18-447 Lecture 8: Data Hazard and Resolution

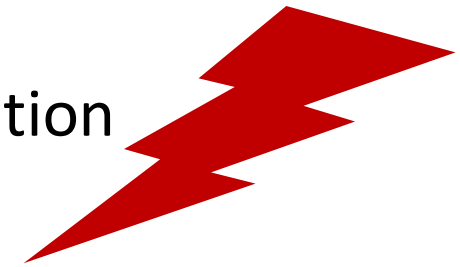
James C. Hoe
Department of ECE
Carnegie Mellon University

Housekeeping

- Your goal today
  - detect and resolve data hazards in in-order instruction pipelines
  - control dependence next time
- Notices
  - HW 2, due Mon 2/21
  - Lab 2, status check wk6, due wk7 (Handout #7)
  - HW 3, due Mon 2/28 (Handout #8)
- Readings
  - P&H Ch 4

Instruction Pipeline Reality

- Not identical tasks
  - coalescing instruction types into one "multi-function" pipe
  - external fragmentation (some idle stages)
- Not uniform suboperations
  - group or sub-divide steps into stages to minimize variance
  - internal fragmentation (some too-fast stages)
- Not independent tasks
  - dependency detection and resolution
  - next lecture(s)



Even more messy if not RISC

Recall

Data Dependence

Data dependence

x3 ← x1 op x2 — **Read-after-Write (RAW)**

. . . .

x5 ← **x3** op x4

false dependence

Anti-dependence

x3 ← **x1** op x2 — **Write-after-Read (WAR)**

. . . .

x1 ← x4 op x5

Output-dependence

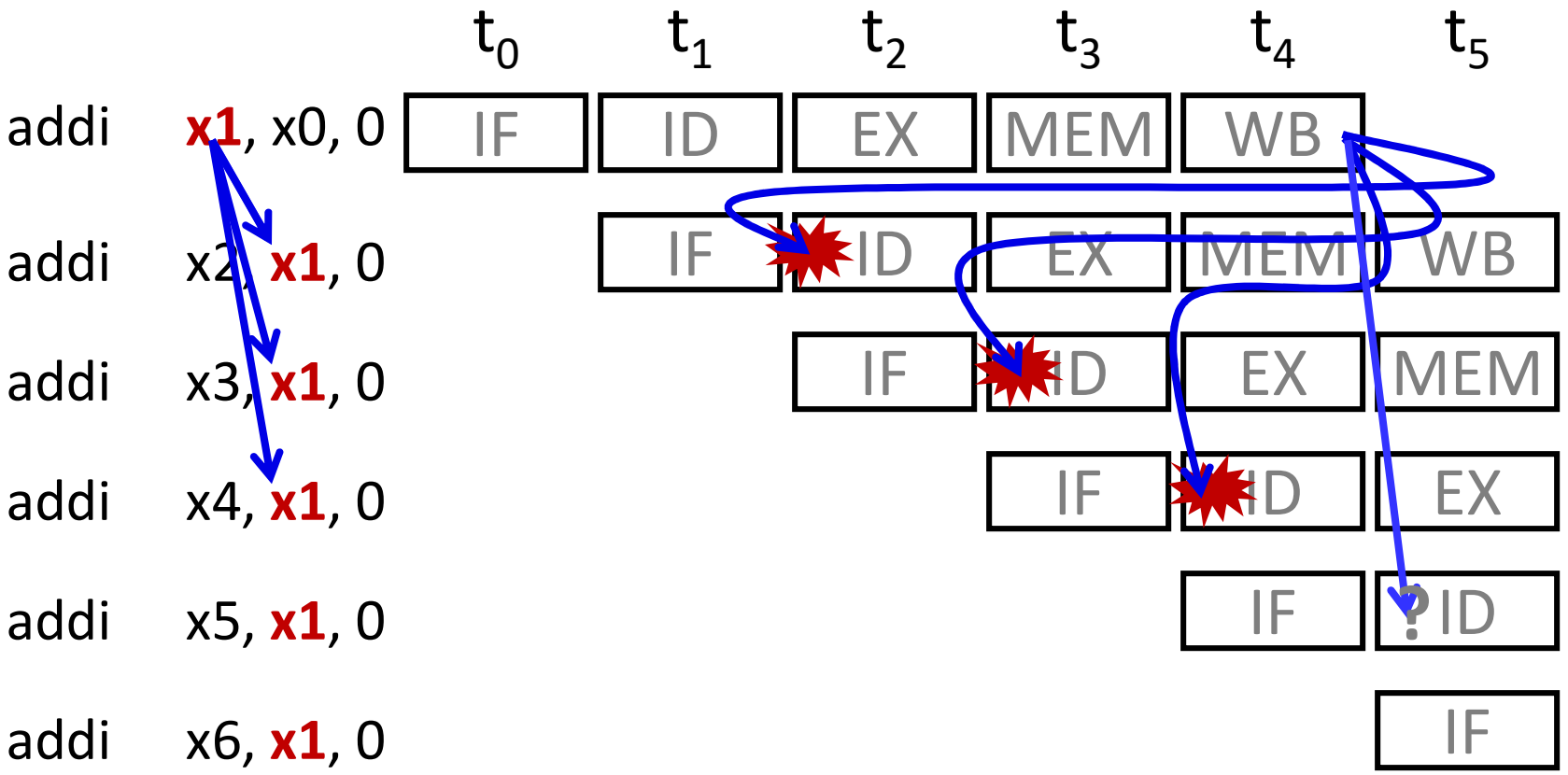
x3 ← x1 op x2 — **Write-after-Write (WAW)**

. . . .

