Fundamentals of Computer Systems

A Pipelined MIPS Processor

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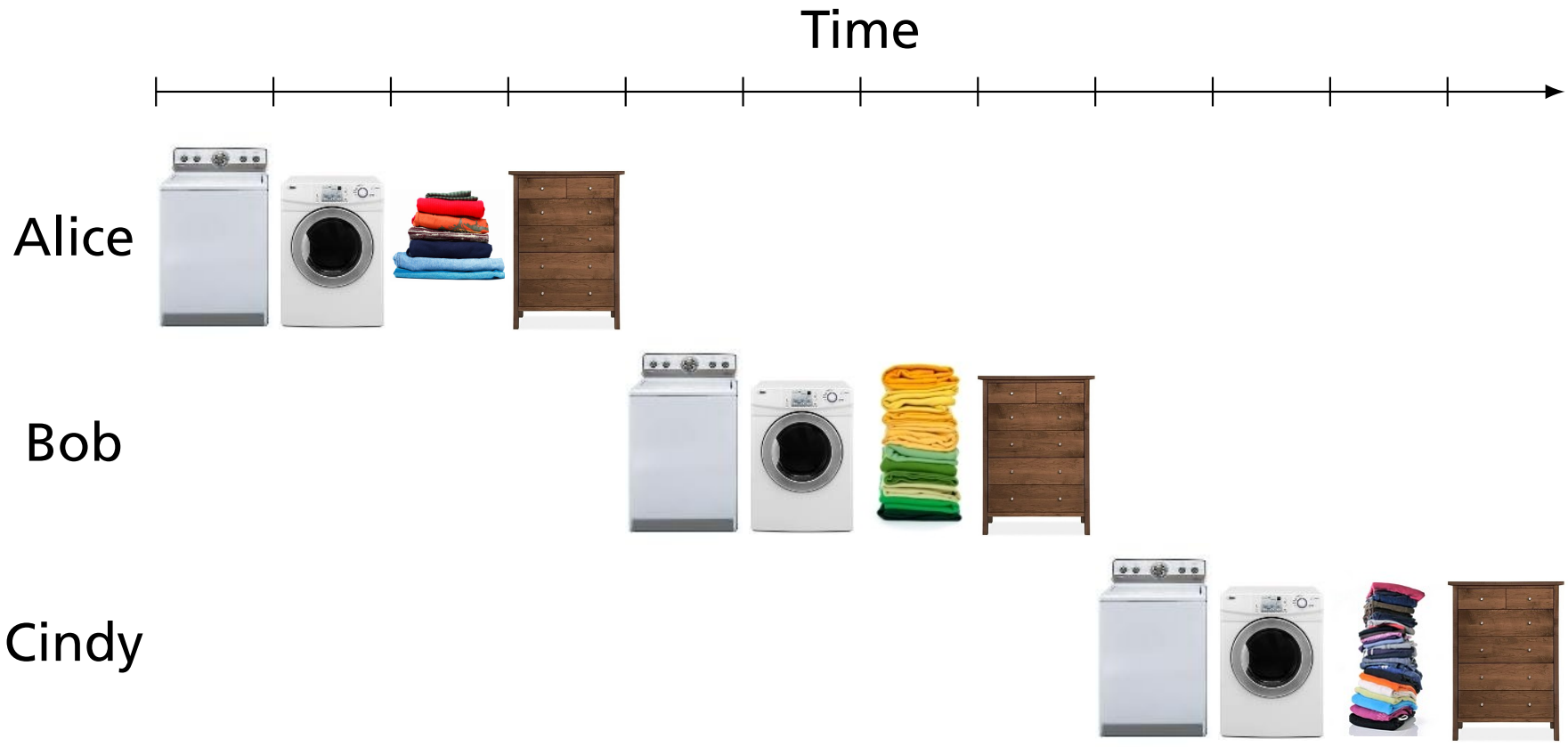
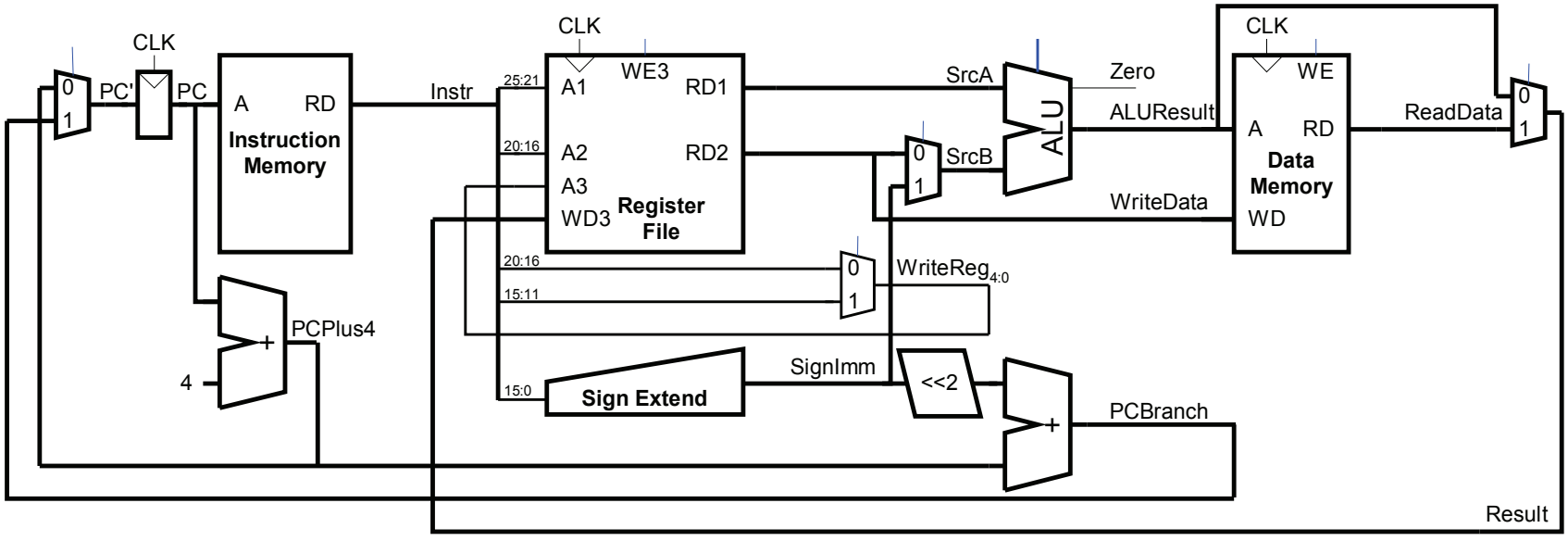
Sequential Laundry

