6, x2
add   x14, x2, x2
sw    x15, 100(x2)
```

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

Dependencies and Forwarding



Detecting the Need to Forward

- Pass register numbers along pipeline
  - e.g., `ID/EX.RegisterRs1` = register # for `Rs1` sitting in ID/EX pipeline register
- ALU operand register numbers in EX stage are given by
  - `ID/EX.RegisterRs1`, `ID/EX.RegisterRs2`
- Data hazards when

```
EX/MEM.RegisterRd = ID/EX.RegisterRs1
EX/MEM.RegisterRd = ID/EX.RegisterRs2
```

Forward from EX/MEM pipeline register

```
MEM/WB.RegisterRd = ID/EX.RegisterRs1
MEM/WB.RegisterRd = ID/EX.RegisterRs2
```

Forward from MEM/WB pipeline register

Detecting the Need to Forward (cont'd)

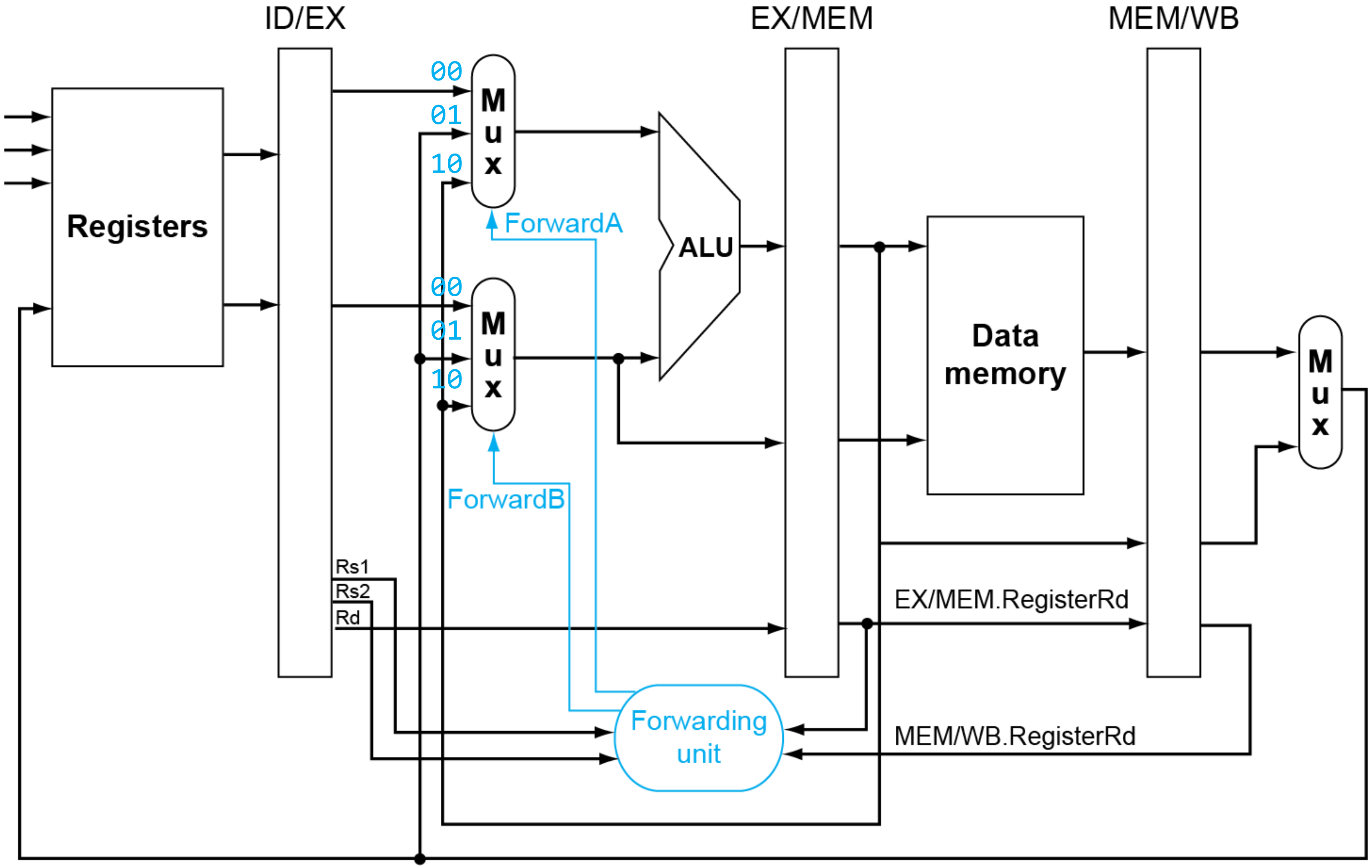
- But only if forwarding instruction will write to a register!

```
EX/MEM.RegWrite, MEM/WB.RegWrite
```

- And only if Rd for that instruction is not `x0`

```
EX/MEM.RegisterRd ≠ 0,
MEM/WB.RegisterRd ≠ 0
```

Forwarding Paths



Forwarding Conditions

- EX hazard

```
if (EX/MEM.RegWrite and (EX/MEM.RegisterRd ≠ 0)
    and (EX/MEM.RegisterRd = ID/EX.RegisterRs1))
    forwardA = 10
if (EX/MEM.RegWrite and (EX/MEM.RegisterRd ≠ 0)
    and (EX/MEM.RegisterRd = ID/EX.RegisterRs2))
    forwardB = 10
```

- MEM hazard

```
if (MEM/WB.RegWrite and (MEM/WB.RegisterRd ≠ 0)
    and (MEM/WB.RegisterRd = ID/EX.RegisterRs1))
    forwardA = 01
if (MEM/WB.RegWrite and (MEM/WB.RegisterRd ≠ 0)
    and (MEM/WB.RegisterRd = ID/EX.RegisterRs2))
    forwardB = 01
```

Forwarding Control

MUX control	Source	Example
`ForwardA = 00`	`ID/EX`	The first ALU operand comes from the register file.
`ForwardA = 10`	`EX/MEM`	The first ALU operand is forwarded from the 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 comes from the register file.
`ForwardB = 10`	`EX/MEM`	The second ALU operand is forwarded from the prior ALU result.
`ForwardB = 01`	`MEM/WB`	The second ALU operand is forwarded from data memory or an earlier ALU result.