x3 ← x6 op x7

Don't forget memory instructions

Dependency vs Hazard: e.g. RAW



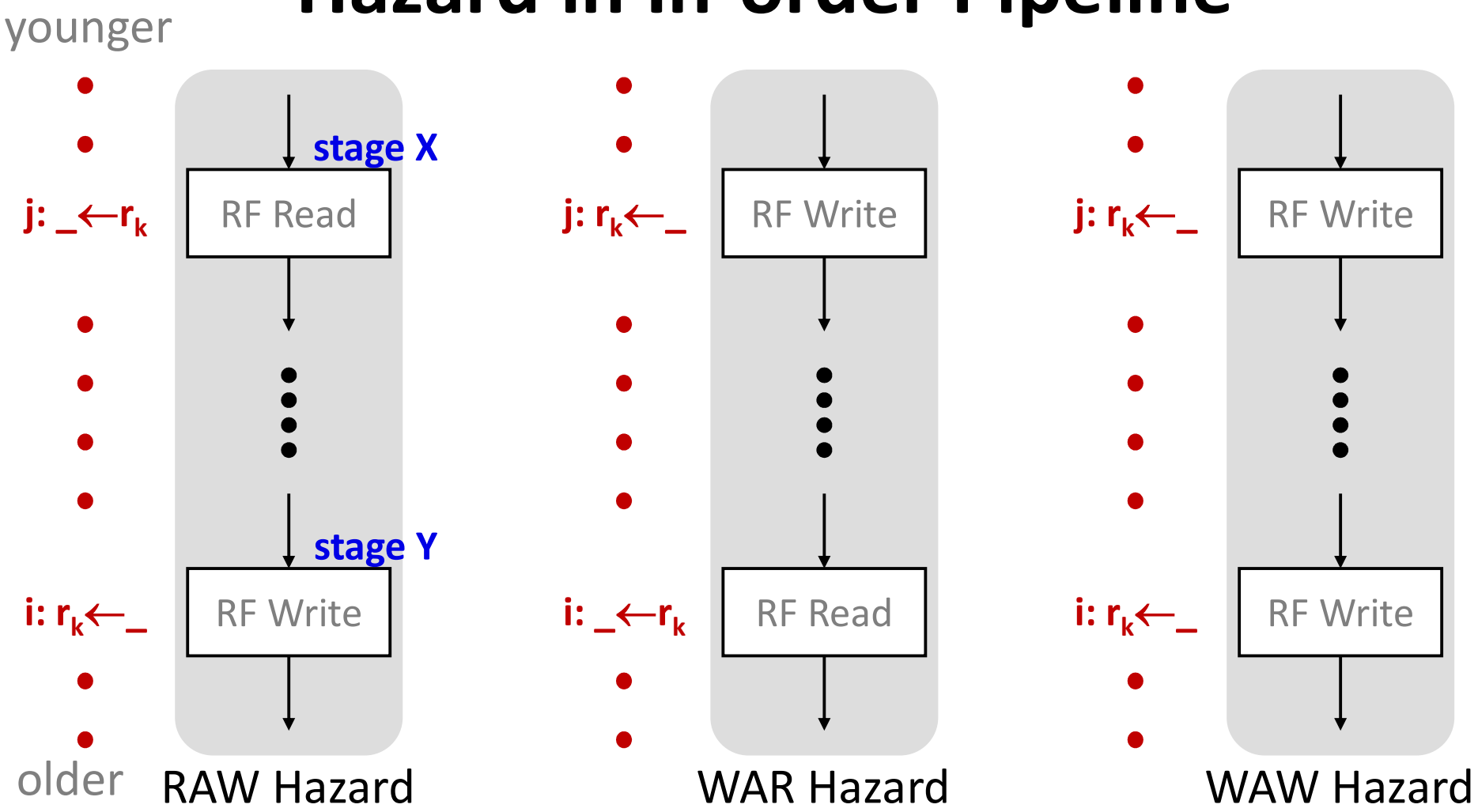
Dependence is property of program; hazards specific to microarchitecture

Register Data Hazard Analysis

	R/I-Type	LW	SW	Bxx	Jal	Jalr
IF						
ID	**read RF**	**read RF**	**read RF**	**read RF**		**read RF**
EX						
MEM						
WB	**write RF**	**write RF**			**write RF**	**write RF**

- For a given pipeline, when is there a register data hazard between 2 dependent instructions?
  - dependence type: RAW, WAR, WAW?
  - instruction types involved?
  - distance between the two instructions?

Hazard in In-order Pipeline



$$dist_{dependence}(i,j) \leq dist_{hazard}(X,Y) \Rightarrow \textbf{Hazard!!}$$
$$dist_{dependence}(i,j) > dist_{hazard}(X,Y) \Rightarrow \textbf{Safe}$$