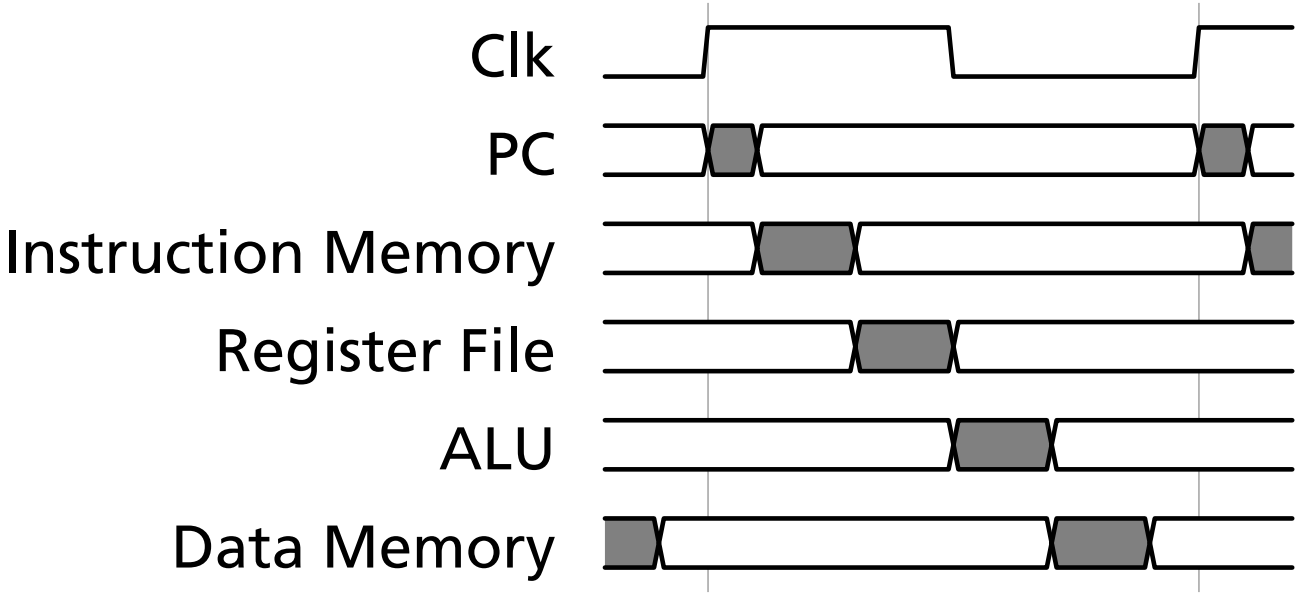


Pipelined Laundry

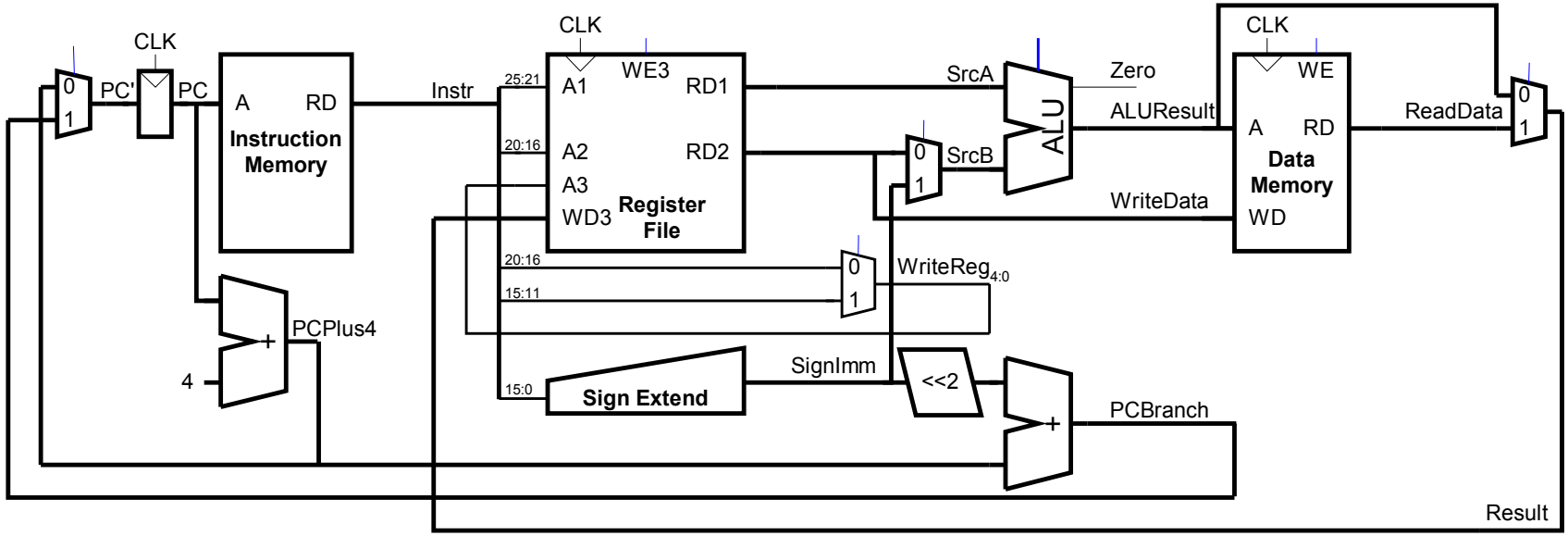
Why let the washer or dryer sit idle when both can be running?