Double Data Hazard

- Consider this sequence:

```
add   x1, x1, x2
add   x1, x1, x3
add   x1, x1, x4
```

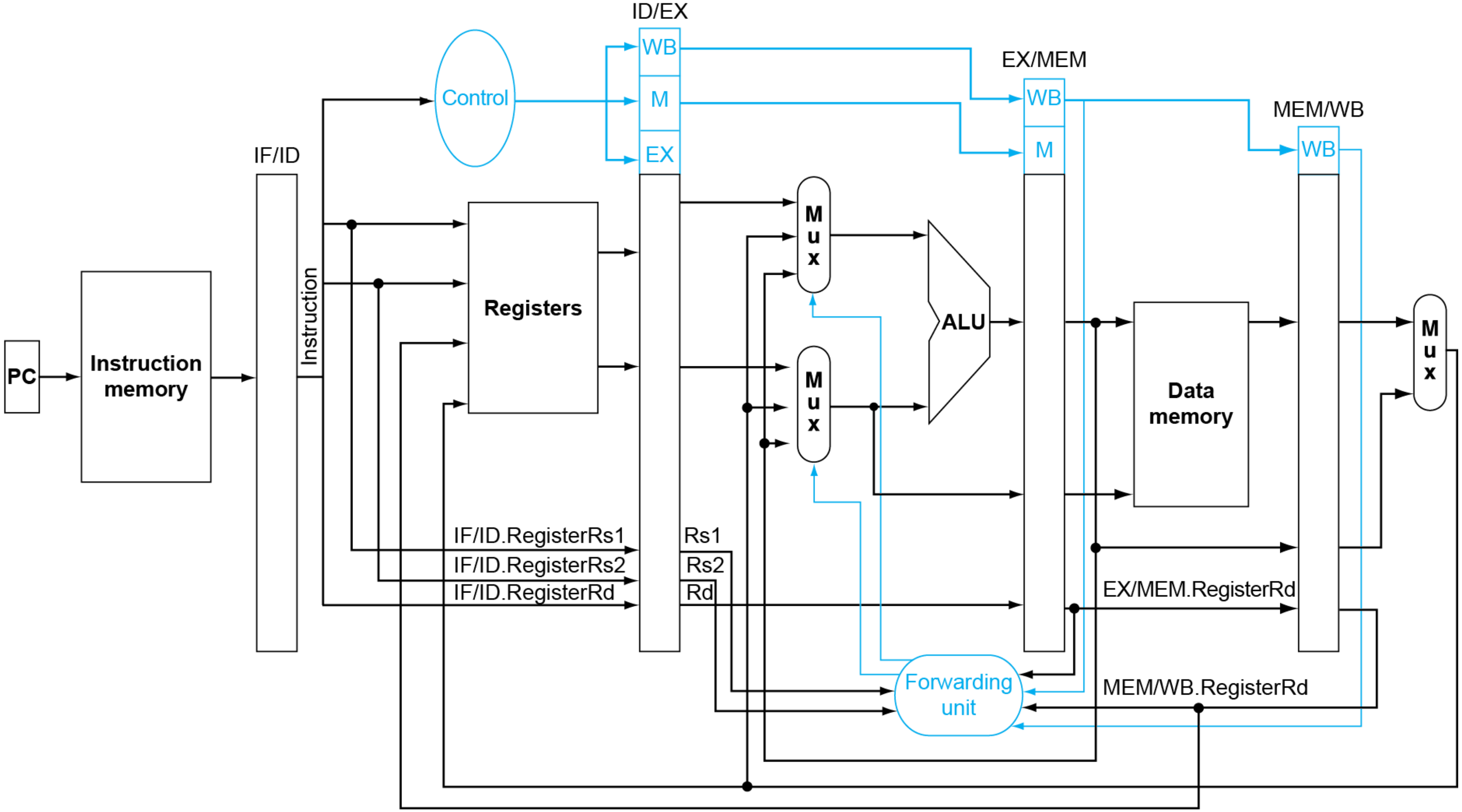
- Both hazards occur
  - Want to use the most recent
- Revise MEM hazard condition
  - Only forward if EX hazard condition isn't true

Revised Forwarding Conditions

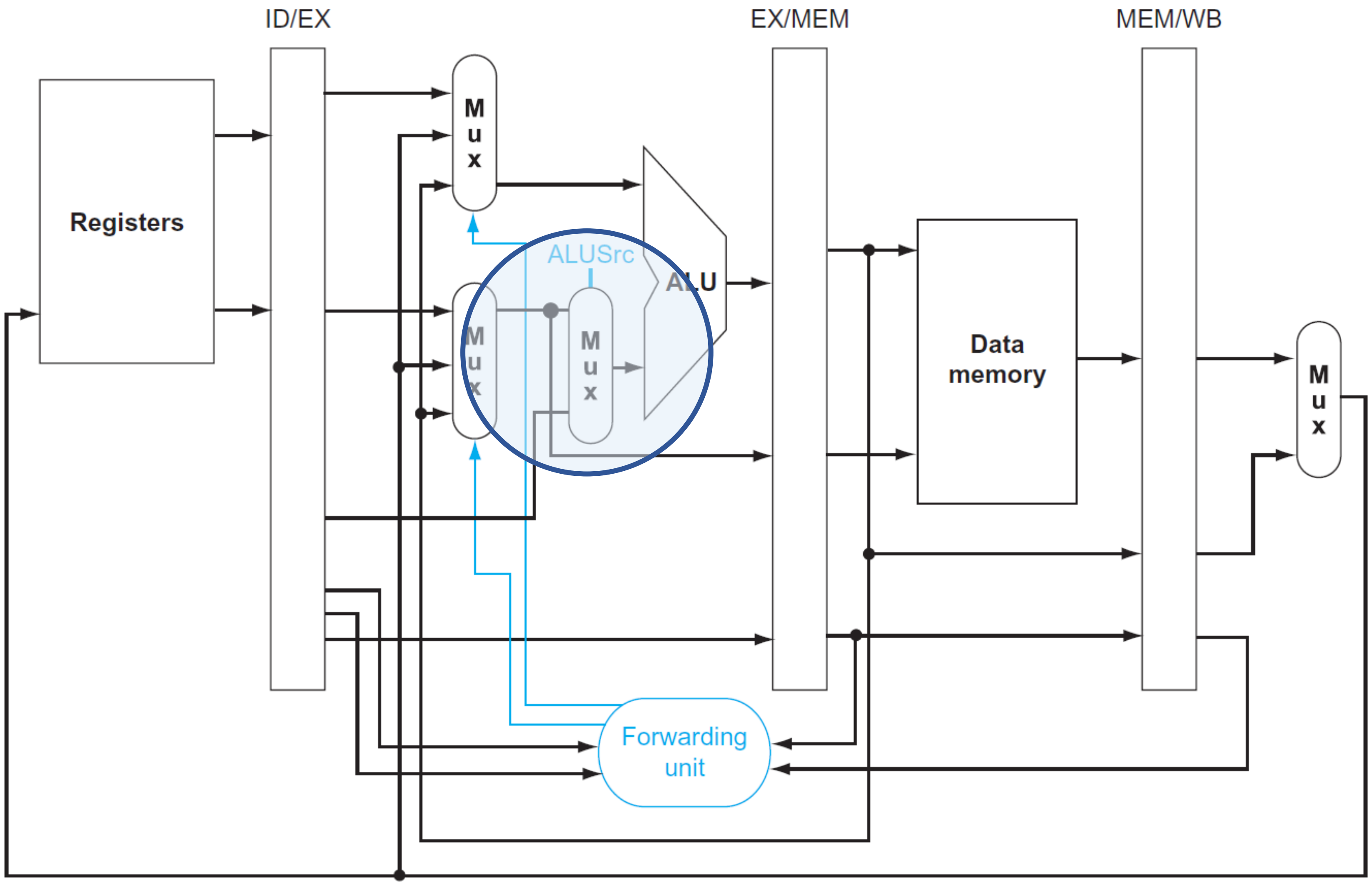
- MEM hazard

```
 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.RegisterRs1))
    and (MEM/WB.RegisterRd = ID/EX.RegisterRs1))
    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.RegisterRs2))