RAW Hazard Analysis Example

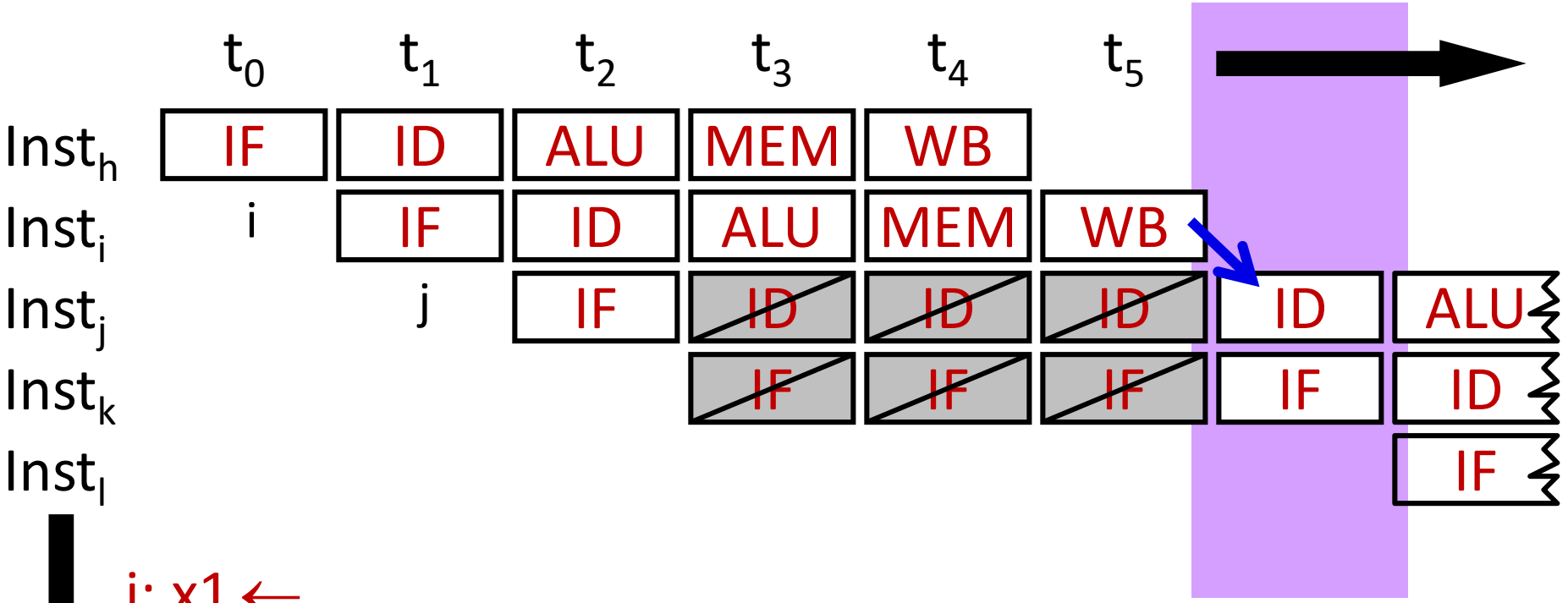
	R/I-Type	LW	SW	Bxx	Jal	Jalr
IF						
ID	**read RF**	**read RF**	**read RF**	**read RF**		**read RF**
EX						
MEM						
WB	**write RF**	**write RF**			**write RF**	**write RF**

- Older I_A and younger I_B have RAW hazard iff
  - I_B (R/I, LW, SW, Bxx or JALR) reads a register written by I_A (R/I, LW, or JAL/R)
  - dist(I_A, I_B) $\leq$ dist(ID, WB) = 3

What about WAW and WAR hazard?

What about memory data hazard?

Pipeline Stall: universal hazard resolution



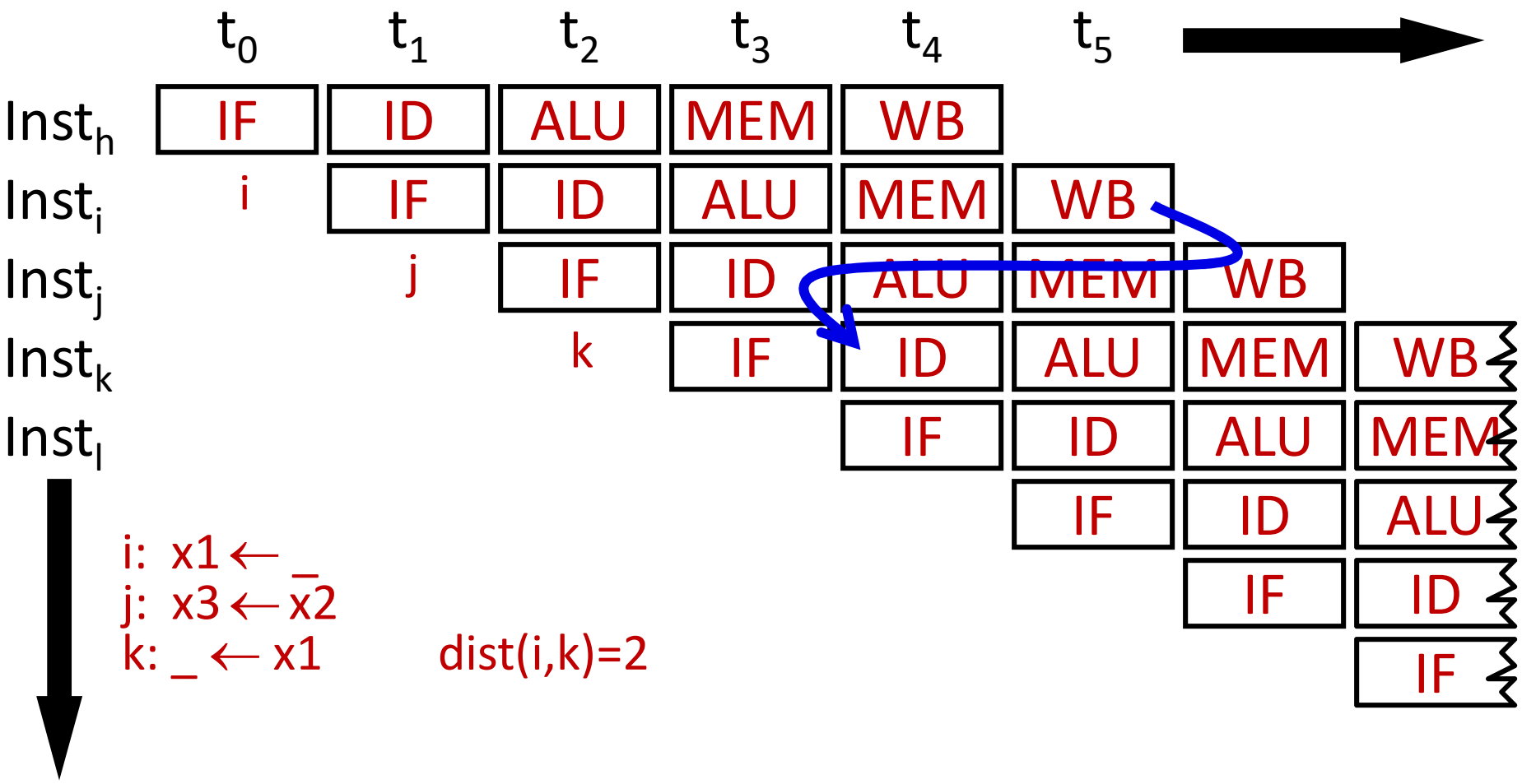
i: x1 ← _
bubble
bubble
bubble
j: _ ← x1

dist(i,j)=4

Stall==make younger instruction wait until hazard passes

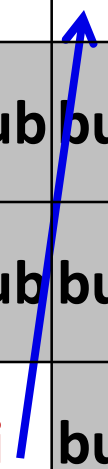
1. stop all up-stream stages
2. drain all down-stream stages

