Instruction Pipelining: Hazard Resolution, Timing Constraints

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Resolving Data Hazards

Strategy 1: *Wait for the result to be available by freezing earlier pipeline stages* → *stall*

Strategy 2: *Route data as soon as possible after it is calculated to the earlier pipeline stage* → *bypass*

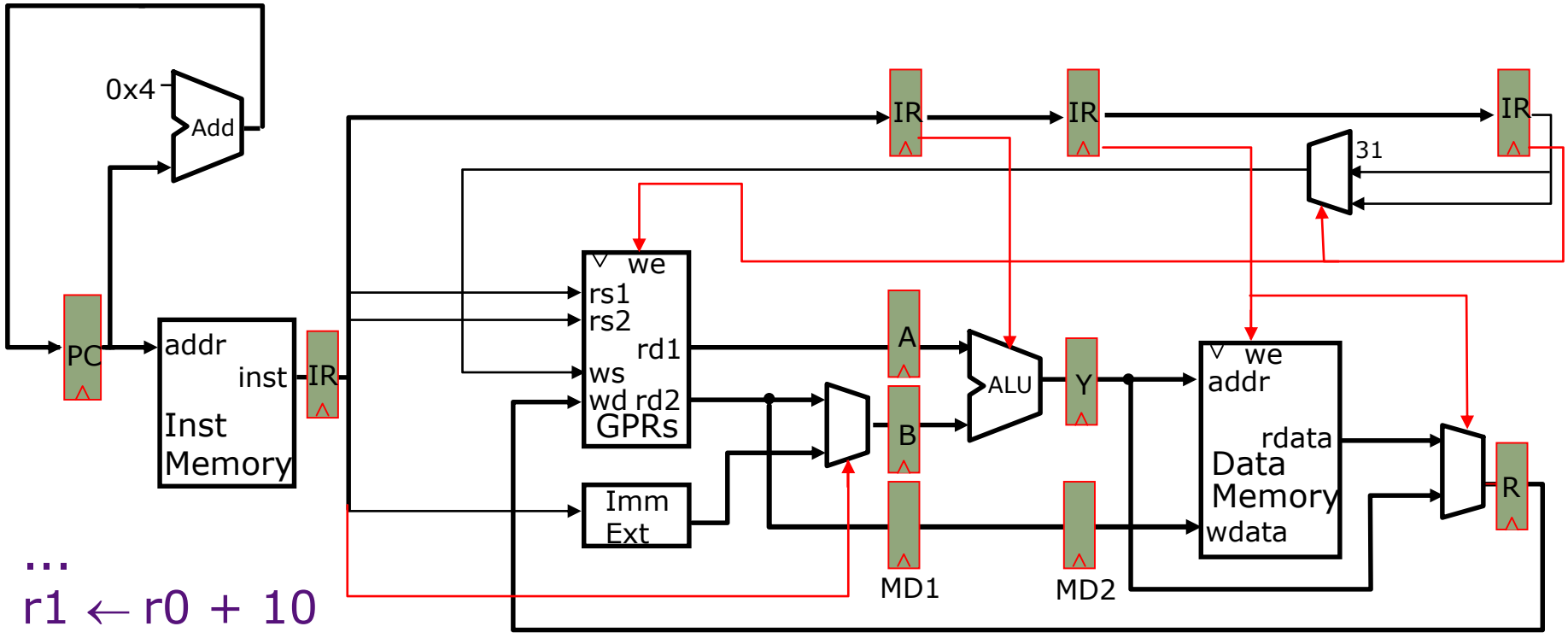
Strategy 3: *Speculate on the dependence*
Two cases:
Guessed correctly → no special action required
Guessed incorrectly → kill and restart

Resolving Data Hazards (1)

Strategy 1:

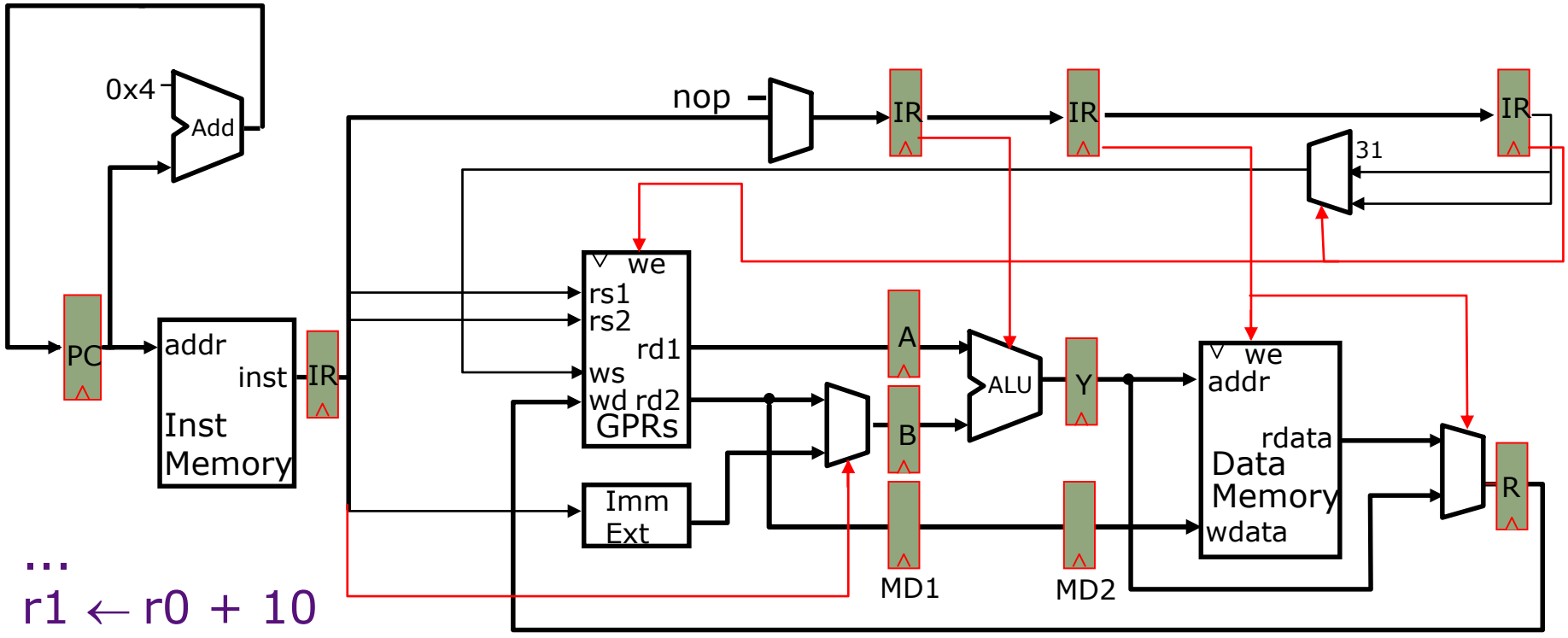
Wait for the result to be available by freezing earlier pipeline stages → stall (interlocks)

Resolving Data Hazards by Stalling



...
r1 ← r0 + 10
r4 ← r1 + 17
...

Resolving Data Hazards by Stalling



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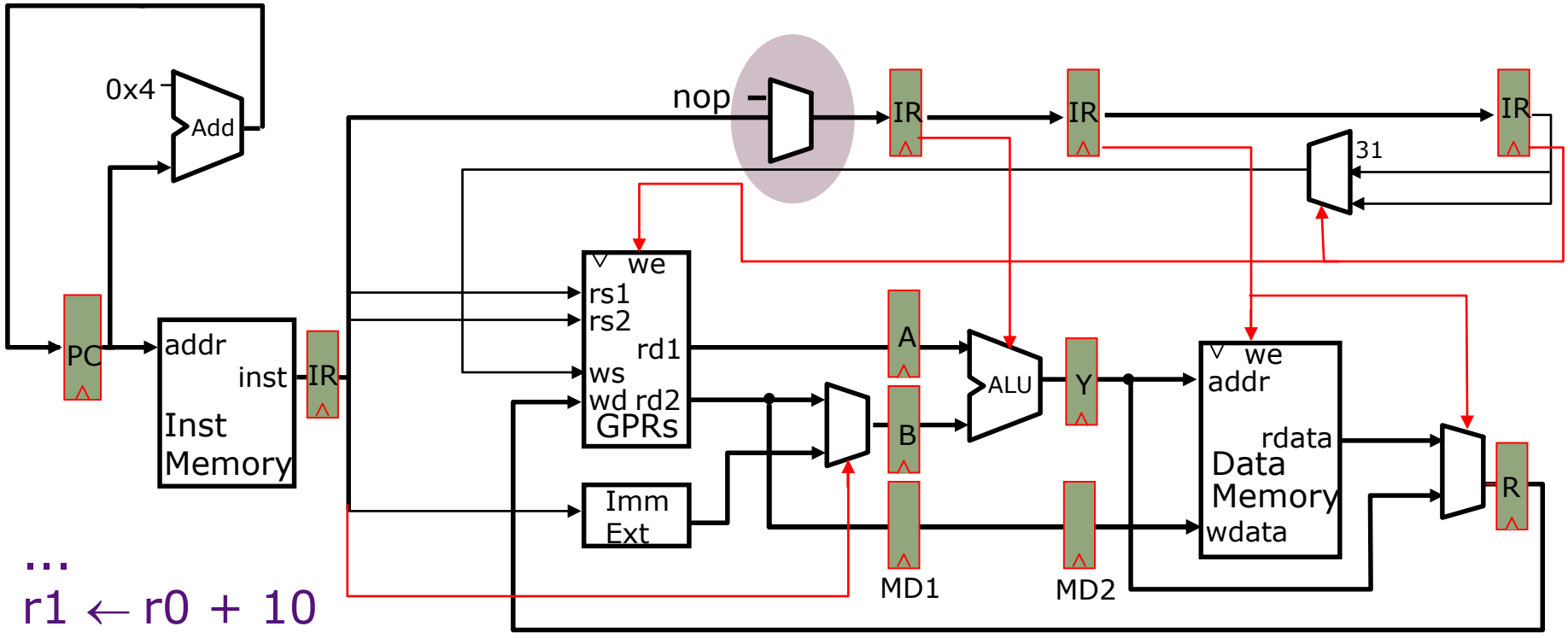
Resolving Data Hazards by Stalling



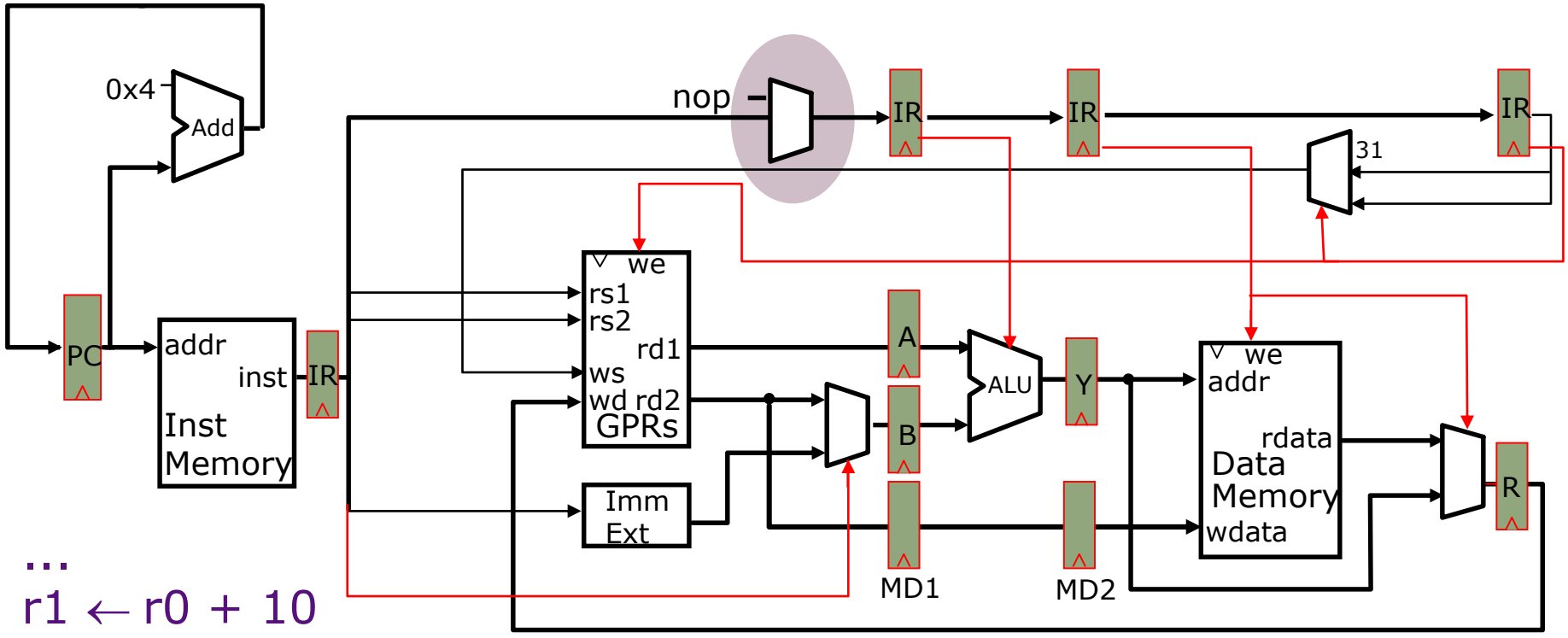
...

$r1 \leftarrow r0 + 10$

$r4 \leftarrow r1 + 17$

...

Resolving Data Hazards by Stalling



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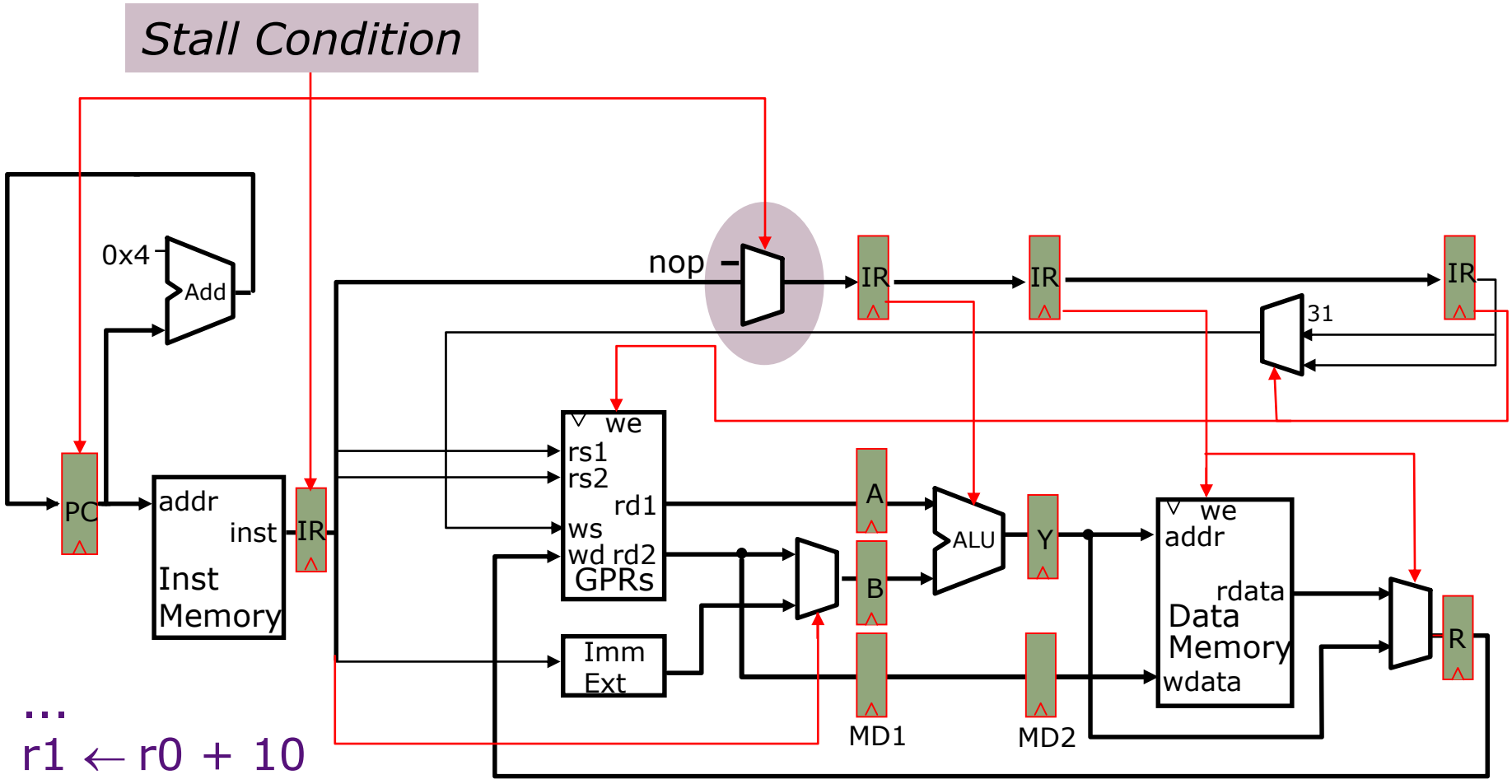
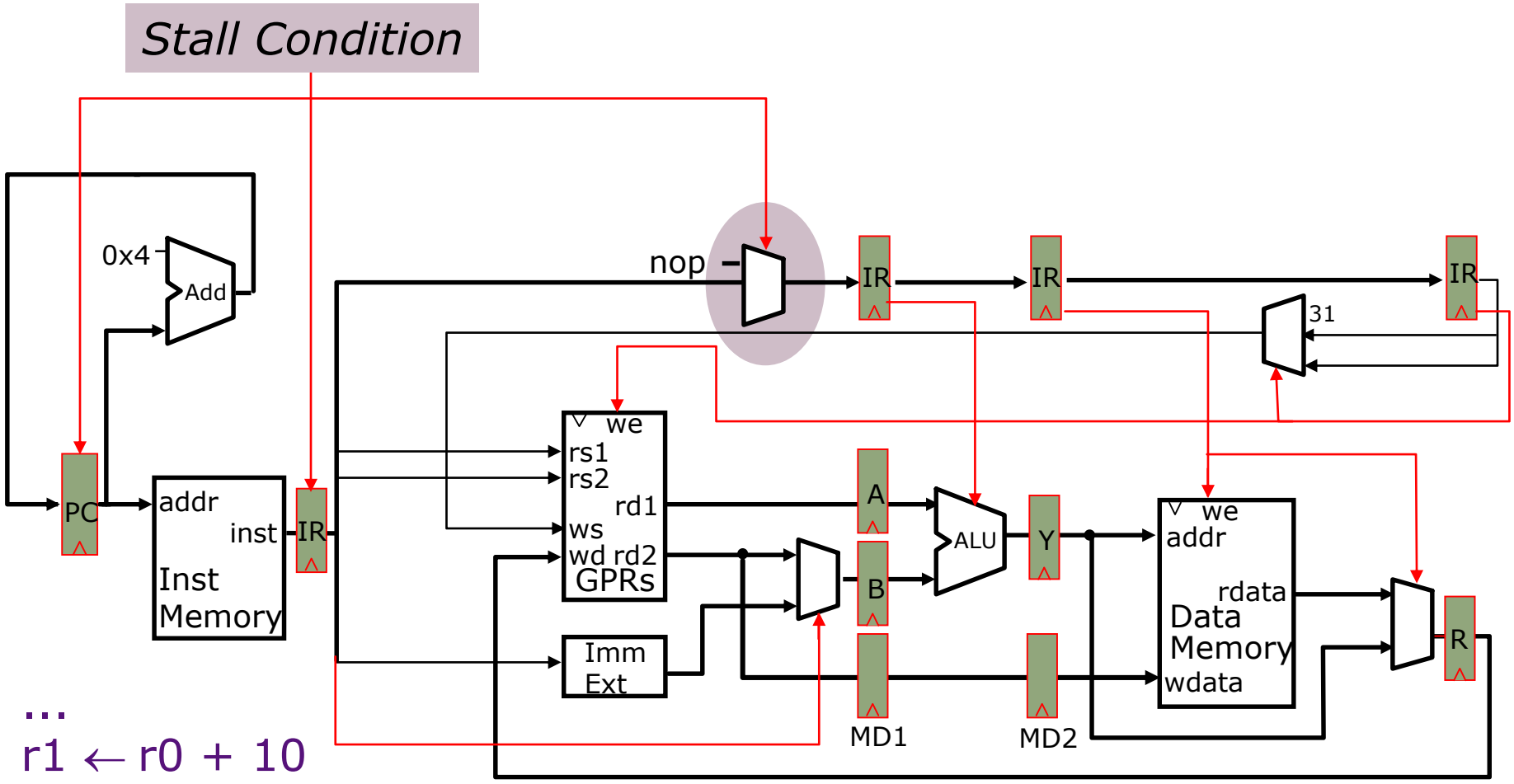
Resolving Data Hazards by Stalling



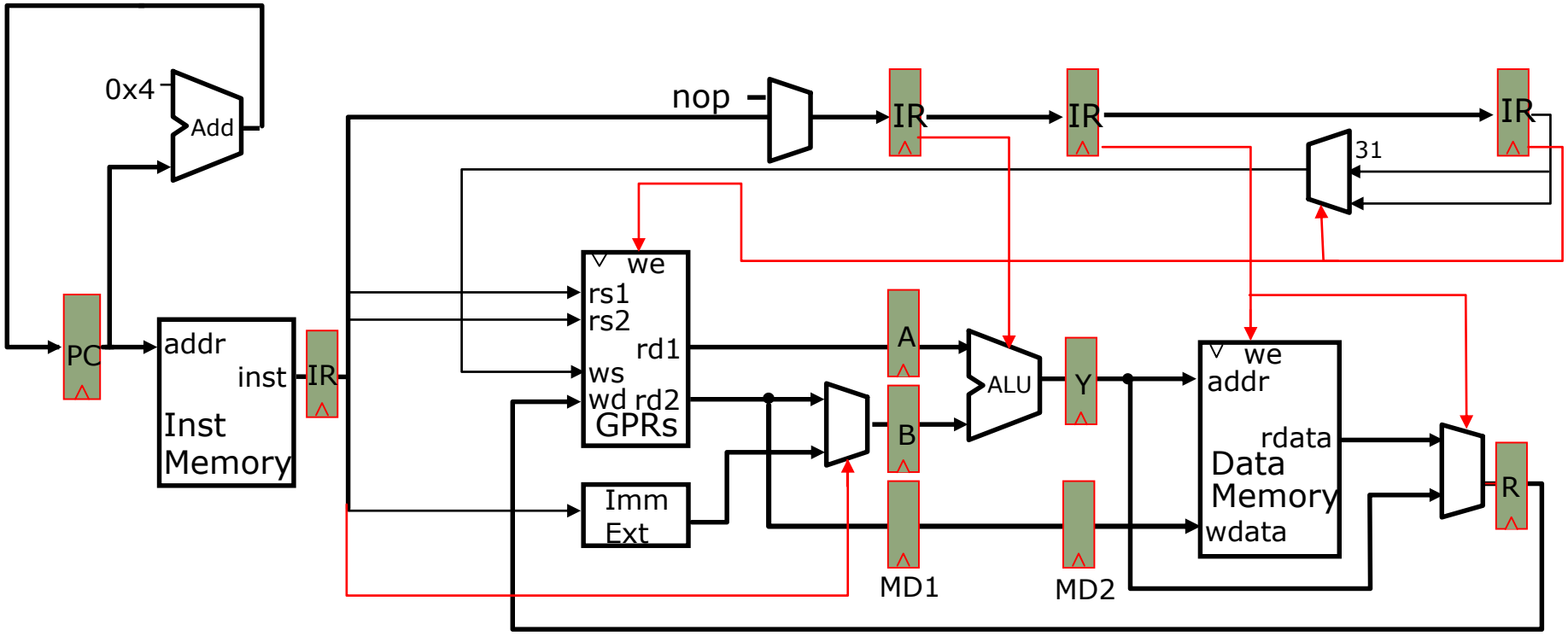
Resolving Data Hazards by Stalling



...
r1 ← r0 + 10
r4 ← r1 + 17
...

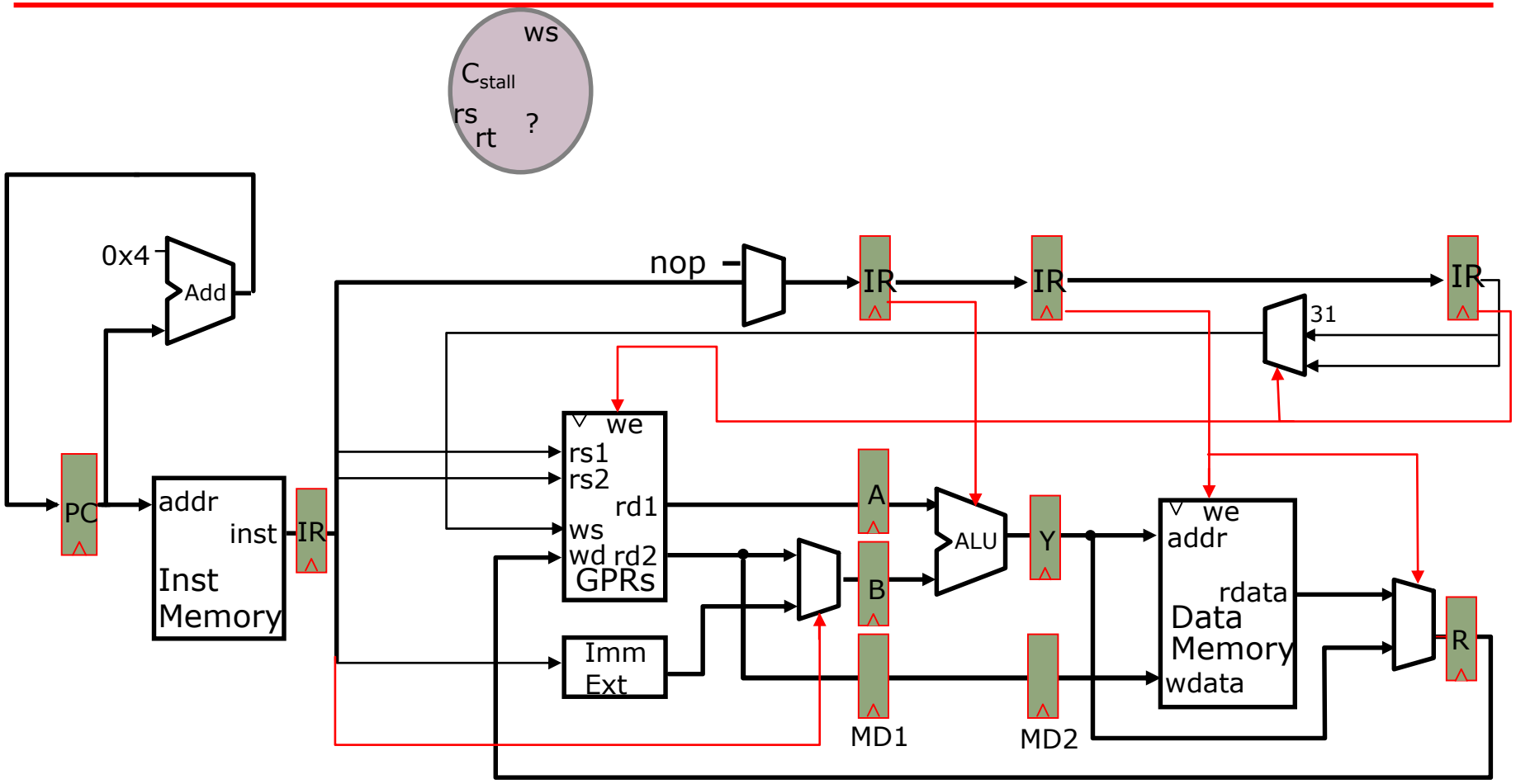
How do we know when to stall?

Stall Control Logic



Compare the *source registers* of the instruction in the decode stage with the *destination register* of the *uncommitted in*structions.

Stall Control Logic



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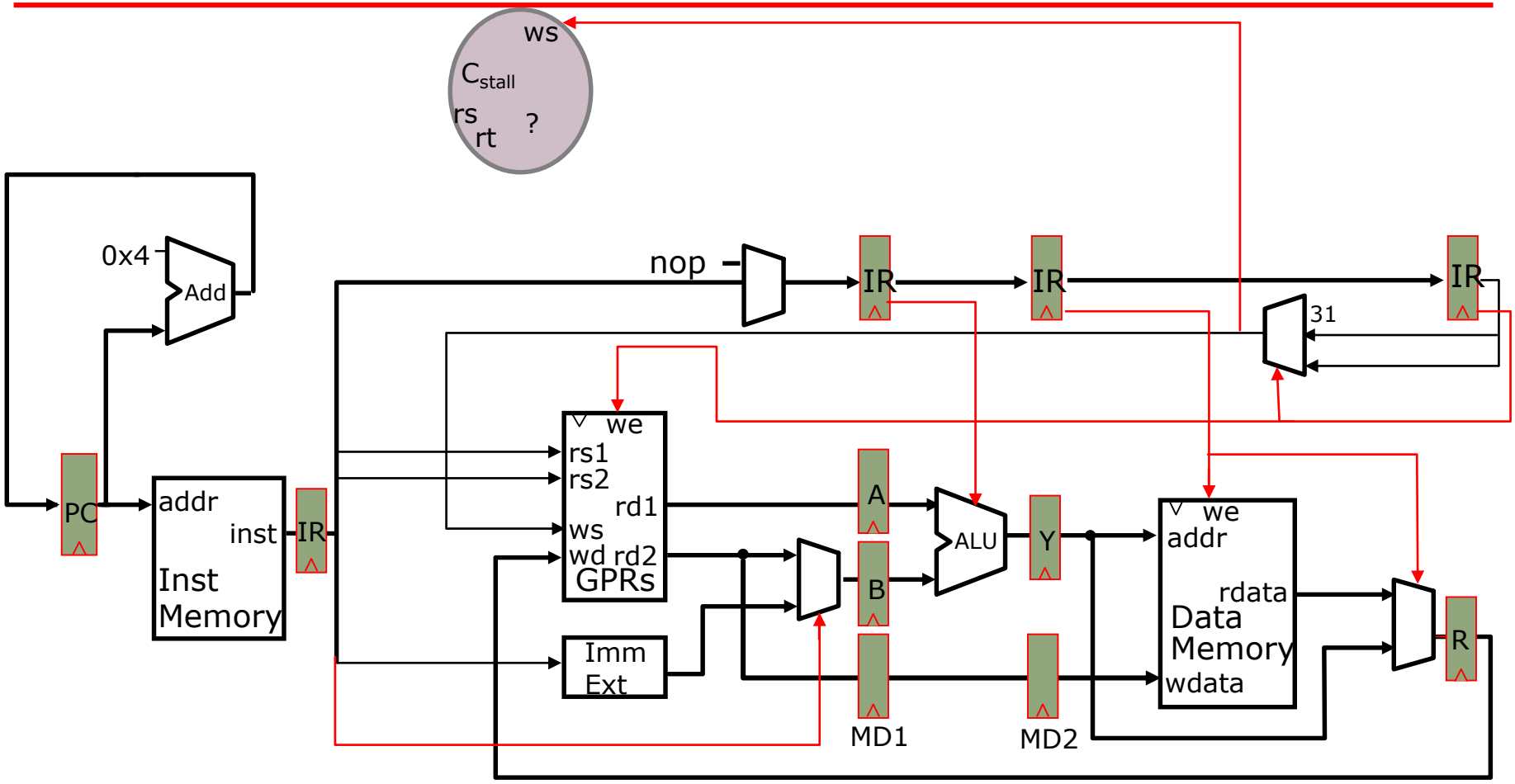
Stall Control Logic



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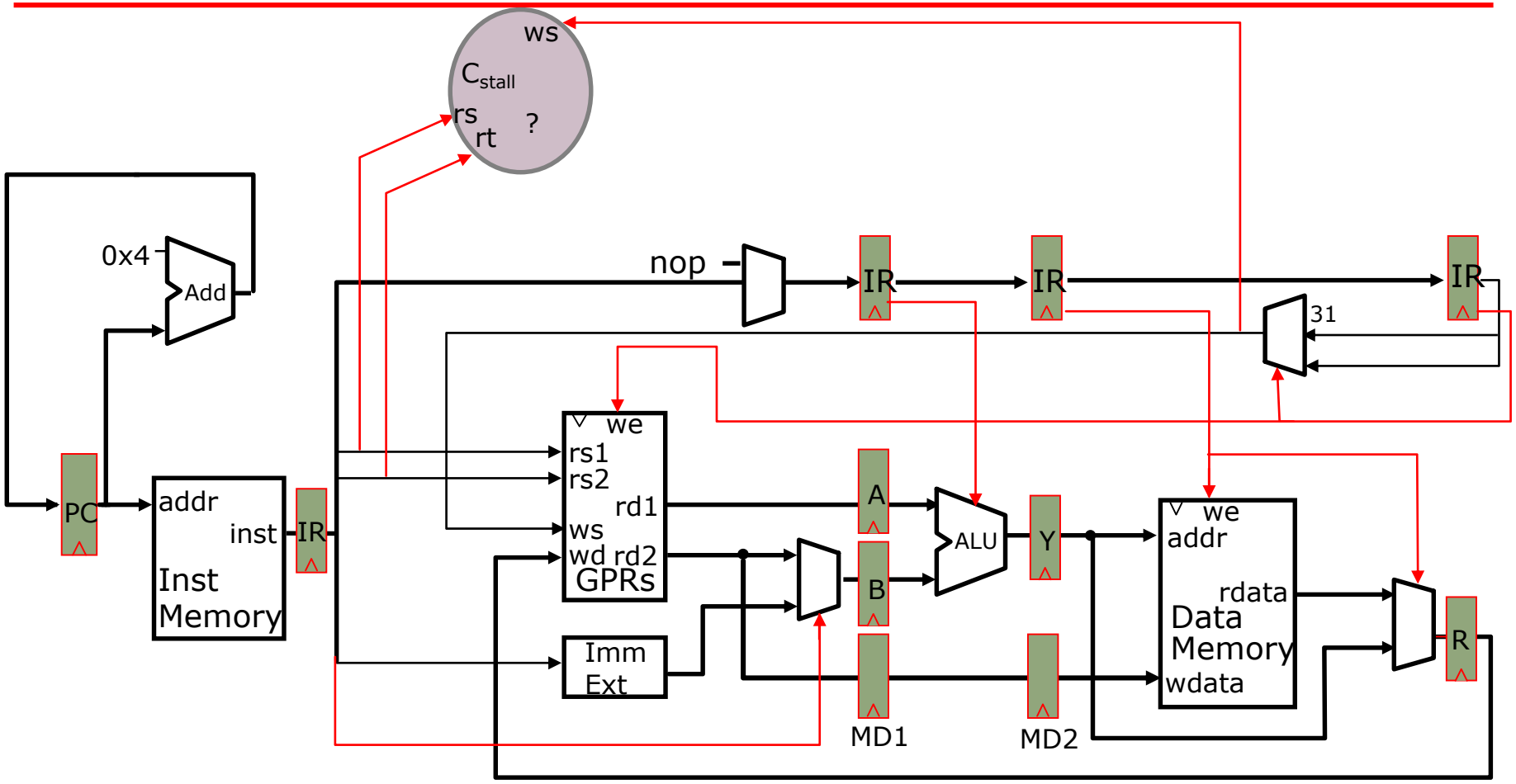
Stall Control Logic