    and (MEM/WB.RegisterRd = ID/EX.RegisterRs2))
    forwardB = 01
```

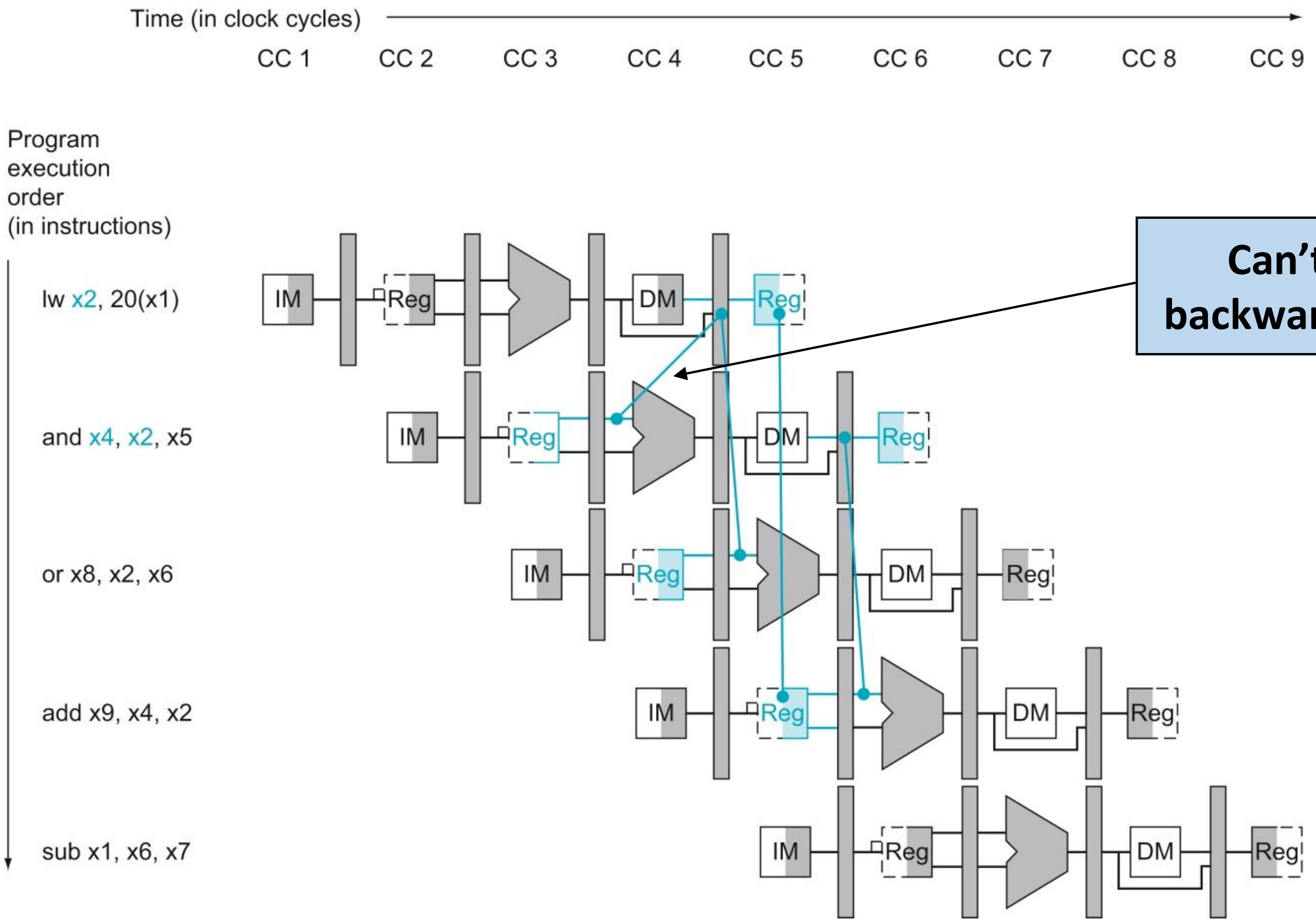
Datapath with Forwarding



Complete Datapath with Forwarding



Load-Use Hazard



Can't go backward here

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.RegisterRs1`, `IF/ID.RegisterRs2`

- Load-use hazard when

```
ID/EX.MemRead and
    ((ID/EX.RegisterRd = IF/ID.RegisterRs1) or
     (ID/EX.RegisterRd = IF/ID.RegisterRs2))
```

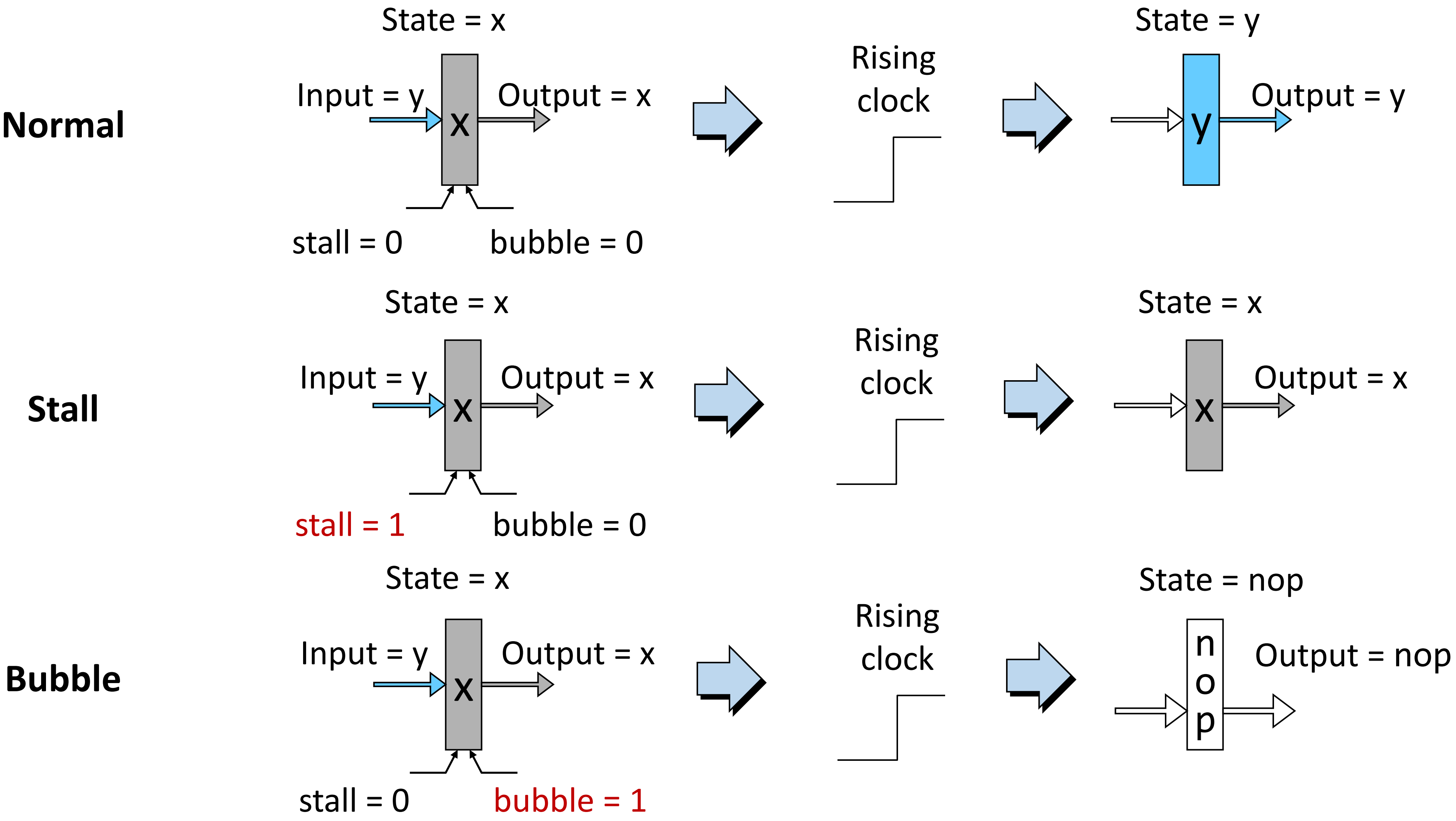
- If detected, stall and insert bubble

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 `ld`