Pop Quiz: What happens in this case?



Pipeline Stall

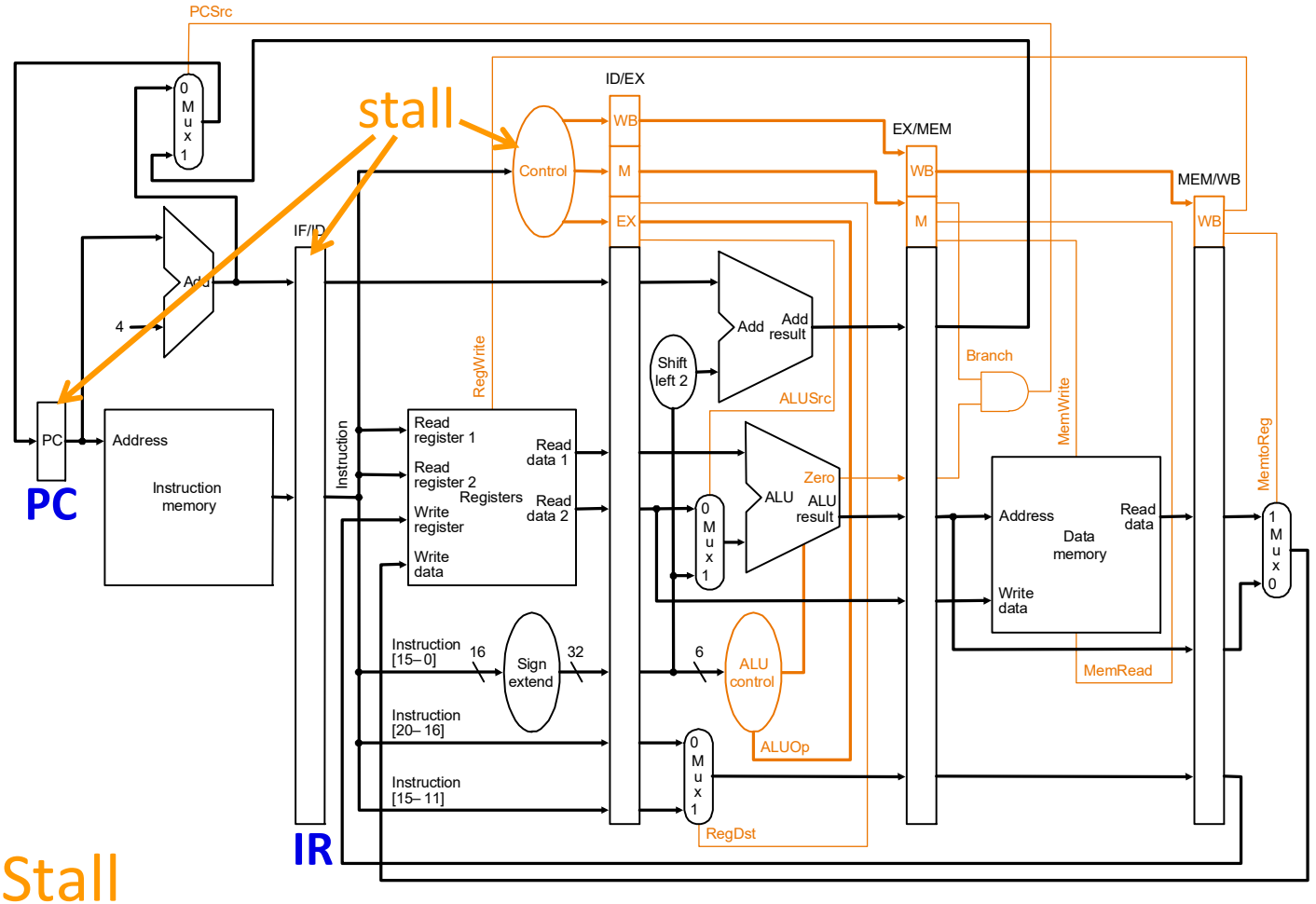
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}
IF	i	j	k	k	k	k	l				
ID	h	i	j	j	j	j	k	l			
EX		h	i	bub	bub	bub	j	k	l		
MEM			h	i	bub	bub	bub	j	k	l	
WB				h	i	bub	bub	bub	j	k	l



i: x1 ← _

j: _ ← x1

Stall



- Stall
  - disable **PC** and **IR** latching
  - set $RegWrite_{ID}$=0 and $MemWrite_{ID}$=0

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When to Stall

- Older I_A and younger I_B have RAW hazard iff
  - I_B (R/I, LW, SW, Bxx or JALR) reads a register written by I_A (R/I, LW, or JAL/R)
  - dist(I_A, I_B) $\leq$ dist(ID, WB) = 3

Above is about existence of hazard

- Operationally, to detect hazard in time to prevent:
  - before I_B in ID reads a register, I_B needs to check if any I_A in EX, MEM or WB is going to update it

(if so, value in RF is "stale")

Watch out for x0!!