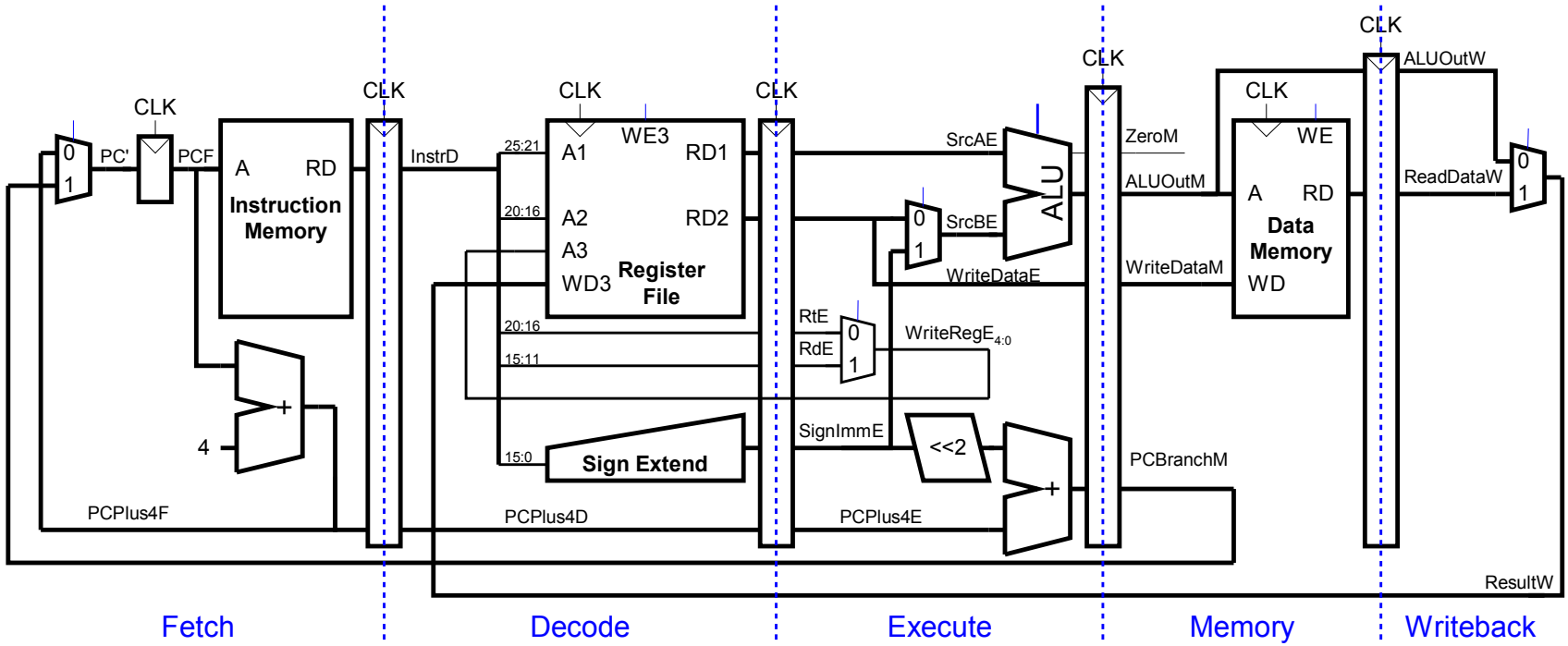
Single-Cycle Datapath Timing





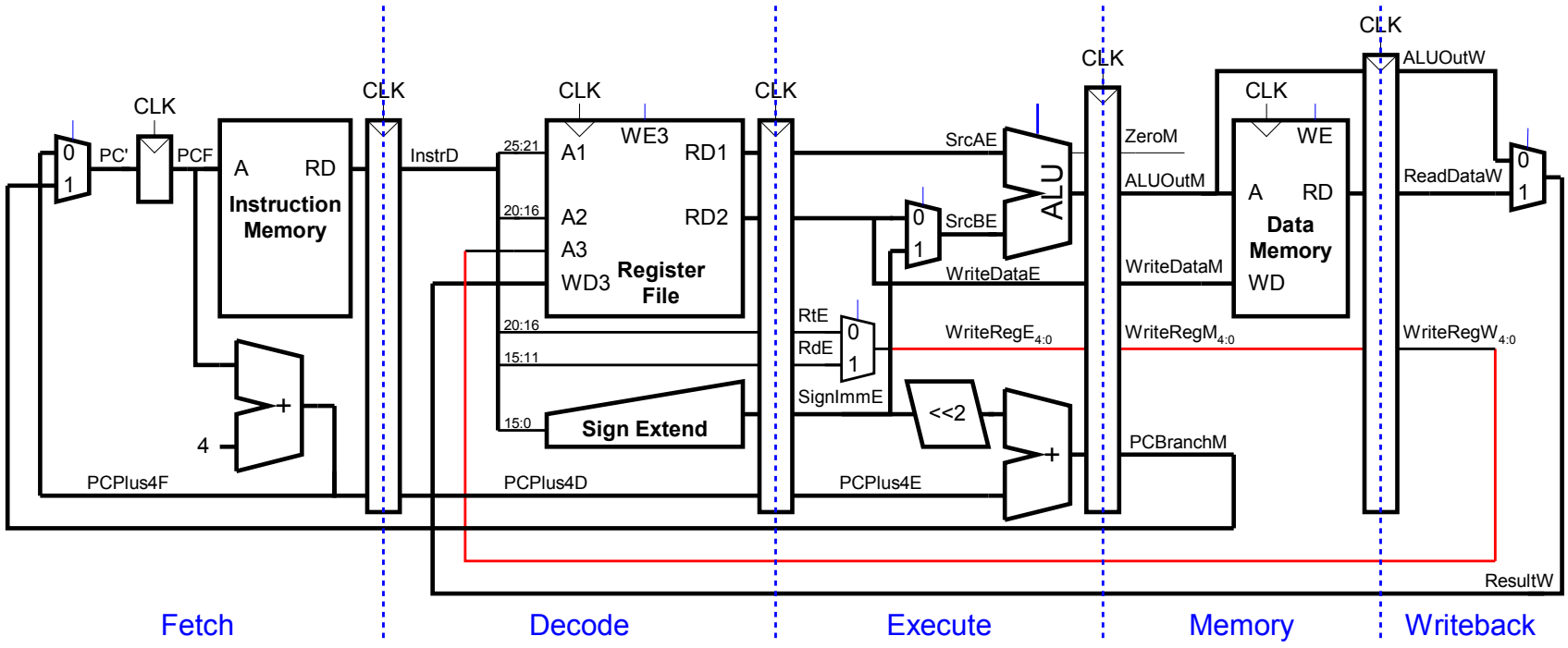
Single-Cycle vs. Pipelined Datapath





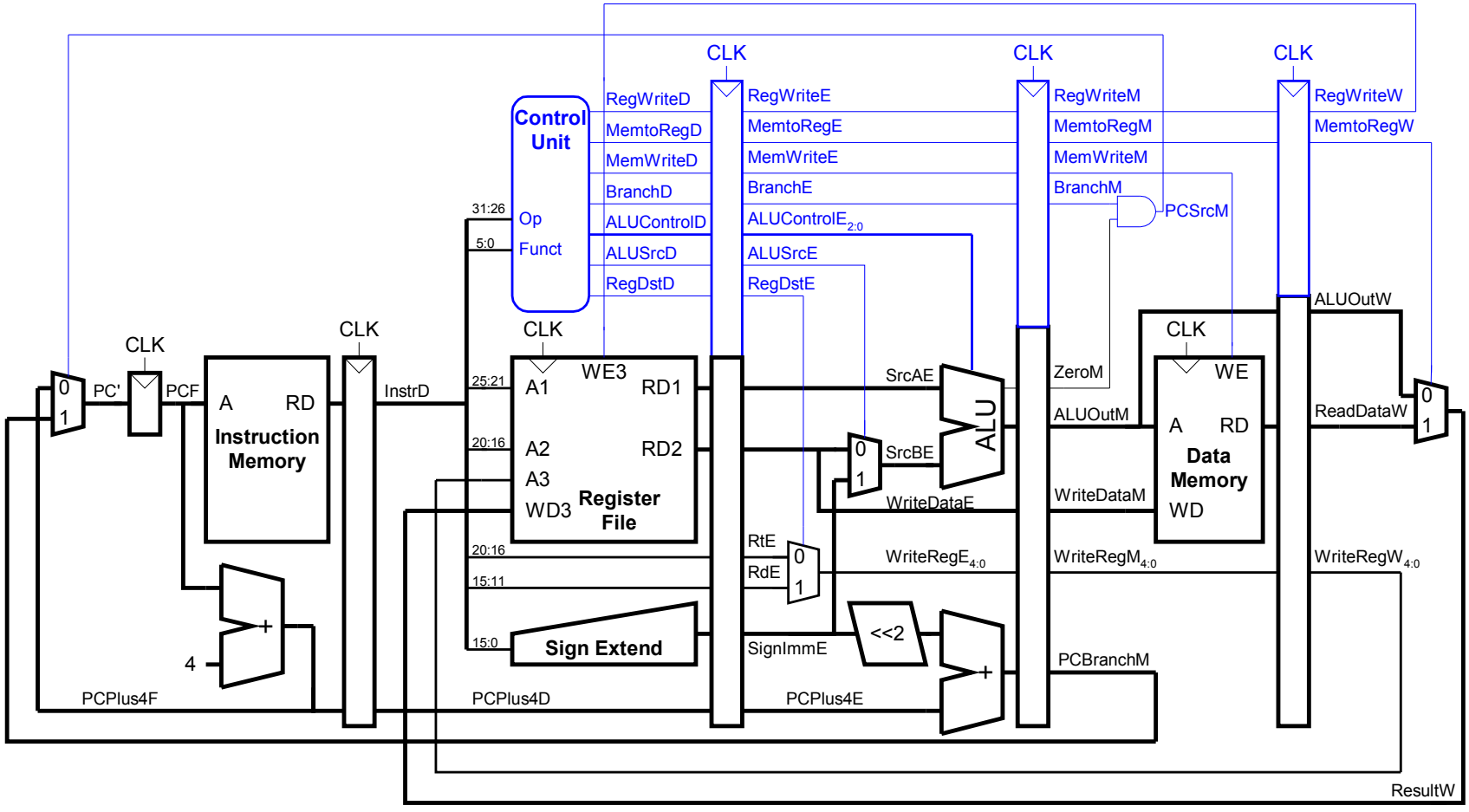
Corrected Pipelined Datapath

The register number to write (WriteReg) must stay synchronized with the result.



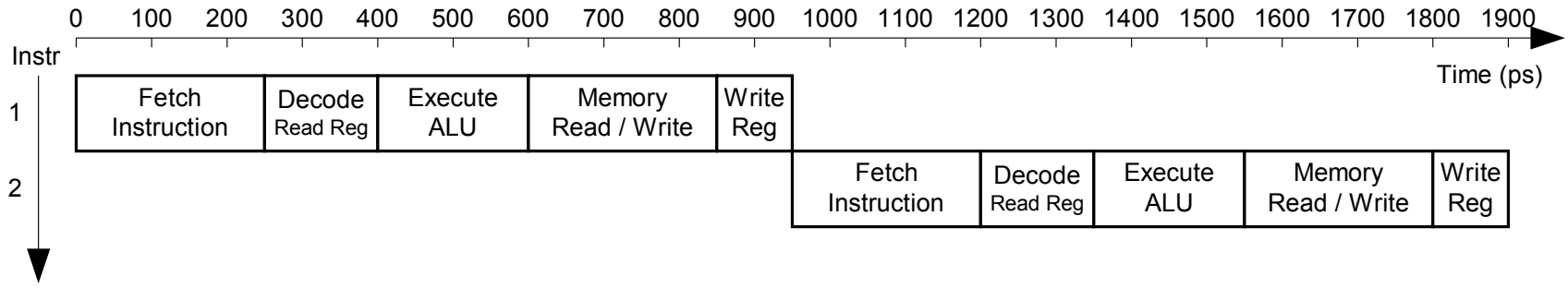
Pipeline Control

Same control unit as the single-cycle processor;
Control signals delayed across pipeline stages