    → Can subsequently forward to EX stage

Pipeline Register Modes



Normal

State = x

Input = y

x

Output = x

stall = 0

bubble = 0

Rising clock

State = y

y

Output = y

Stall

State = x

Input = y

x

Output = x

stall = 1

bubble = 0

Rising clock

State = x

x

Output = x

Bubble

State = x

Input = y

x

Output = x

stall = 0

bubble = 1

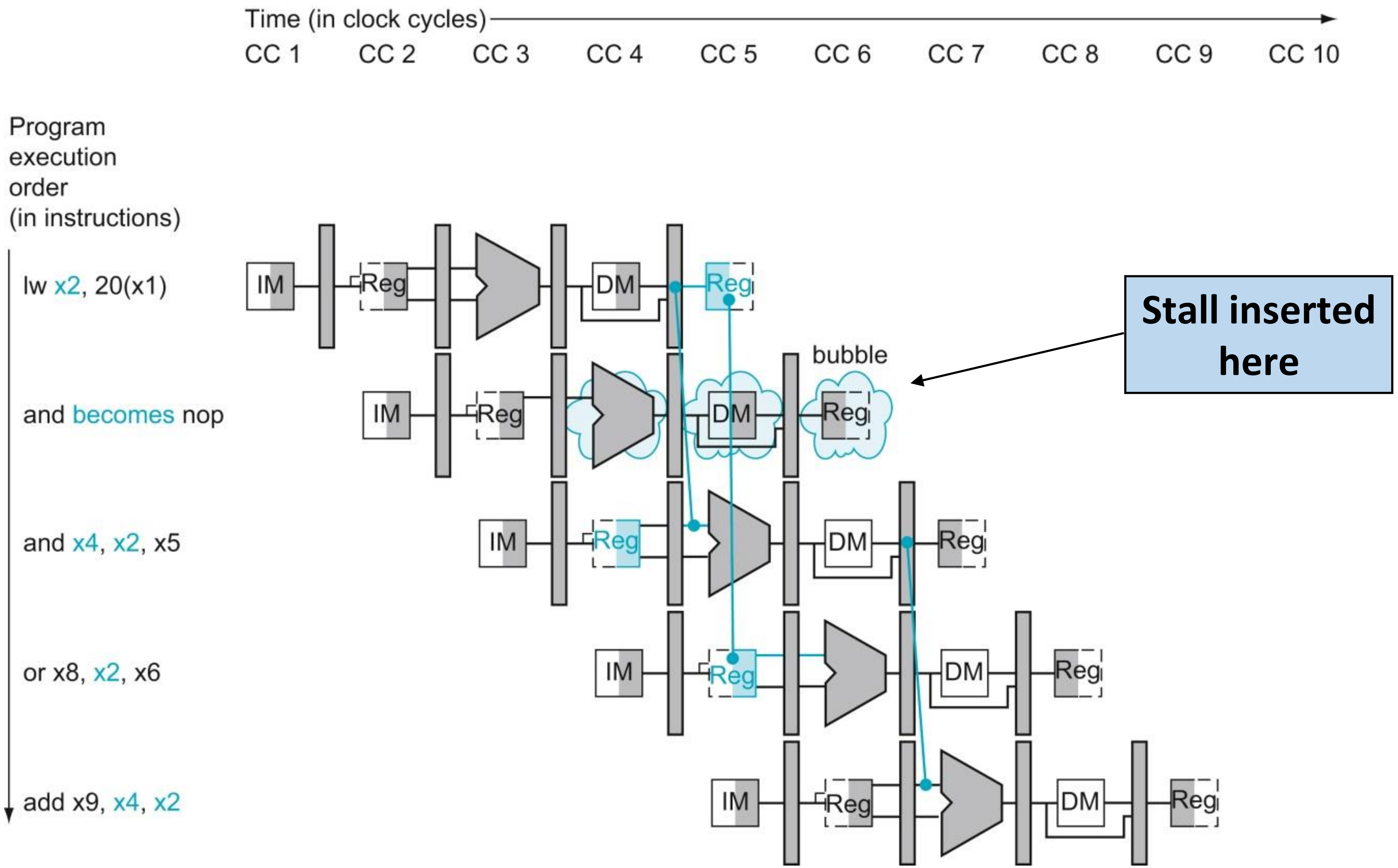
Rising clock

State = nop

n o p

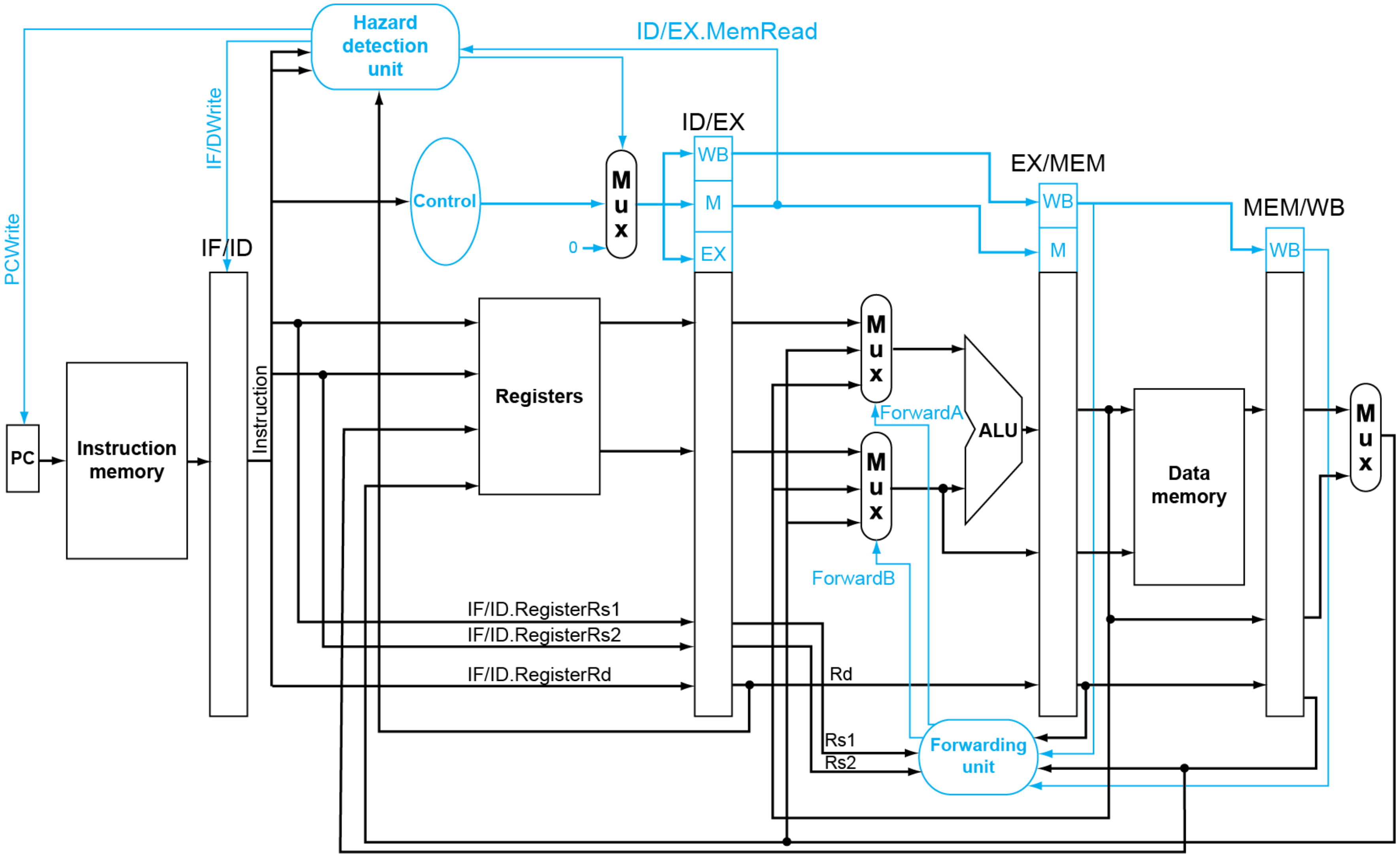
Output = nop

Load-Use Data Hazard



Stall inserted here

Datapath with Hazard Detection