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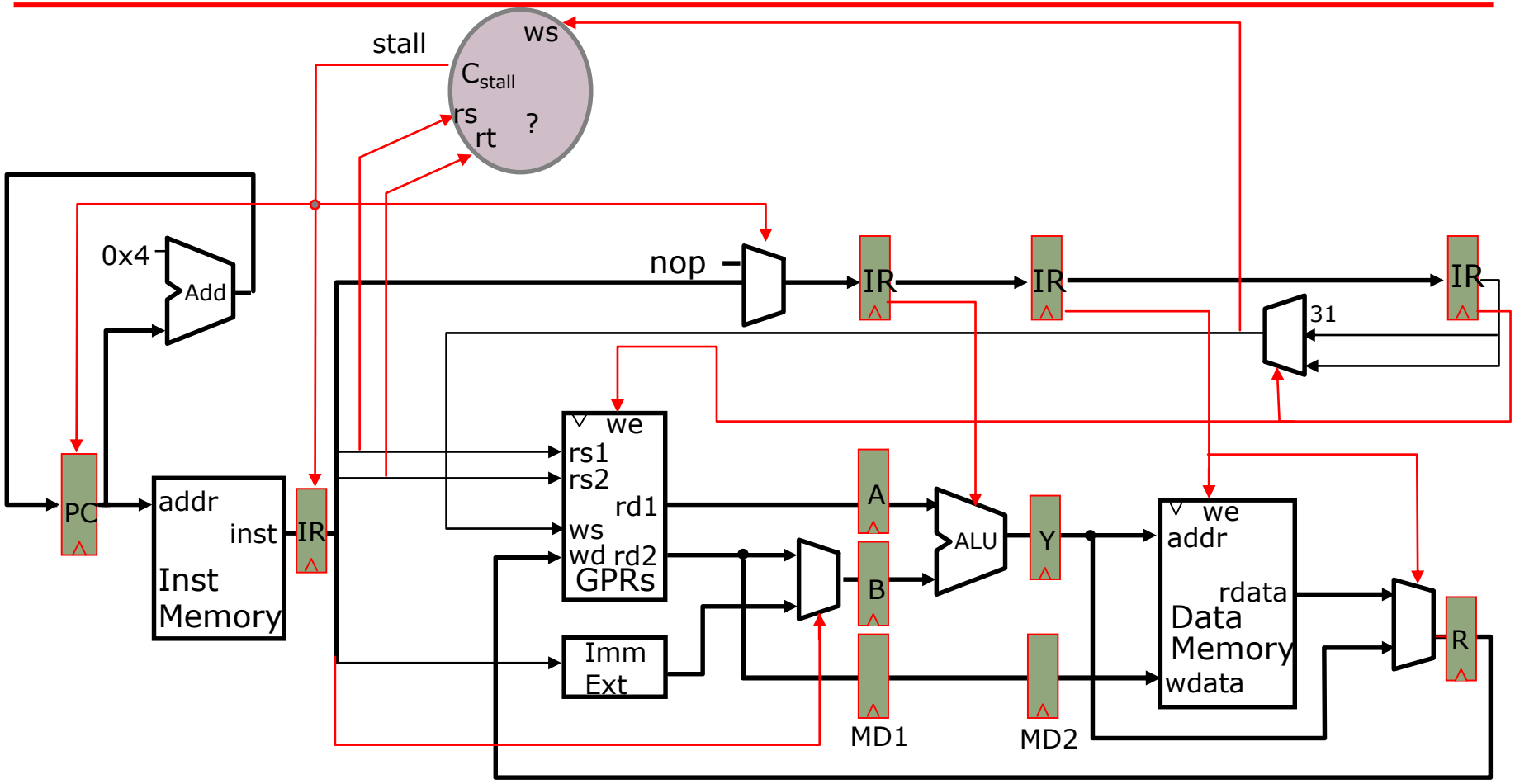
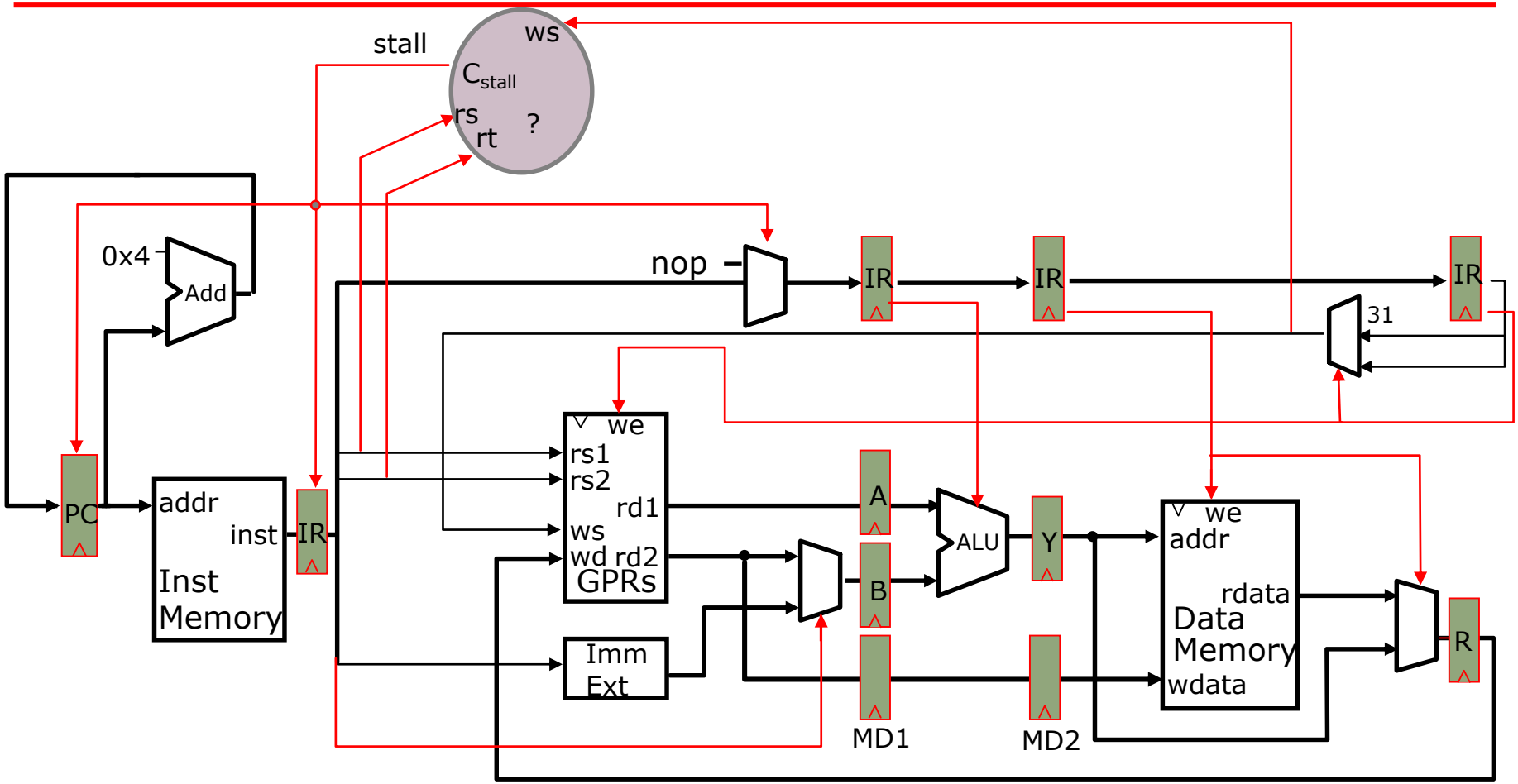
Stall Control Logic



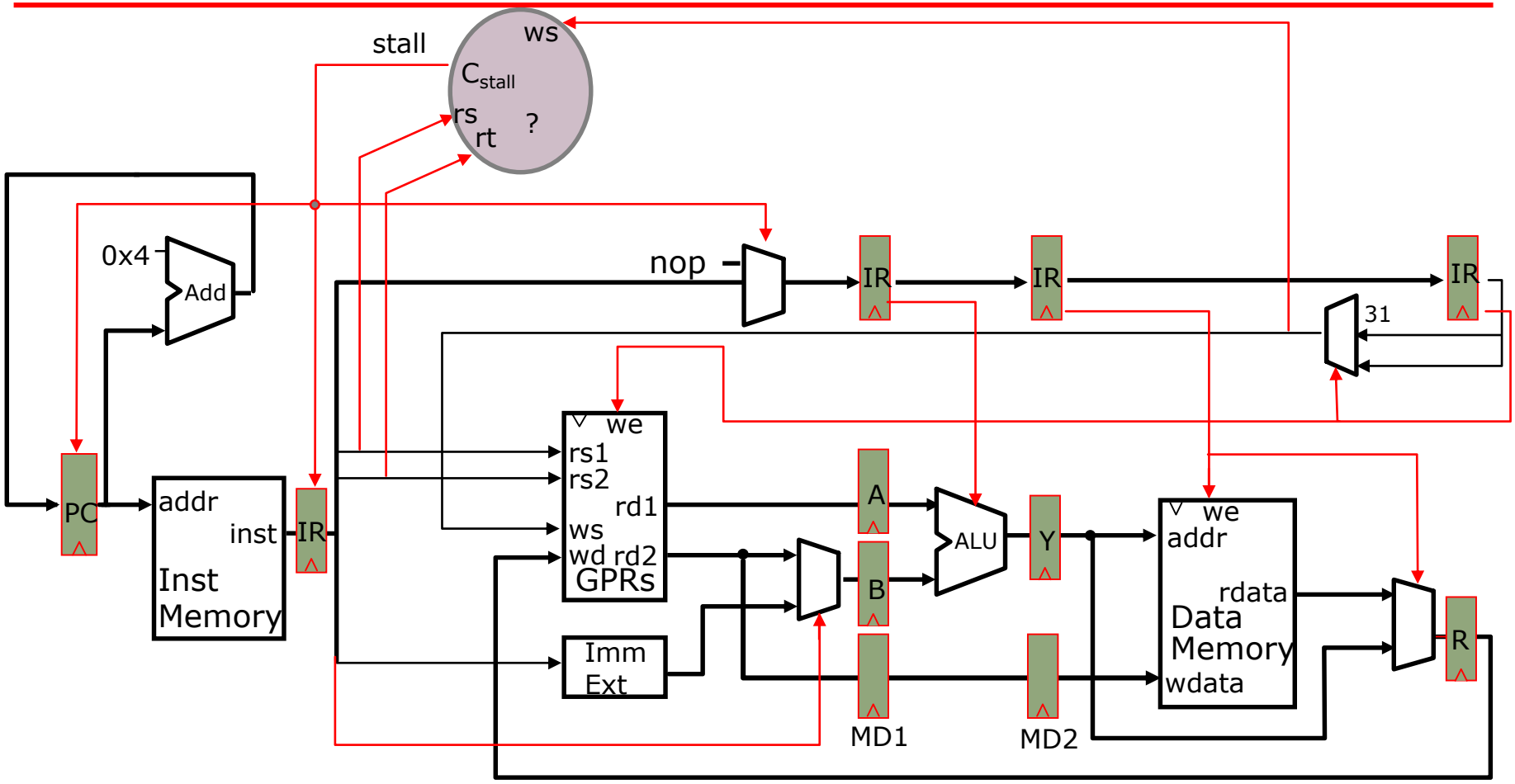
Compare the *source registers* of the instruction in the decode stage with the *destination register* of the *uncommitted in*structions.

Stall Control Logic
ignoring jumps & branches



Should we always stall if the rs field matches some rd?

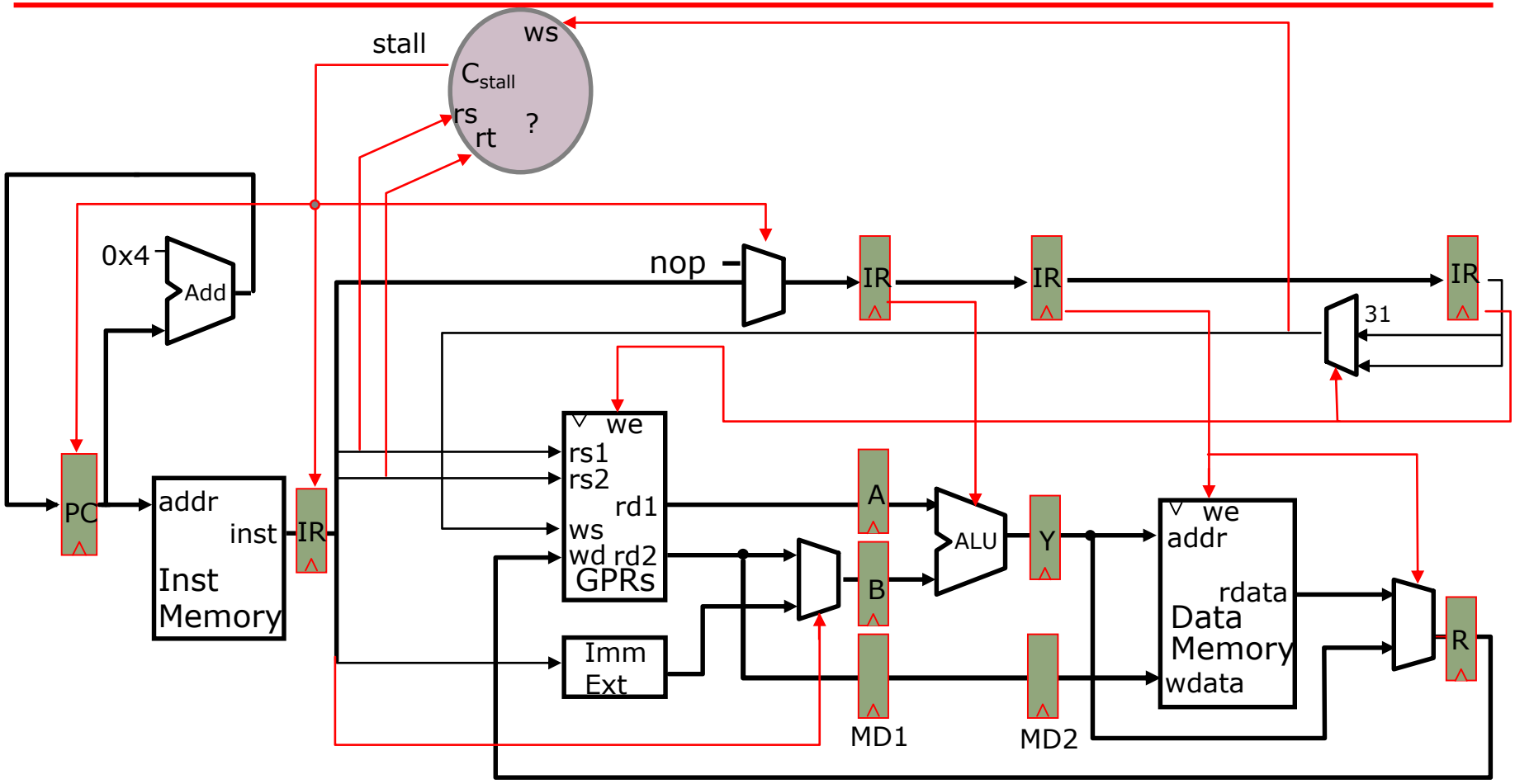
Stall Control Logic
ignoring jumps & branches



Should we always stall if the rs field matches some rd?

not every instruction writes a register ⇒ we

Stall Control Logic
ignoring jumps & branches



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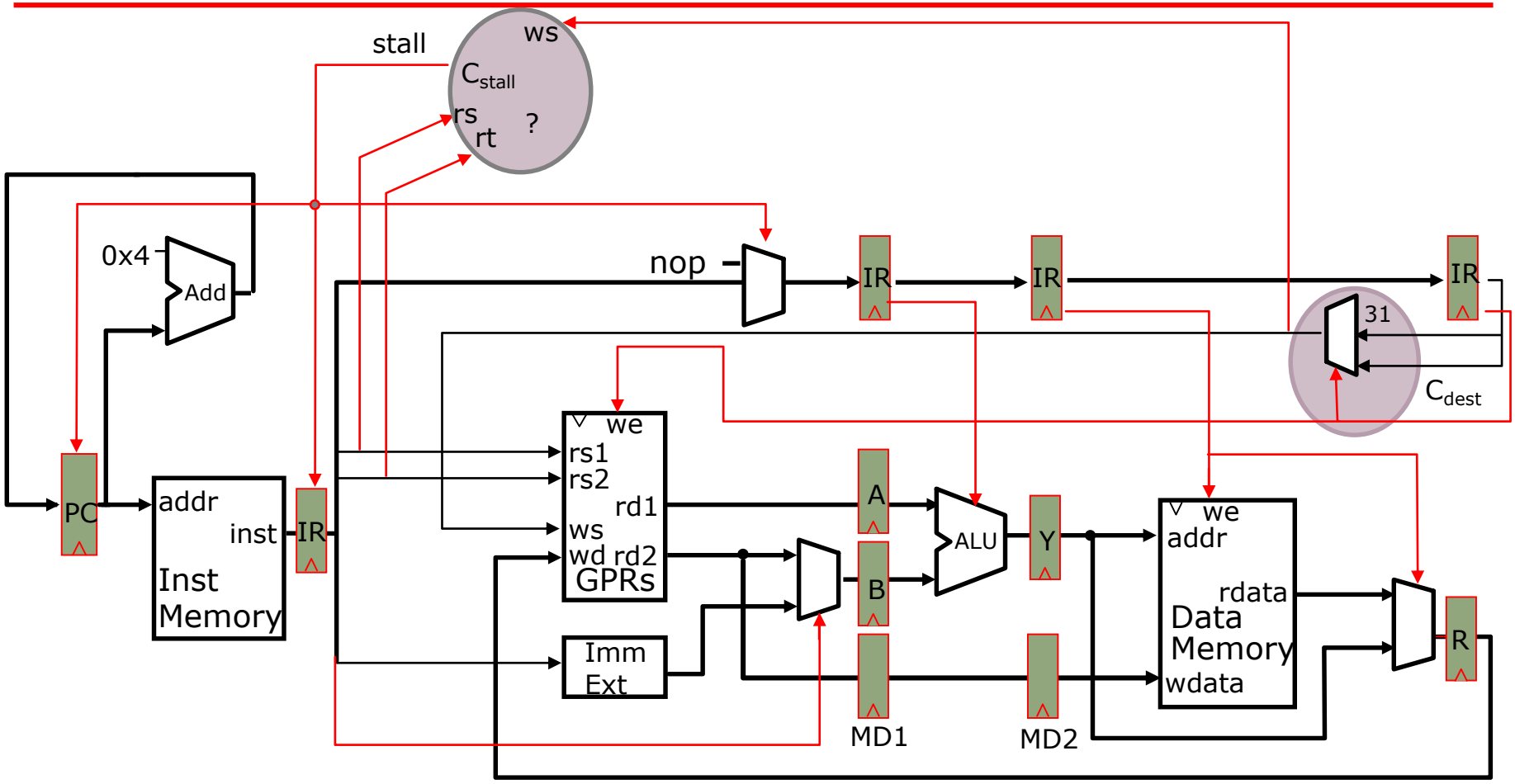
ignoring jumps & branches



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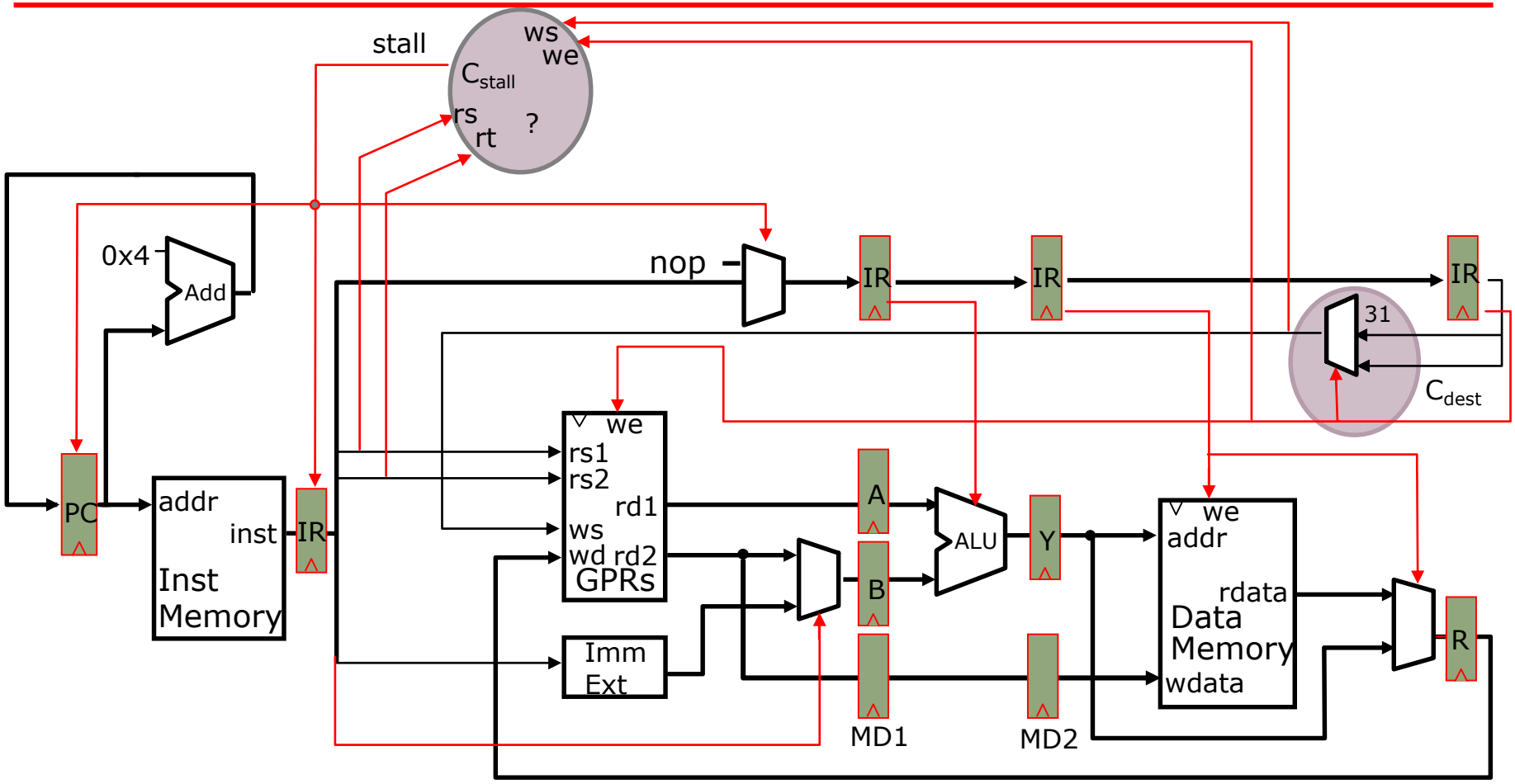

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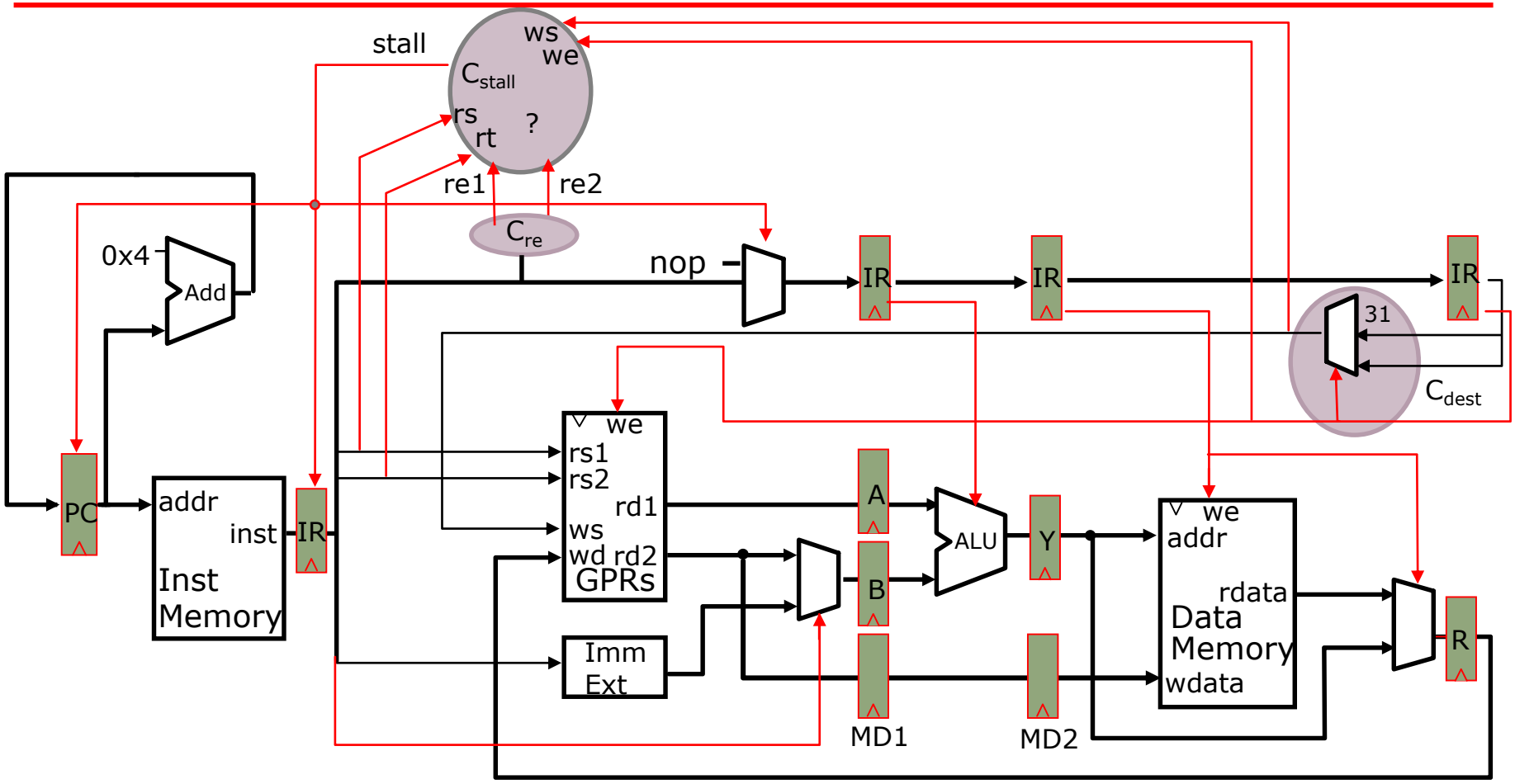
Stall Control Logic
ignoring jumps & branches



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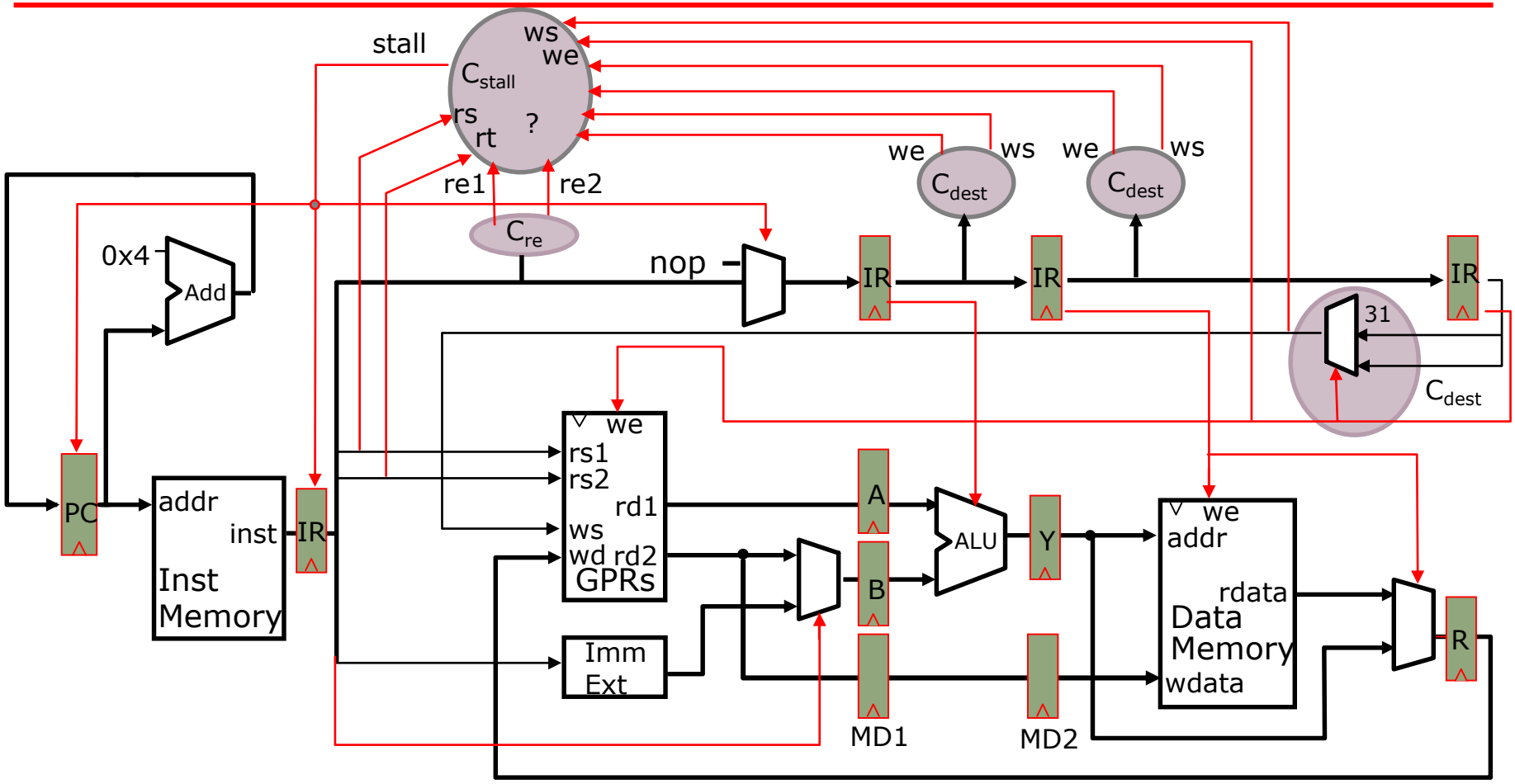
Stall Control Logic
ignoring jumps & branches



Should we always stall if the rs field matches some rd?

not every instruction writes a register ⇒ we

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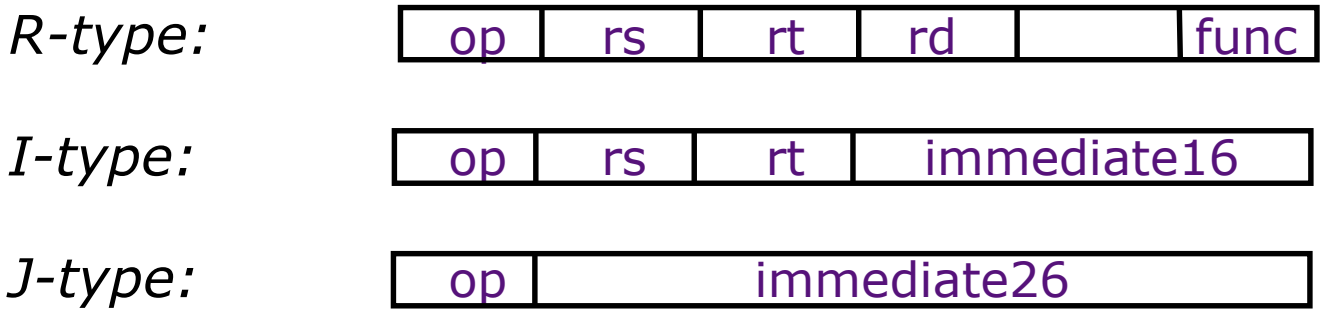
Source & Destination Registers



		source(s)	*destination*
ALU	rd ← (rs) func (rt)	rs, rt	rd
ALUi	rt ← (rs) op imm	rs	rt
LW	rt ← M [(rs) + imm]	rs	rt
SW	M [(rs) + imm] ← (rt)	rs, rt	
BZ	*cond* (rs)		
	true: PC ← (PC) + imm	rs	
	false: PC ← (PC) + 4	rs	
J	PC ← (PC) + imm		
JAL	r31 ← (PC), PC ← (PC) + imm		31
JR	PC ← (rs)	rs	
JALR	r31 ← (PC), PC ← (rs)	rs	31

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒ (ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi,	
	⇒ on
	⇒ off

re2 = *Case* opcode

	⇒ on
	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ,	⇒ on
	⇒ off

re2 = *Case* opcode

	⇒ on
	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
	⇒ off

re2 = *Case* opcode

	⇒ on
	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
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JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