Stall Condition

- Helper function
  - *waitForRs1*(I) returns true if I uses rs1 && rs1!=x0
- Stall IF and ID when
  - ($rs1_{ID}$==rd_{EX}) && $RegWrite_{EX}$ && *waitForRs1*(IR_{ID}) or
  - ($rs1_{ID}$==rd_{MEM}) && $RegWrite_{MEM}$ && *waitForRs1*(IR_{ID}) or
  - ($rs1_{ID}$==rd_{WB}) && $RegWrite_{WB}$ && *waitForRs1*(IR_{ID}) or
  - ($rs2_{ID}$==rd_{EX}) && $RegWrite_{EX}$ && *waitForRs2*(IR_{ID}) or
  - ($rs2_{ID}$ ==rd_{MEM}) && $RegWrite_{MEM}$ && *waitForRs2*(IR_{ID}) or
  - ($rs2_{ID}$==rd_{WB}) && $RegWrite_{WB}$ && *waitForRs2*(IR_{ID})

It is crucial that EX, MEM and WB continue to advance during stall

Impact of Stall on Performance

- Each stall cycle corresponds to 1 lost ALU cycle
- A program with N instructions and S stall cycles:

$$\text{average IPC} = N/(N+S)$$

- S depends on
  - frequency of hazard-causing dependencies
  - distance between hazard-causing instruction pairs
  - distance between hazard-causing dependencies

(suppose i_1,i_2 and i_3 all depend on i_0, once i_1's hazard is resolved by stalling, i_2 and i_3 do not stall)

Sample Assembly [P&H]

for (j=i-1; j>=0 && v[j] > v[j+1]; j-=1) { ..... }

```
                addi    $s1, $s0, -1
for2tst:        slti    $t0, $s1, 0
                bne     $t0, $zero, exit2
                sll     $t1, $s1, 2
                add     $t2, $a0, $t1
                lw      $t3, 0($t2)
                lw      $t4, 4($t2)
                slt     $t0, $t4, $t3
                beq     $t0, $zero, exit2
                .........
                addi    $s1, $s1, -1
                j       for2tst
exit2:
```

3 stalls

3 stalls

3 stalls

3 stalls

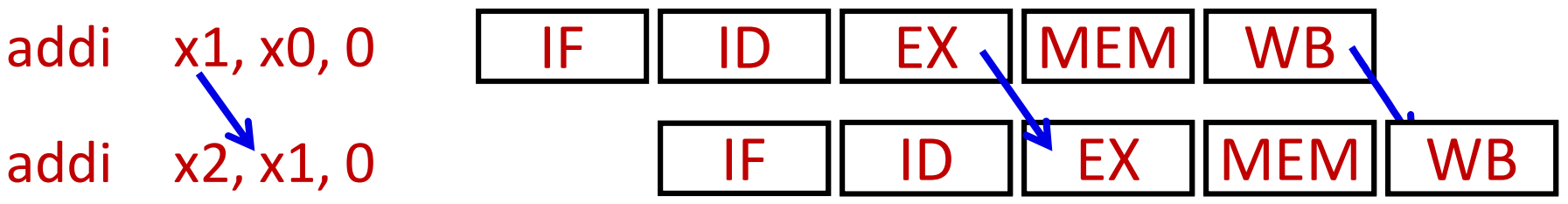
3 stalls

3 stalls

Data Forwarding (or Register Bypassing)

- What does "ADD r_x r_y r_z" mean? Get inputs from RF[r_y] and RF[r_z] and put result in RF[r_x]?
- But, RF is just a part of an abstraction
  - a way to connect dataflow between instructions

    "operands to ADD are resulting **values** of the last instructions to assign to RF[r_y] and RF[r_z]"
  - RF doesn't have to exist/behave as a literal object!!!
- If only dataflow matters, don't wait for WB . . .