Stalls and Performance

- Stalls reduce performance
  - But they are required to get correct results

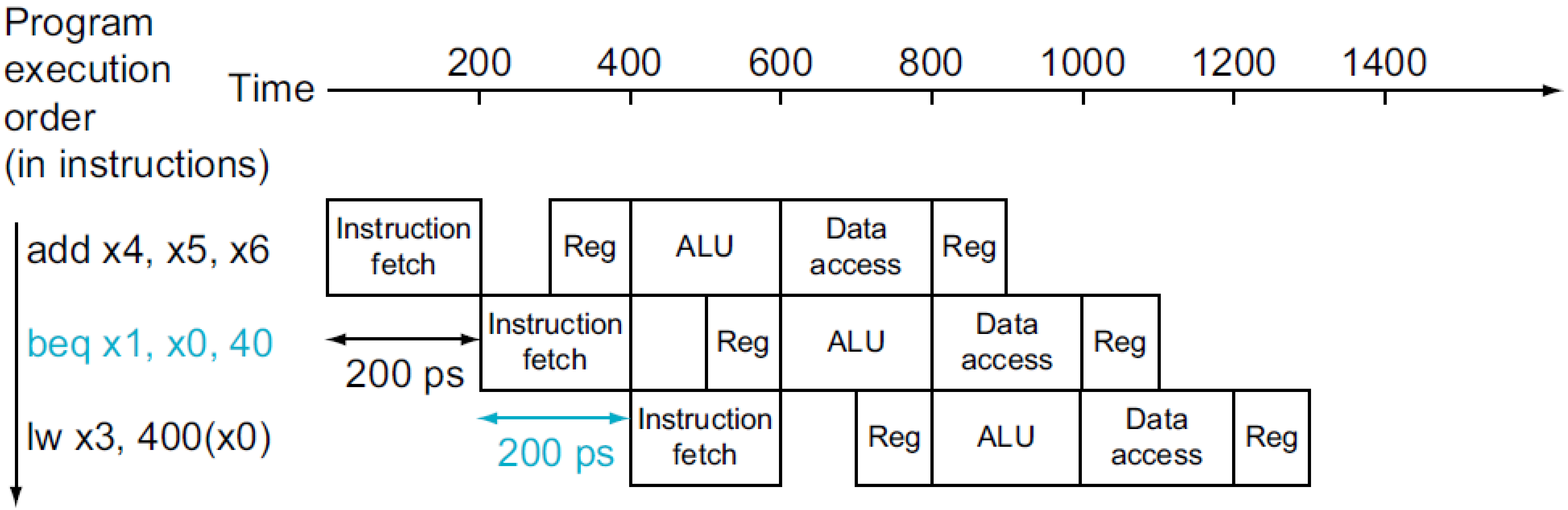
- Compiler can arrange code to avoid hazards and stalls
  - Requires knowledge of the pipeline structure

Control Hazards

Chap. 4.9

Control Hazard

- 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



Solutions to Control Hazard

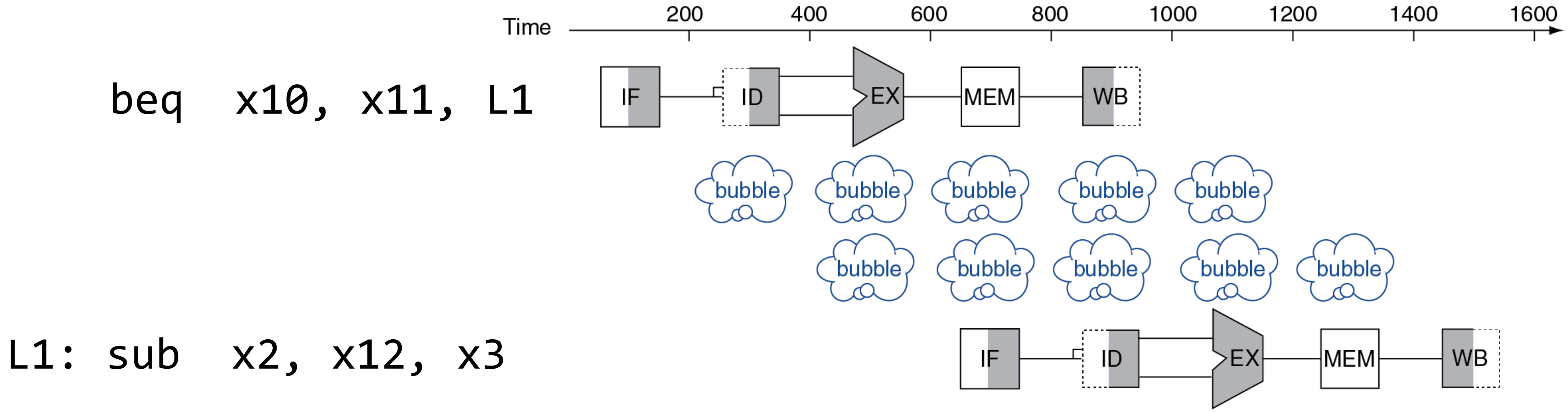
- Stall on branch

- Branch prediction

- Delayed branch (compiler scheduling to avoid stalls)

Stall on Branch