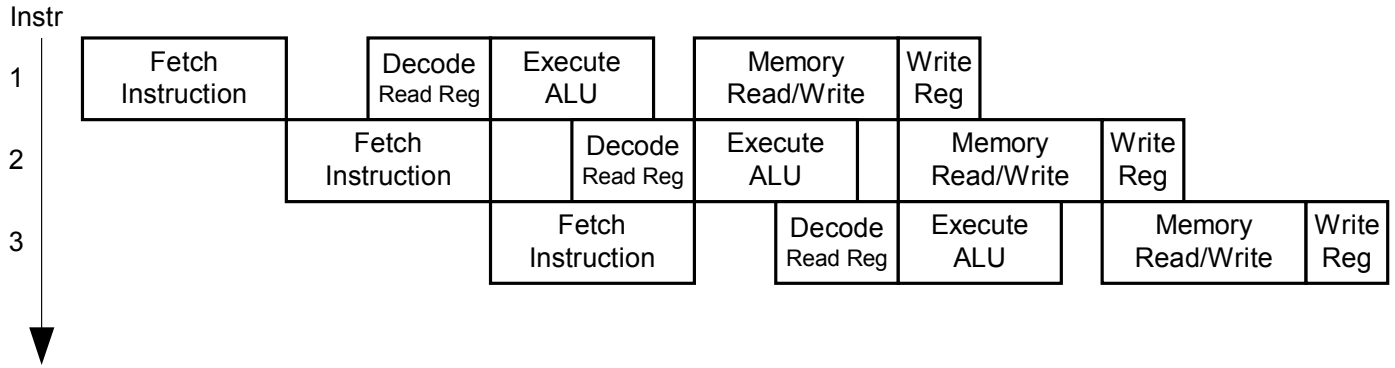


Single-Cycle vs. Pipeline Timing

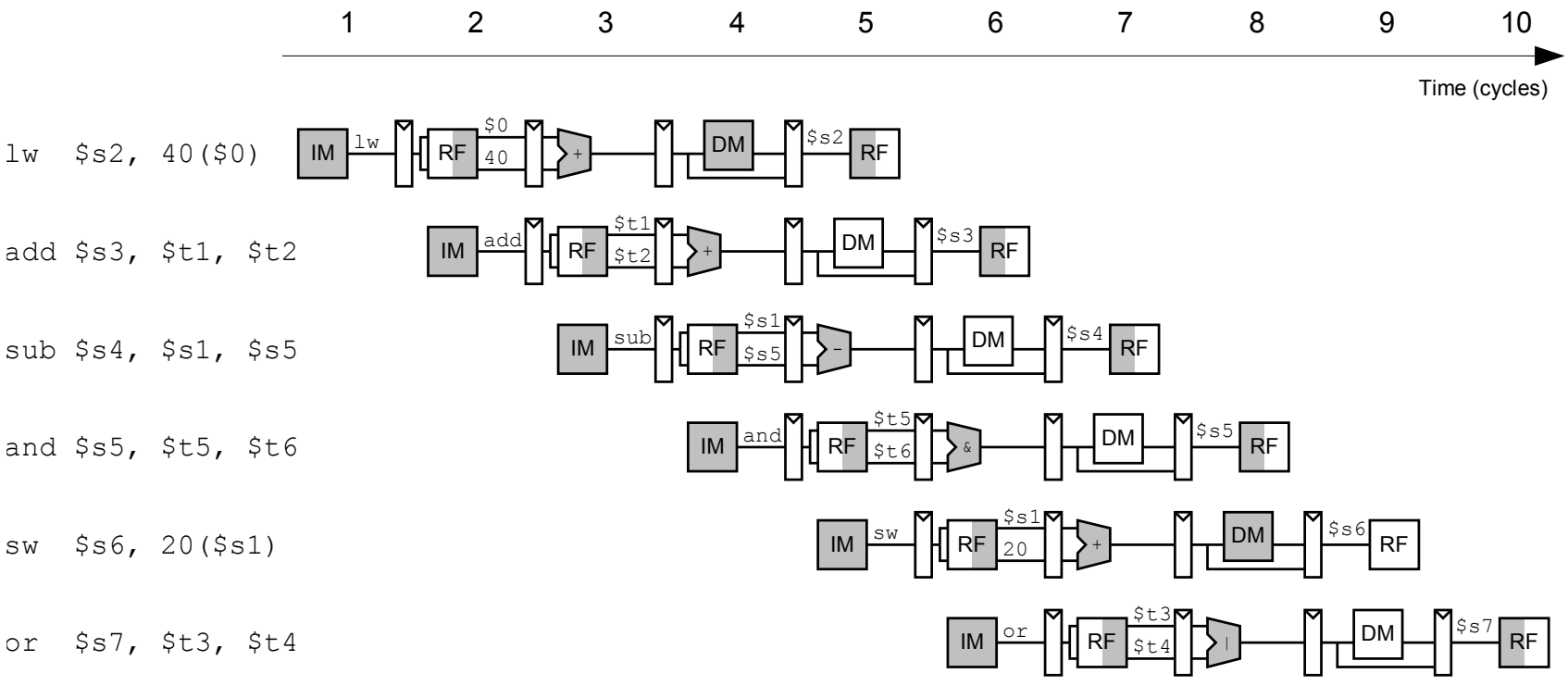
Single-Cycle



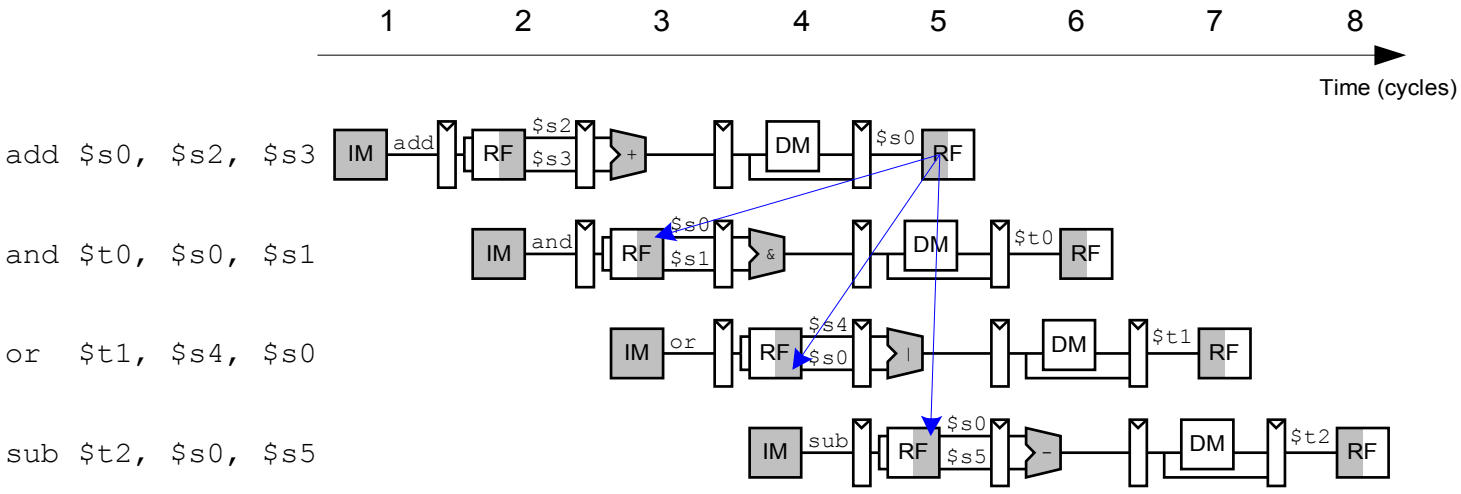
Pipelined



Pipelining Abstraction



Data Hazard



The first instruction produces a result (in $s0) that later instructions need.

The ALU has computed the value in cycle 3, but it won't be written to the register file until cycle 5.

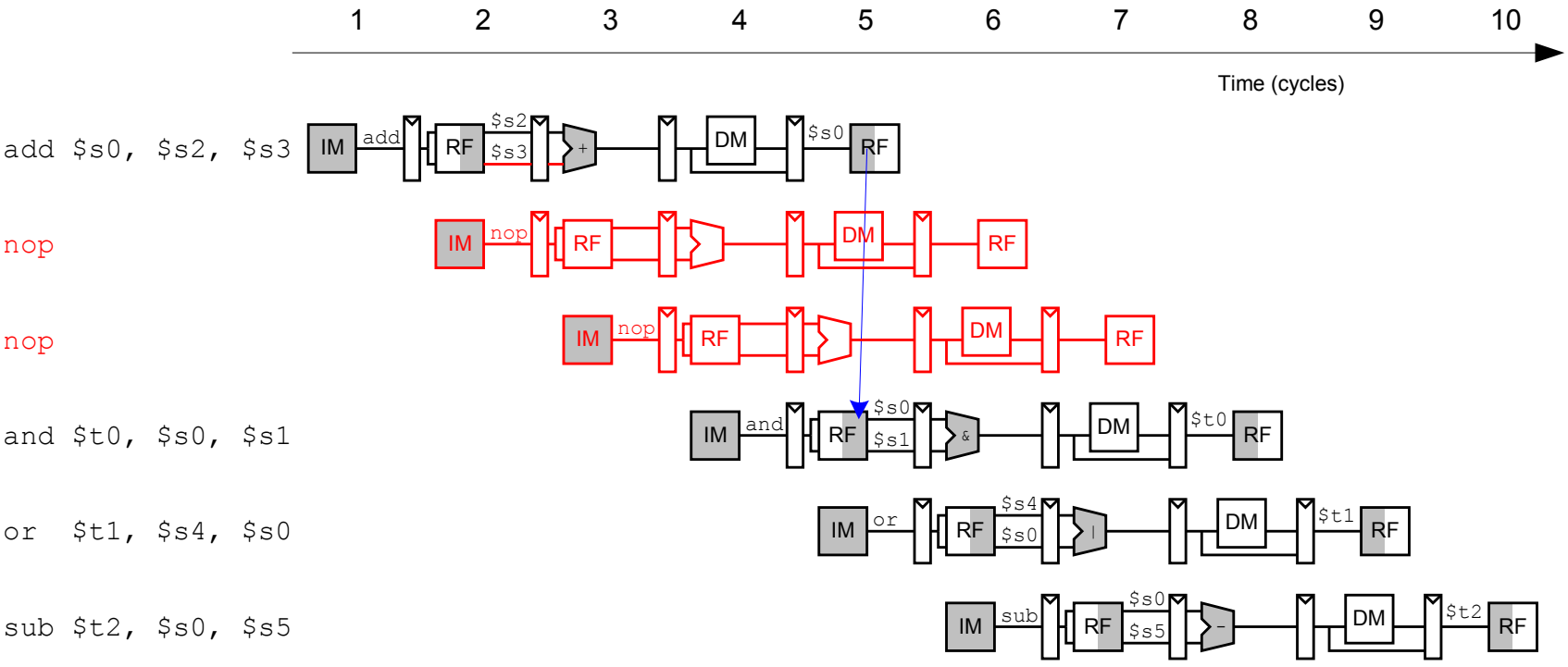
Biohazard

Water Hazard

Hazard Lights

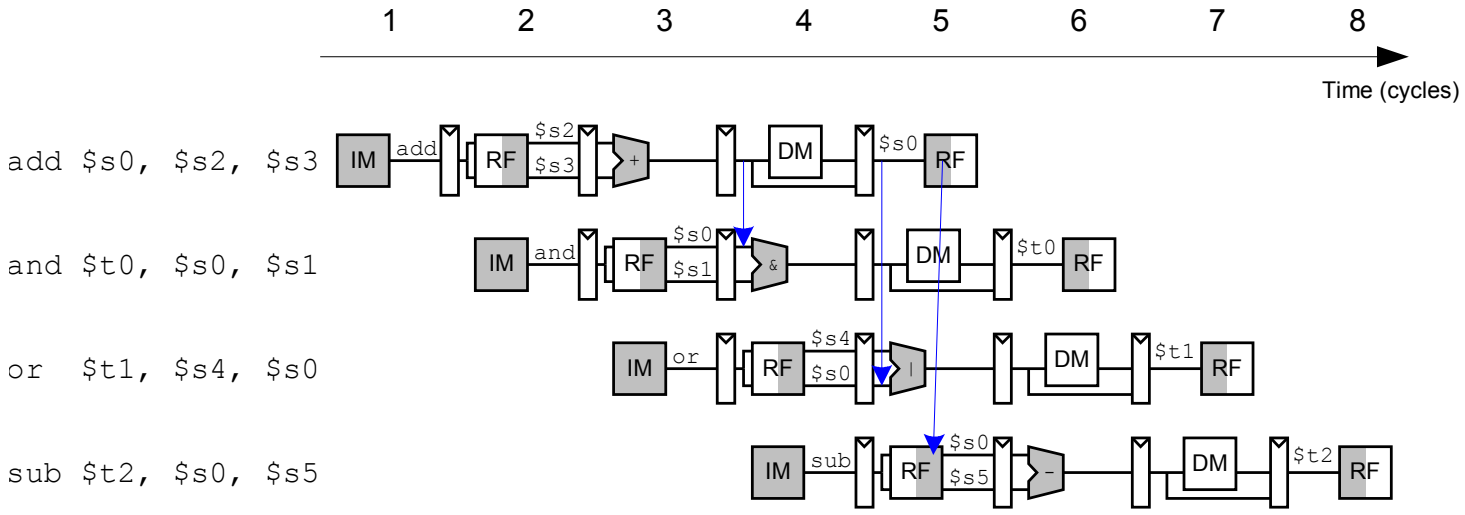
Dukes of Hazzard

Eliminating Hazards at Compile-Time



Insert *nop*s to delay later instructions; sometimes possible to put useful work in those slots.