	⇒ on
	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E) \cdot we_E +$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E) \cdot we_E + (rs_D == ws_M) \cdot we_M +$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒ (ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E) \cdot we_E + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D \quad +$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E) \cdot we_E + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D + ((rt_D == ws_E) \cdot we_E +$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E) \cdot we_E + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D + ((rt_D == ws_E) \cdot we_E +$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒ (ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E) \cdot we_E + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D + ((rt_D == ws_E) \cdot we_E + (rt_D == ws_M) \cdot we_M +$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒ (ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$\begin{aligned} stall = ((rs_D == ws_E)\cdot we_E + \\ (rs_D == ws_M)\cdot we_M + \\ (rs_D == ws_W)\cdot we_W)\cdot re1_D \quad + \\ ((rt_D == ws_E)\cdot we_E + \\ (rt_D == ws_M)\cdot we_M + \\ (rt_D == ws_W)\cdot we_W)\cdot re2_D \end{aligned}$$

Deriving the Stall Signal

C_{dest}

ws = *Case* opcode

ALU	⇒ rd
ALUi, LW	⇒ rt
JAL, JALR	⇒ R31

we = *Case* opcode

ALU, ALUi, LW	⇒(ws ≠ 0)
JAL, JALR	⇒ on
...	⇒ off

C_{re}

re1 = *Case* opcode

ALU, ALUi, LW, SW, BZ, JR, JALR	⇒ on
J, JAL	⇒ off

re2 = *Case* opcode

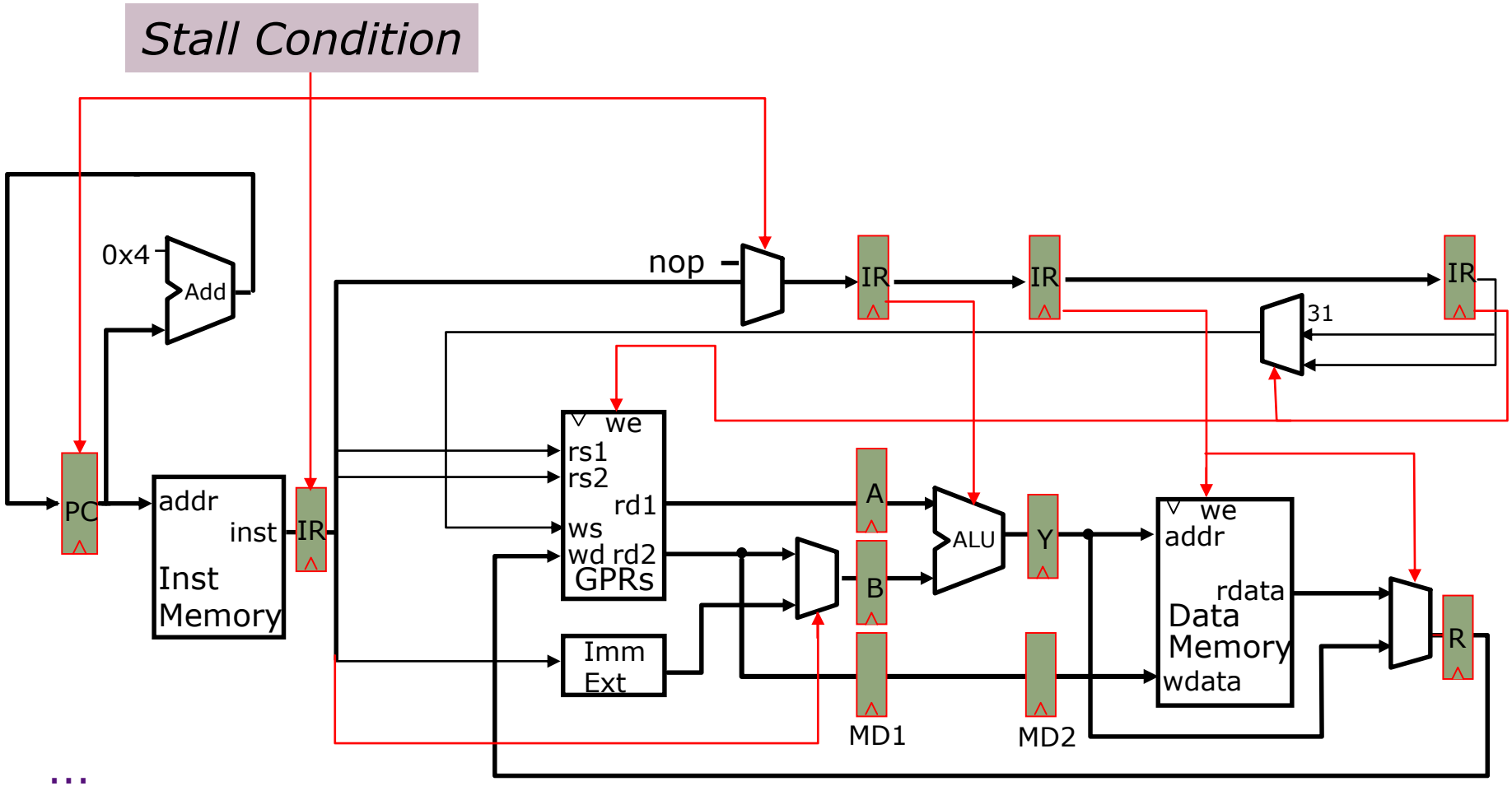
ALU, SW	⇒ on
...	⇒ off

C_{stall}

$$stall = ((rs_D == ws_E)\cdot we_E + (rs_D == ws_M)\cdot we_M + (rs_D == ws_W)\cdot we_W)\cdot re1_D + ((rt_D == ws_E)\cdot we_E + (rt_D == ws_M)\cdot we_M + (rt_D == ws_W)\cdot we_W)\cdot re2_D$$

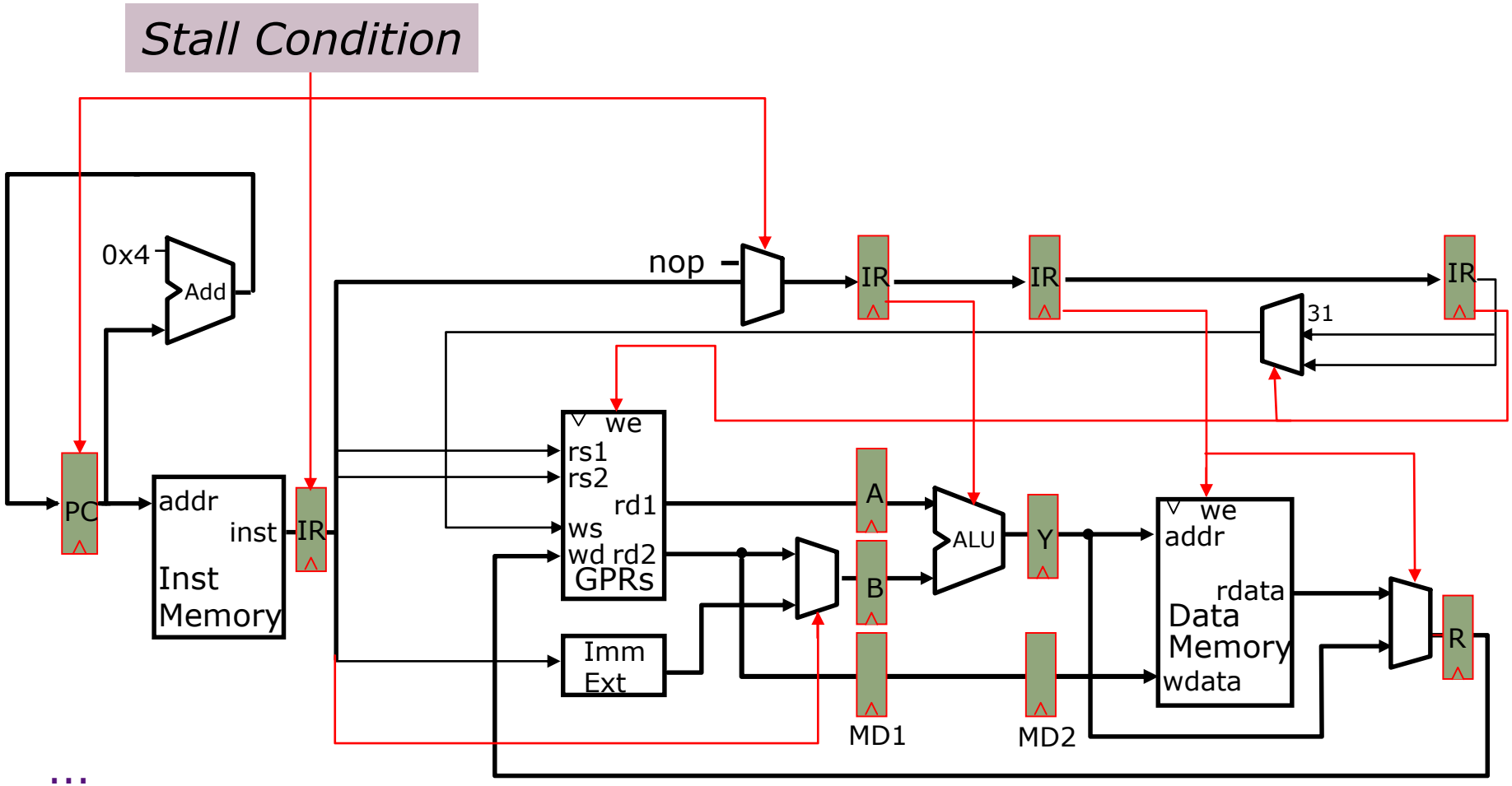
This is not the full story !

Hazards due to Loads & Stores



...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...

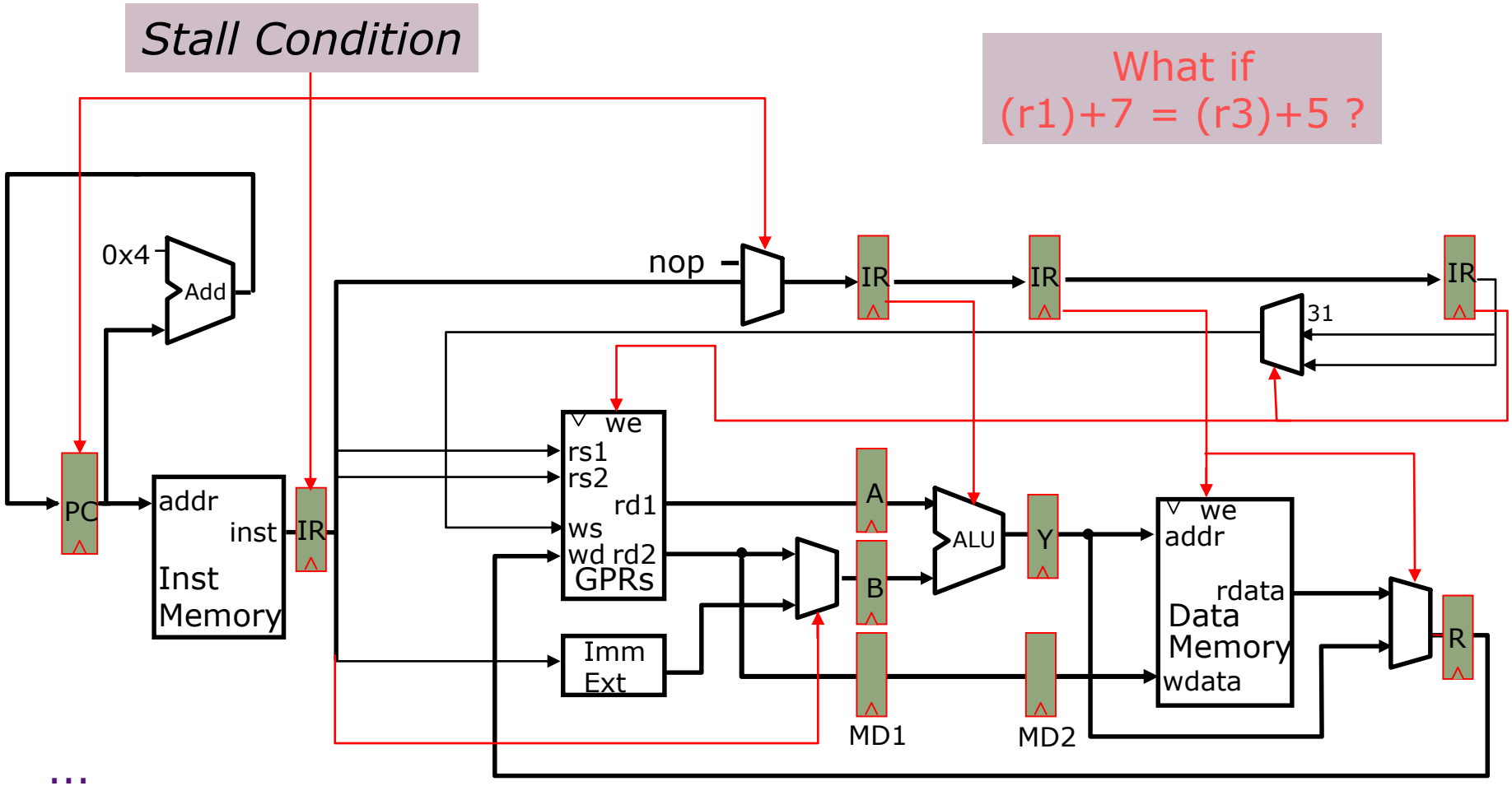
Hazards due to Loads & Stores



...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...

Is there any possible data hazard in this instruction sequence?

Hazards due to Loads & Stores



...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...

Is there any possible data hazard in this instruction sequence?

Load & Store Hazards

```
...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...
```

(r1)+7 = (r3)+5 ⇒ *data hazard*

Load & Store Hazards

```
...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...
```

(r1)+7 = (r3)+5 ⇒ *data hazard*

However, the hazard is avoided because *our memory system completes writes in one cycle!*

Load & Store Hazards

```
...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...
```

(r1)+7 = (r3)+5 ⇒ *data hazard*

However, the hazard is avoided because *our memory system completes writes in one cycle!*

Load/Store hazards are sometimes resolved in the pipeline and sometimes in the memory system itself.

Load & Store Hazards

```
...
M[(r1)+7] ← (r2)
r4 ← M[(r3)+5]
...
```

(r1)+7 = (r3)+5 ⇒ *data hazard*

However, the hazard is avoided because *our memory system completes writes in one cycle!*

Load/Store hazards are sometimes resolved in the pipeline and sometimes in the memory system itself.

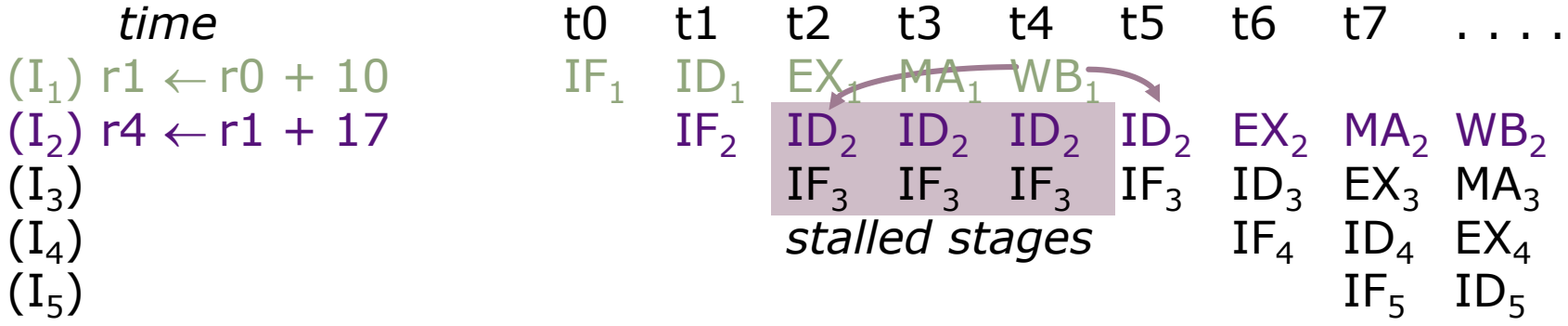
More on this later in the course.

Resolving Data Hazards (2)

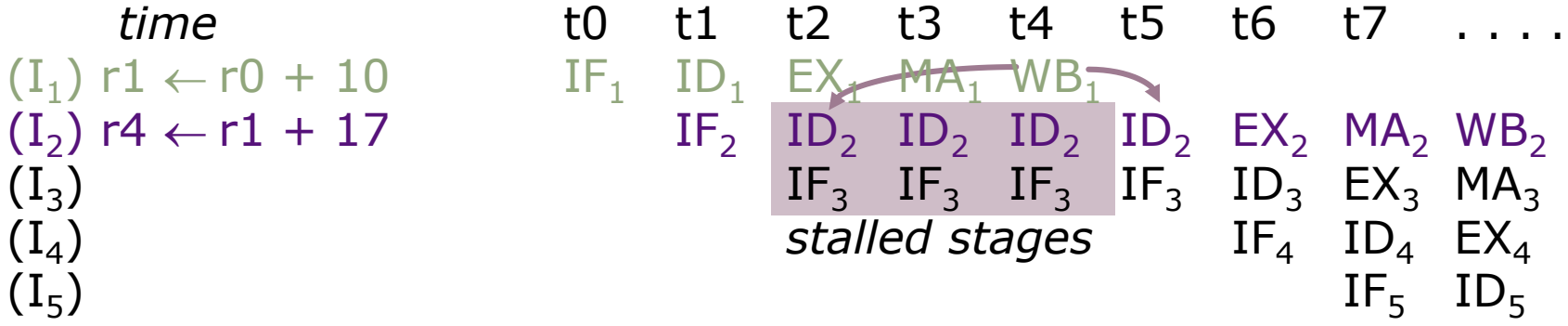
Strategy 2:

Route data as soon as possible after it is calculated to the earlier pipeline stage → *bypass*

Bypassing

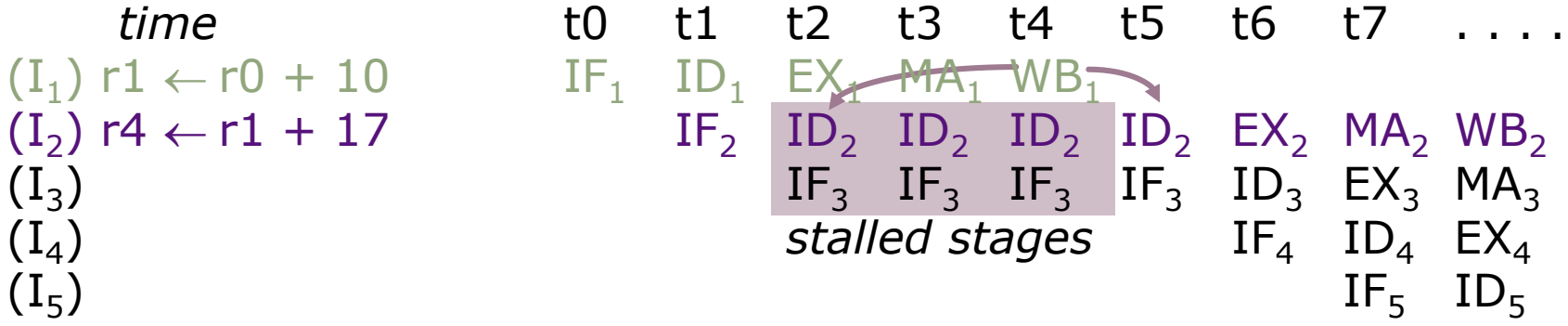

time
t0 t1 t2 t3 t4 t5 t6 t7 . . . .
(I1) r1 ← r0 + 10
IF1 ID1 EX1 MA1 WB1
(I2) r4 ← r1 + 17
IF2 ID2 ID2 ID2 ID2 EX2 MA2 WB2
(I3)
IF3 IF3 IF3 IF3 ID3 EX3 MA3
(I4)
stalled stages
IF4 ID4 EX4
(I5)
IF5 ID5

Bypassing



Each *stall or kill* introduces a bubble $\Rightarrow$ *CPI* > *1*

Bypassing



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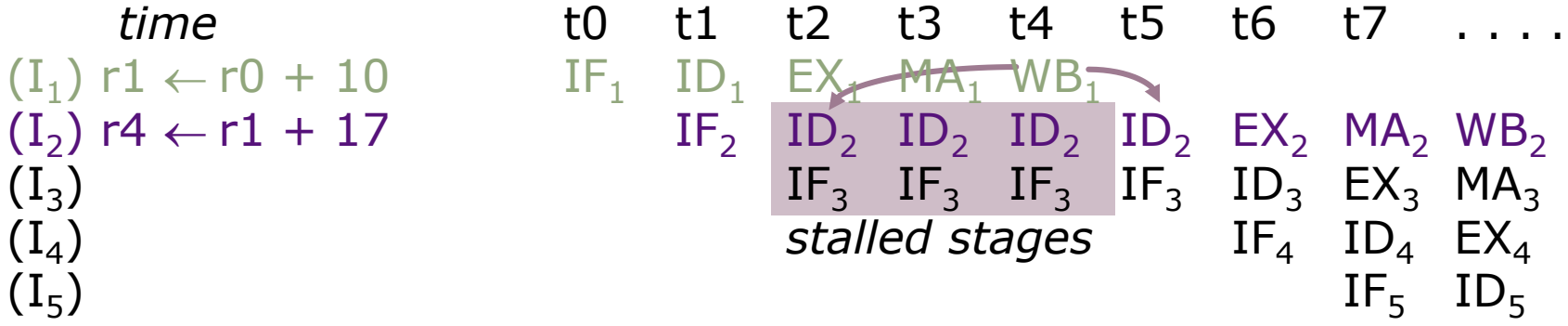
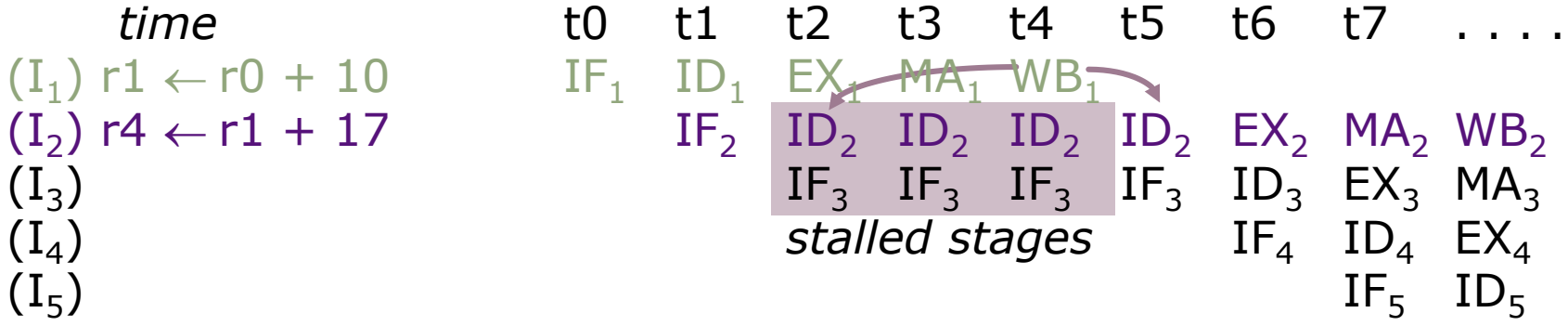


Each *stall or kill* introduces a bubble $\Rightarrow$ *CPI* > *1*

When is data actually available?

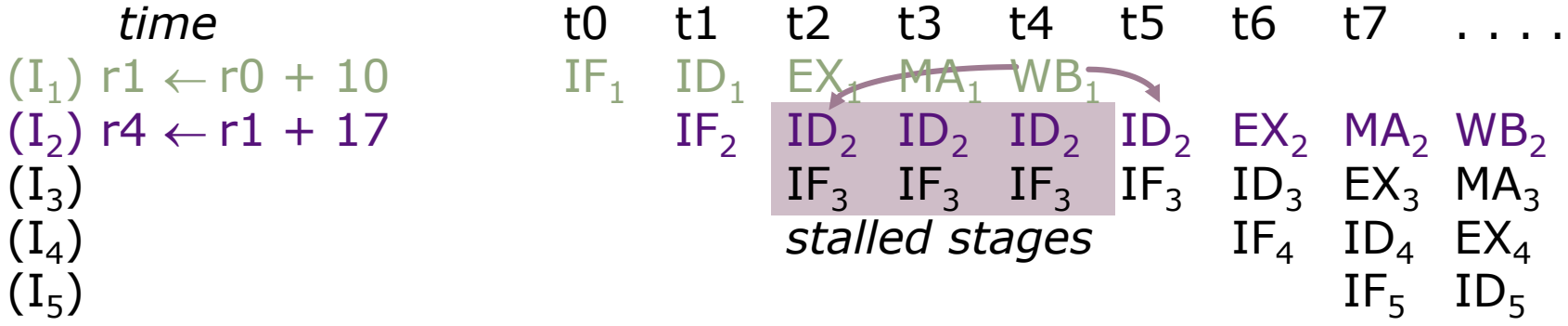
Bypassing



Each *stall or kill* introduces a bubble $\Rightarrow$ *CPI* > *1*

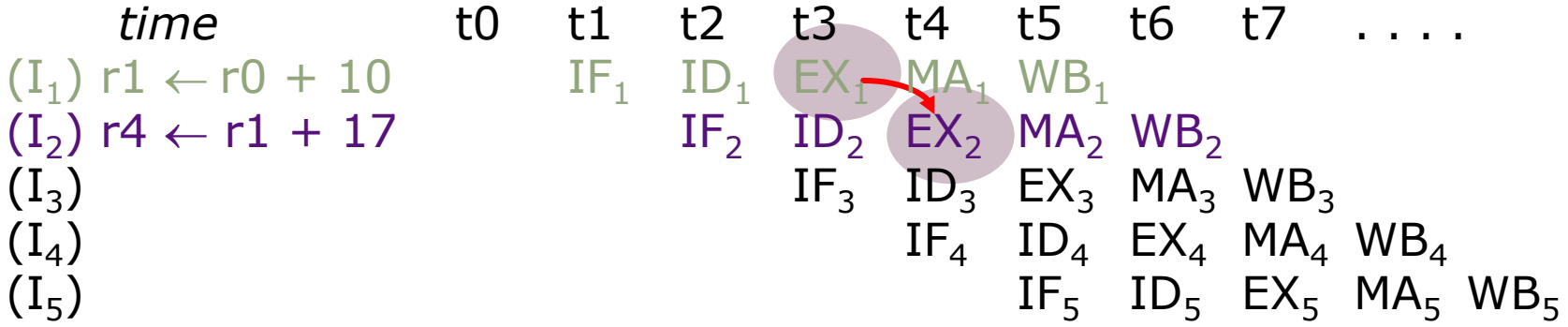
When is data actually available? At Execute

Bypassing

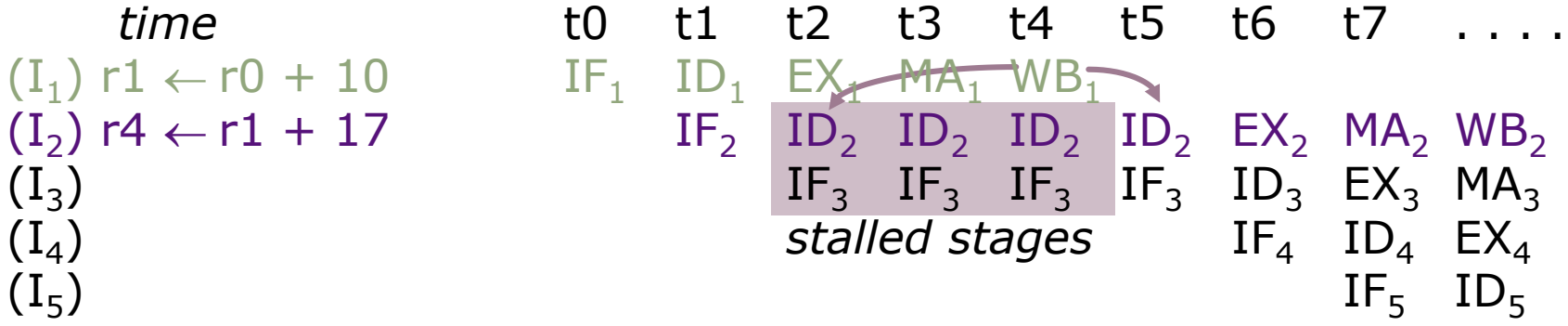


Each *stall or kill* introduces a bubble ⇒ *CPI > 1*

When is data actually available? At Execute



Bypassing



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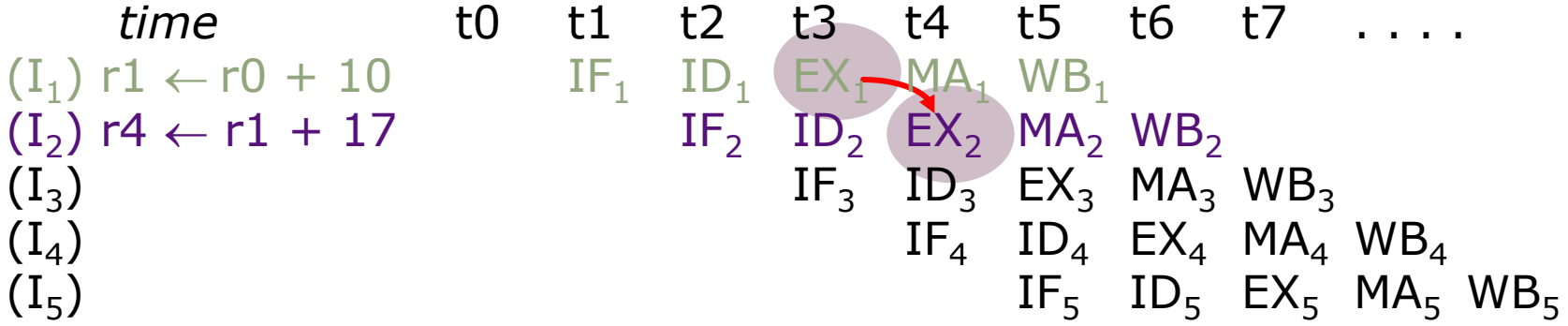
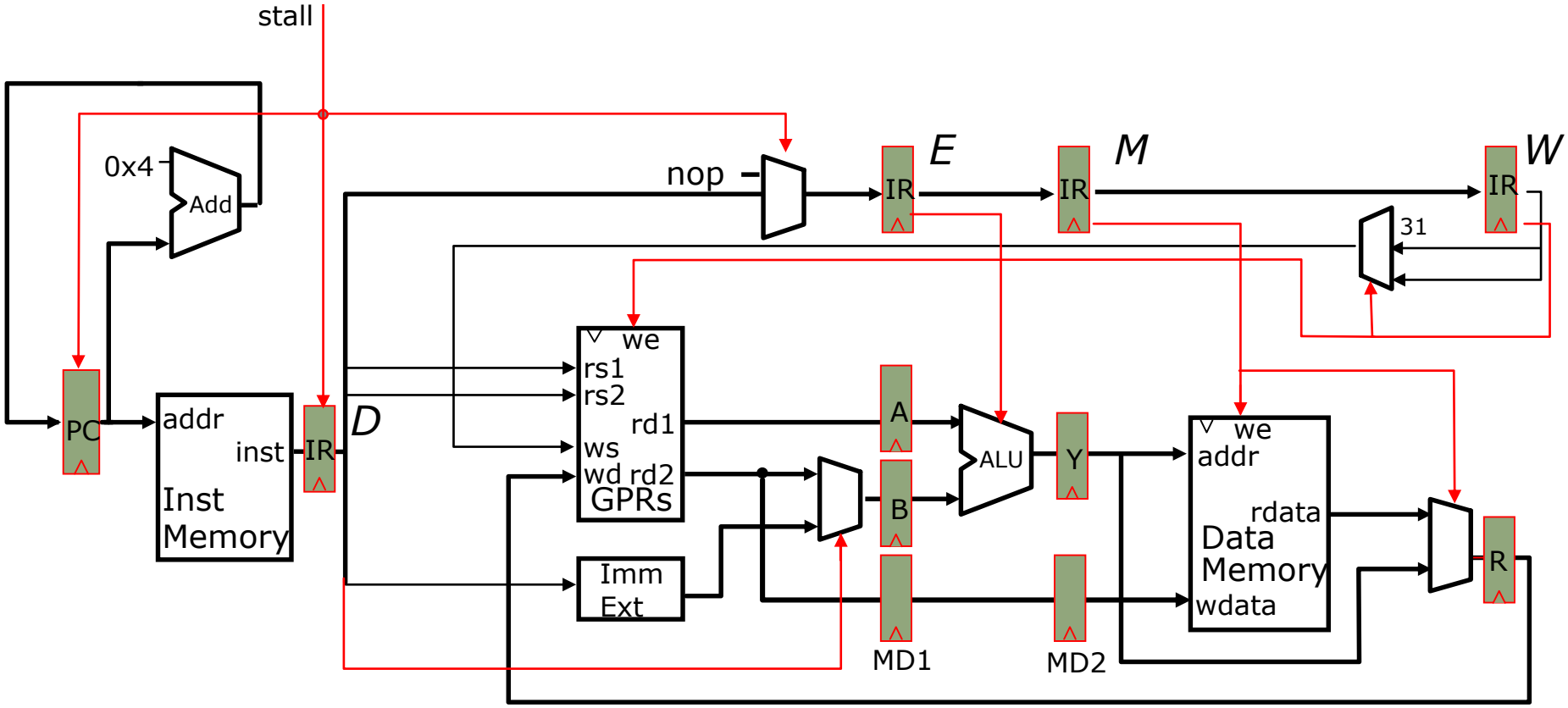
When is data actually available? At Execute