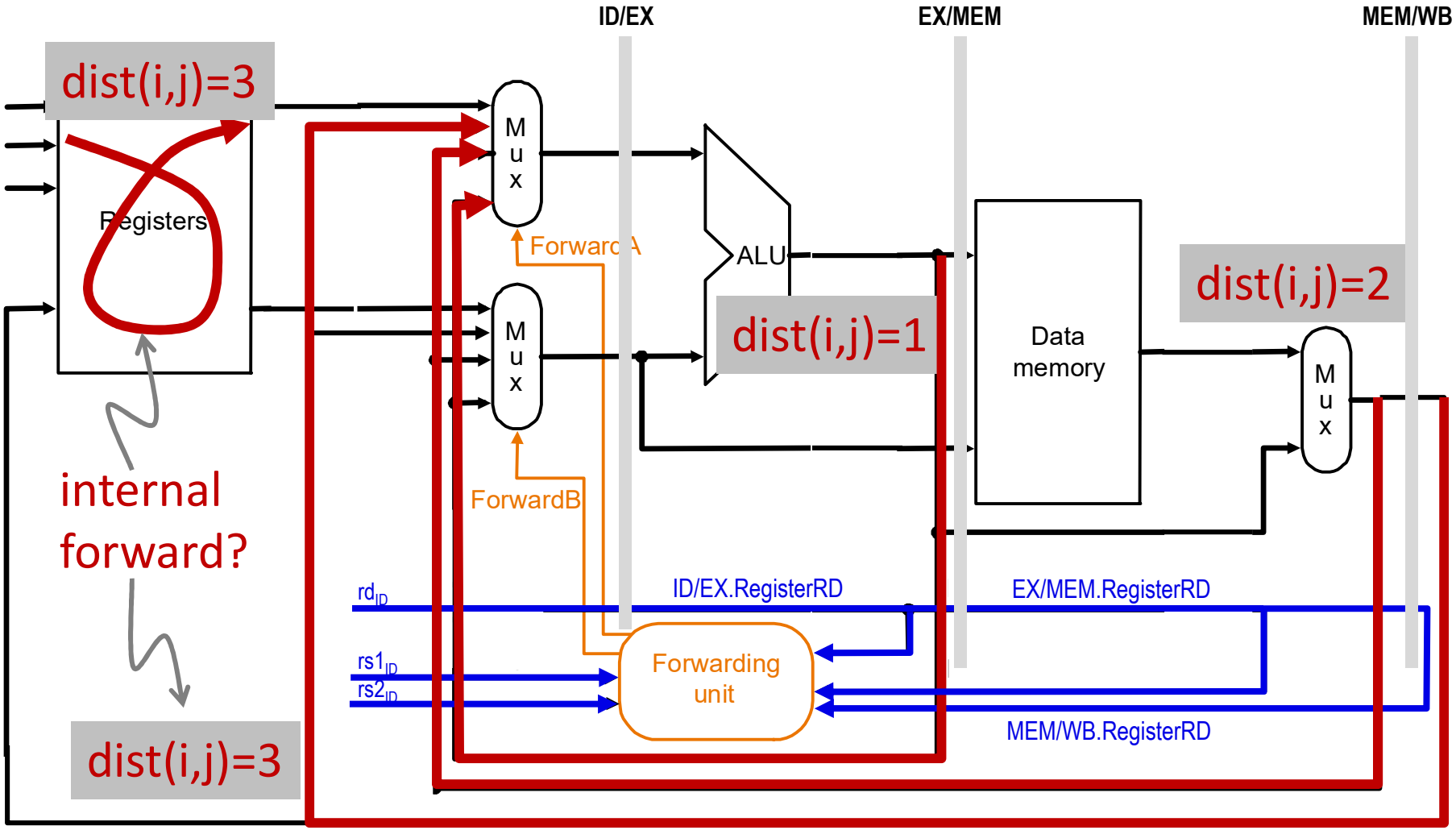


Resolving RAW Hazard by Forwarding

A hazard exits

- Older I_A and younger I_B have RAW hazard iff
  - I_B (R/I, LW, SW, Bxx or JALR) reads a register written by I_A (R/I, LW, or JAL/R)
  - dist(I_A, I_B) $\leq$ dist(ID, WB) = 3
- To detect hazard in time to prevent, before I_B in ID reads a register, I_B needs to check if any I_A in EX, MEM or WB is going to update it
- Before: I_B need to stall for I_A to update RF
- Now: I_B need to stall for I_A to produce result
  - retrieve I_A result from datapath when ready
  - must retrieve from **youngest** if multiple hazards

Forwarding Paths (v1)



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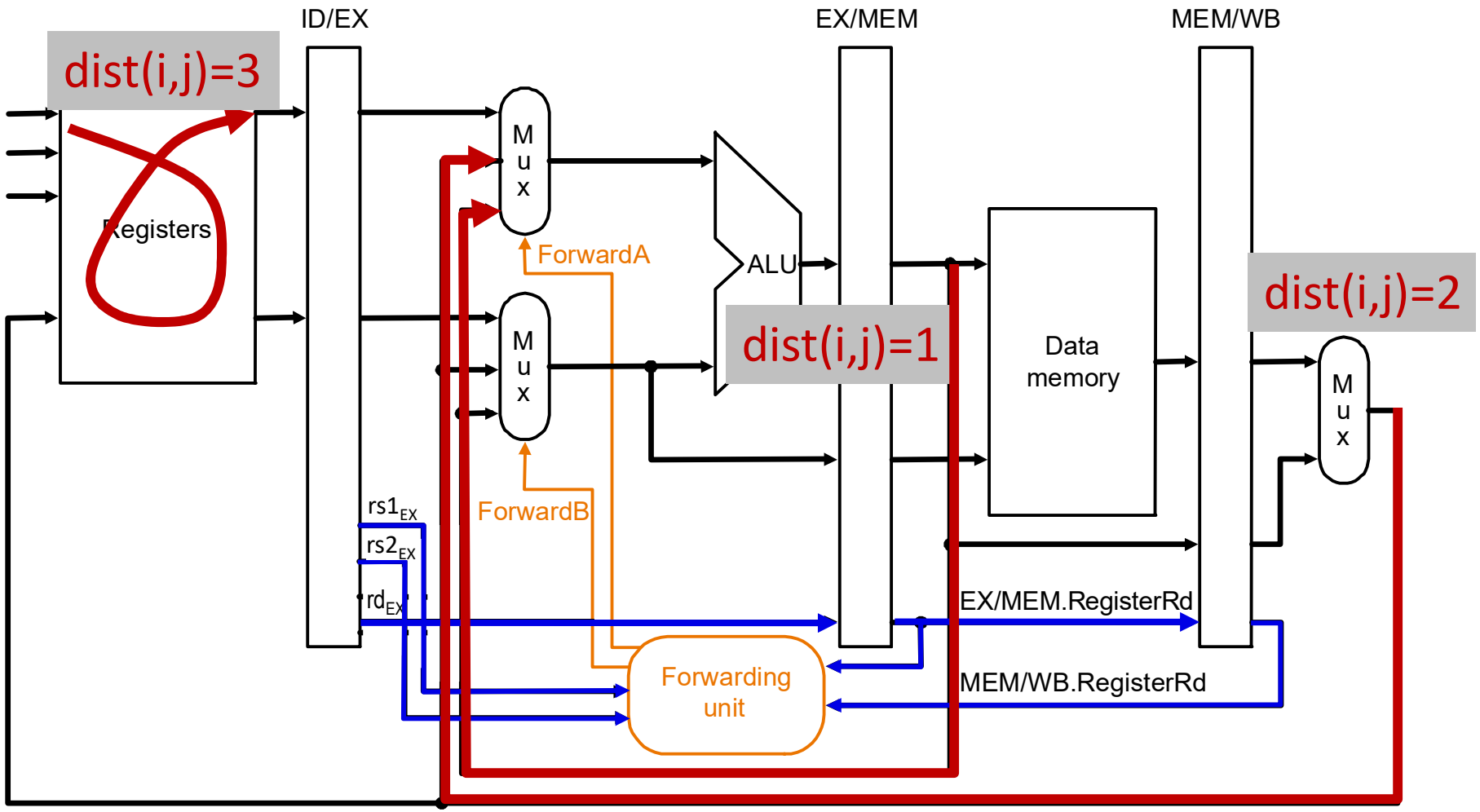
Forwarding Paths (v2)