- Wait until branch outcome determined before fetching next instruction
- Assuming the branch outcome is available at the end of the EX stage, we need 2 stall cycles



Branch Prediction

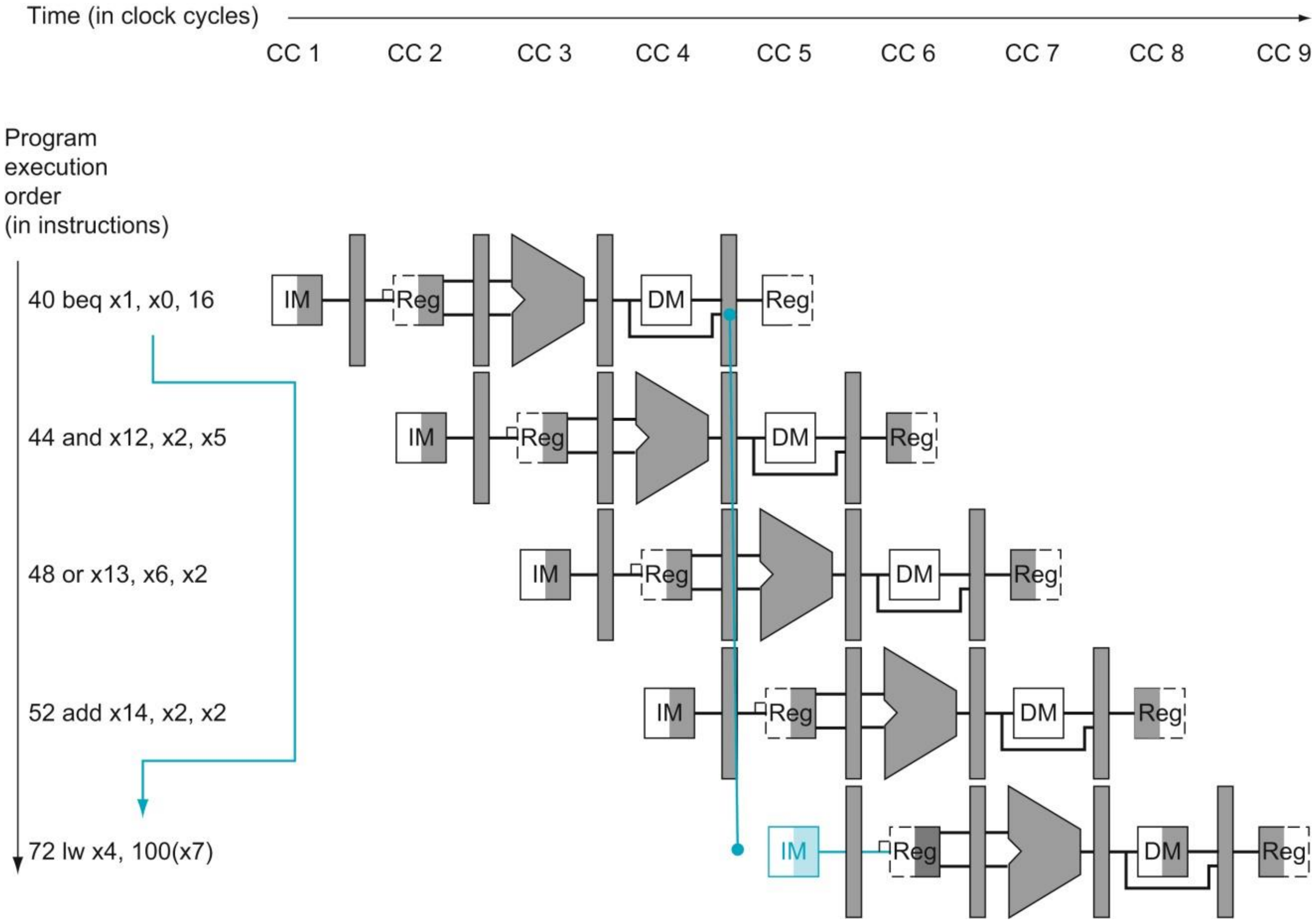
- Longer pipelines can’t readily determine branch outcome early
  - Stall penalty becomes unacceptable

- Predict outcome of branch
  - Only stall if prediction is wrong

- Example: Always-not-taken branch prediction
  - Can predict branches not taken
  - Fetch instruction after branch, with no delay
  - Cancel the fetched instruction if the prediction was wrong