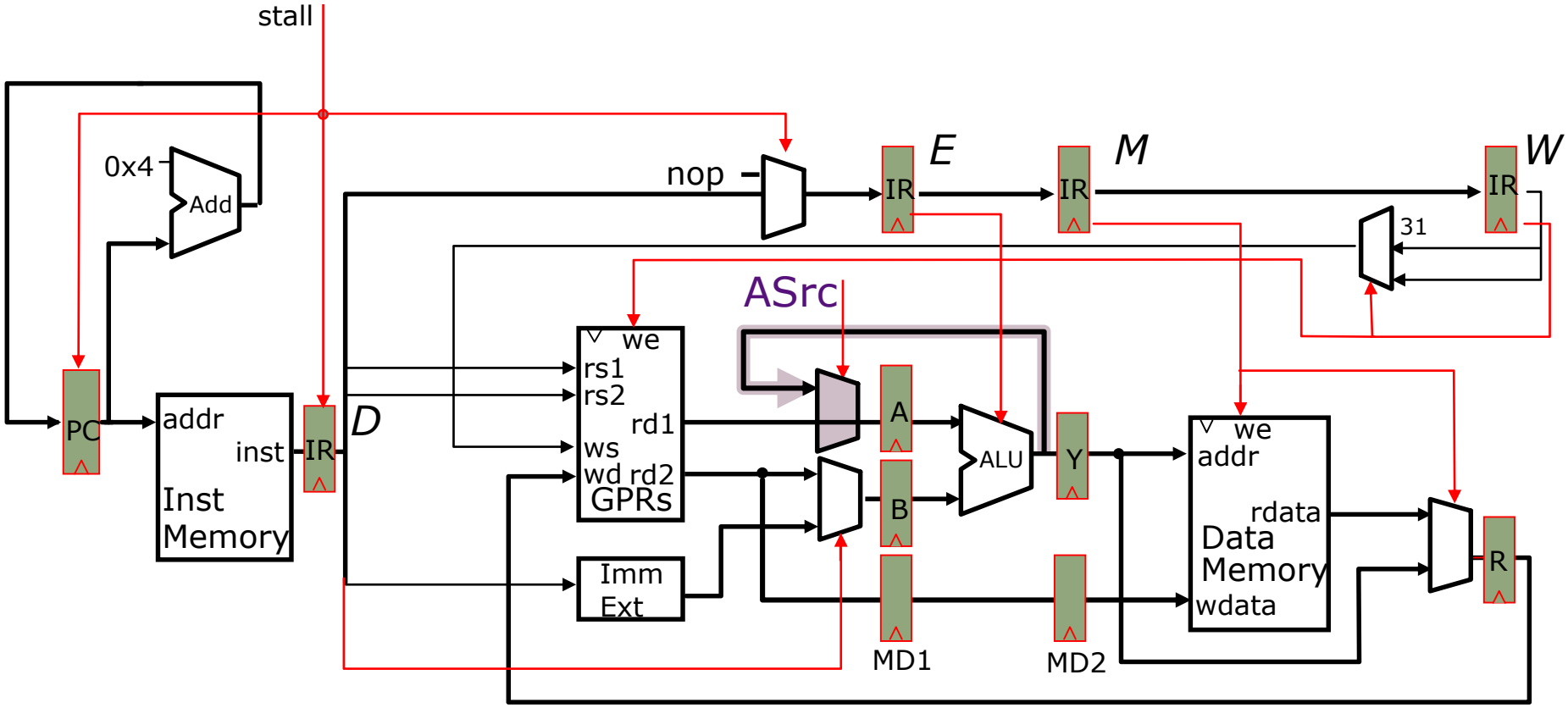


A new datapath, i.e., *a bypass*, can get the data from the output of the ALU to its input

Adding a Bypass



Adding a Bypass



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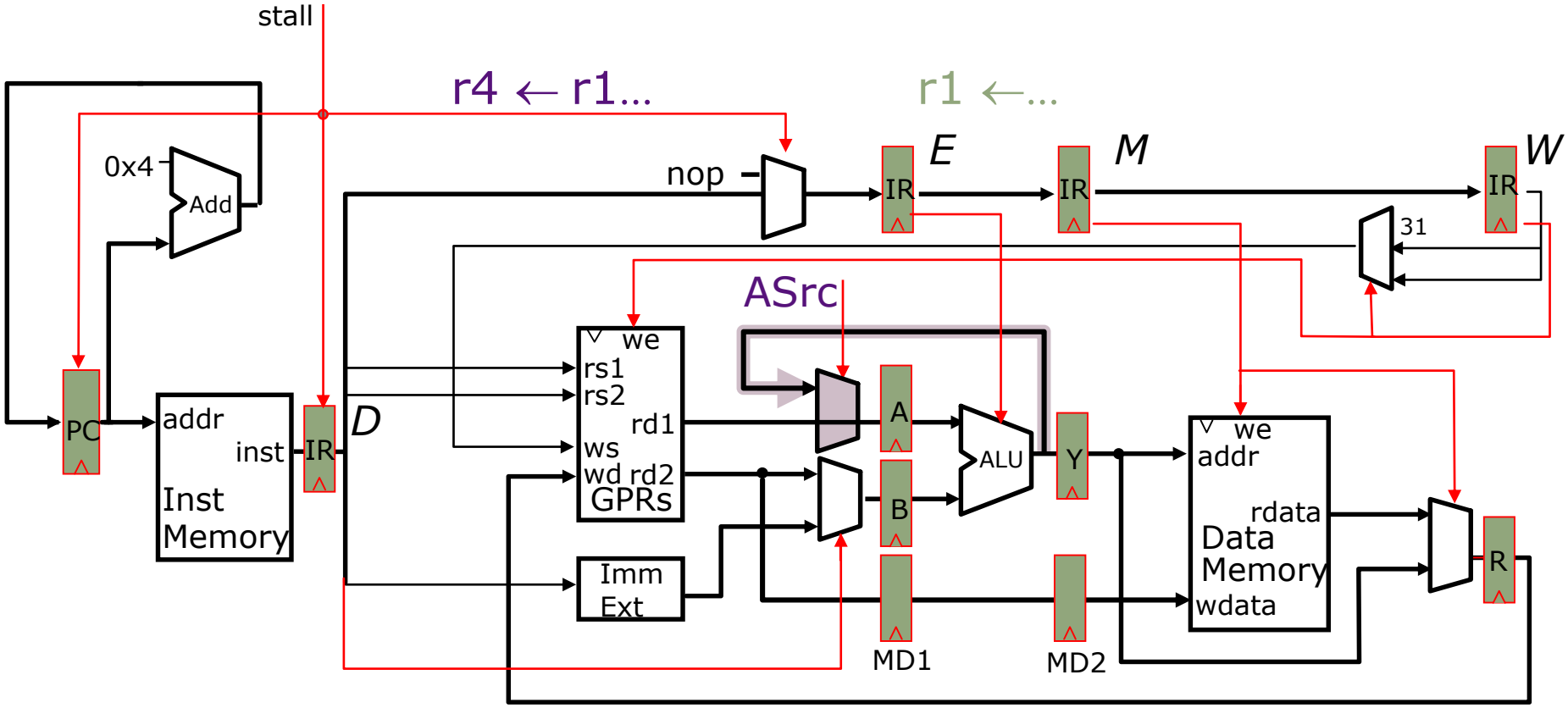
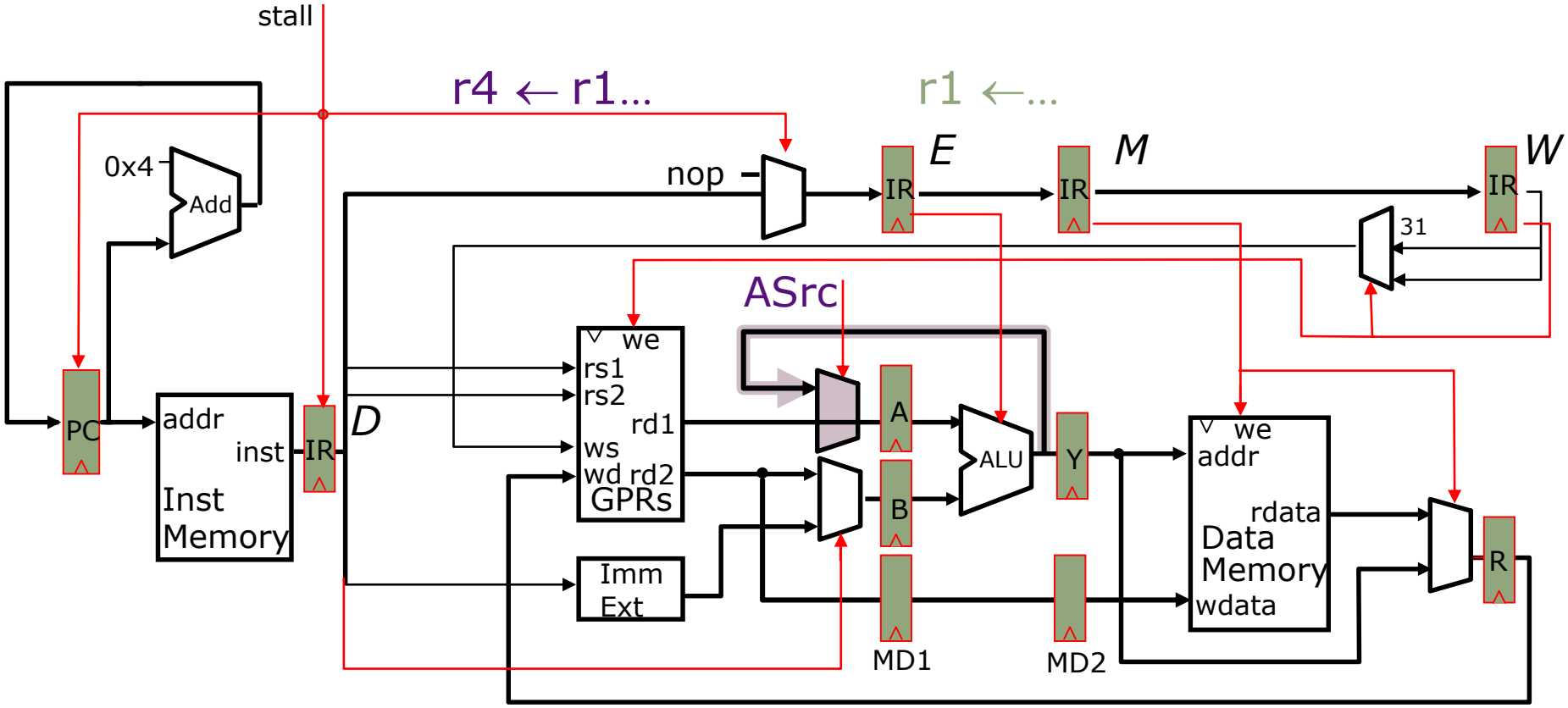


...

(I_1) r1 ← r0 + 10

(I_2) r4 ← r1 + 17

Adding a Bypass



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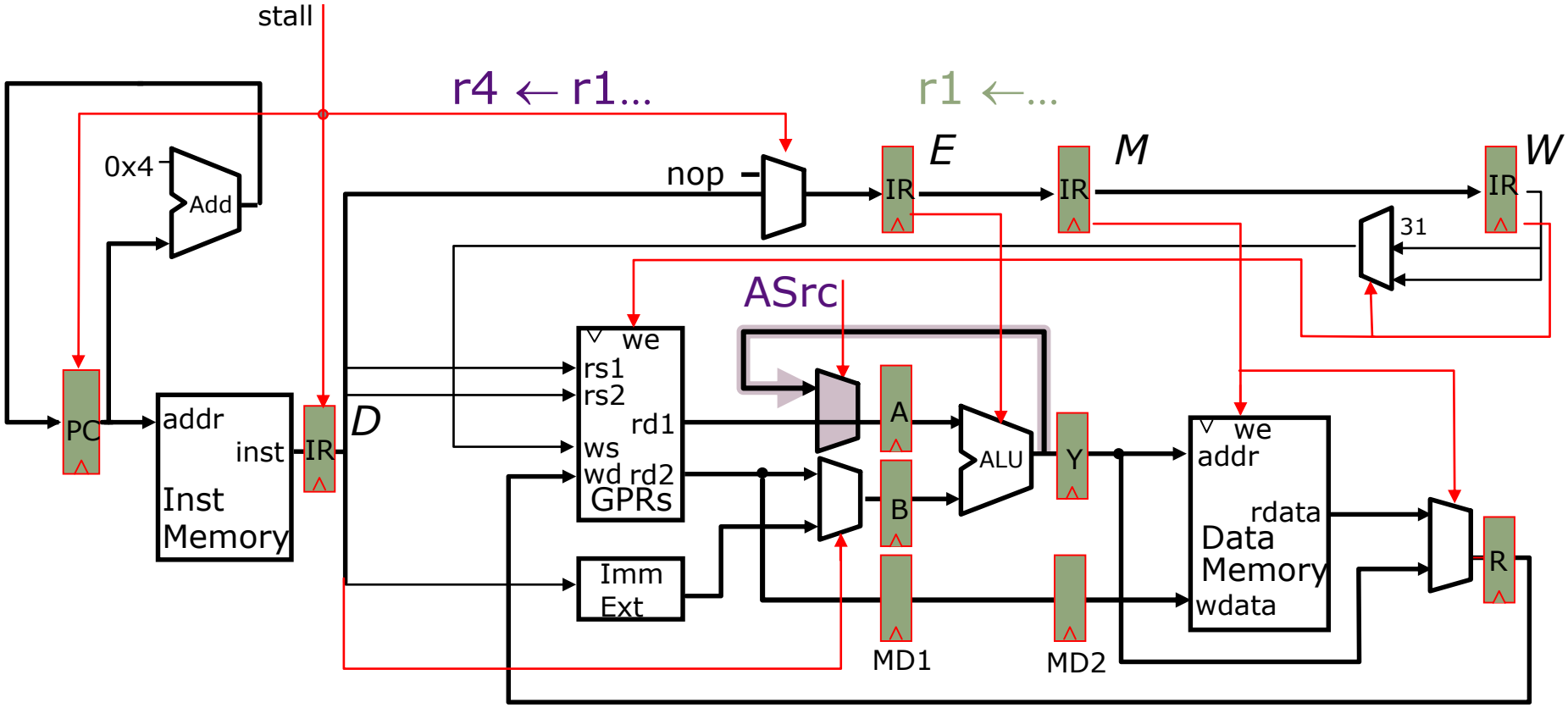

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...

(I_1) r1 ← r0 + 10

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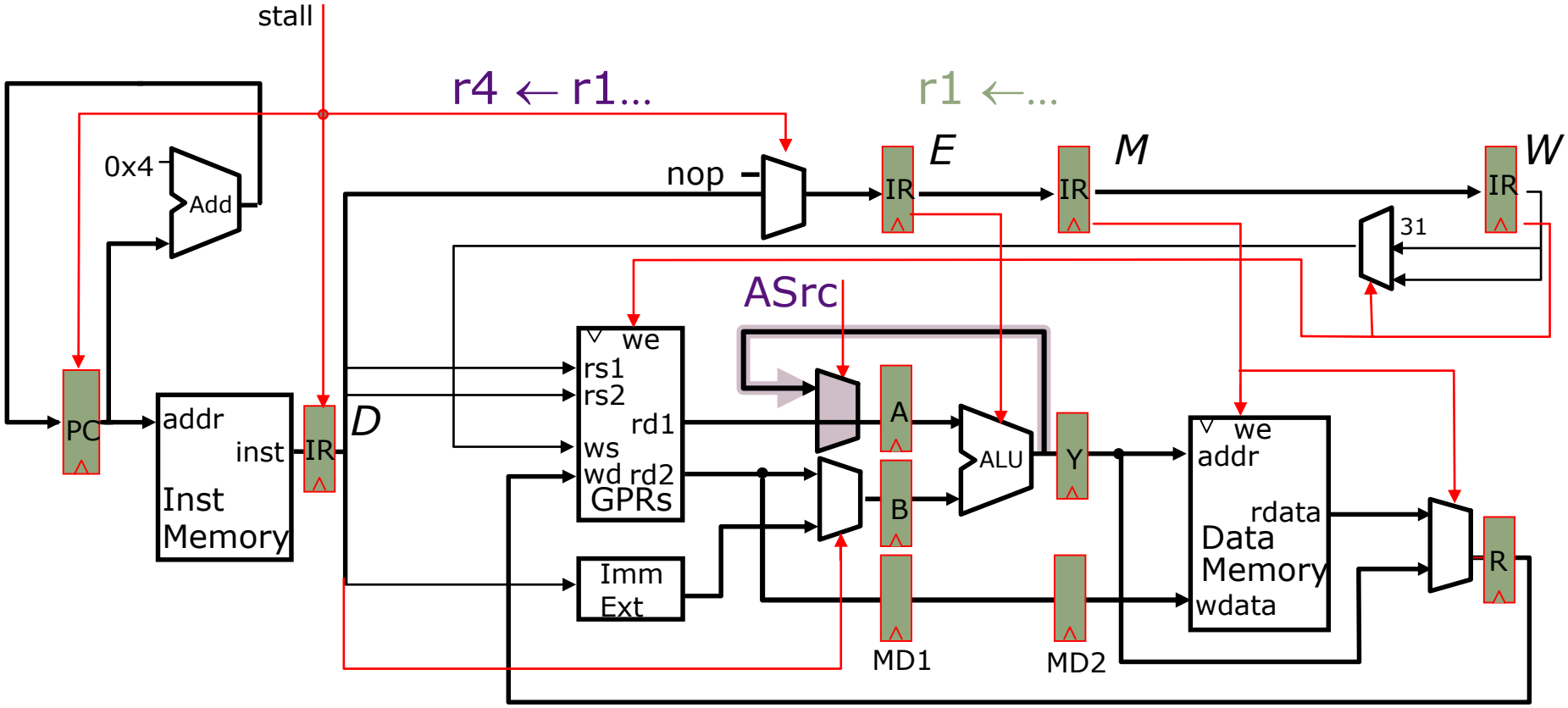


When does <u>this</u> bypass help?

...

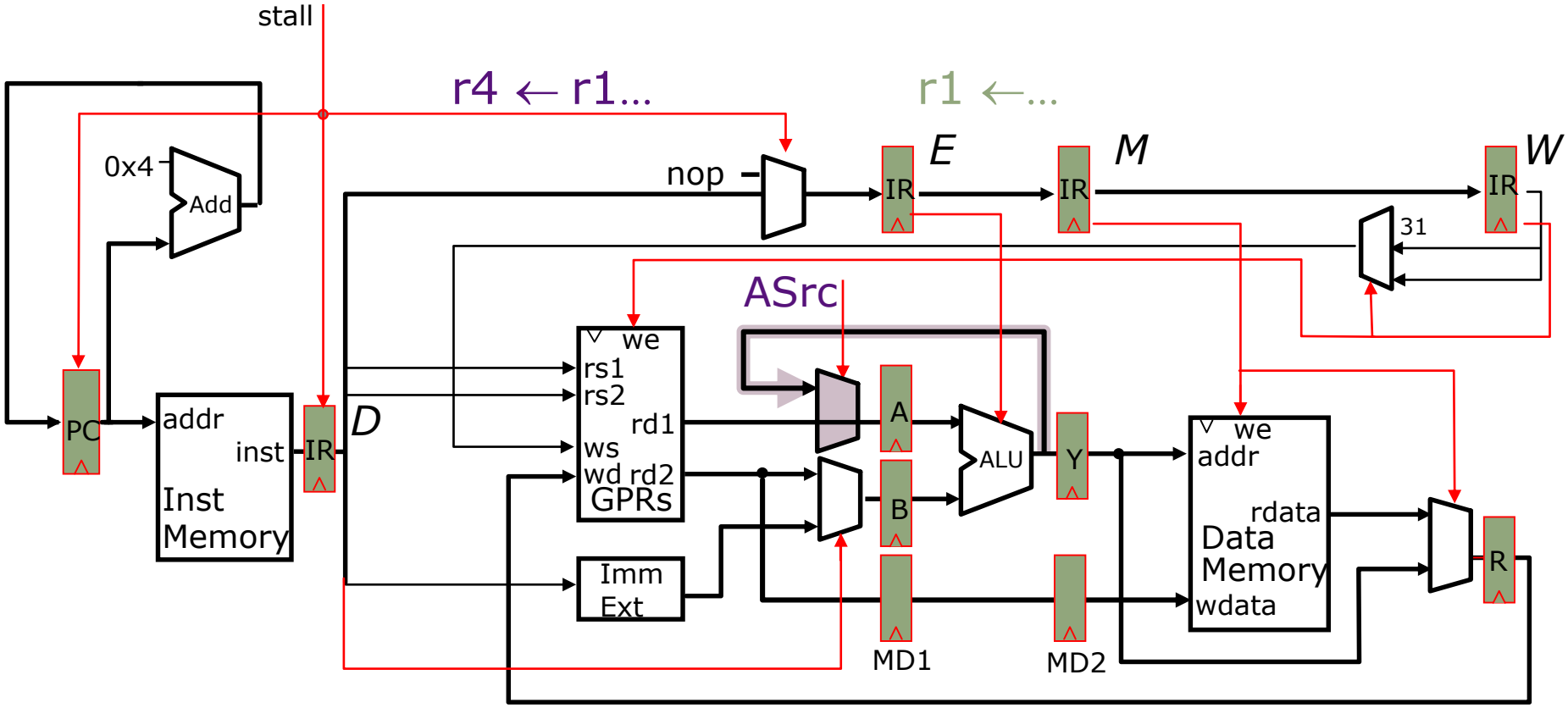
(I_1) r1 ← r0 + 10

(I_2) r4 ← r1 + 17 *yes*

r1 ← M[r0 + 10]

r4 ← r1 + 17

Adding a Bypass



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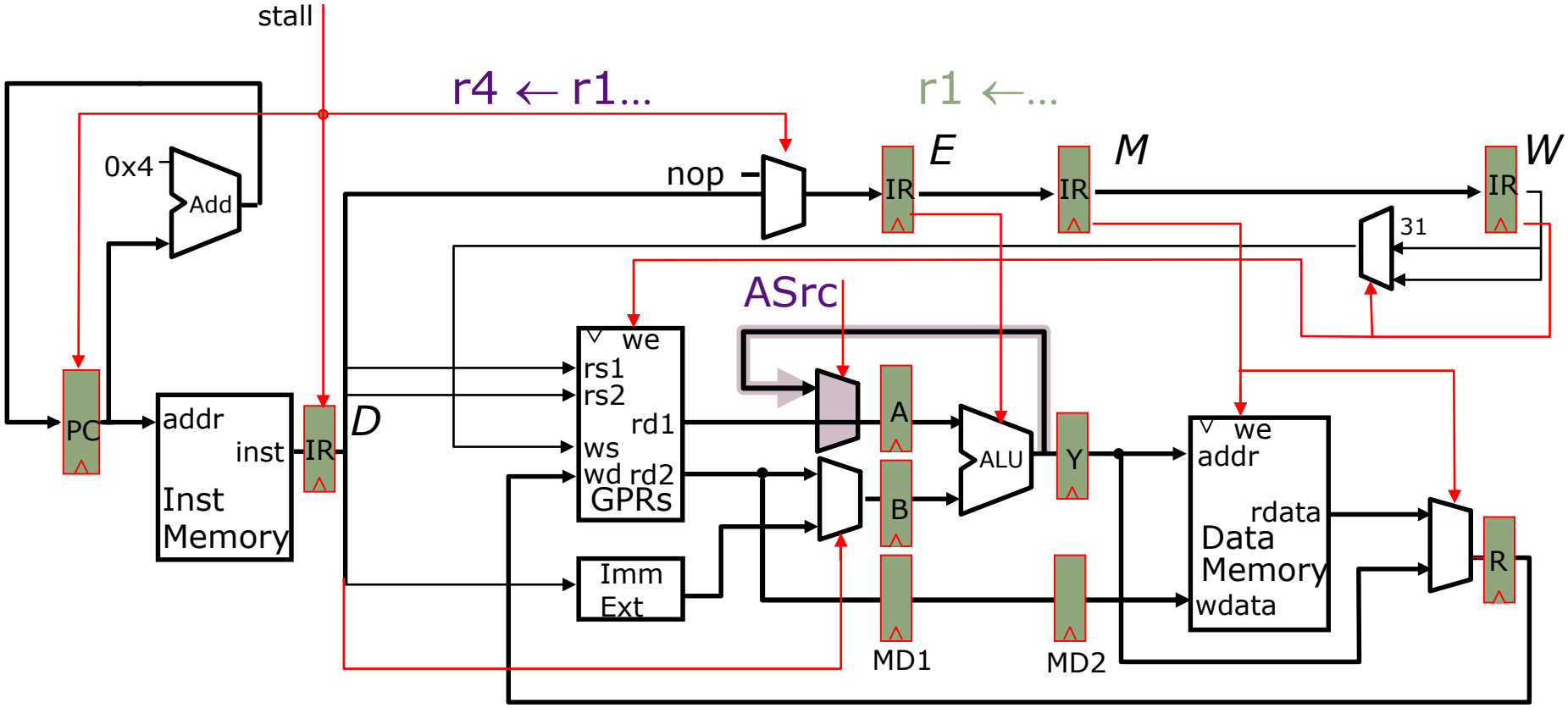
…

(I_1)	r1 ← r0 + 10	r1 ← M[r0 + 10]
(I_2)	r4 ← r1 + 17 *yes*	r4 ← r1 + 17 *no*

Adding a Bypass

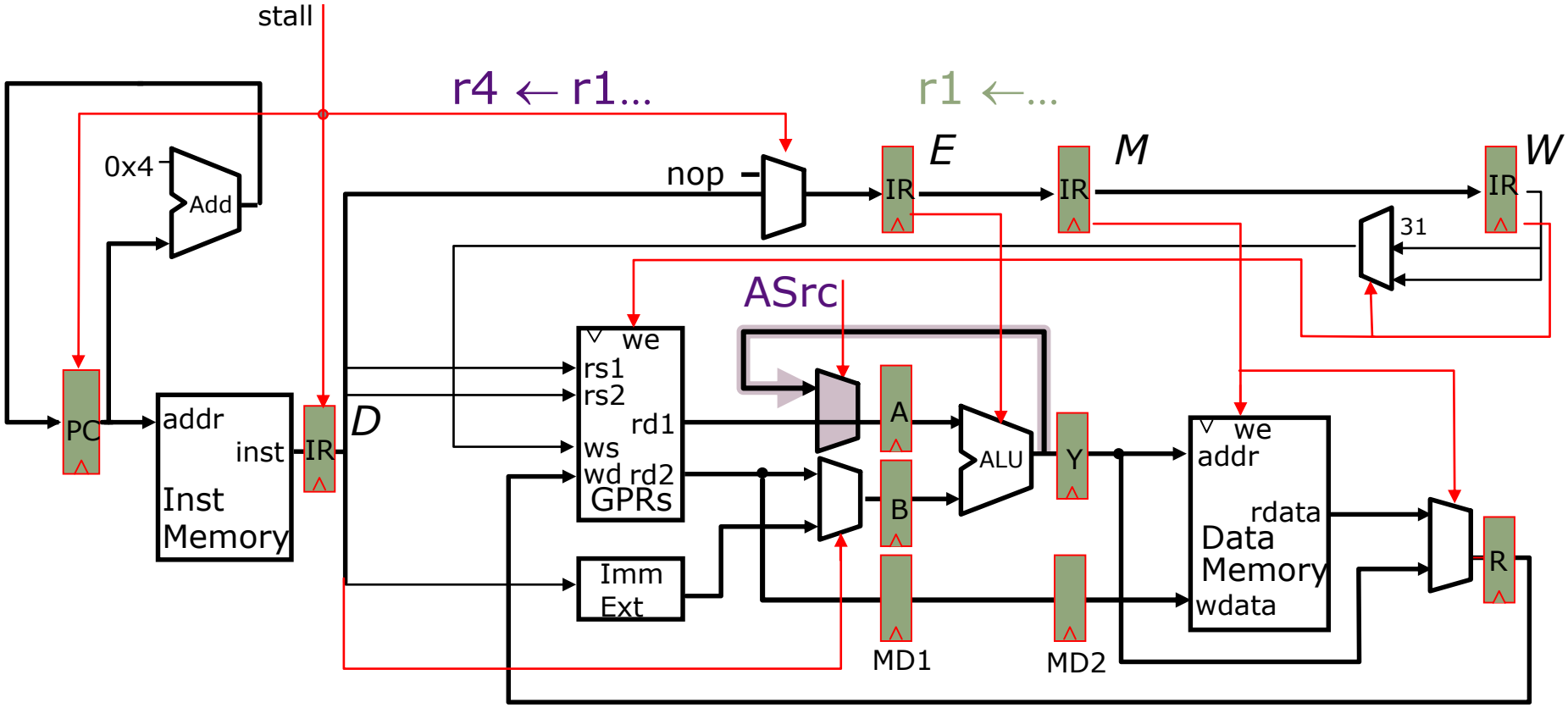


When does <u>this</u> bypass help?

…

(I_1)	r1 ← r0 + 10	r1 ← M[r0 + 10]	JAL 500
(I_2)	r4 ← r1 + 17 *yes*	r4 ← r1 + 17 *no*	r4 ← r31 + 17

Adding a Bypass



When does <u>this</u> bypass help?

…

(I_1)	r1 ← r0 + 10	r1 ← M[r0 + 10]	JAL 500
(I_2)	r4 ← r1 + 17 *yes*	r4 ← r1 + 17 *no*	r4 ← r31 + 17 *no*

The Bypass Signal

Deriving it from the Stall Signal

$$\begin{aligned}\text{stall} = {} & ((rs_D == ws_E)\cdot we_E + (rs_D == ws_M)\cdot we_M + (rs_D == ws_W)\cdot we_W)\cdot re1_D \\ & +((rt_D == ws_E)\cdot we_E + (rt_D == ws_M)\cdot we_M + (rt_D == ws_W)\cdot we_W)\cdot re2_D\end{aligned}$$

ws = *Case* opcode

ALU	$\Rightarrow$ rd
ALUi, LW	$\Rightarrow$ rt
JAL, JALR	$\Rightarrow$ R31

we = *Case* opcode

ALU, ALUi, LW	$\Rightarrow (ws \neq 0)$
JAL, JALR	$\Rightarrow$ on
...	$\Rightarrow$ off

The Bypass Signal

Deriving it from the Stall Signal

$$\text{stall} = ((\cancel{rs_D == ws_E) \cdot we_E} + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D$$
$$+((rt_D == ws_E) \cdot we_E + (rt_D == ws_M) \cdot we_M + (rt_D == ws_W) \cdot we_W) \cdot re2_D$$

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...	$\Rightarrow$ off

$$ASrc = (rs_D == ws_E) \cdot we_E \cdot re1_D$$

The Bypass Signal

Deriving it from the Stall Signal

$$\text{stall} = ((\cancel{rs_D == ws_E) \cdot we_E} + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D$$
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Is this correct?

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$$ASrc = (rs_D == ws_E) \cdot we_E \cdot re1_D$$

Is this correct?

No, because only ALU and ALUi instructions can benefit from this bypass

The Bypass Signal

Deriving it from the Stall Signal

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How might we address this?

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Deriving it from the Stall Signal

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How might we address this?