better if EX is the fastest stage

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Forwarding Logic (for v1)

if ($rs1_{ID}$!=0) && ($rs1_{ID}$==rd_{EX}) && $RegWrite_{EX}$ then

    forward writeback value from EX // dist=1

else if ($rs1_{ID}$!=0) && ($rs1_{ID}$==rd_{MEM}) && $RegWrite_{MEM}$ then

    forward writeback value from MEM // dist=2

else if ($rs1_{ID}$!=0) && ($rs1_{ID}$==rd_{WB}) && $RegWrite_{WB}$ then

    forward writeback value from WB // dist=3

else

    use $\mathbf{A_{ID}}$ // dist > 3

Must prioritize young-to-old

Why doesn't *waitForRs1*( ) appear?

Isn't it bad to forward from LW in EX?

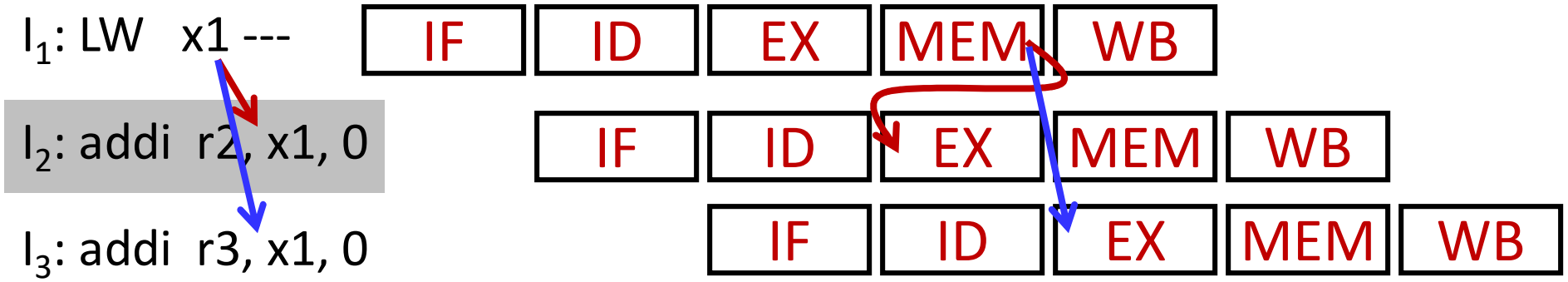
Data Hazard Analysis (with Forwarding)

	R/I-Type	LW	SW	Bxx	Jal	Jalr
IF						
ID						
EX	**use produce**	**use**	**use**	**use**	**produce**	**use produce**
MEM		**produce**	(**use**)			
WB						

- Even with forwarding, RAW dependence on immediate preceding LW results in hazard
- Stall = {[($rs1_{ID}$ ==rd_{EX}) && *waitForRs1*($\mathbf{IR_{ID}}$)] ||
  [($rs2_{ID}$ ==rd_{EX}) && *waitForRs2*($\mathbf{IR_{ID}}$)]} && $MemRead_{EX}$

i.e., op_{EX}=Lx

Historical: MIPS Load "Delay Slot"



- R2000 defined LW with arch. latency of 1 inst
  - invalid for I_2 (in LW's delay slot) to ask for LW's result
  - any dependence on LW at least distance 2
- Delay slot vs dynamic stalling
  - fill with an independent instruction (no difference)
  - if not, fill with a NOP (no difference)
- Can't lose on 5-stage . . . good idea?

Hint: 1. non-atomic instruction; 2. μarch influence

Sample Assembly [P&H]

for (j=i-1; j>=0 && v[j] > v[j+1]; j-=1) { ..... }

```
                addi    $s1, $s0, -1
for2tst:        slti    $t0, $s1, 0
                bne     $t0, $zero, exit2
                sll     $t1, $s1, 2
                add     $t2, $a0, $t1
                lw      $t3, 0($t2)
                lw      $t4, 4($t2)
                slt     $t0, $t4, $t3
                beq     $t0, $zero, exit2
                .........
                addi    $s1, $s1, -1
                j       for2tst
exit2:
```

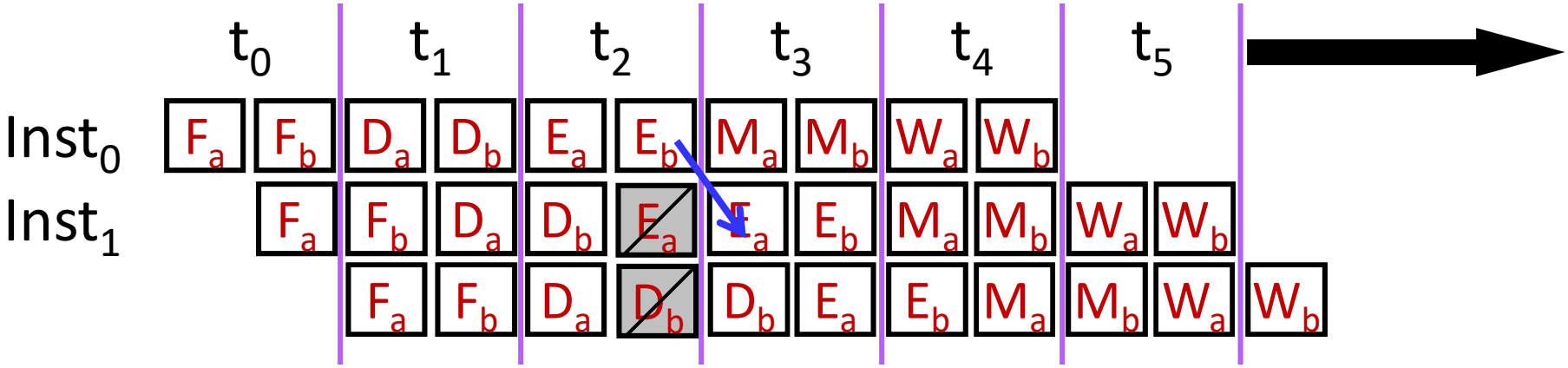
1 stall or
1 nop (MIPS)

Why not very deep pipelines?