Control Hazards in RISC-V

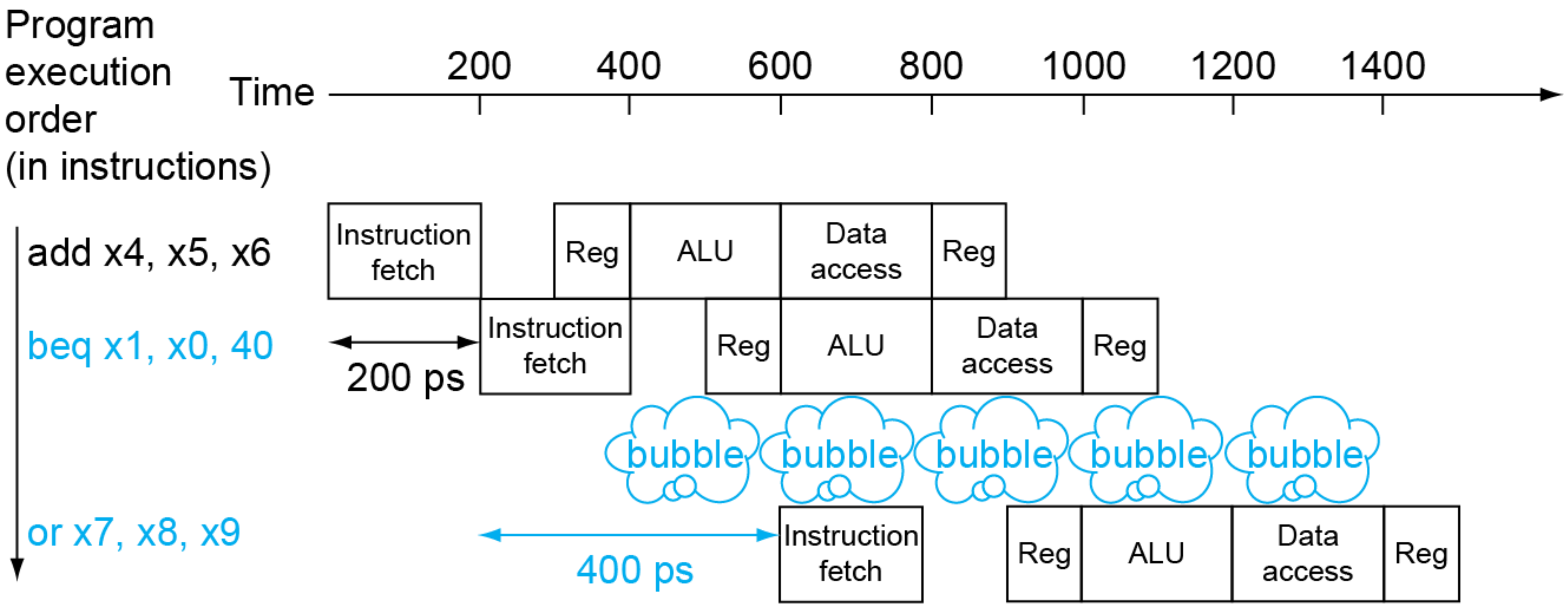
- If branch outcome determined in MEM



Flush these instructions (Set control values to 0)

Reducing Branch Delay

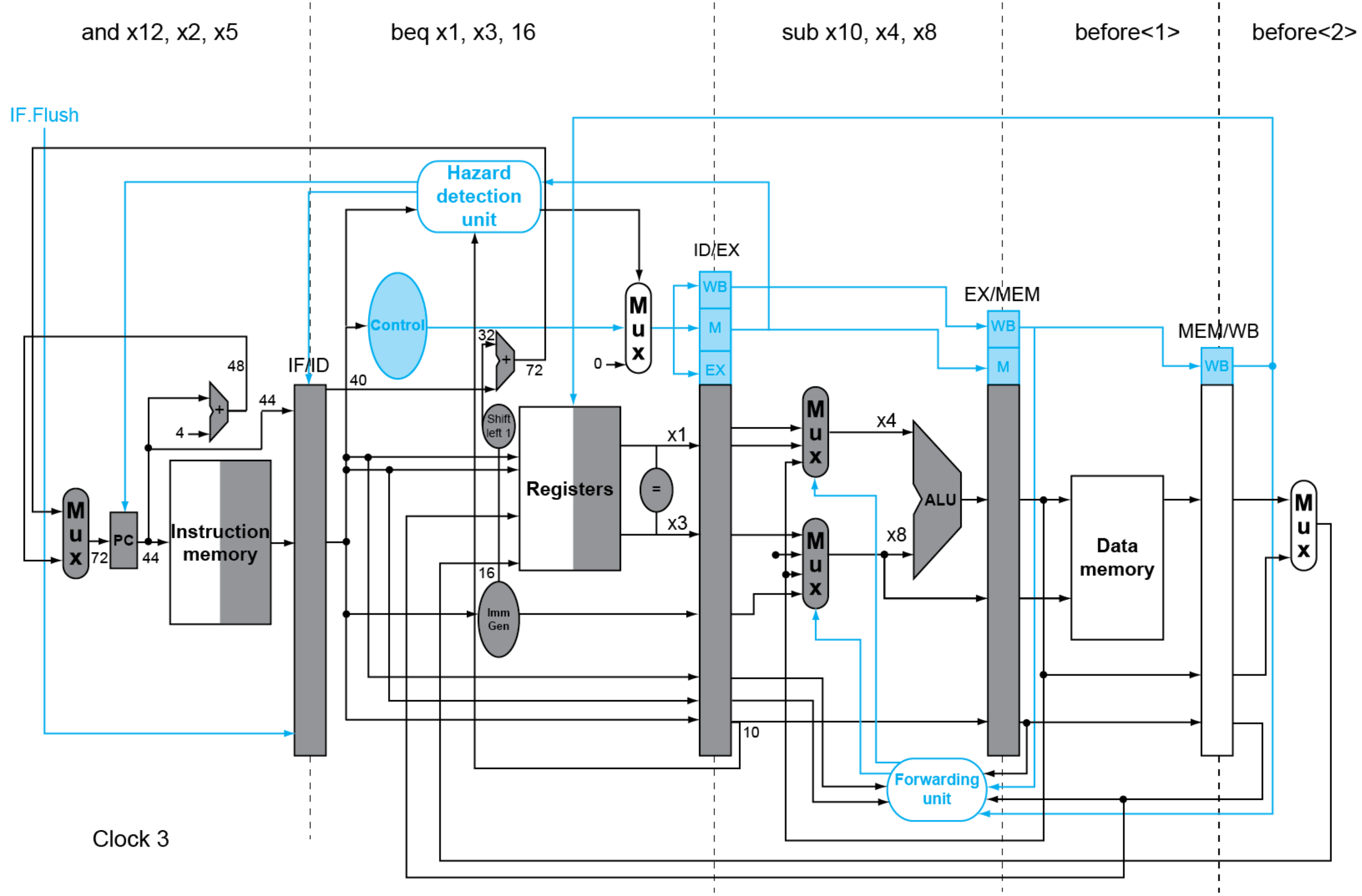
- Move hardware to determine outcome to ID stage (1 stall)
  - Target address adder
  - Register comparator



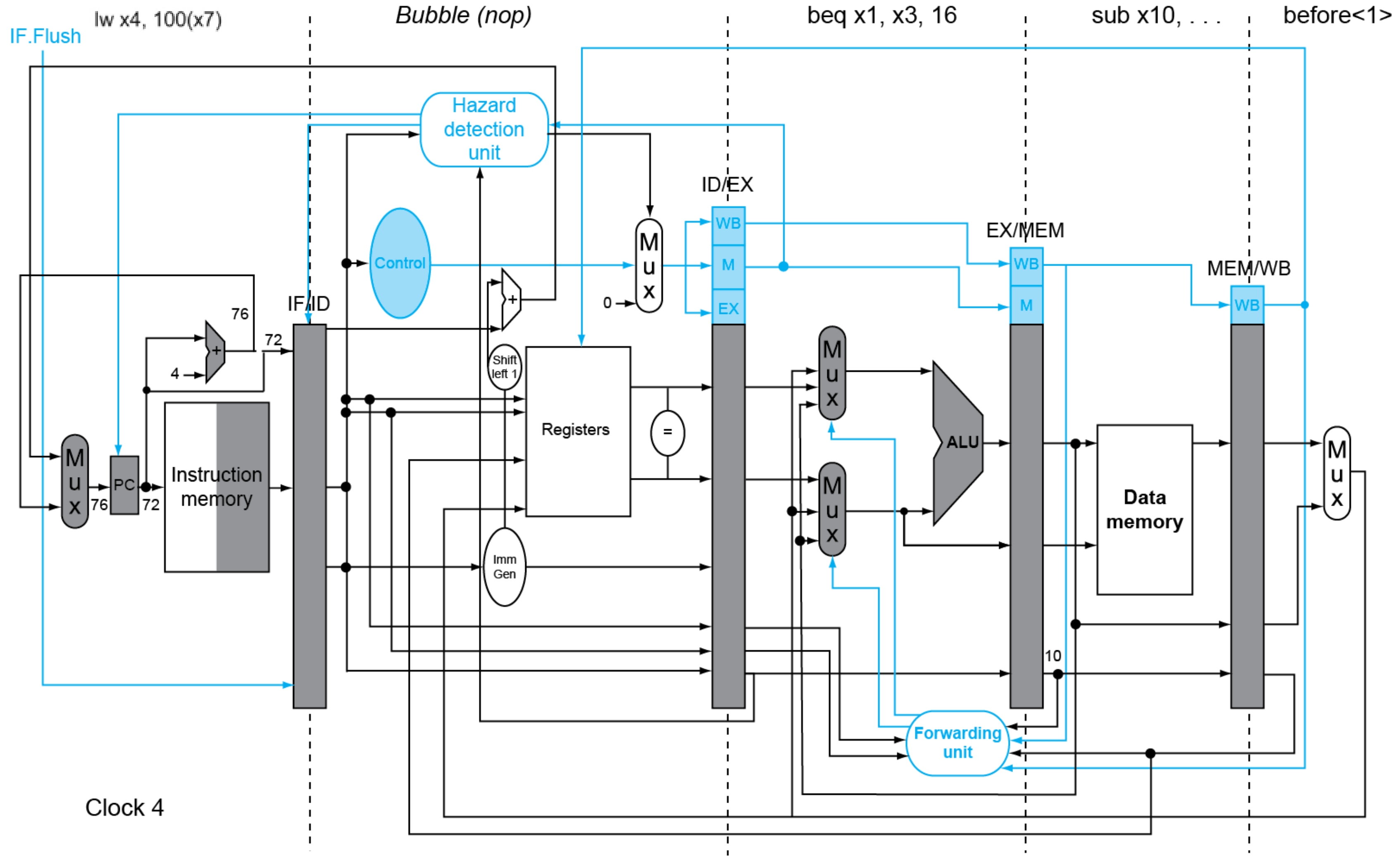
Example

```
36:   sub   x10, x4, x8
40:   beq   x1, x3, 16     // PC-relative branch to 40+16*2 = 72
44:   and   x12, x2, x5
48:   or    x13, x2, x6
52:   add   x14, x4, x2
56:   sub   x15, x6, x7
      ...