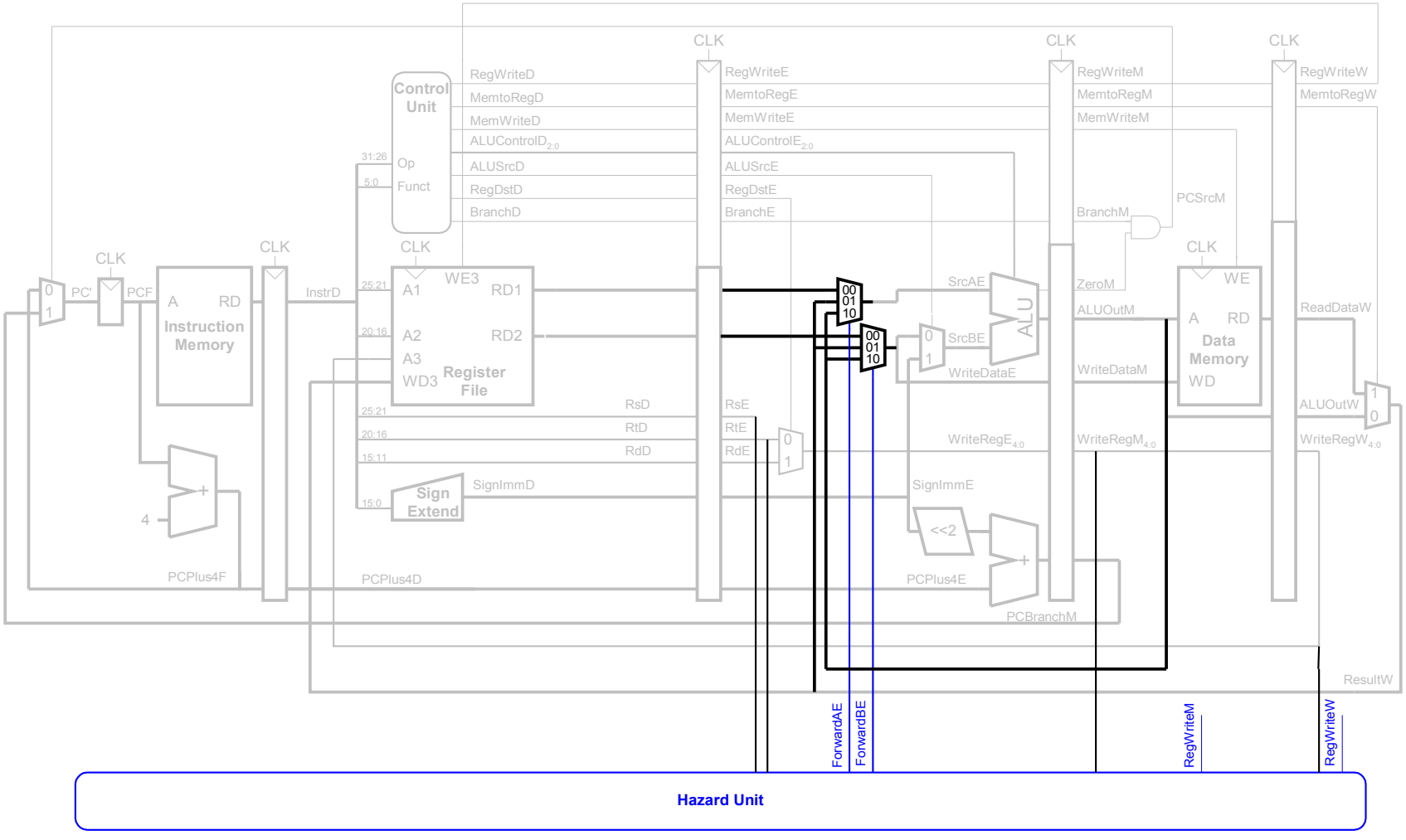
Eliminating Data Hazards through Forwarding



Add logic to send data “between” instructions; register file eventually written.

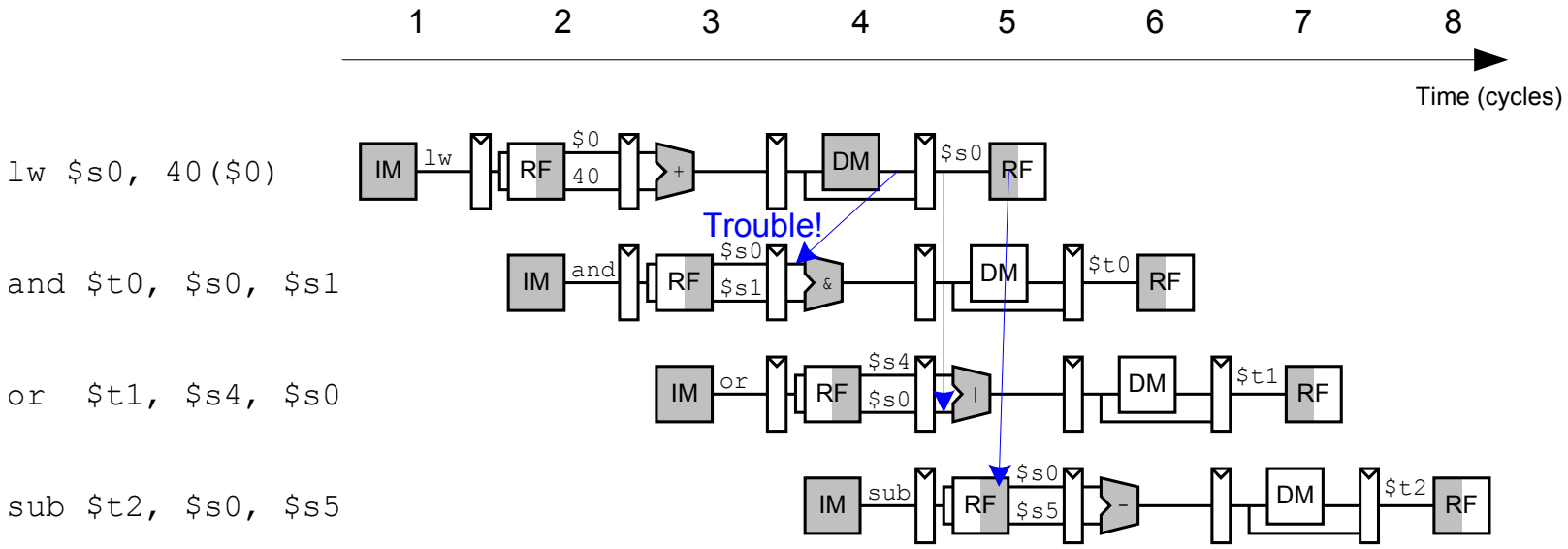
Here, the result is available at the end of cycle 3 and needed in cycles 4 and 5.

Datapath with Data Forwarding



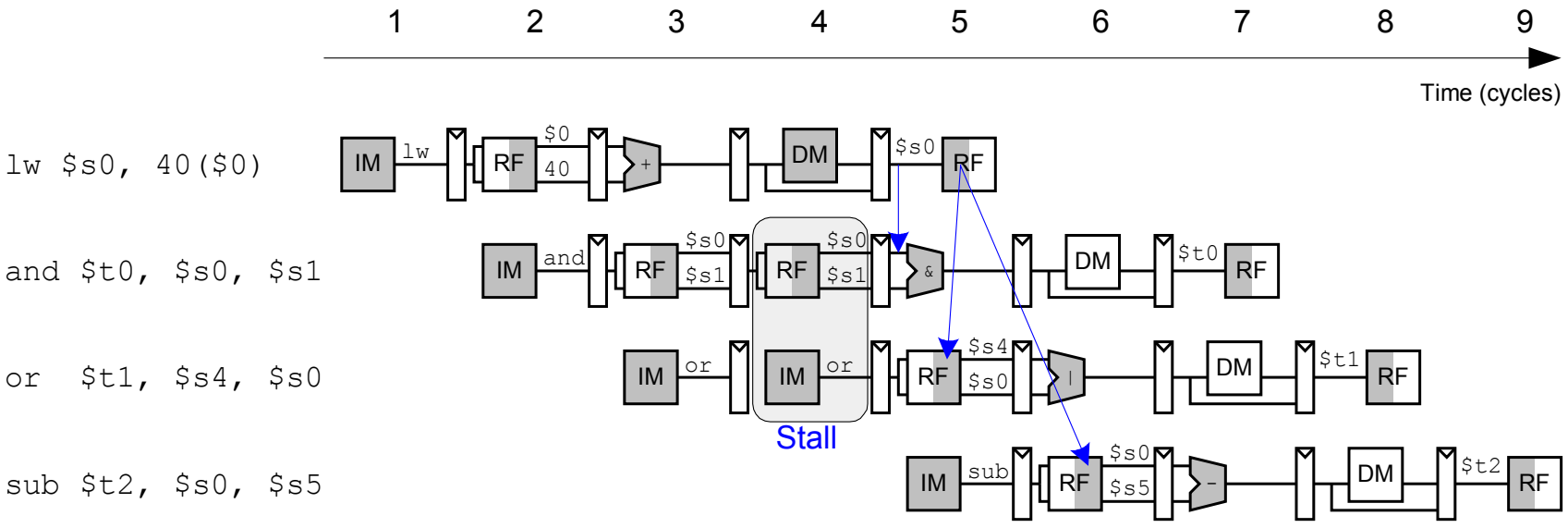
$$\text{ForwardAE} = \begin{cases} 10 & \text{if } rsE \neq 0 \wedge rsE = \text{WriteRegM} \wedge \text{RegWriteM}, \\ 01 & \text{if } rsE \neq 0 \wedge rsE = \text{WriteRegW} \wedge \text{RegWriteW}, \\ 00 & \text{otherwise.} \end{cases}$$