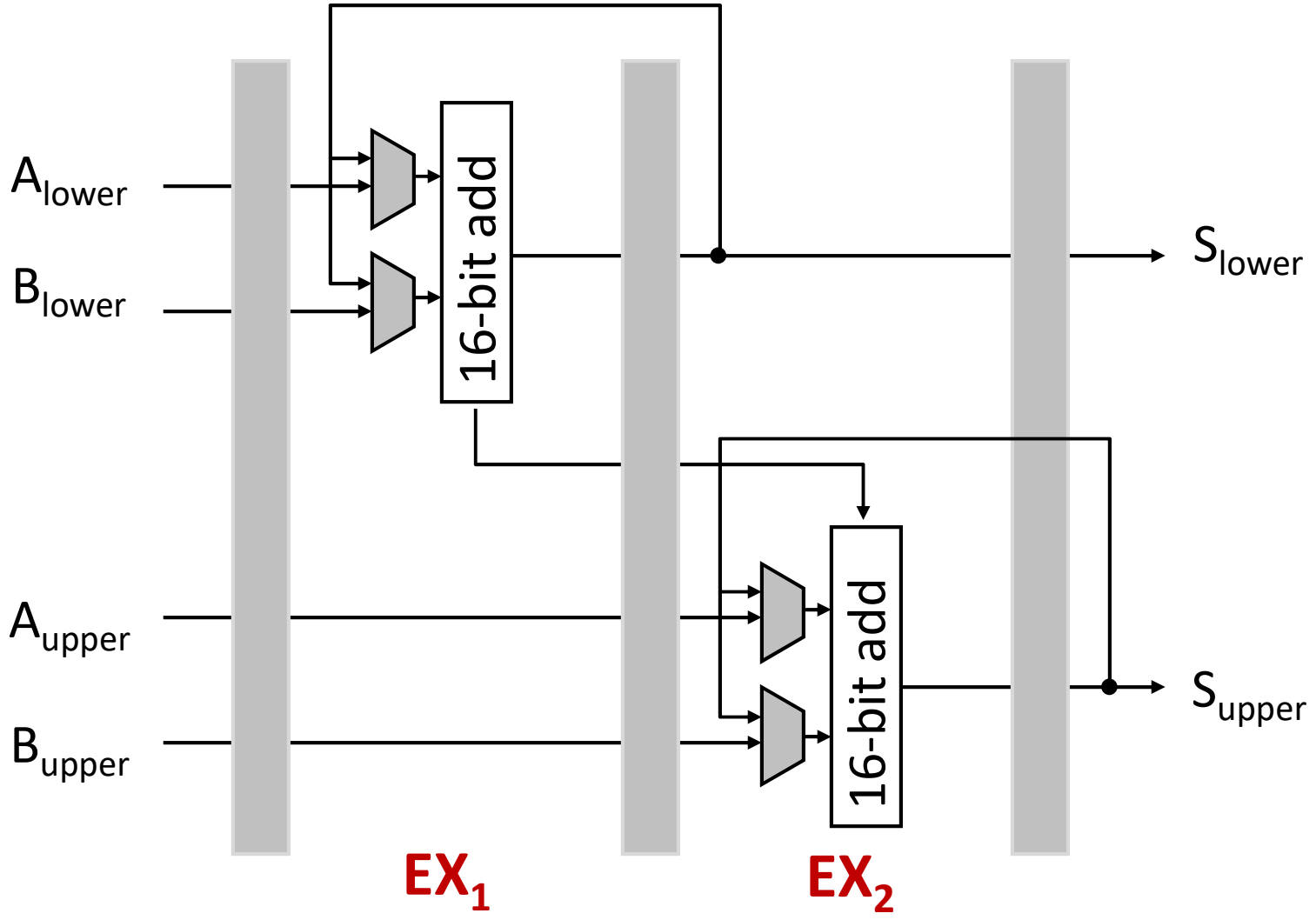
- With only 5 stages, still plenty of combinational logic between registers
- "Superpipelining" ⇒ increase pipelining such that even intrinsic operations (e.g. ALU, RF access, memory access) require multiple stages
- What's the problem?

$Inst_0$: addi x1, x0, 0

$Inst_1$: addi x2, x1, 0



Intel P4's Superpipelined Adder Hack



32-bit addition pipelined over 2 stages, BW=1/latency$_{16\text{-bit-add}}$

No stall between back-to-back dependencies

Terminology

- Dependency
  - property of program
  - ordering requirement between instructions
- Pipeline Hazard:
  - property of uarch when interacting with program
  - (potential) violation of dependencies in program
- Hazard Resolution:
  - static $\Rightarrow$ schedule instructions at compile time to avoid hazards
  - dynamic $\Rightarrow$ detect hazard and adjust pipeline operation

Stall, Flush or Forward

Dependencies and Pipelining
(architecture vs. microarchitecture)

Sequential and atomic instruction semantics

Defines what is correct; doesn't say do it this way

True dependence between two instructions may only require ordering of certain sub-operations