Split we_E into two components: we-bypass, we-stall

Bypass and Stall Signals

Split we_E into two components: we-bypass, we-stall

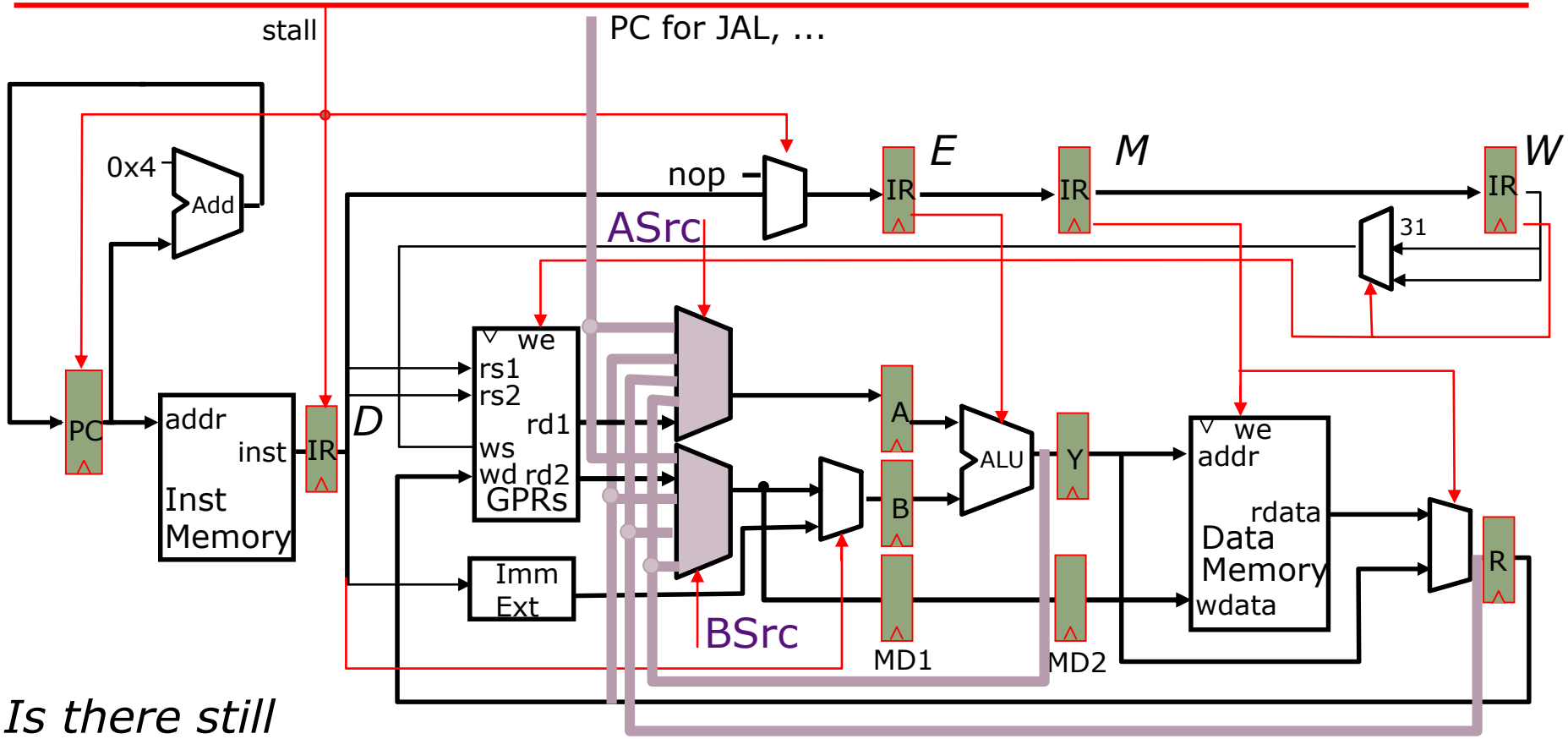
$we\text{-}bypass_E$ = *Case* $opcode_E$
- ALU, ALUi $\Rightarrow (ws \neq 0)$
- ... $\Rightarrow$ off

$we\text{-}stall_E$ = *Case* $opcode_E$
- LW $\Rightarrow (ws \neq 0)$
- JAL, JALR $\Rightarrow$ on
- ... $\Rightarrow$ off

$$ASrc = (rs_D == ws_E) \cdot we\text{-}bypass_E \cdot re1_D$$

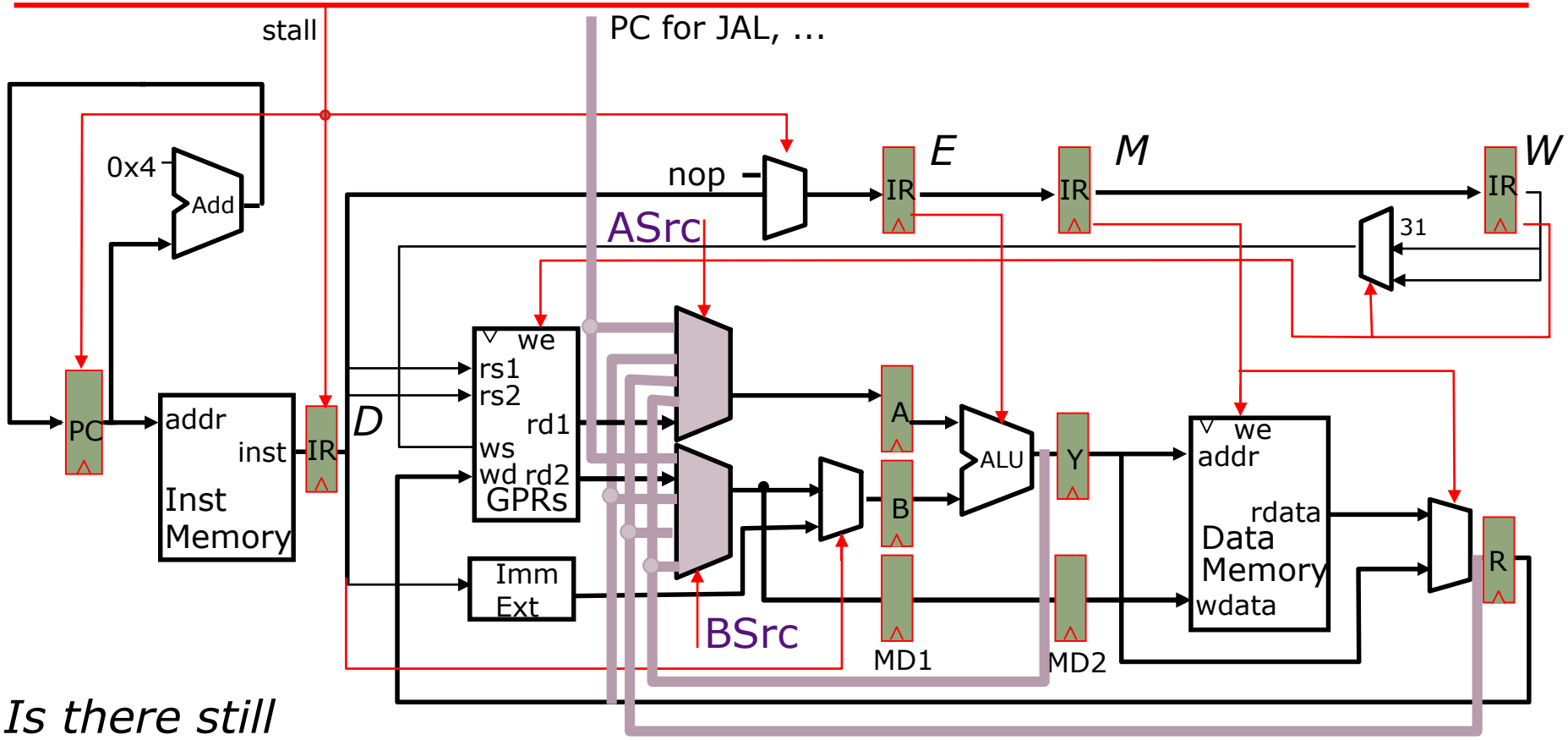
$$stall = ((rs_D == ws_E) \cdot we\text{-}stall_E + (rs_D == ws_M) \cdot we_M + (rs_D == ws_W) \cdot we_W) \cdot re1_D + ((rt_D == ws_E) \cdot we_E + (rt_D == ws_M) \cdot we_M + (rt_D == ws_W) \cdot we_W) \cdot re2_D$$

Fully Bypassed Datapath



Is there still a need for the stall signal?

Fully Bypassed Datapath



Is there still a need for the stall signal?

$$\text{stall} = (rs_D == ws_E)\cdot(opcode_E == LW_E)\cdot(ws_E \neq 0)\cdot re1_D + (rt_D == ws_E)\cdot(opcode_E == LW_E)\cdot(ws_E \neq 0)\cdot re2_D$$

Resolving Data Hazards (3)

Strategy 3:

Speculate on the dependence. Two cases:

Resolving Data Hazards (3)

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Guessed correctly ◊ no special action required

Resolving Data Hazards (3)

Strategy 3:

Speculate on the dependence. Two cases:

Guessed correctly ◊ no special action required

Guessed incorrectly → kill and restart

Instruction to Instruction Dependence

- What do we need to calculate next PC?
  - For Jumps

Instruction to Instruction Dependence

- What do we need to calculate next PC?
  - For Jumps
    - Opcode, offset, and PC

Instruction to Instruction Dependence

- What do we need to calculate next PC?
  - For Jumps
    - Opcode, offset, and PC
  - For Jump Register

Instruction to Instruction Dependence

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Instruction to Instruction Dependence

- What do we need to calculate next PC?
  - For Jumps
    - Opcode, offset, and PC
  - For Jump Register
    - Opcode and register value

Instruction to Instruction Dependence

- What do we need to calculate next PC?
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  - For Jump Register
    - Opcode and register value
  - For Conditional Branches

Instruction to Instruction Dependence

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    - Opcode, offset, and PC
  - For Jump Register
    - Opcode and register value
  - For Conditional Branches
    - Opcode, offset, PC, and register (for condition)

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    - Opcode, offset, PC, and register (for condition)
  - For all others

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    - Opcode and PC
- In what stage do we know these?

Instruction to Instruction Dependence

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    - Opcode, offset, PC, and register (for condition)
  - For all others
    - Opcode and PC
- In what stage do we know these?
  - PC → Fetch

Instruction to Instruction Dependence

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    - Opcode and register value
  - For Conditional Branches
    - Opcode, offset, PC, and register (for condition)
  - For all others
    - Opcode and PC
- In what stage do we know these?
  - PC → Fetch
  - Opcode, offset → Decode (or Fetch?)

Instruction to Instruction Dependence

- What do we need to calculate next PC?
  - For Jumps
    - Opcode, offset, and PC
  - For Jump Register
    - Opcode and register value
  - For Conditional Branches
    - Opcode, offset, PC, and register (for condition)
  - For all others
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  - Register value → Decode

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    - Opcode and register value
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    - Opcode, offset, PC, and register (for condition)
  - For all others
    - Opcode and PC
- In what stage do we know these?
  - PC → Fetch
  - Opcode, offset → Decode (or Fetch?)
  - Register value → Decode
  - Branch condition ((rs)==0) → Execute (or Decode?)

NextPC Calculation Bubbles

NextPC Calculation Bubbles

time

t0 t1 t2 t3 t4 t5 t6 t7 . . . .

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		

NextPC Calculation Bubbles

	time								
	t0	t1	t2	t3	t4	t5	t6	t7	. . . .
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(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3

NextPC Calculation Bubbles

	time								
	t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3

NextPC Calculation Bubbles

	time									
	t0	t1	t2	t3	t4	t5	t6	t7	. . . .	
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1					
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3	
(I_4)						IF_4	IF_4	ID_4	EX_4	MA_4	WB_4

NextPC Calculation Bubbles

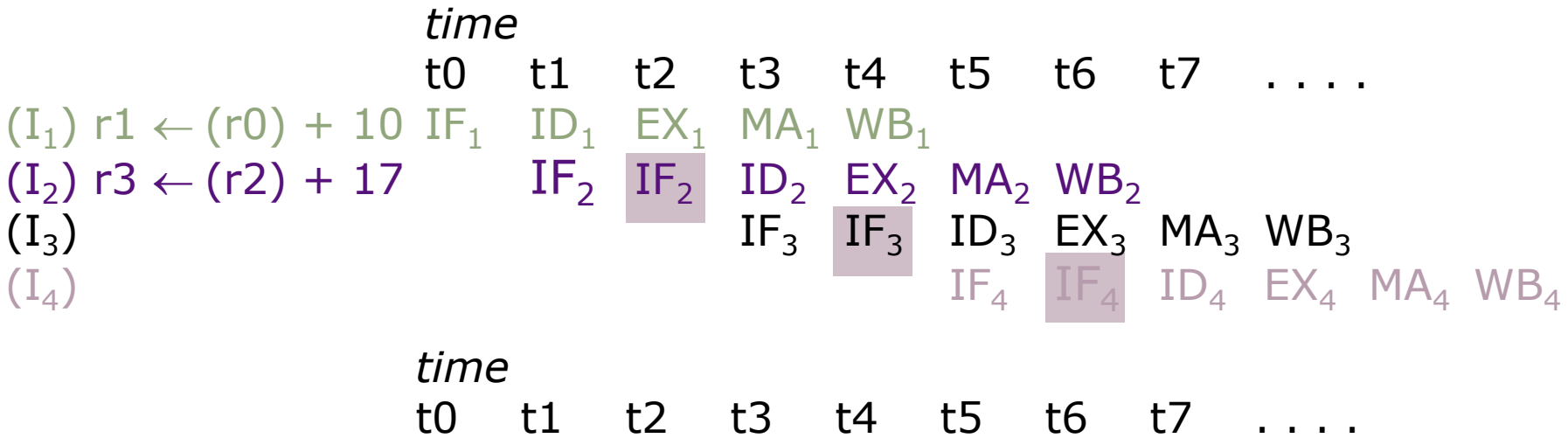
	time									
	t0	t1	t2	t3	t4	t5	t6	t7	. . . .	
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1					
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3	
(I_4)						IF_4	IF_4	ID_4	EX_4	MA_4	WB_4

NextPC Calculation Bubbles

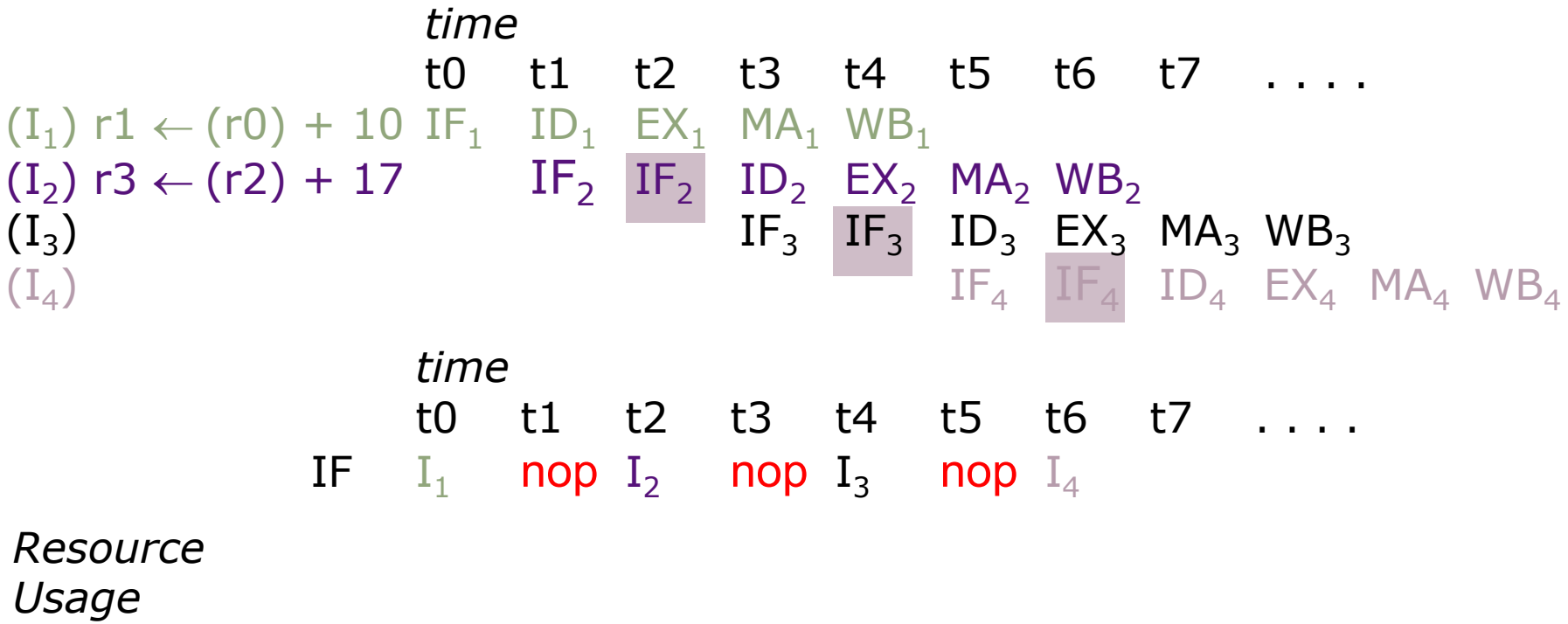
	time									
	t0	t1	t2	t3	t4	t5	t6	t7	. . . .	
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1					
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3	
(I_4)						IF_4	IF_4	ID_4	EX_4	MA_4 WB_4

Resource Usage

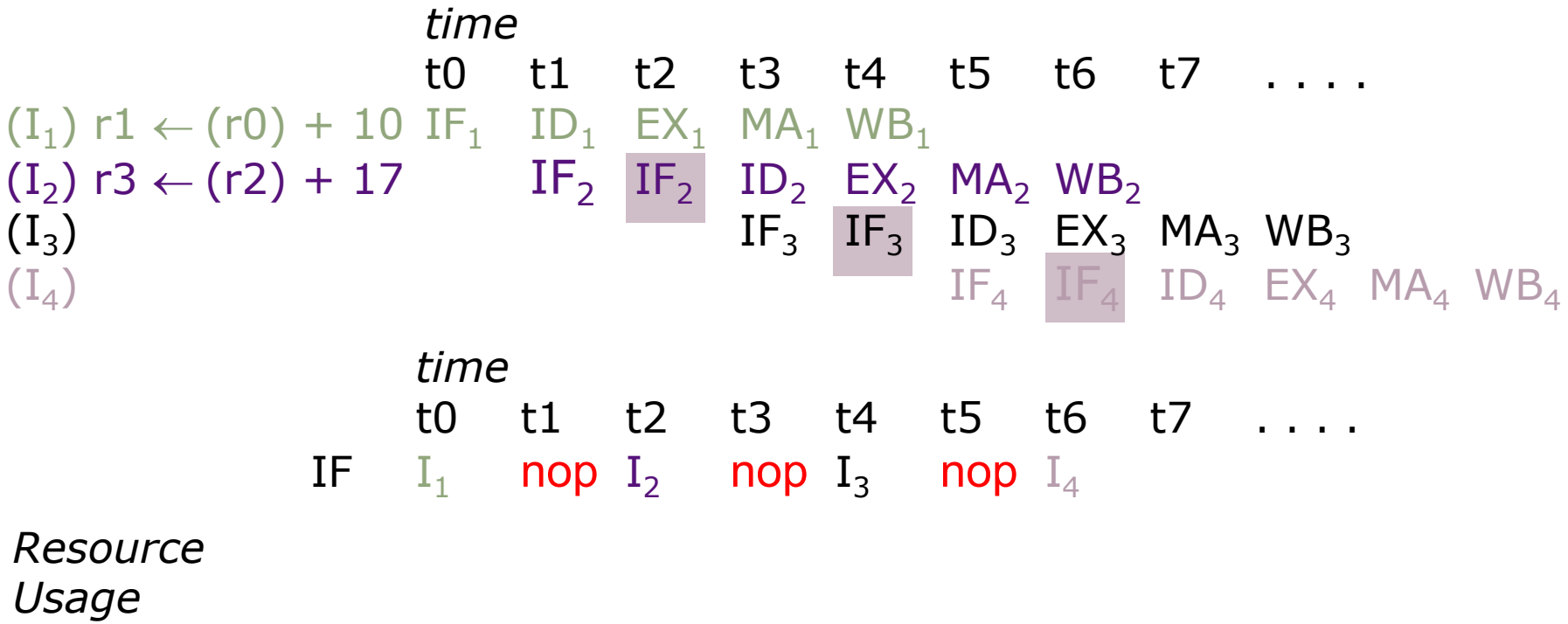
NextPC Calculation Bubbles



NextPC Calculation Bubbles



NextPC Calculation Bubbles



NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4 MA_4 WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4 MA_4 WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4	MA_4	WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop	I_4

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4	MA_4	WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop	I_4
WB					I_1	nop	I_2	nop	I_3	nop	I_4

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4	MA_4	WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop	I_4
WB					I_1	nop	I_2	nop	I_3	nop	I_4

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4 MA_4 WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop I_4
WB					I_1	nop	I_2	nop	I_3 nop I_4

nop ⇒ *pipeline bubble*

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4 MA_4 WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop I_4
WB					I_1	nop	I_2	nop	I_3 nop I_4

nop ⇒ *pipeline bubble*

What's a good guess for next PC?

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4 MA_4 WB_4

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop I_4
WB					I_1	nop	I_2	nop	I_3 nop I_4

nop ⇒ *pipeline bubble*

What's a good guess for next PC?

NextPC Calculation Bubbles

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) r1 ← (r0) + 10	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) r3 ← (r2) + 17		IF_2	IF_2	ID_2	EX_2	MA_2	WB_2		
(I_3)				IF_3	IF_3	ID_3	EX_3	MA_3	WB_3
(I_4)						IF_4	IF_4	ID_4	EX_4 MA_4 WB_4

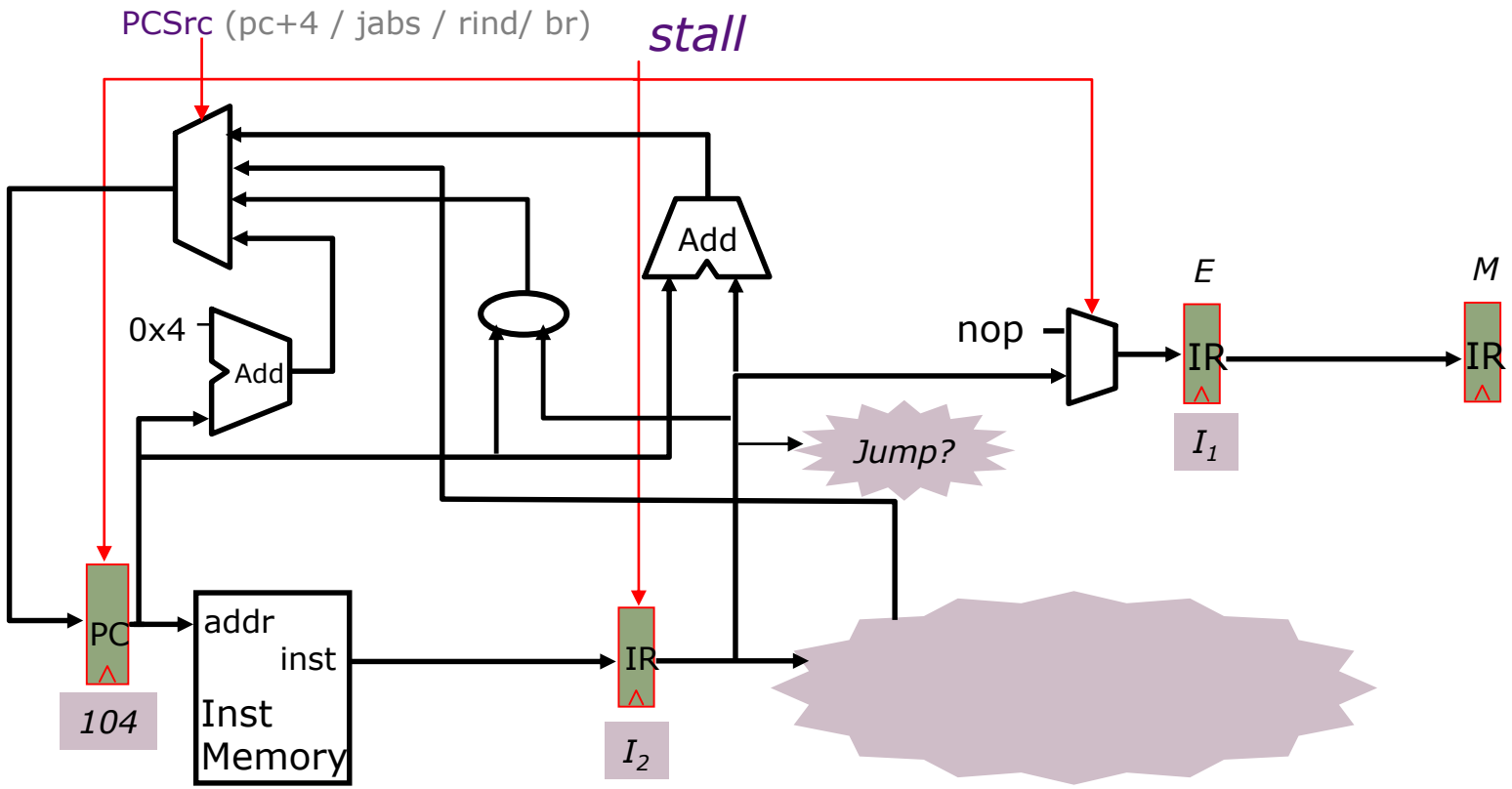
Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	nop	I_2	nop	I_3	nop	I_4		
ID		I_1	nop	I_2	nop	I_3	nop	I_4	
EX			I_1	nop	I_2	nop	I_3	nop	I_4
MA				I_1	nop	I_2	nop	I_3	nop I_4
WB					I_1	nop	I_2	nop	I_3 nop I_4

nop ⇒ *pipeline bubble*

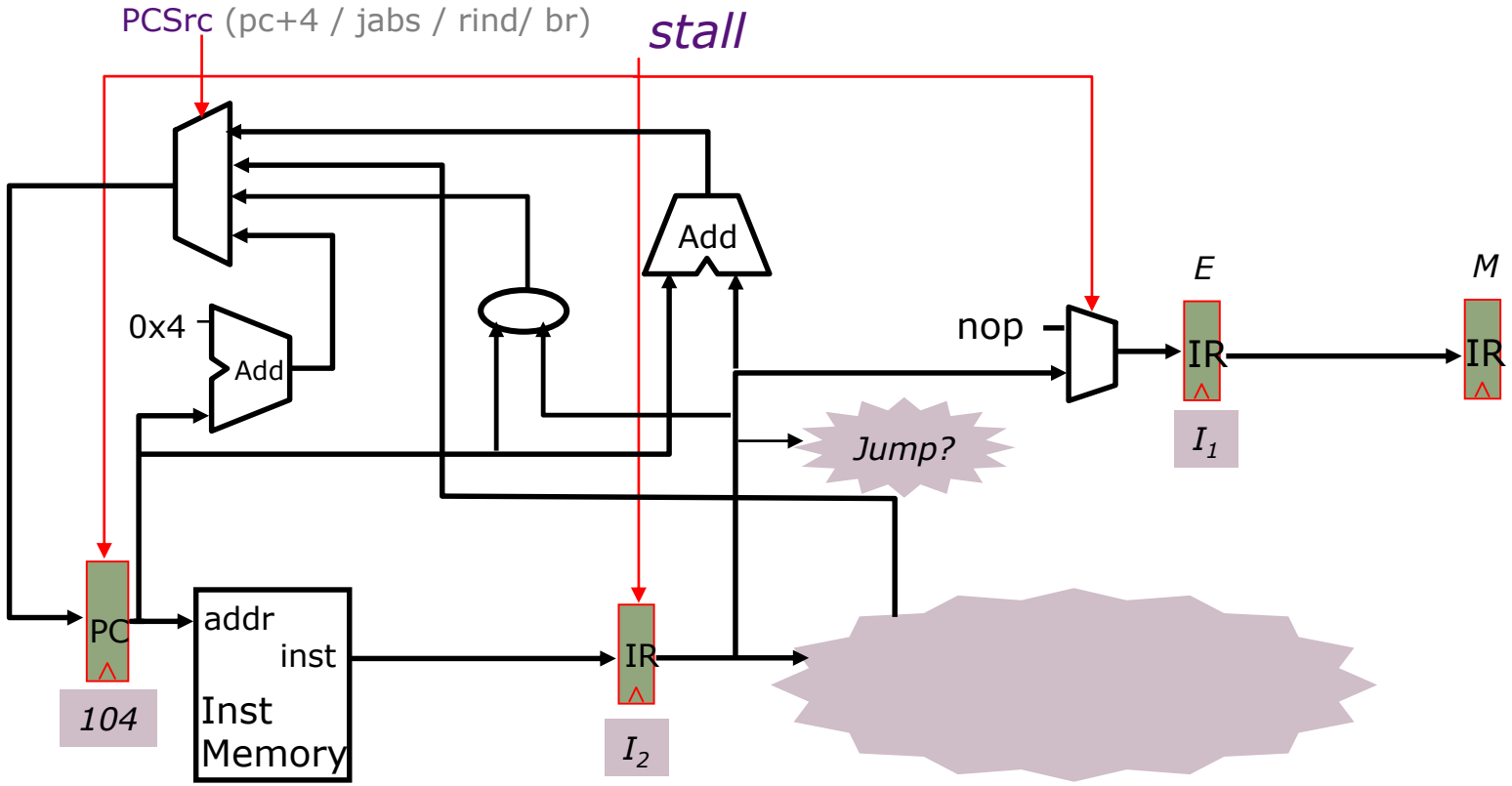
What's a good guess for next PC? PC+4

Speculate NextPC is PC+4



I_1	096	ADD	
I_2	100	J	200
I_3	104	ADD	
I_4	304	ADD	

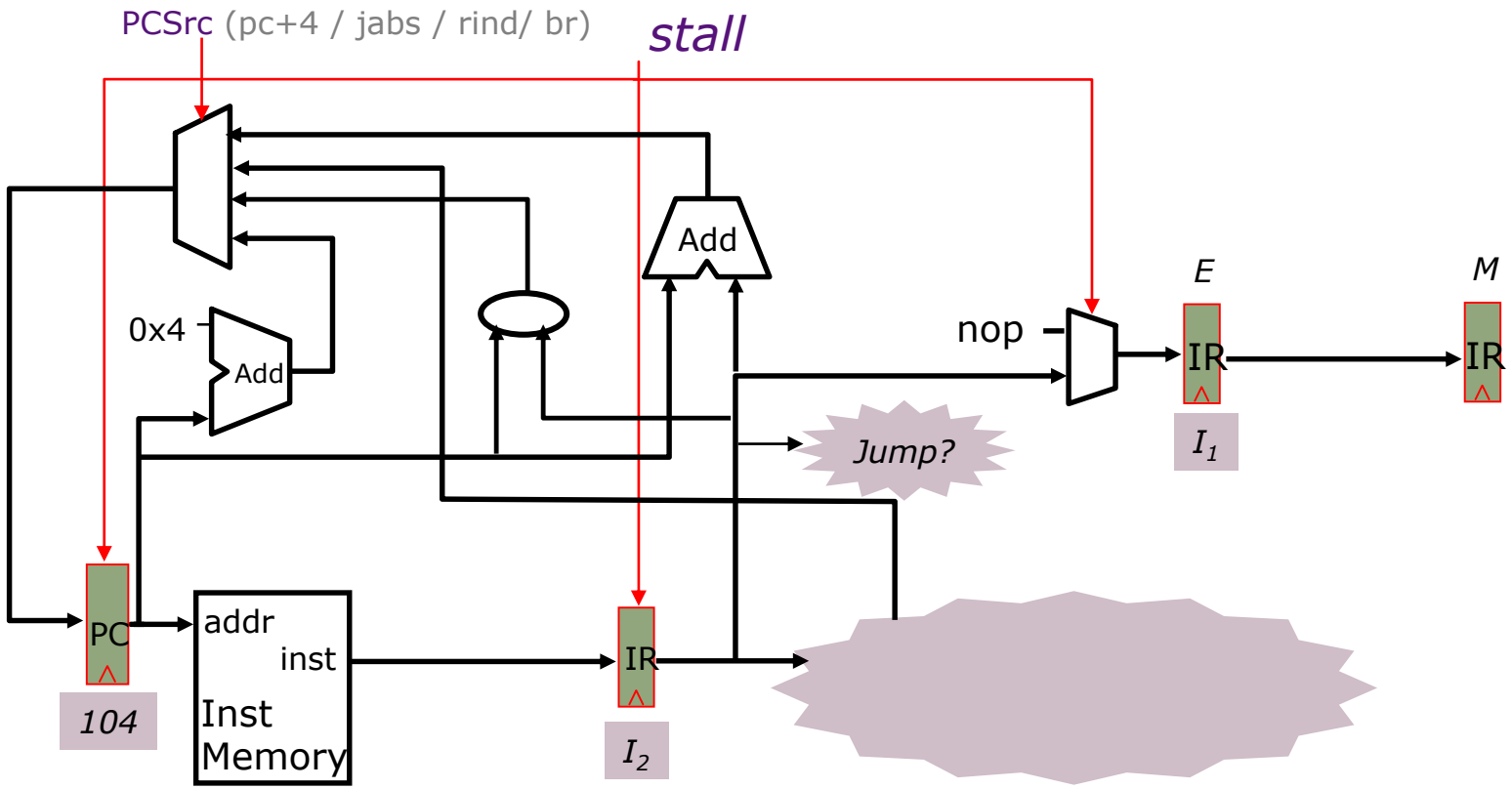
Speculate NextPC is PC+4



I_1	096	ADD	
I_2	100	J	200
I_3	104	ADD	
I_4	304	ADD	

What happens on mis-speculation, i.e., when next instruction is not PC+4?

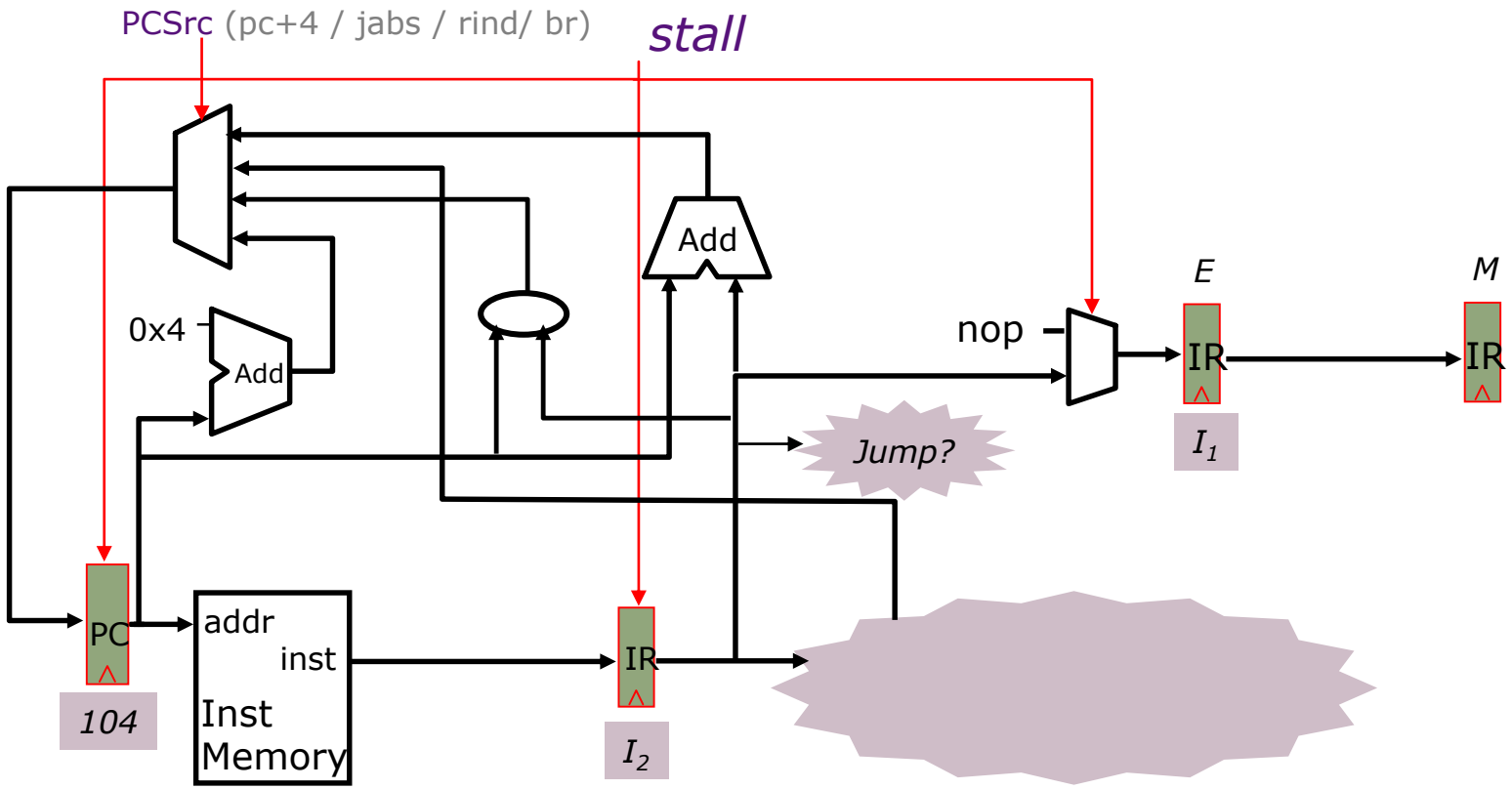
Speculate NextPC is PC+4



I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

What happens on mis-speculation, i.e., when next instruction is not PC+4?