Data Hazard that Demands a Stall



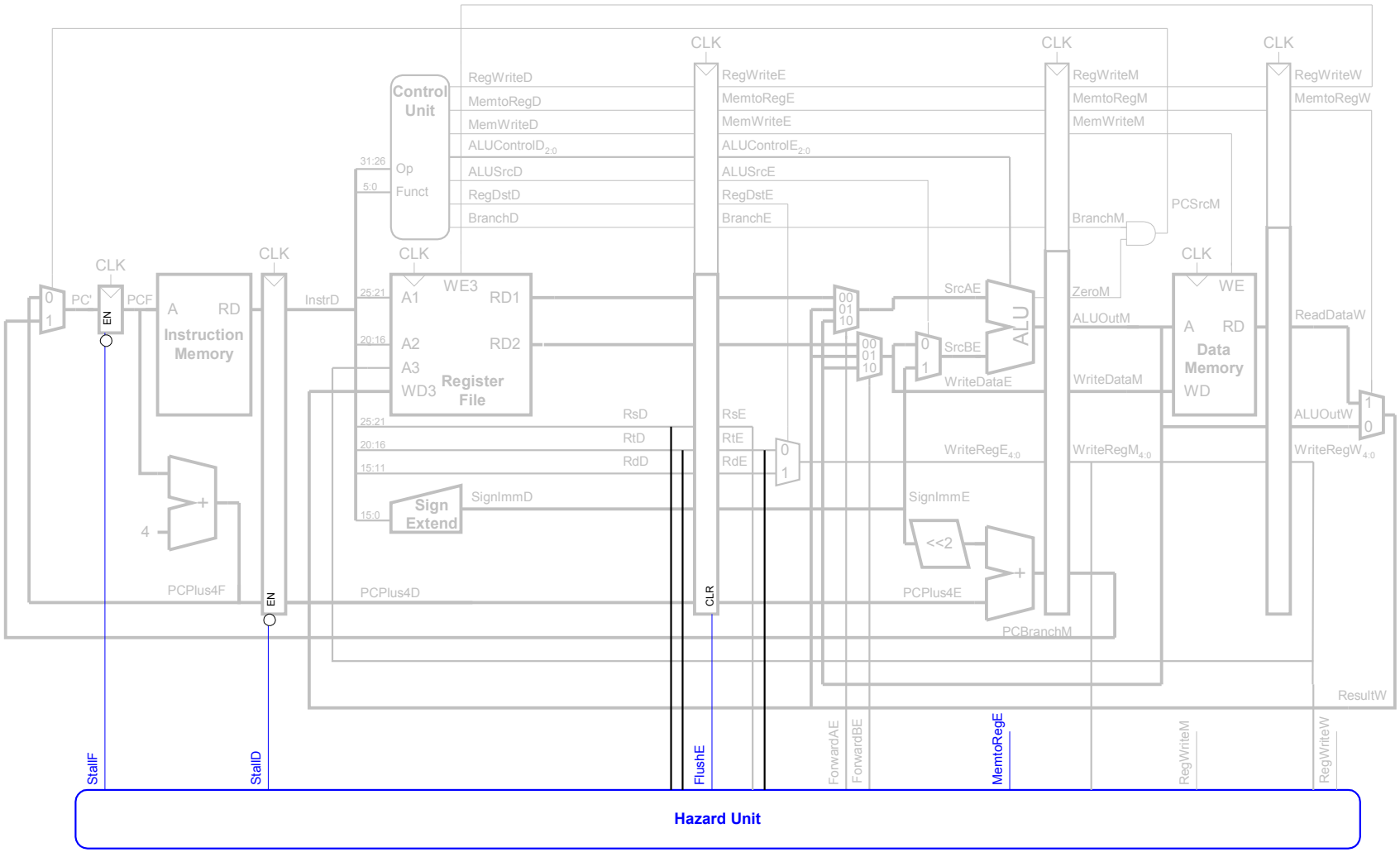
This data hazard can't be solved with forwarding because the value is only available at the end of cycle 4, yet is needed at the beginning.

Stalling a Pipeline



A *stall* tells an instruction to wait for a cycle before proceeding.

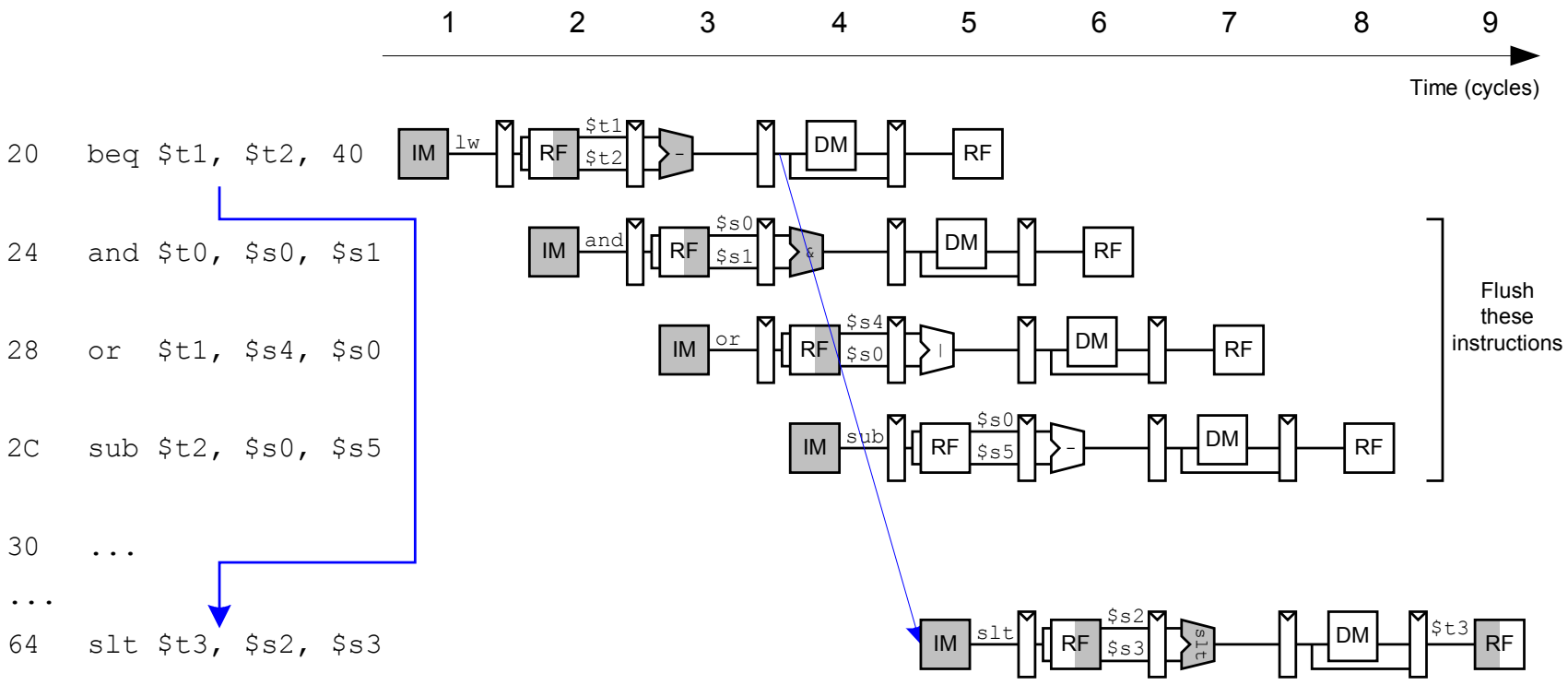
Stalling Hardware



$$\text{lwstall} = \text{MemToRegE} \wedge ((\text{rsD} = \text{rtE}) \vee (\text{rtD} = \text{rtE}))$$

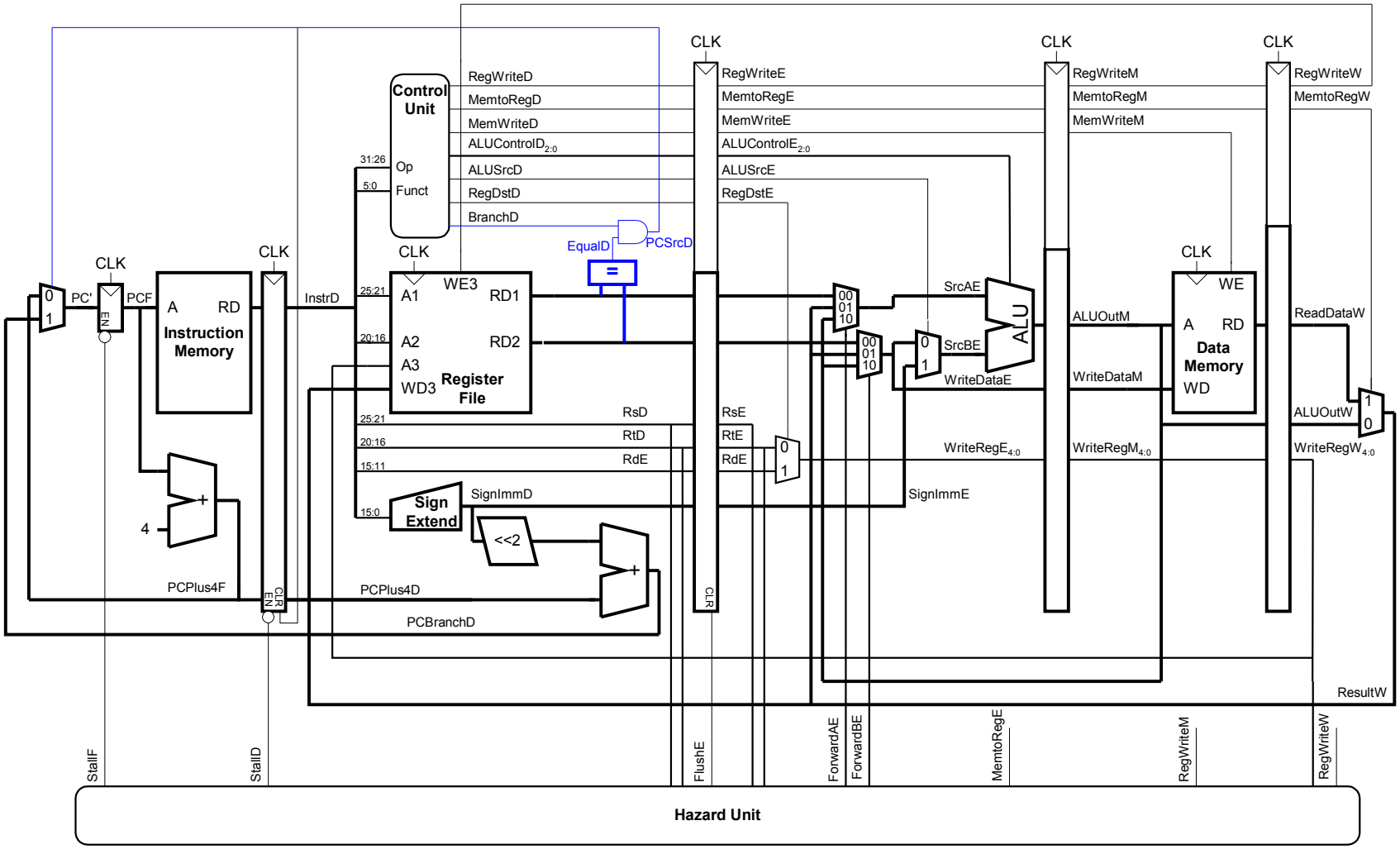
$$\text{StallF}, \text{StallD}, \text{FlushE} = \text{lwstall}$$