72:   lw    x4, 50(x7)
```

Example: Branch Taken



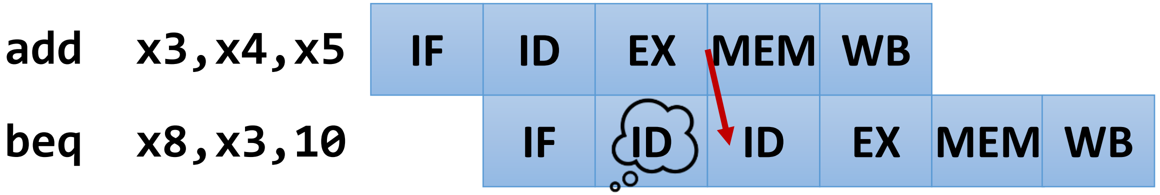
Example: Branch Taken (cont'd)



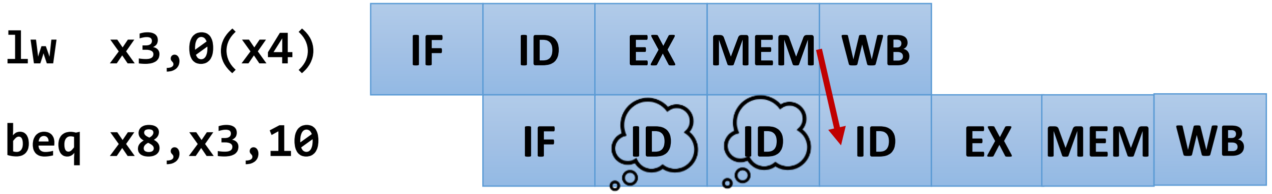
Another Cost of Branch Test in ID

- Register operands may require forwarding
  - New forwarding logic from EX/MEM or MEM/WB pipeline registers to ID needed

- Stalls due to data hazard
  - 1-cycle stall if the preceding instruction is an ALU instruction



  - 2-cycle stall if the preceding instruction is the load instruction



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

Dynamic Branch Prediction

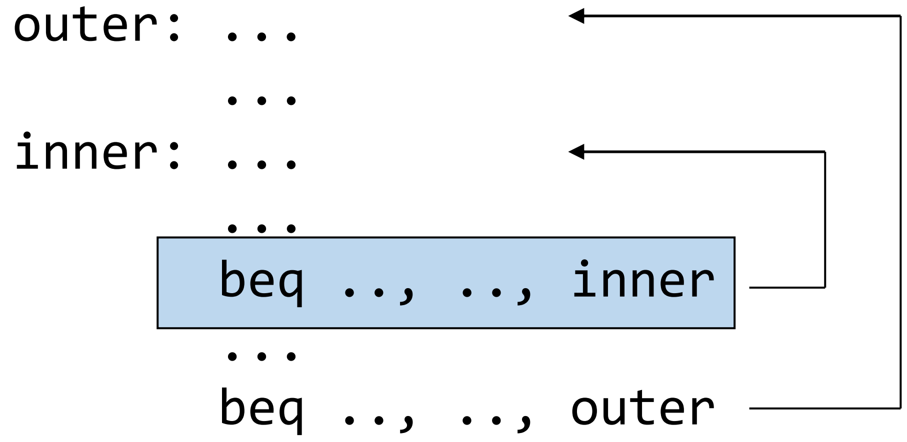
- In deeper and superscalar pipelines, branch penalty is more significant

- Use dynamic prediction
  - Branch prediction buffer (or branch history table)
  - Indexed by recent branch instruction addresses
  - Stores outcome (taken / not taken)

- To execute a branch
  - Check table, expect the same outcome
  - Start fetching from fall-through or target
  - If wrong, flush pipeline and flip prediction

1-Bit Predictor: Shortcoming

- Inner loop branches mispredicted twice!

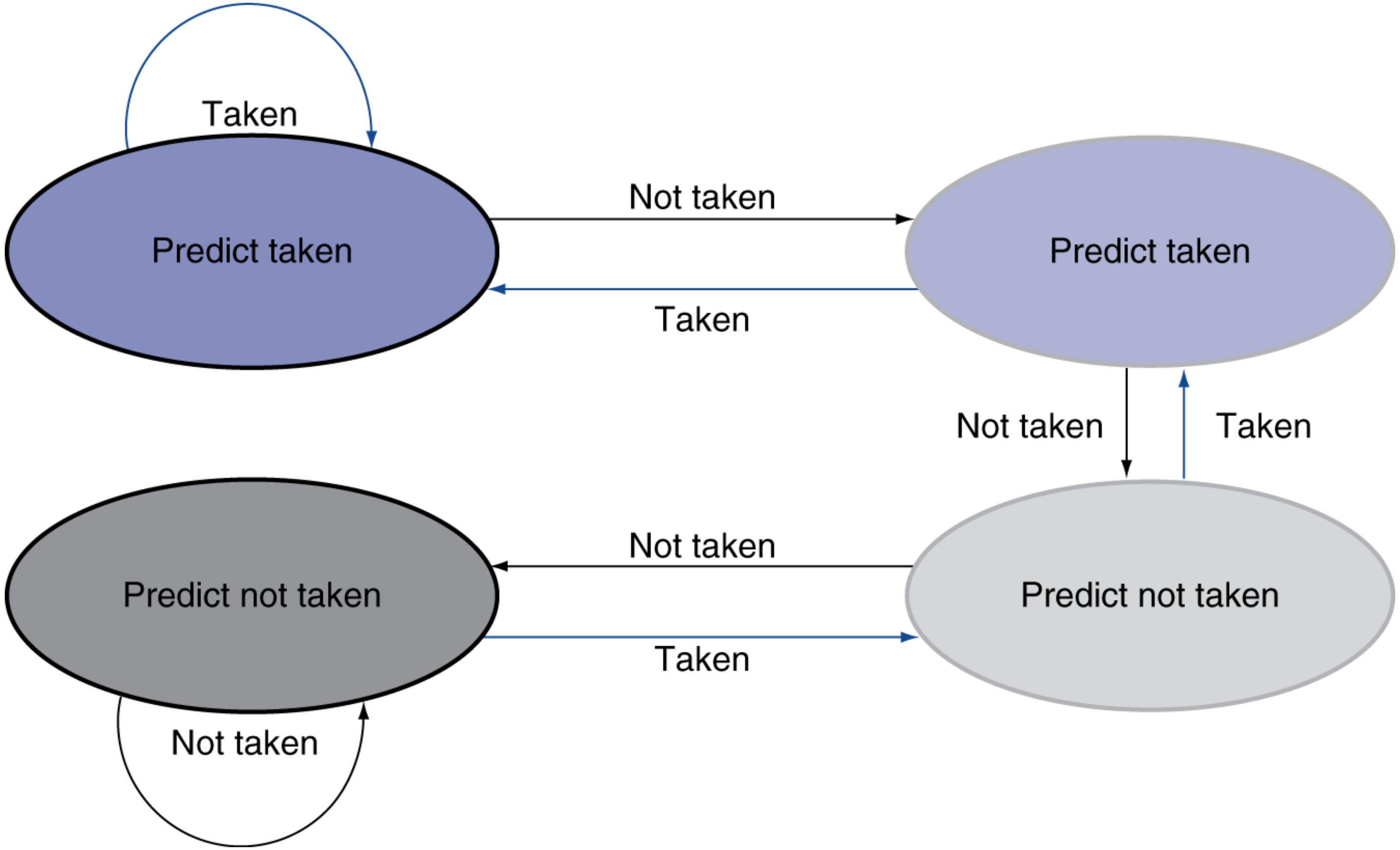


```
outer: ...
       ...
inner: ...
       ...
       beq .., .., inner
       ...
       beq .., .., outer
```

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

2-bit Predictor

- Only change prediction on two successive mispredictions



Calculating Branch Target

- Even with predictor, still need to calculate the target address
  - 1-cycle penalty for a taken branch

- Branch target buffer (BTB)
  - Cache of target addresses
  - Indexed by PC when instruction fetched
  - If hit and instruction is branch predicted taken, can fetch target immediately

Summary

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