Speculate NextPC is PC+4

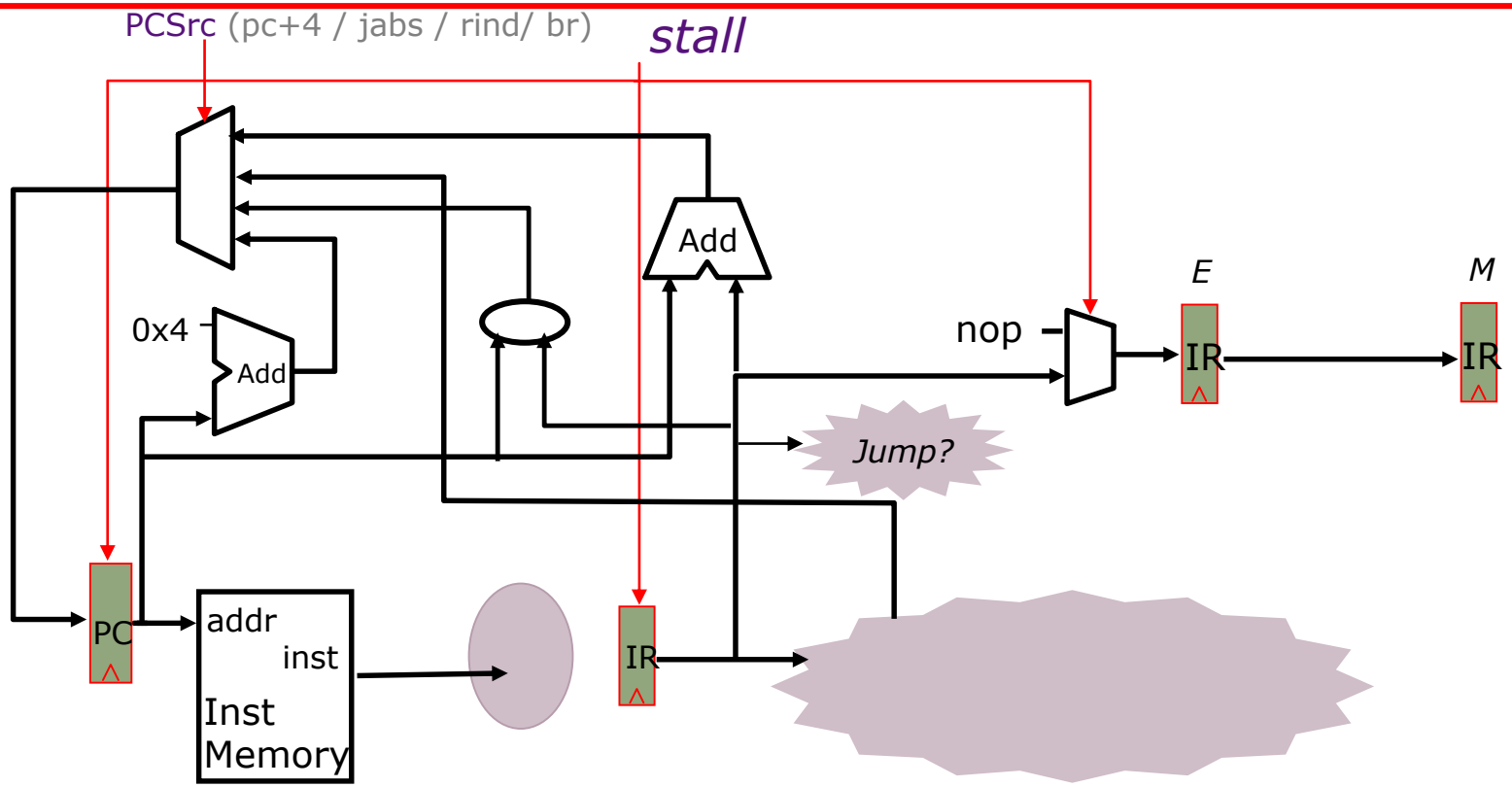


I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

What happens on mis-speculation, i.e., when next instruction is not PC+4?

How?

Pipelining Jumps



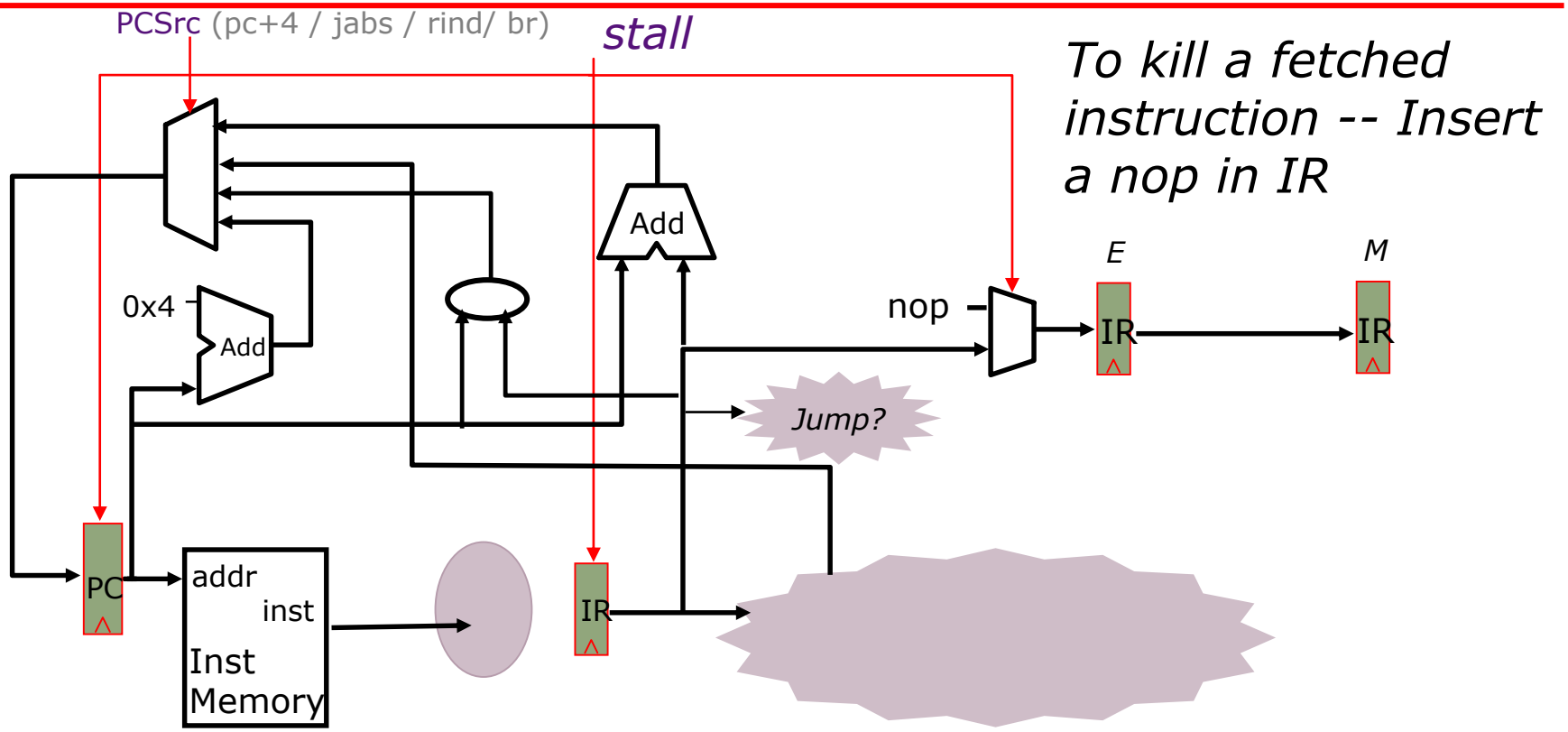
I_1 096 ADD

I_2 100 J 200

I_3 ~~104 ADD~~ *kill*

I_4 304 ADD

Pipelining Jumps



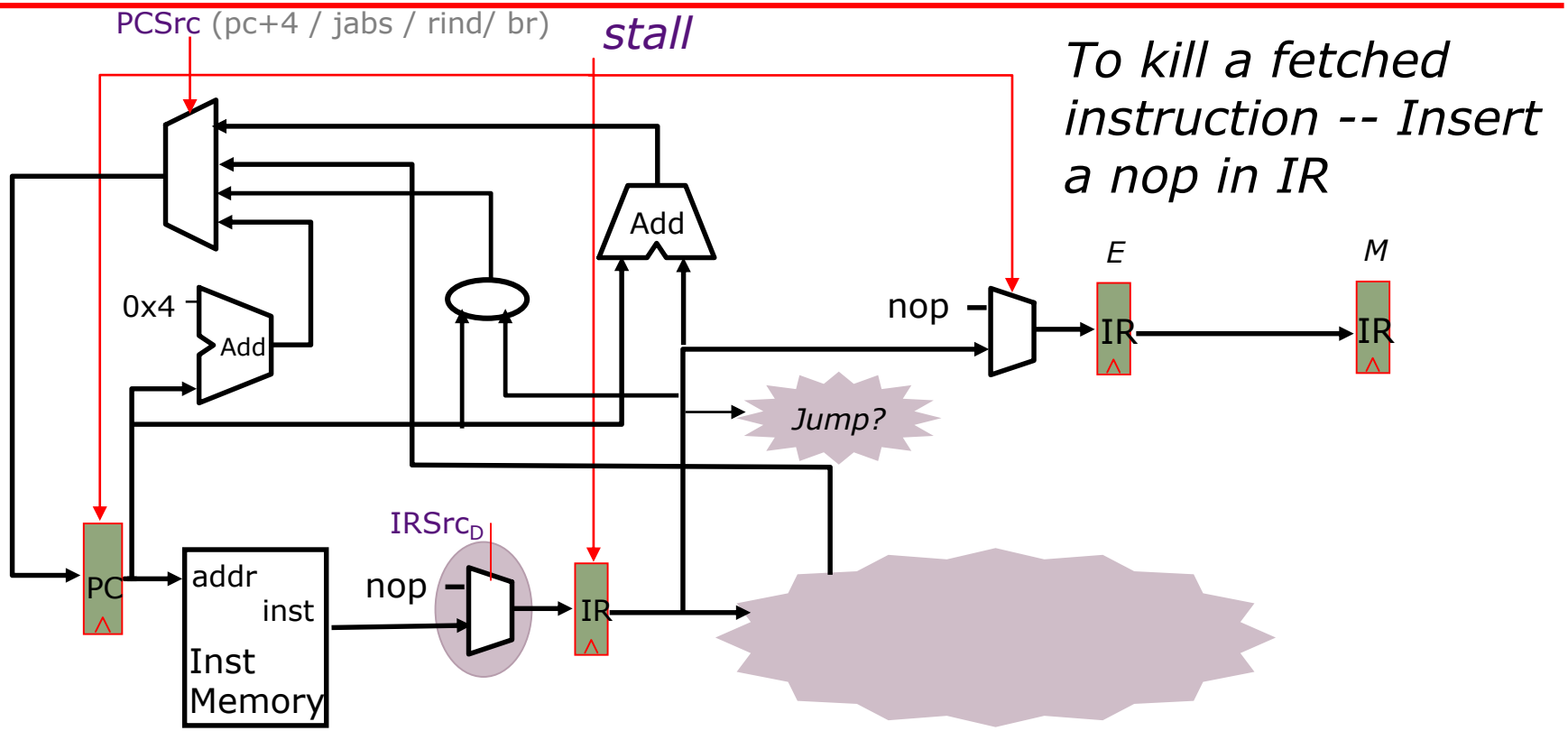
I_1 096 ADD

I_2 100 J 200

I_3 ~~104 ADD~~ *kill*

I_4 304 ADD

Pipelining Jumps



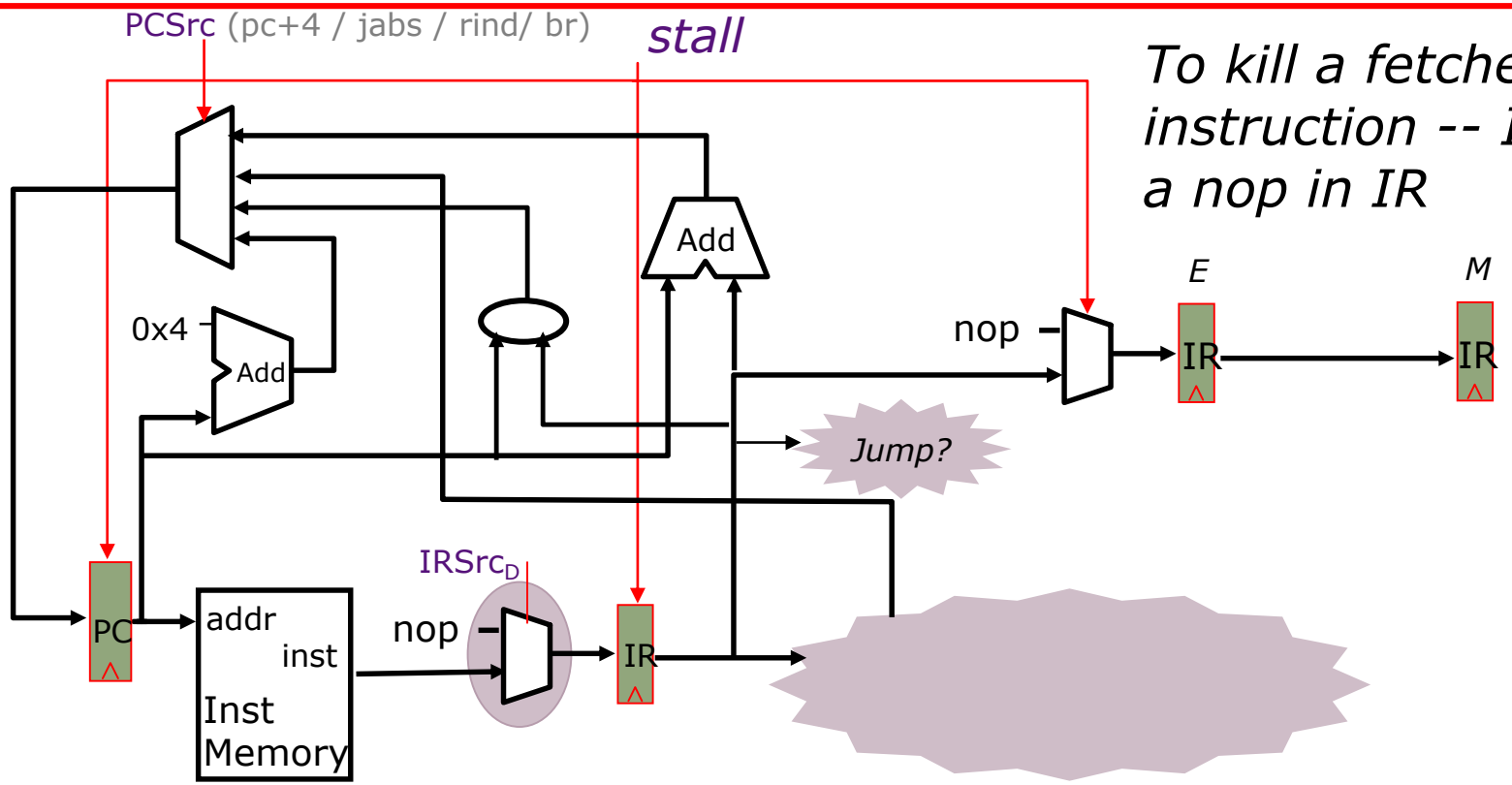
I_1 096 ADD

I_2 100 J 200

I_3 ~~104 ADD~~ *kill*

I_4 304 ADD

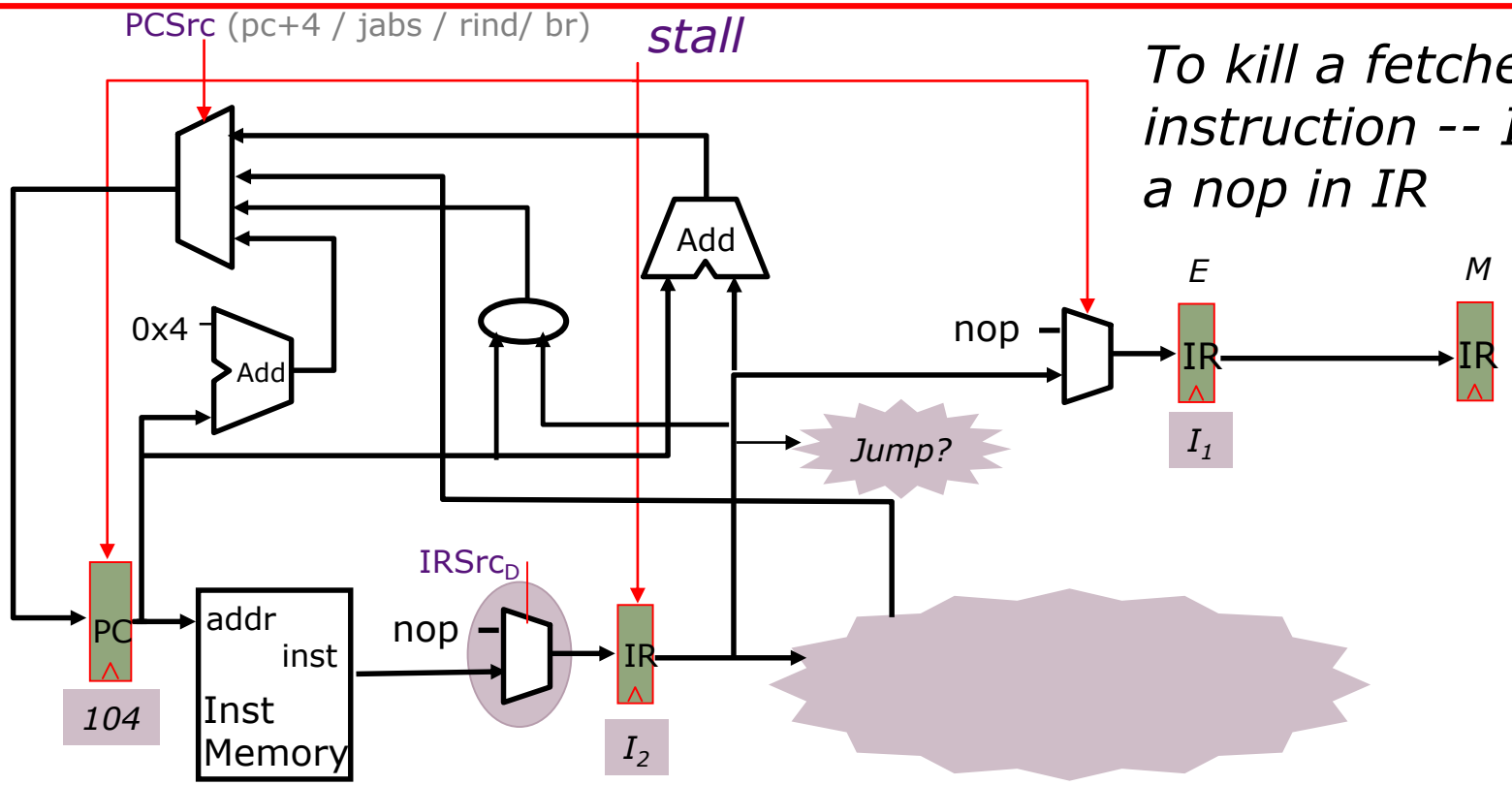
Pipelining Jumps



I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

IRSrc$_D$ = *Case* opcode$_D$
J, JAL ⇒ nop
... ⇒ IM

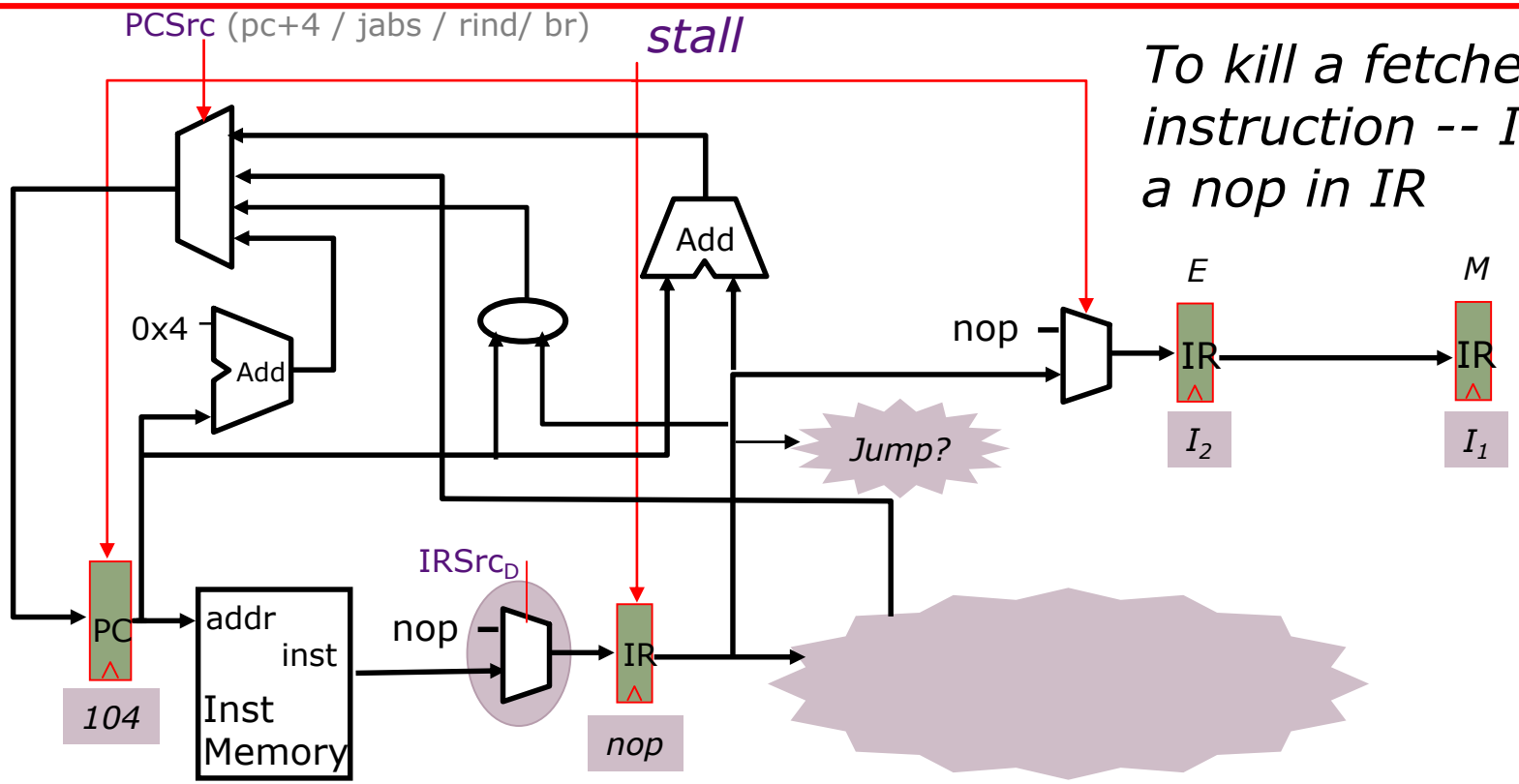
Pipelining Jumps



I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

IRSrc$_D$ = *Case* opcode$_D$
- J, JAL ⇒ nop
- ... ⇒ IM

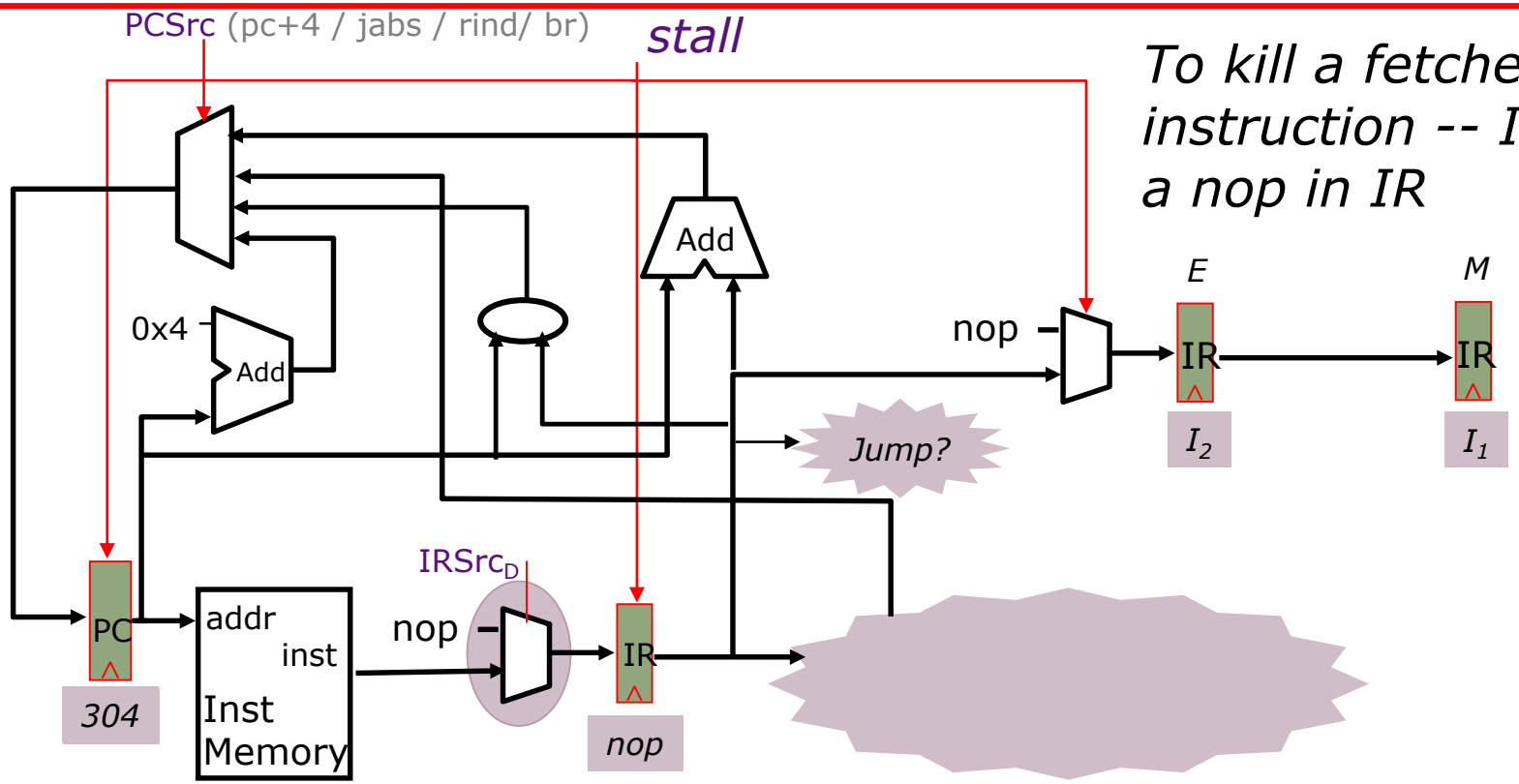
Pipelining Jumps



I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

$IRSrc_D$ = *Case* $opcode_D$
- J, JAL ⇒ nop
- ... ⇒ IM

Pipelining Jumps

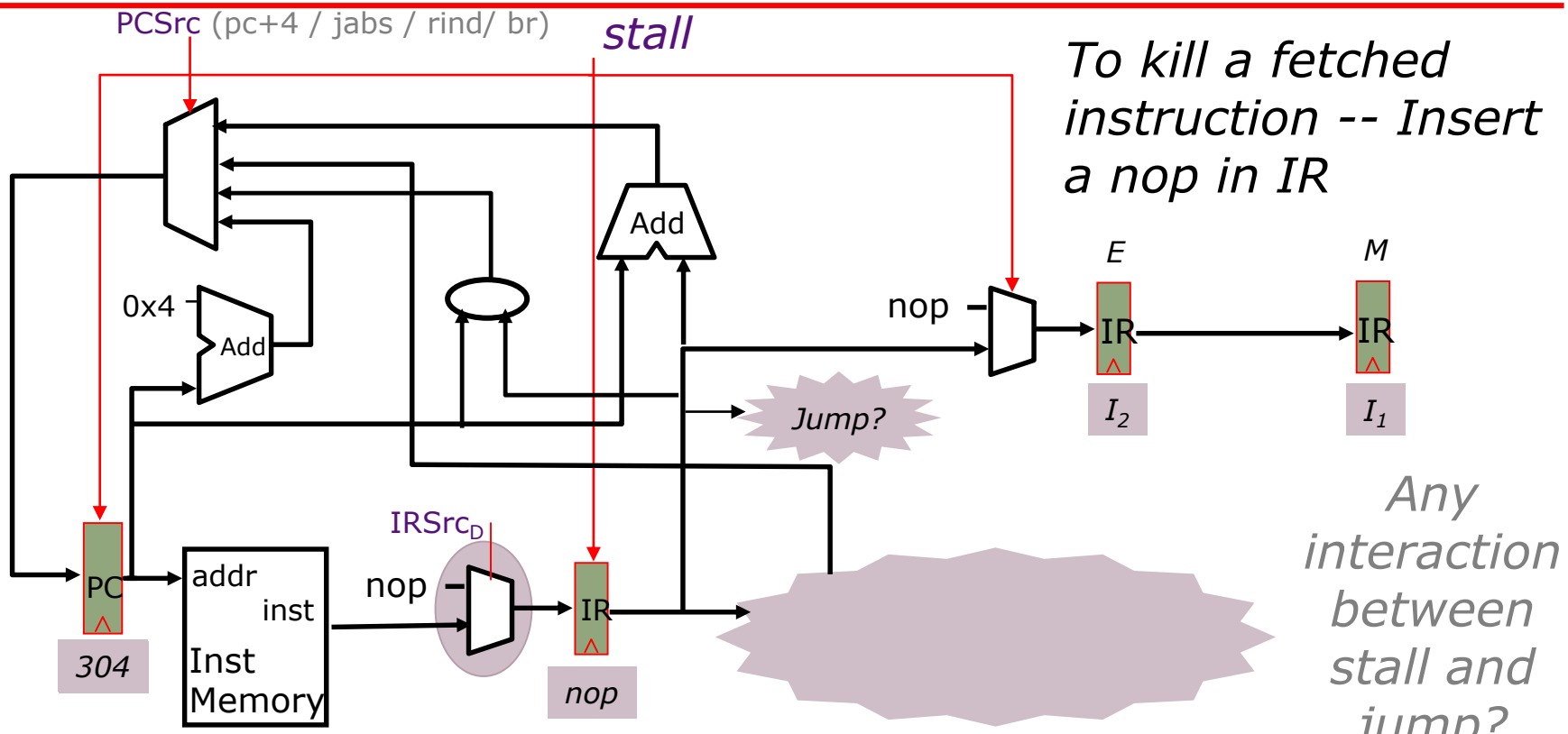


I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

IRSrc$_D$ = *Case* opcode$_D$

J, JAL	⇒ nop
...	⇒ IM

Pipelining Jumps



I_1	096	ADD	
I_2	100	J	200
I_3	~~104~~	~~ADD~~	*kill*
I_4	304	ADD	

IRSrc$_D$ = *Case* opcode$_D$
- J, JAL ⇒ nop
- ... ⇒ IM

Jump Pipeline Diagrams

Jump Pipeline Diagrams

time

t0 t1 t2 t3 t4 t5 t6 t7 . . . .