Control Hazards



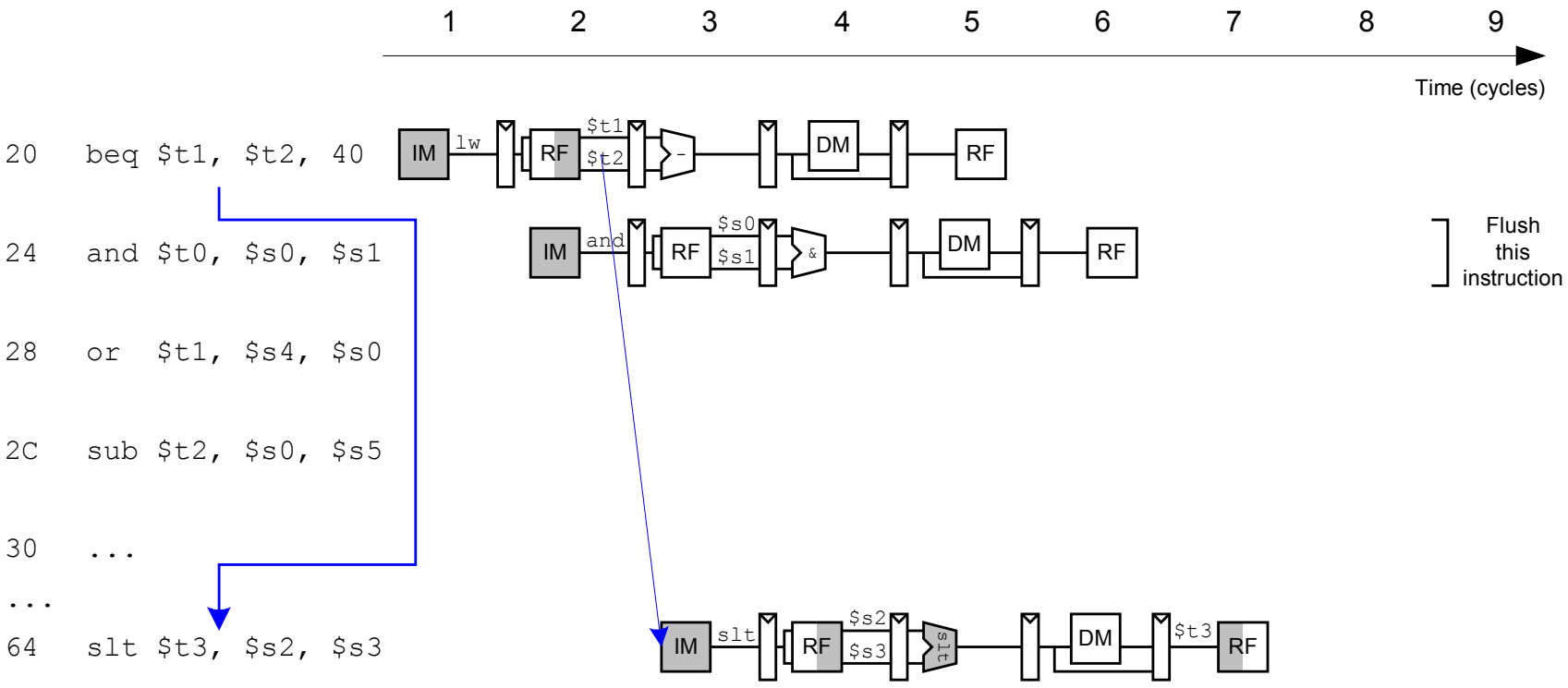
Whether to branch isn't determined until the beginning of the fourth cycle; three instructions would be executed erroneously if the branch were taken.

Early Branch Resolution

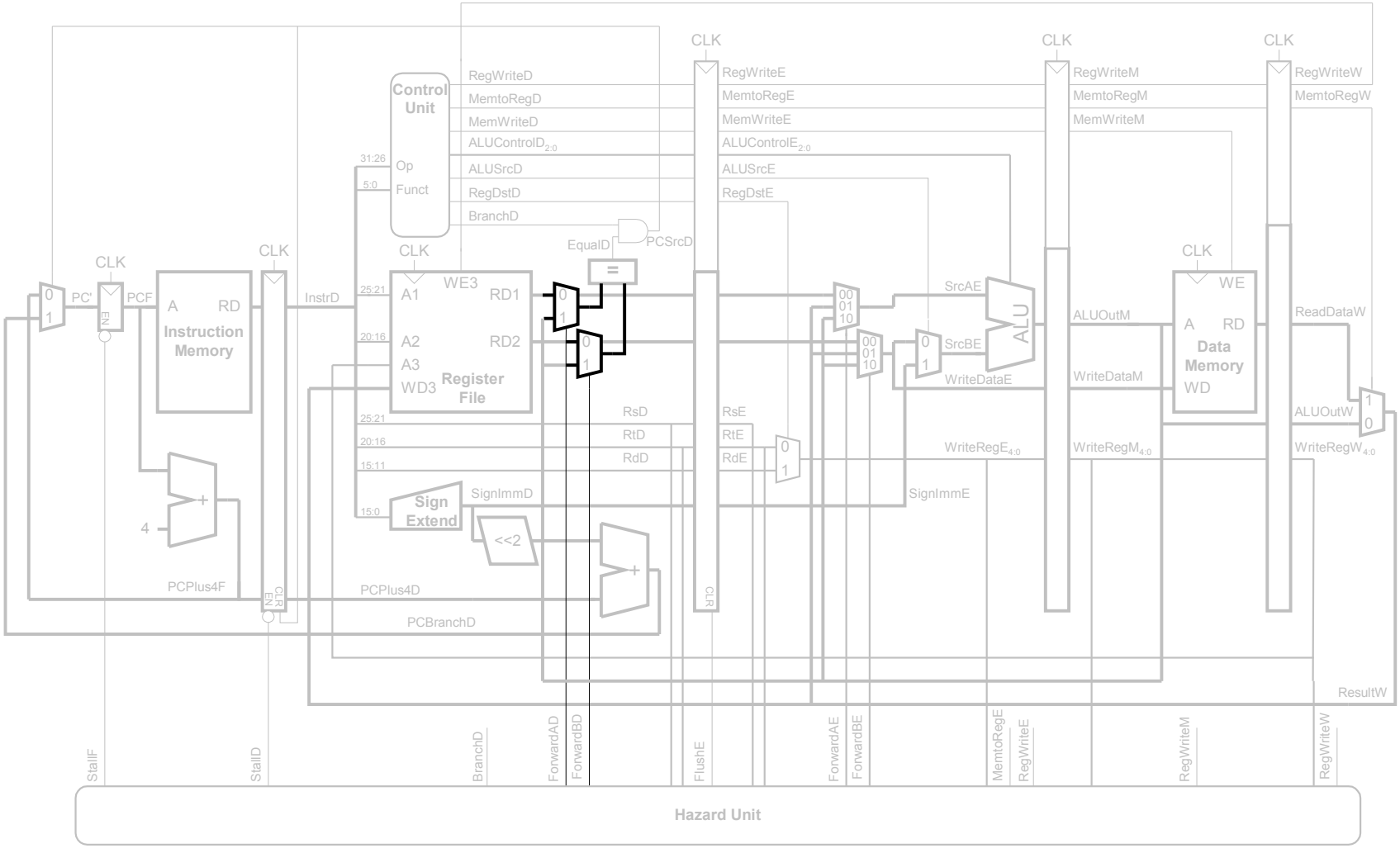


Introduced another data hazard in the decode stage

Control Hazards w/ Early Branch Resolution



Handling Data and Control Hazards



Forwarding and Stalling Logic

"Forward ALU result to branch-if-equal comparator if we would read its destination register"

$$\text{ForwardAD} = (\text{rsD} \neq 0 \wedge \text{rsD} = \text{WriteRegM} \wedge \text{RegWriteM})$$

$$\text{ForwardBD} = (\text{rtD} \neq 0 \wedge \text{rtD} = \text{WriteRegM} \wedge \text{RegWriteM})$$

"Stall if the branch would test the result of an ALU operation or a memory read"

$$\begin{aligned}\text{branchstall} = \\ &(\text{BranchD} \wedge \text{RegWriteE} \wedge (\text{WriteRegE} = \text{rsD} \vee \text{WriteRegE} = \text{rtD})) \vee \\ &(\text{BranchD} \wedge \text{MemToRegM} \wedge (\text{WriteRegM} = \text{rsD} \vee \text{WriteRegM} = \text{rtD}))\end{aligned}$$

"Stall if we need to read the result of a memory read or of a branch"

$$\text{StallF}, \text{StallD}, \text{FlushE} = \text{lwstall} \vee \text{branchstall}$$

Pipeline Performance CPI Example

Ideal CPI = 1; stalls reduce this, but how much?