Jump Pipeline Diagrams

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				

Jump Pipeline Diagrams

	time								
	t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: J 200		IF_2	ID_2	EX_2	MA_2	WB_2			

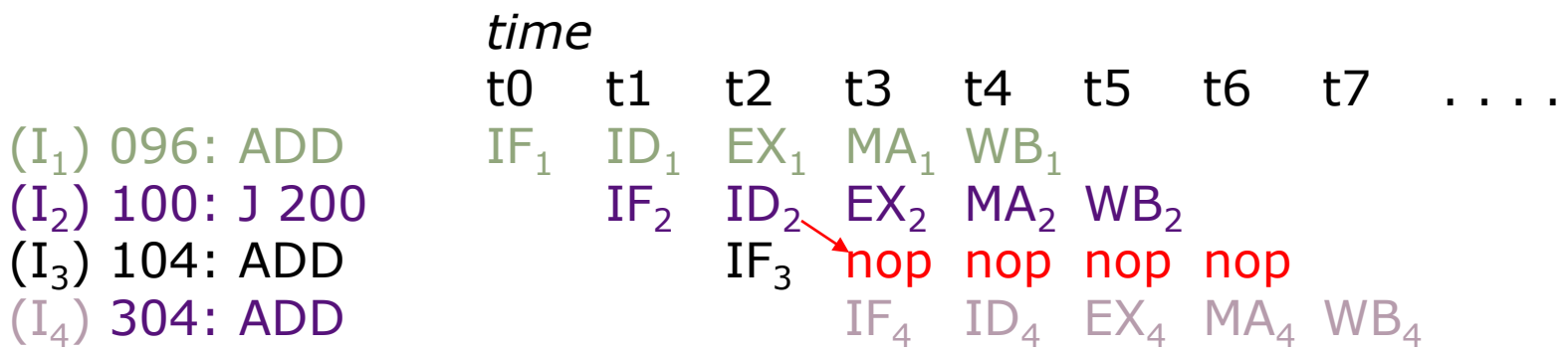
Jump Pipeline Diagrams

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: J 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	nop	nop	nop	nop		

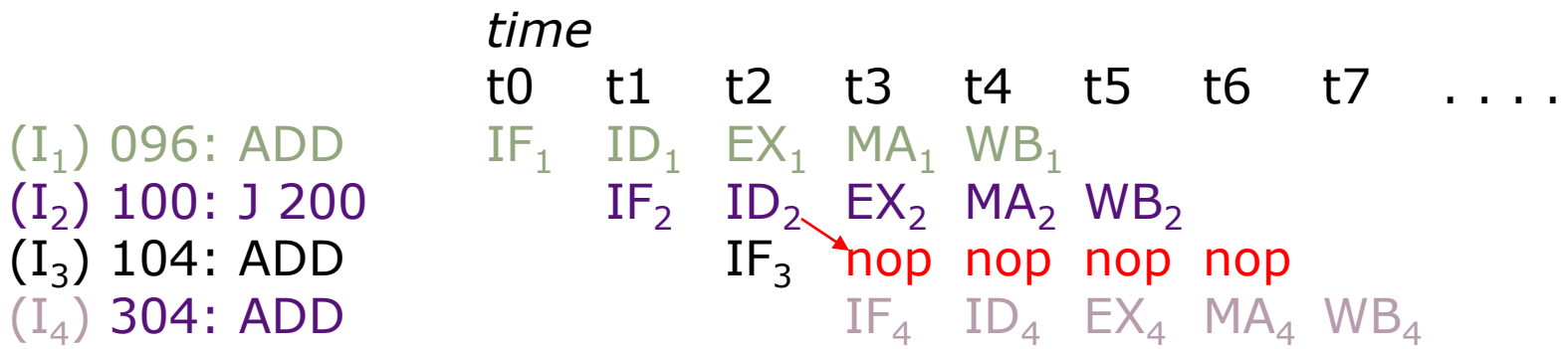
Jump Pipeline Diagrams

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: J 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	nop	nop	nop	nop		
(I_4) 304: ADD				IF_4	ID_4	EX_4	MA_4	WB_4	

Jump Pipeline Diagrams



Jump Pipeline Diagrams



Resource Usage

Jump Pipeline Diagrams

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: J 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	nop	nop	nop	nop		
(I_4) 304: ADD				IF_4	ID_4	EX_4	MA_4	WB_4	

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	I_2	I_3	I_4	I_5				
ID		I_1	I_2	nop	I_4	I_5			
EX			I_1	I_2	nop	I_4	I_5		
MA				I_1	I_2	nop	I_4	I_5	
WB					I_1	I_2	nop	I_4	I_5

Jump Pipeline Diagrams

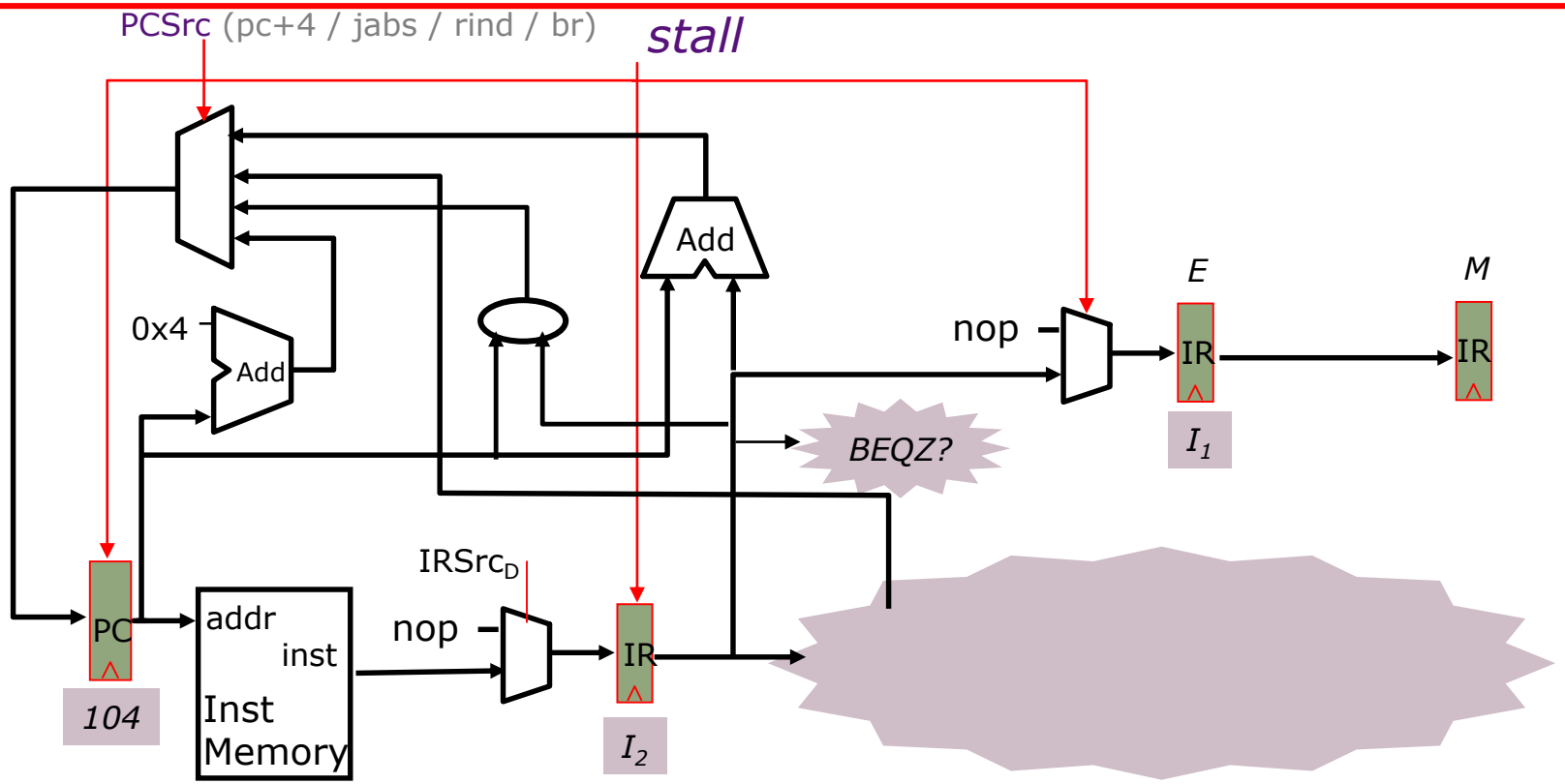
	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: J 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	nop	nop	nop	nop		
(I_4) 304: ADD				IF_4	ID_4	EX_4	MA_4	WB_4	

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	I_2	I_3	I_4	I_5				
ID		I_1	I_2	nop	I_4	I_5			
EX			I_1	I_2	nop	I_4	I_5		
MA				I_1	I_2	nop	I_4	I_5	
WB					I_1	I_2	nop	I_4	I_5

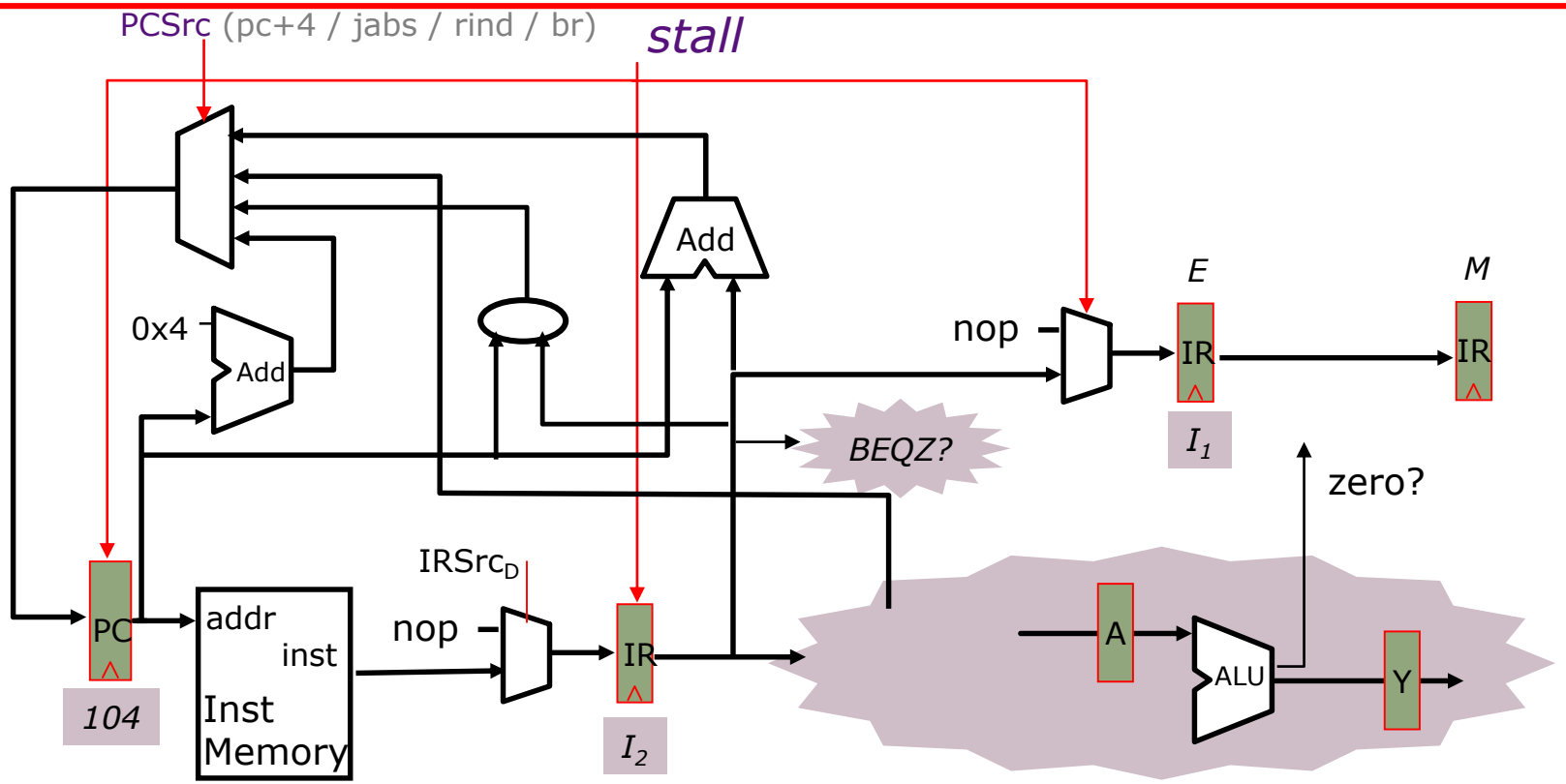
nop ⇒ *pipeline bubble*

Pipelining Conditional Branches



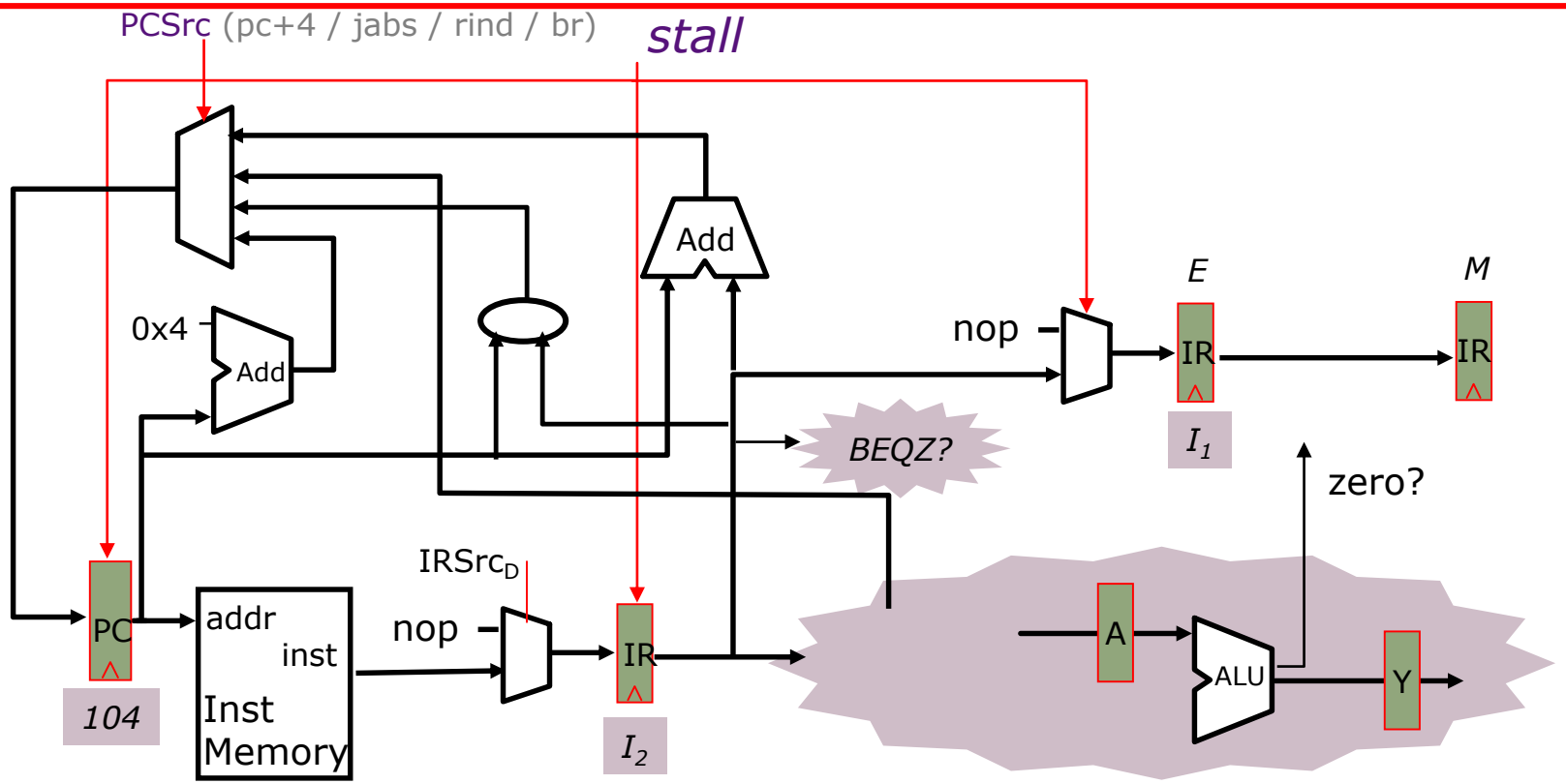
I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

Pipelining Conditional Branches



I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

Pipelining Conditional Branches

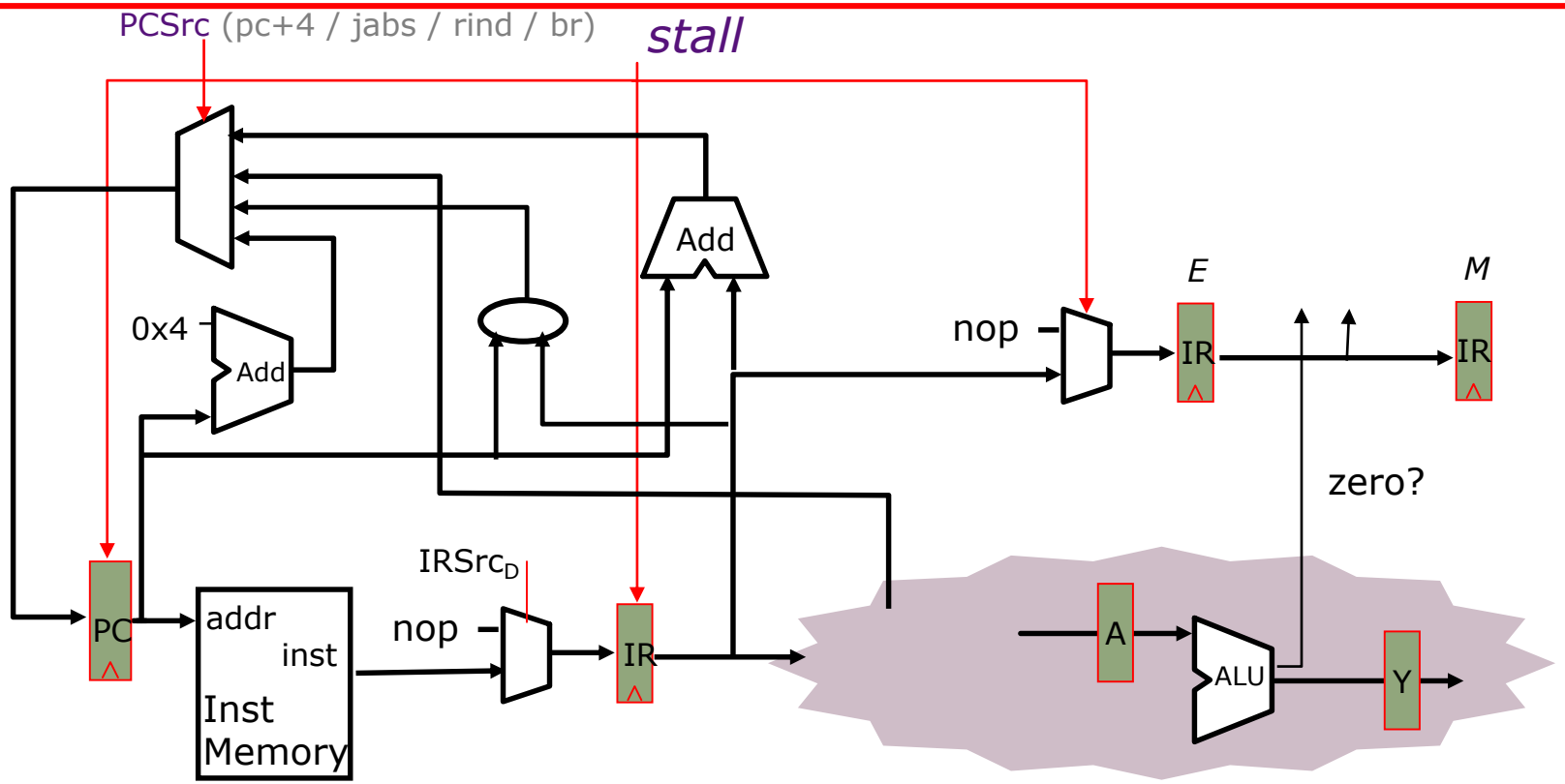


I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

Branch condition is not known until the execute stage

what action should be taken in the decode stage?

Pipelining Conditional Branches



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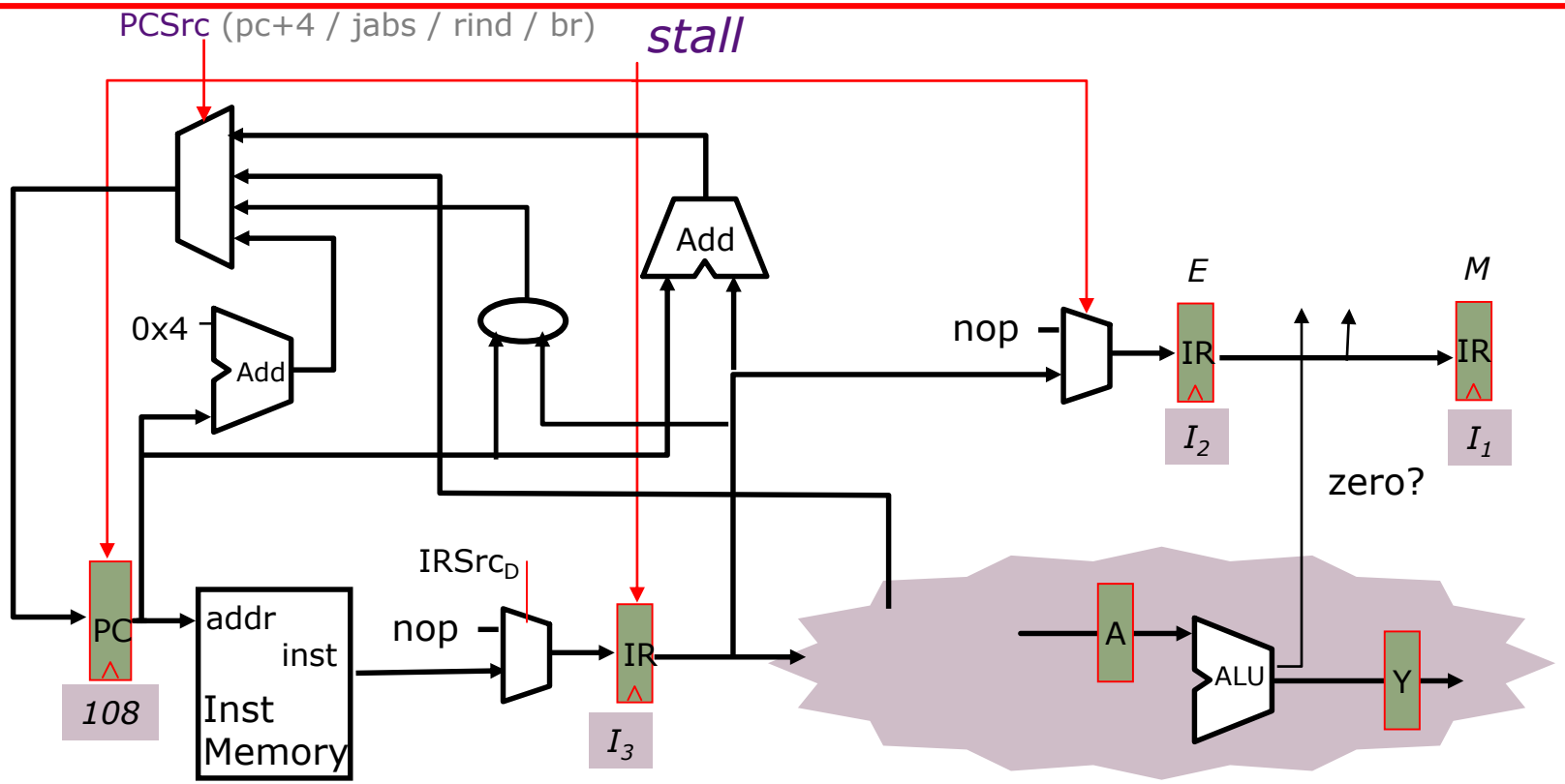

I_1	096	ADD
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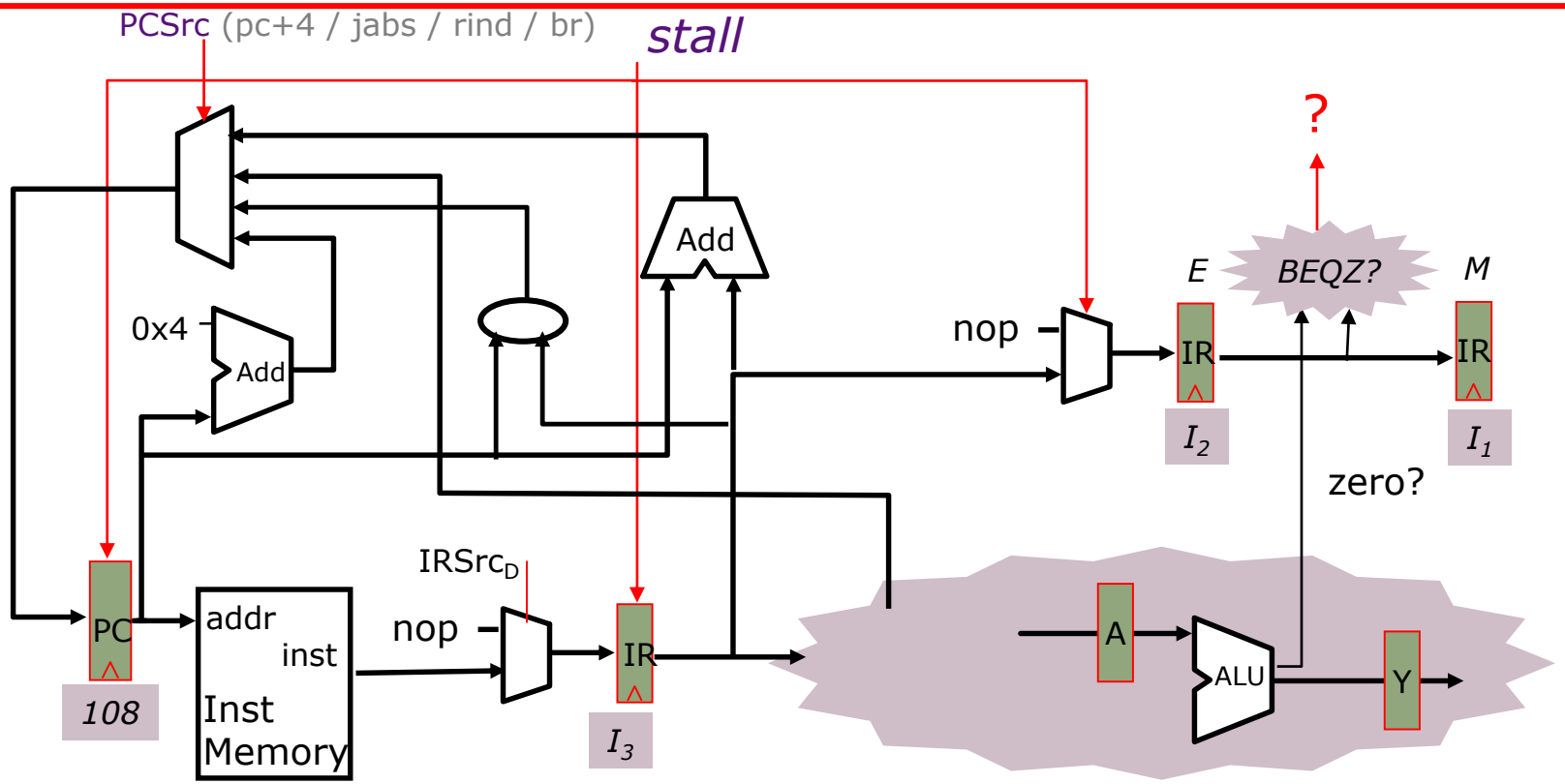
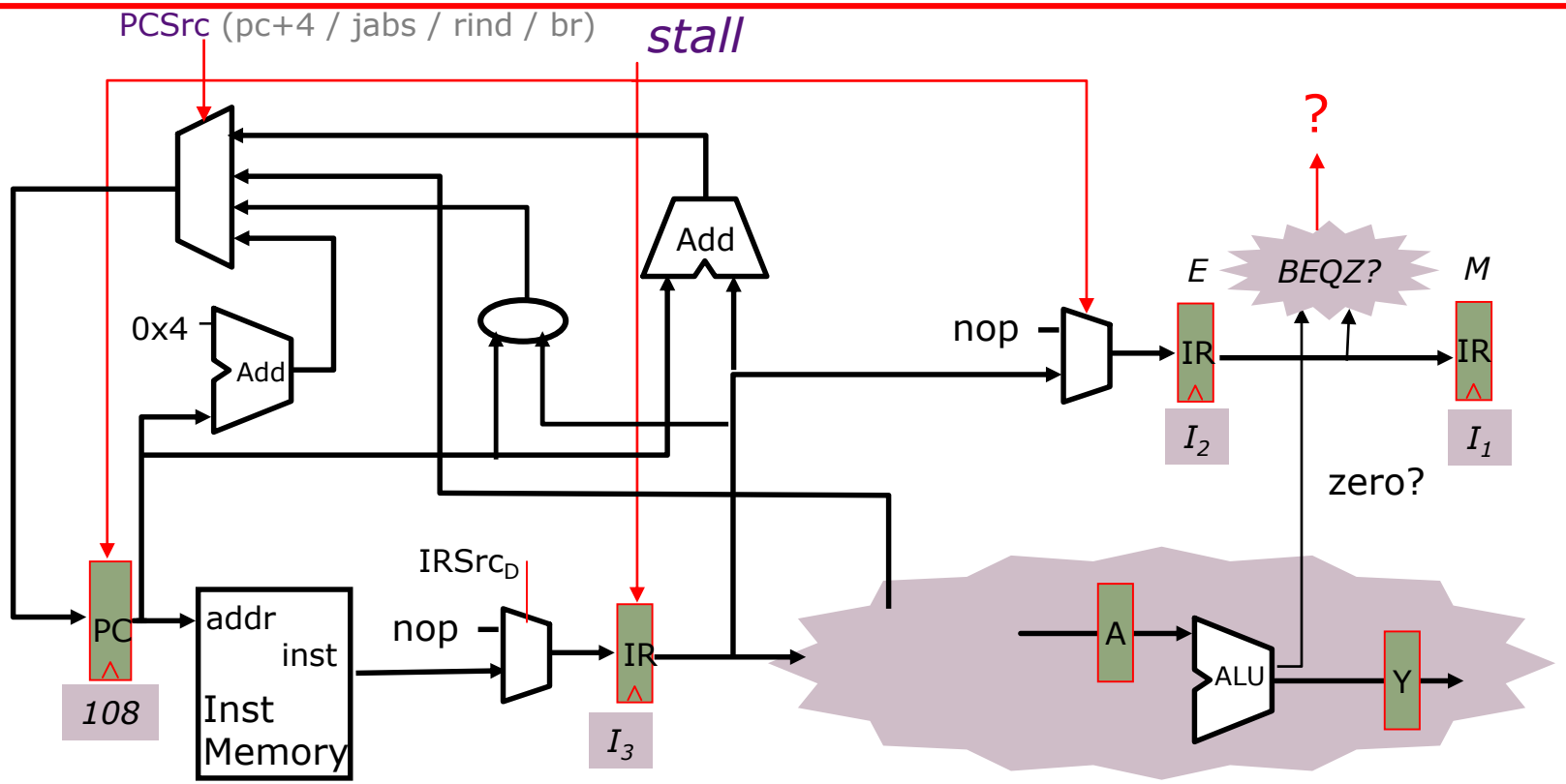
Pipelining Conditional Branches



I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

Pipelining Conditional Branches

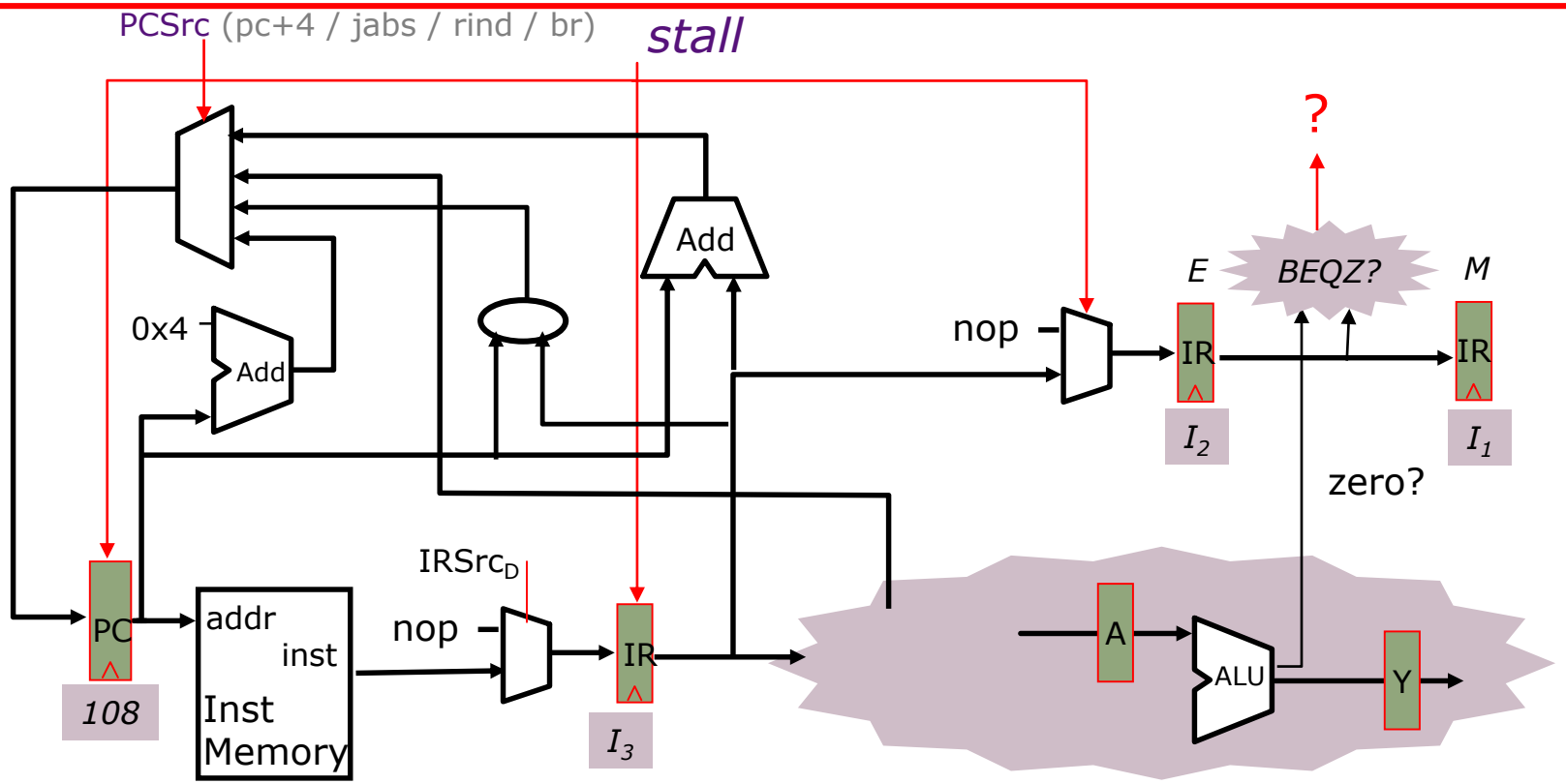


If the branch is taken

- kill the two following instructions
- the instruction at the decode stage is not valid