Instructions in SPECINT2000 benchmark:

- 52% R-type
- 25% Loads
- 10% Stores
- 11% Branches
- 2% Jumps

If 40% of loads are used by the next instruction and 25% of branches are mispredicted, what is the average CPI?

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10%	Stores
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If 40% of loads are used by the next instruction and 25% of branches are mispredicted, what is the average CPI?

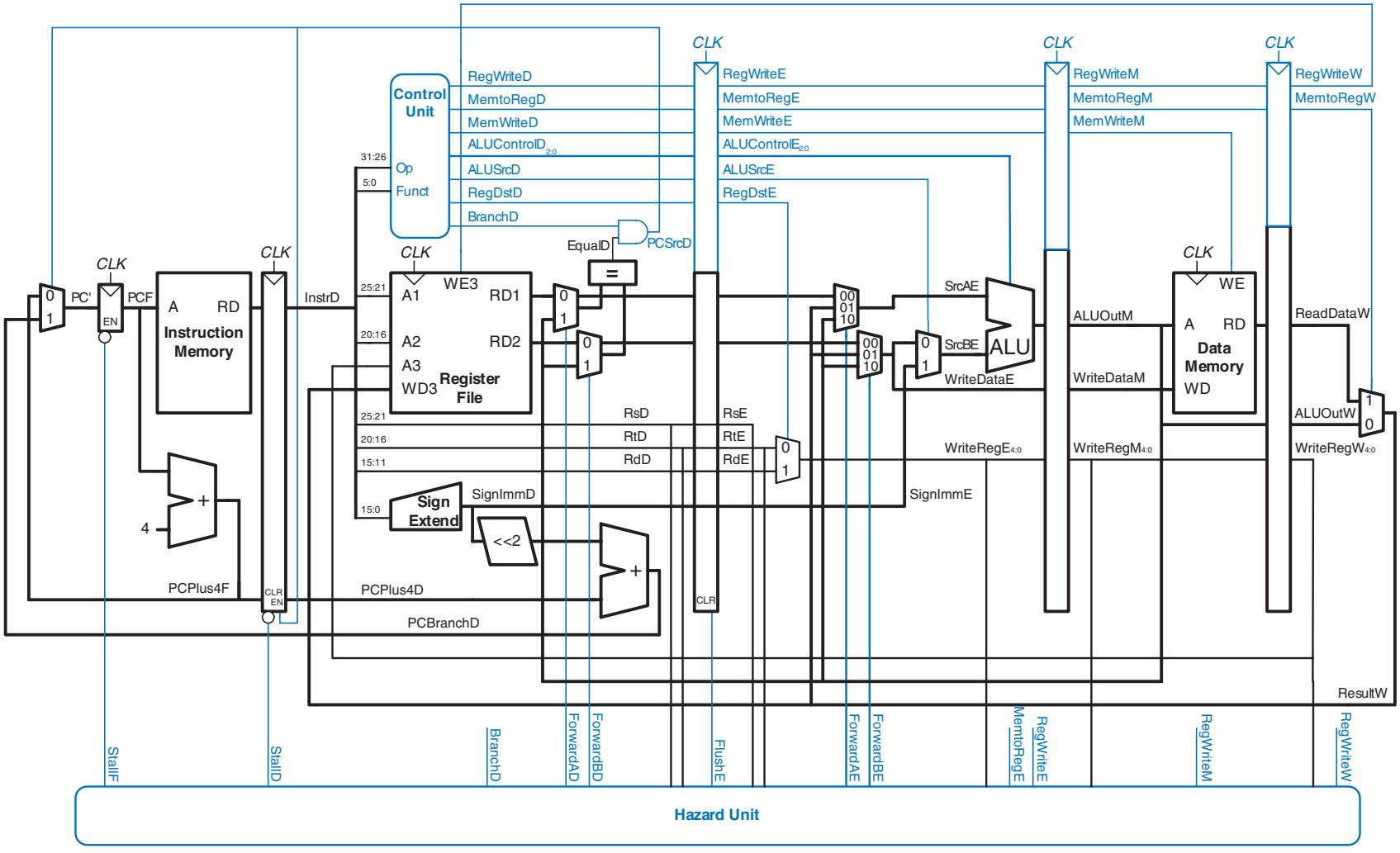
Load CPI = 2 when next instruction uses; 1 otherwise

Branch CPI = 2 when mispredicted; 1 otherwise

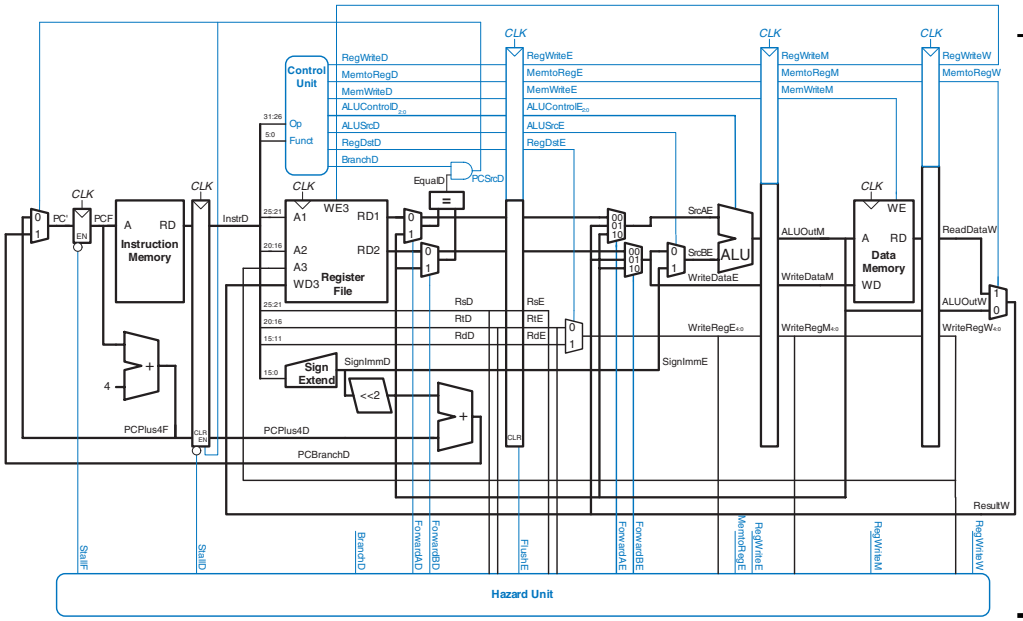
Jump CPI = 2

$$
\begin{aligned}
\text{Average CPI} &= 1 \cdot 0.52 + && \textit{R-type} \\
&\quad (2 \cdot 0.40 + 1 \cdot 0.60) \cdot 0.25 + && \textit{Loads} \\
&\quad 1 \cdot 0.10 + && \textit{Stores} \\
&\quad (2 \cdot 0.25 + 1 \cdot 0.75) \cdot 0.11 + && \textit{Branches} \\
&\quad 2 \cdot 0.02 && \textit{Jumps} \\
&= 1.1475
\end{aligned}
$$

Fully Bypassed Processor



Pipelined Processor Critical Path



Element		Delay
Register clk-to-Q	t_{pcq}	30 ps
Register setup	t_{setup}	20
Multiplexer	t_{mux}	25
ALU	t_{ALU}	200
Memory Read	$t_{memread}$	250
Register file read	t_{RFread}	150
Register file setup	$t_{RFsetup}$	20
Equality	t_{eq}	40
AND gate	t_{AND}	15
Memory Write	$t_{memwrite}$	220
Register file write	$t_{RFwrite}$	100

$$T_c = \max \left\{ \begin{array}{ll} t_{pcq} + t_{memread} + t_{setup} & \textit{Fetch} \\ 2(t_{RFread} + t_{mux} + t_{eq} + t_{AND} + t_{mux} + t_{RFsetup}) & \textit{Decode} \\ t_{pcq} + t_{mux} + t_{mux} + t_{ALU} + t_{setup} & \textit{Execute} \\ t_{pcq} + t_{memwrite} + t_{setup} & \textit{Memory} \\ 2(t_{pcq} + t_{mux} + t_{RFwrite}) & \textit{Writeback} \end{array} \right\}$$

$$= 2(150 + 25 + 40 + 15 + 25 + 20)\ \text{ps} = 550\ \text{ps}$$

Why 2? We assume it takes half a cycle for a newly written register's value (WD3) to propagate to RD1 or RD2, i.e., when an earlier instruction writes a register used by the current one.

Pipelined Processor Performance

For a 100 billion-instruction task on our pipelined processor, each instruction takes 1.15 cycles on average. With a 550 ps clock period,

$$\text{time} = 100 \times 10^9 \times 1.15 \times 550 \text{ ps} = 63 \text{ seconds}$$

Processor	Execution Time	Speedup
Single-Cycle	92.5 s	1.00 (by definition)
Multi-Cycle	133.9	0.70
Pipelined	63.25	1.46