I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

Pipelining Conditional Branches



I_1	096	ADD
I_2	100	BEQZ r1 200
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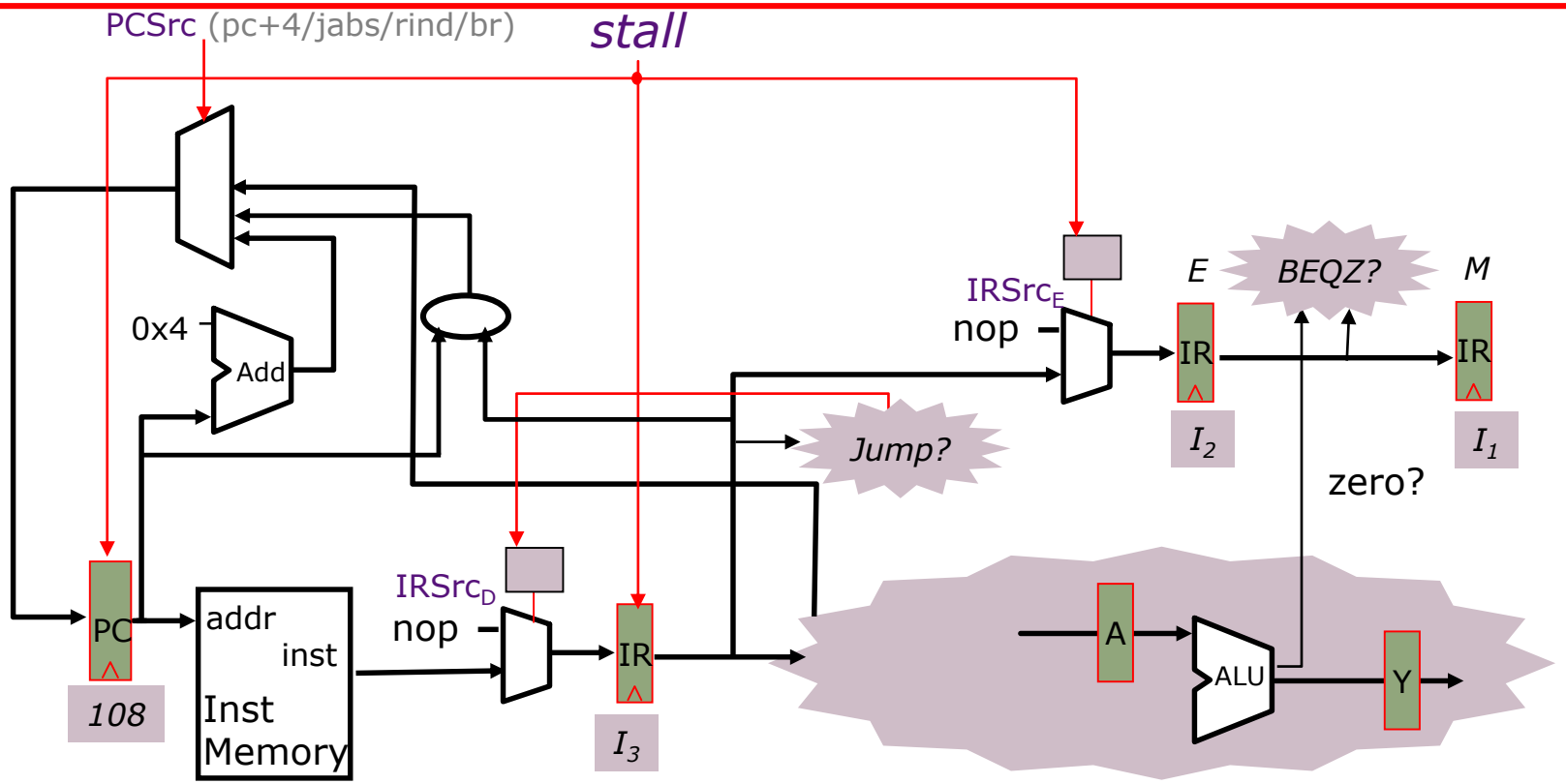
If the branch is taken

- kill the two following instructions
- the instruction at the decode stage is not valid

$\Rightarrow$ *stall signal is not valid*

Pipelining Conditional Branches



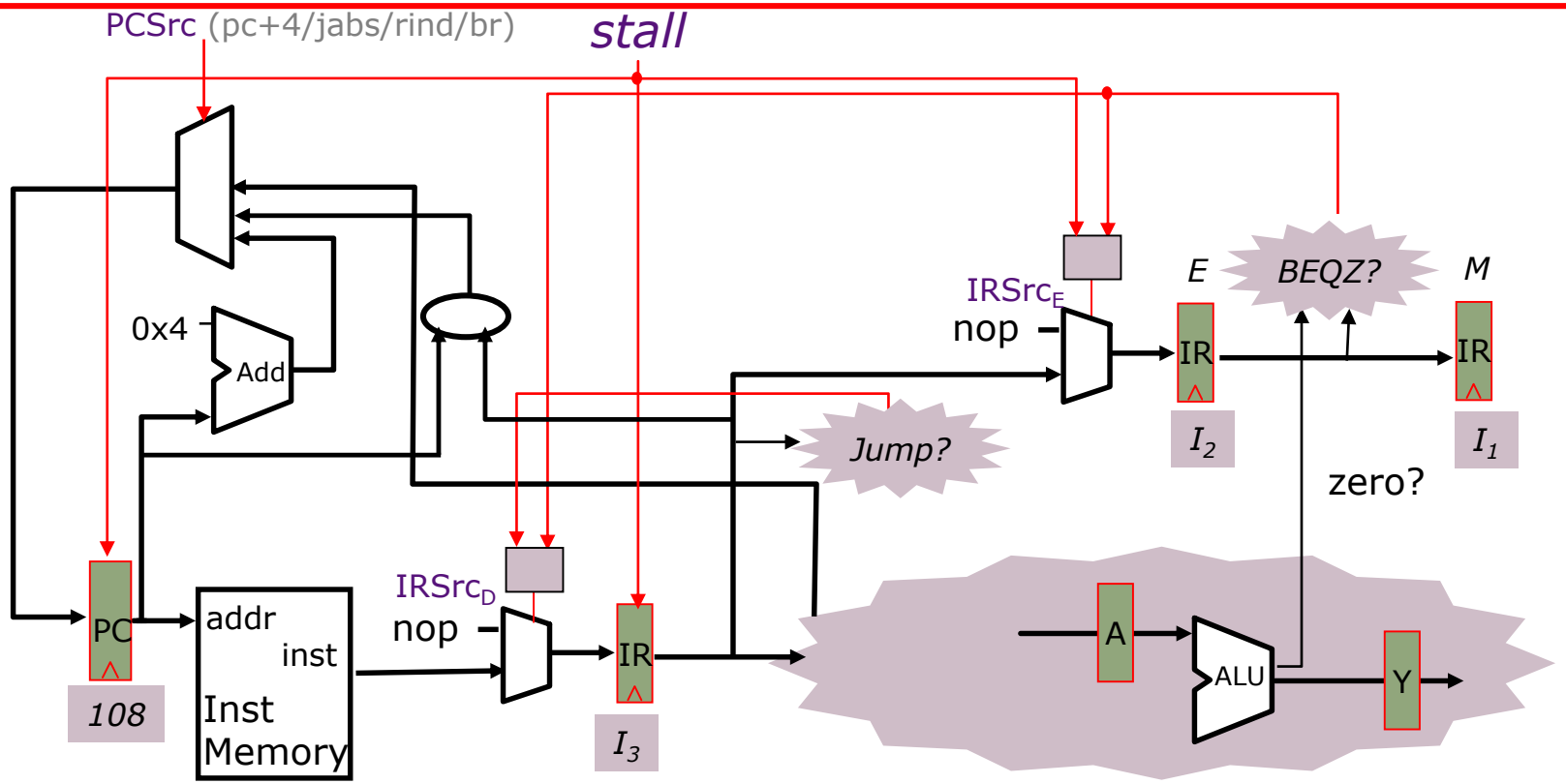
I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

If the branch is taken

- kill the two following instructions
- the instruction at the decode stage is not valid

$\Rightarrow$ *stall signal is not valid*

Pipelining Conditional Branches



I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
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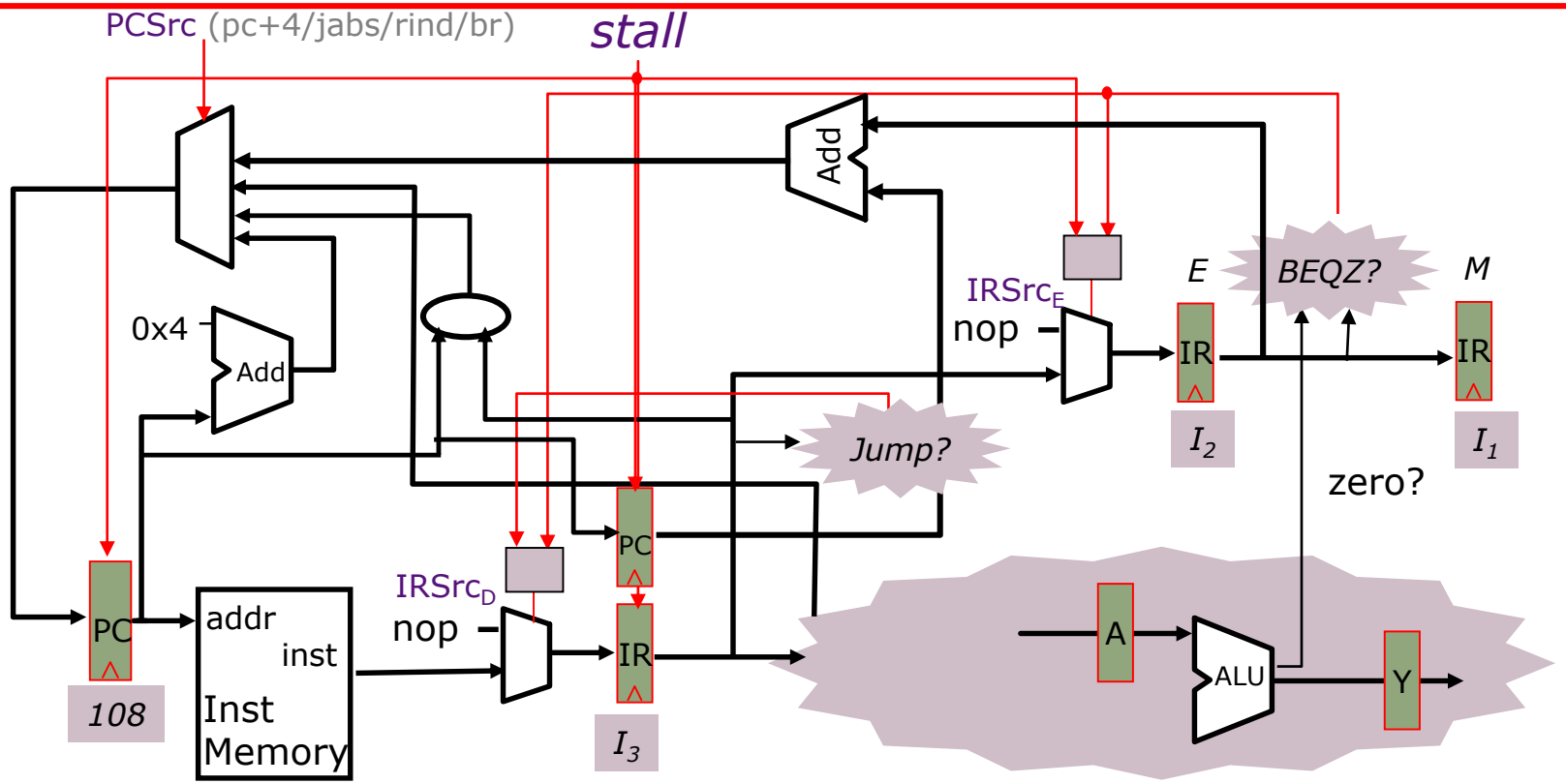
- the instruction at the decode stage is not valid

$\Rightarrow$ *stall signal is not valid*

Pipelining Conditional Branches



If the branch is taken

- kill the two following instructions
- the instruction at the decode stage is not valid

⇒ *stall signal is not valid*

I_1	096	ADD
I_2	100	BEQZ r1 200
I_3	104	ADD
I_4	304	ADD

New Stall Signal

$$
\begin{aligned}
\text{stall} = (\ & ((rs_D == ws_E)\cdot we_E + (rs_D == ws_M)\cdot we_M + (rs_D == ws_W)\cdot we_W)\cdot re1_D \\
& + ((rt_D == ws_E)\cdot we_E + (rt_D == ws_M)\cdot we_M + (rt_D == ws_W)\cdot we_W)\cdot re2_D \\
&) \cdot !((opcode_E == BEQZ)\cdot z + (opcode_E == BNEZ)\cdot !z)
\end{aligned}
$$

Don’t stall if the branch is taken. Why?

New Stall Signal

$$
\begin{aligned}
\text{stall} = (\ & ((rs_D == ws_E)\cdot we_E + (rs_D == ws_M)\cdot we_M + (rs_D == ws_W)\cdot we_W)\cdot re1_D \\
& + ((rt_D == ws_E)\cdot we_E + (rt_D == ws_M)\cdot we_M + (rt_D == ws_W)\cdot we_W)\cdot re2_D \\
&) \cdot !((opcode_E == BEQZ)\cdot z + (opcode_E == BNEZ)\cdot !z)
\end{aligned}
$$

Don't stall if the branch is taken. Why?

Instruction at the decode stage is invalid

Control Equations for PC and IR Muxes

$IRSrc_D$ = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ nop
- ... ⇒
  - *Case* $opcode_D$
    - J, JAL, JR, JALR ⇒ nop
    - ... ⇒ IM

$IRSrc_E$ = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ nop
- ... ⇒ stall·nop + !stall·IR_D

PCSrc = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ br
- ... ⇒
  - *Case* $opcode_D$
    - J, JAL ⇒ jabs
    - JR, JALR ⇒ rind
    - ... ⇒ pc+4

nop ⇒ Kill

br/jabs/rind ⇒ Restart

pc+4 ⇒ Speculate

Control Equations for PC and IR Muxes

$IRSrc_D$ = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ nop
- ... ⇒
  - *Case* $opcode_D$
    - J, JAL, JR, JALR ⇒ nop
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PCSrc = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ br
- ... ⇒
  - *Case* $opcode_D$
    - J, JAL ⇒ jabs
    - JR, JALR ⇒ rind
    - ... ⇒ pc+4

Give priority to the older instruction, i.e., execute stage instruction over decode stage instruction

nop ⇒ Kill
br/jabs/rind ⇒ Restart
pc+4 ⇒ Speculate

Control Equations for PC and IR Muxes

$IRSrc_D$ = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ nop
- ... ⇒
  - *Case* $opcode_D$
    - J, JAL, JR, JALR ⇒ nop
    - ... ⇒ IM

$IRSrc_E$ = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ nop
- ... ⇒ stall·nop + !stall·IR_D

PCSrc = *Case* $opcode_E$
- BEQZ·z, BNEZ·!z ⇒ br
- ... ⇒
  - *Case* $opcode_D$
    - J, JAL ⇒ jabs
    - JR, JALR ⇒ rind
    - ... ⇒ pc+4

Give priority to the older instruction, i.e., execute stage instruction over decode stage instruction

pc+4 is a speculative guess

nop ⇒ Kill
br/jabs/rind ⇒ Restart
pc+4 ⇒ Speculate

Branch Pipeline Diagrams
(resolved in execute stage)

Branch Pipeline Diagrams
(resolved in execute stage)

time

t0 t1 t2 t3 t4 t5 t6 t7 . . . .

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	ID_3	nop	nop	nop		

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	ID_3	nop	nop	nop		
(I_4) 108:				IF_4	nop	nop	nop	nop	

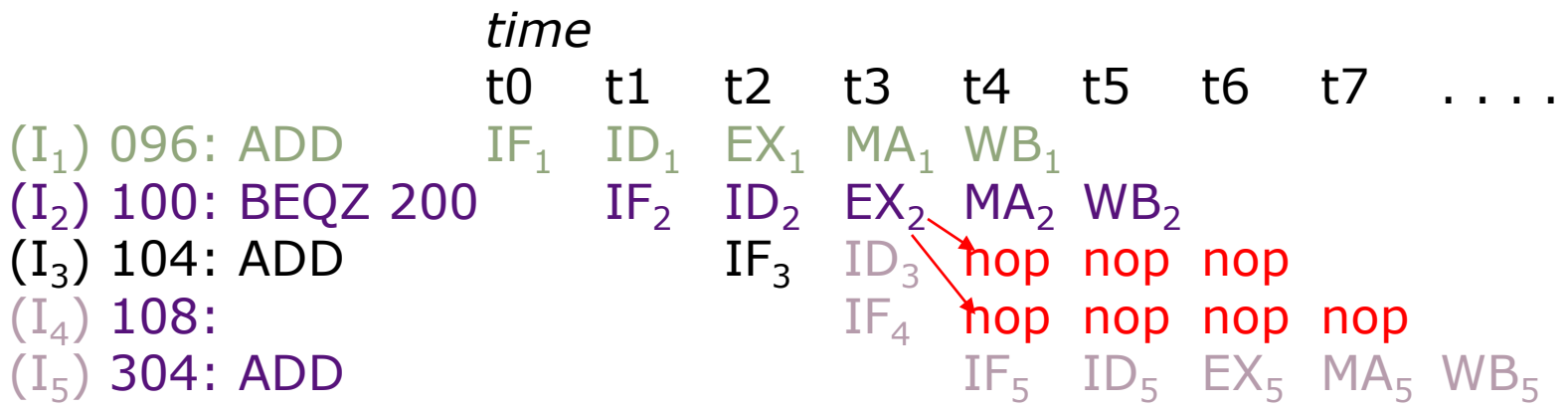
Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	ID_3	nop	nop	nop		
(I_4) 108:				IF_4	nop	nop	nop	nop	
(I_5) 304: ADD					IF_5	ID_5	EX_5	MA_5	WB_5

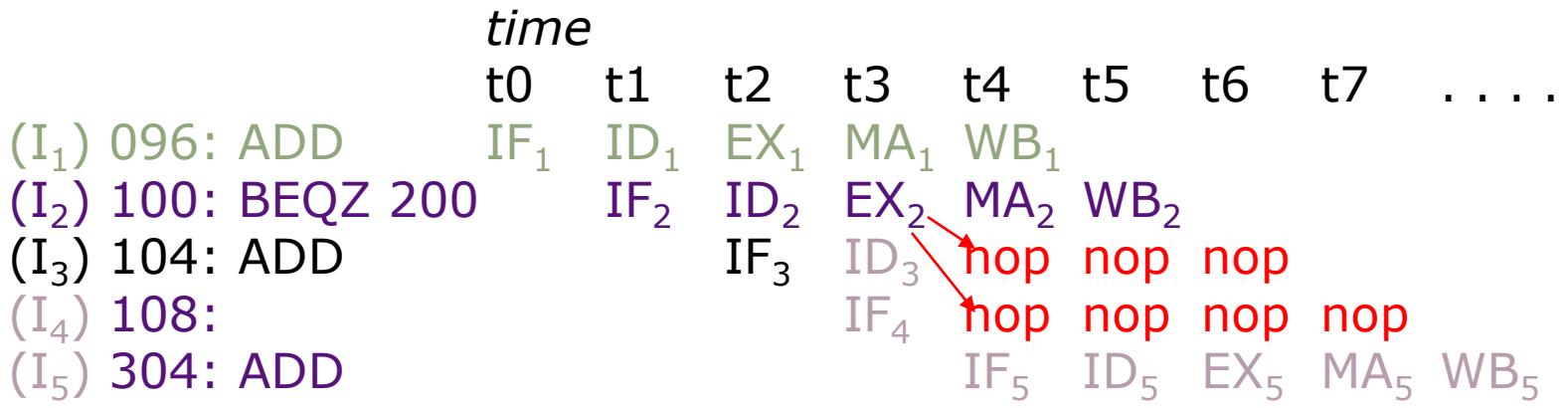
Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	ID_3	nop	nop	nop		
(I_4) 108:				IF_4	nop	nop	nop	nop	
(I_5) 304: ADD					IF_5	ID_5	EX_5	MA_5	WB_5

Branch Pipeline Diagrams
(resolved in execute stage)

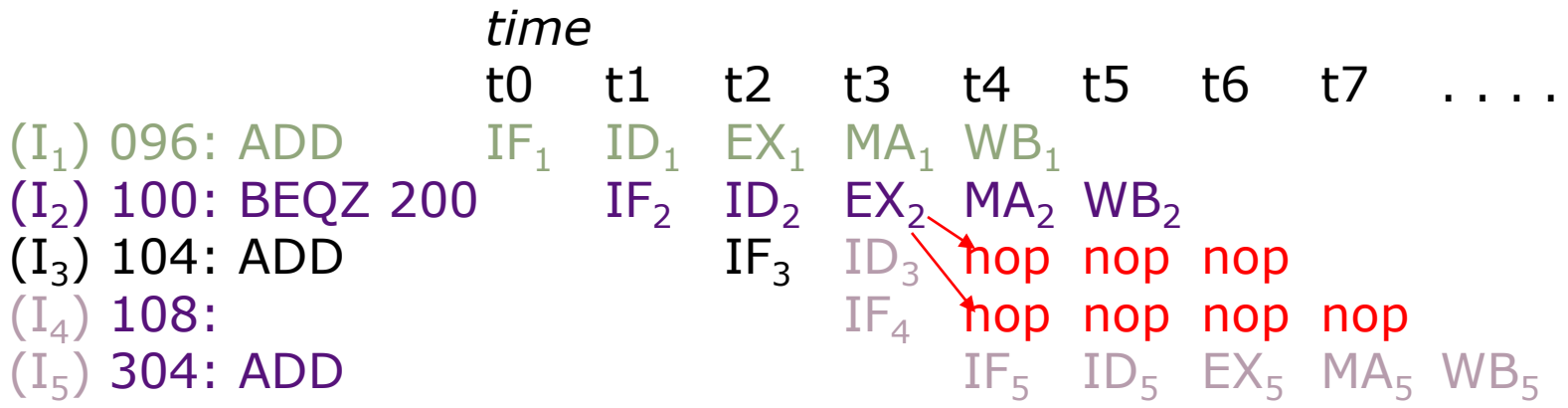


Branch Pipeline Diagrams
(resolved in execute stage)



Resource Usage

Branch Pipeline Diagrams
(resolved in execute stage)



Resource Usage

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	ID_3	nop	nop	nop		
(I_4) 108:				IF_4	nop	nop	nop	nop	
(I_5) 304: ADD					IF_5	ID_5	EX_5	MA_5	WB_5

Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	I_2	I_3	I_4	I_5				
ID		I_1	I_2	I_3	nop	I_5			
EX			I_1	I_2	nop	nop	I_5		
MA				I_1	I_2	nop	nop	I_5	
WB					I_1	I_2	nop	nop	I_5

Branch Pipeline Diagrams
(resolved in execute stage)

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	WB_1				
(I_2) 100: BEQZ 200		IF_2	ID_2	EX_2	MA_2	WB_2			
(I_3) 104: ADD			IF_3	ID_3	nop	nop	nop		
(I_4) 108:				IF_4	nop	nop	nop	nop	
(I_5) 304: ADD					IF_5	ID_5	EX_5	MA_5	WB_5

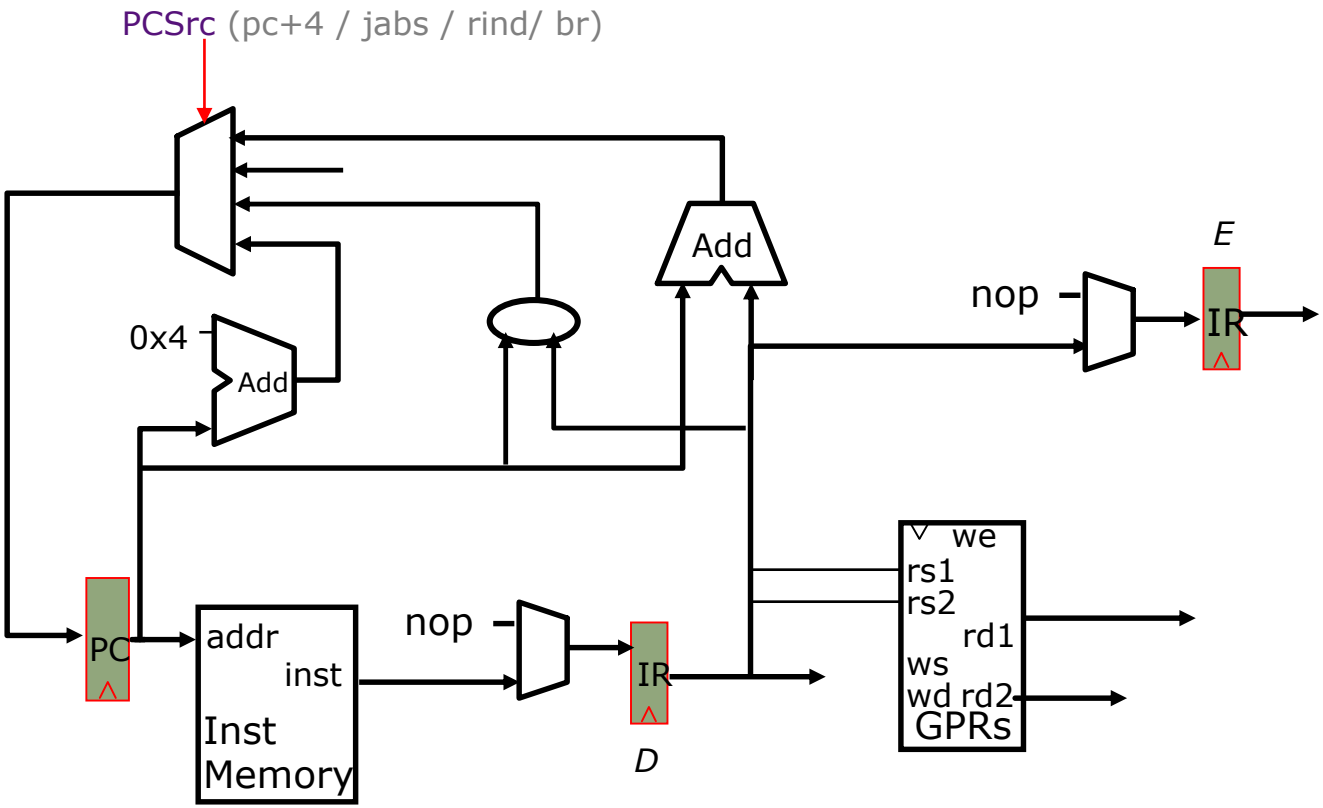
Resource Usage

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
IF	I_1	I_2	I_3	I_4	I_5				
ID		I_1	I_2	I_3	nop	I_5			
EX			I_1	I_2	nop	nop	I_5		
MA				I_1	I_2	nop	nop	I_5	
WB					I_1	I_2	nop	nop	I_5

nop ⇒ *pipeline bubble*

Reducing Branch Penalty (resolve in decode stage)

- One pipeline bubble can be removed if an extra comparator is used in the Decode stage



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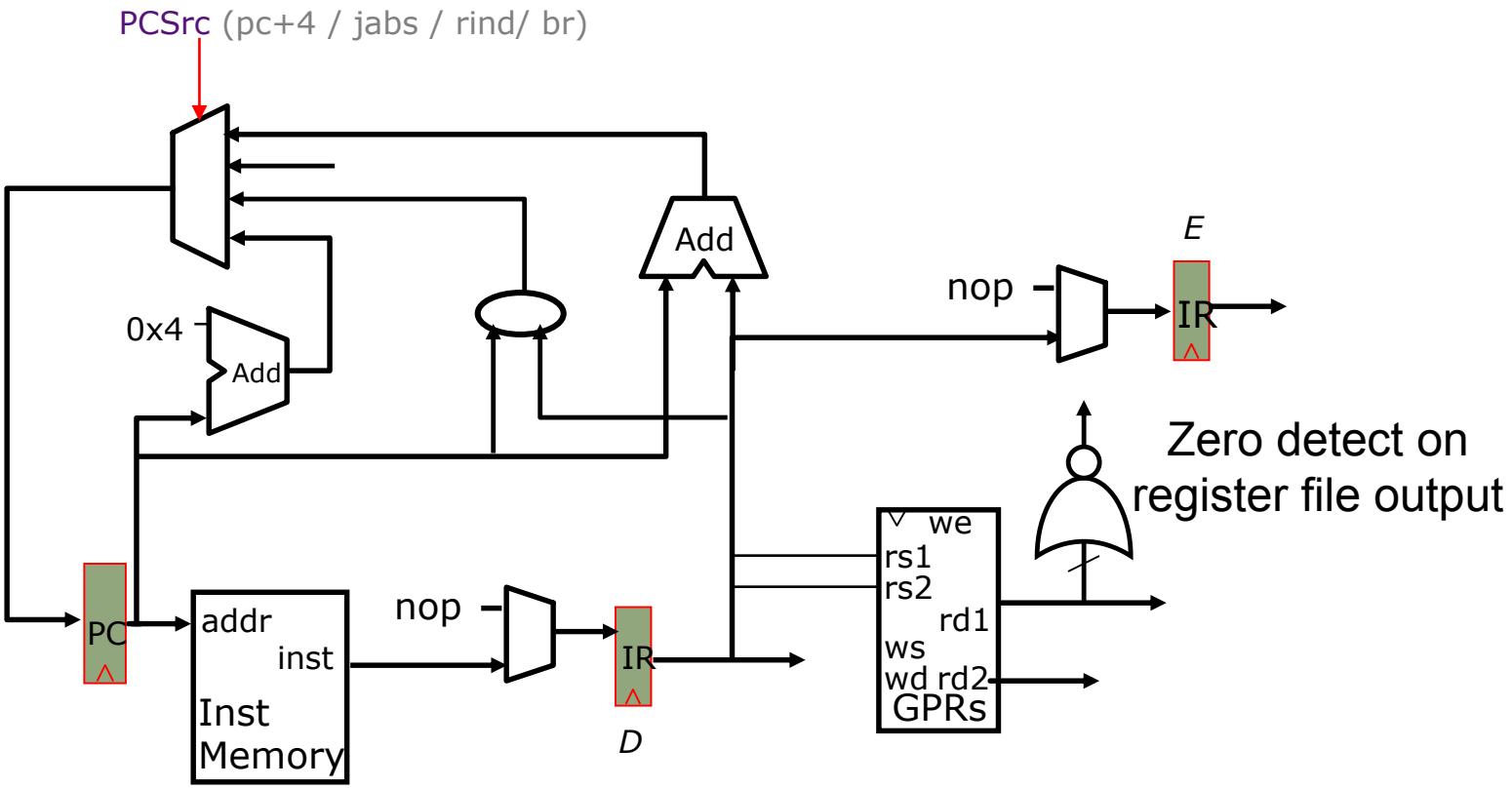

Reducing Branch Penalty (resolve in decode stage)

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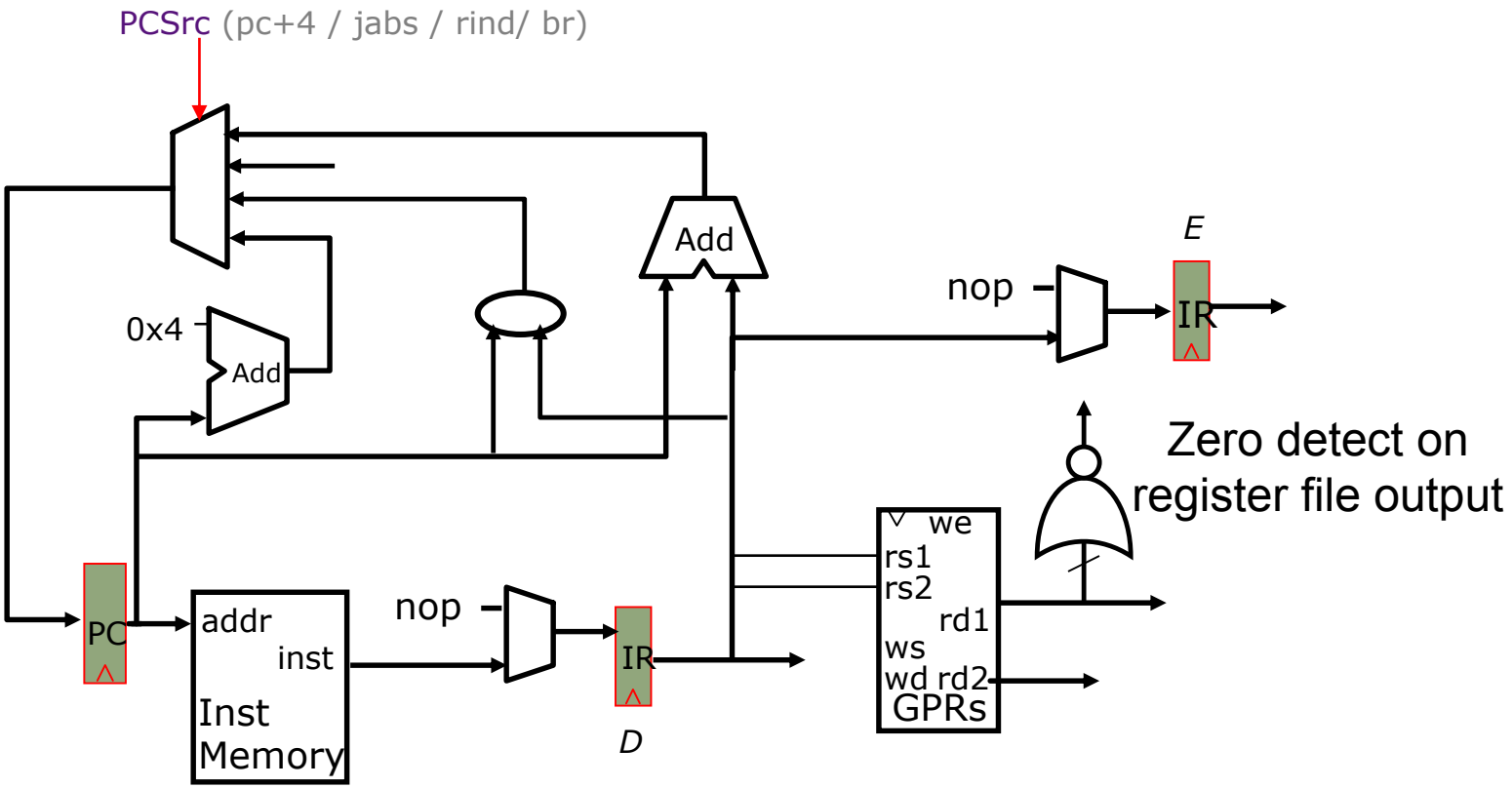

Pipeline diagram now same as for jumps

Branch Delay Slots
(expose control hazard to software)

- Change the ISA semantics so that the instruction that follows a jump or branch is always executed
  - gives compiler the flexibility to put in a useful instruction where normally a pipeline bubble would have resulted.

- Other techniques include branch prediction, which can dramatically reduce the branch penalty... *to come later*

Why an instruction may not be dispatched every cycle (CPI>1)

- Full bypassing may be too expensive to implement
  - Typically all frequently used paths are provided
  - Some infrequently used bypass paths may increase cycle time and counteract the benefit of reducing CPI
- Loads have two cycle latency
  - Instruction after load cannot use load result
  - MIPS-I ISA defined *load delay slots*, a software-visible pipeline hazard (compiler schedules independent instruction or inserts NOP to avoid hazard). Removed in MIPS-II.
- Conditional branches may cause bubbles
  - Kill following instruction(s) if no delay slots

Machines with software-visible delay slots may execute significant number of NOP instructions inserted by the compiler.

Next lecture: Superscalar & Scoreboarded Pipelines