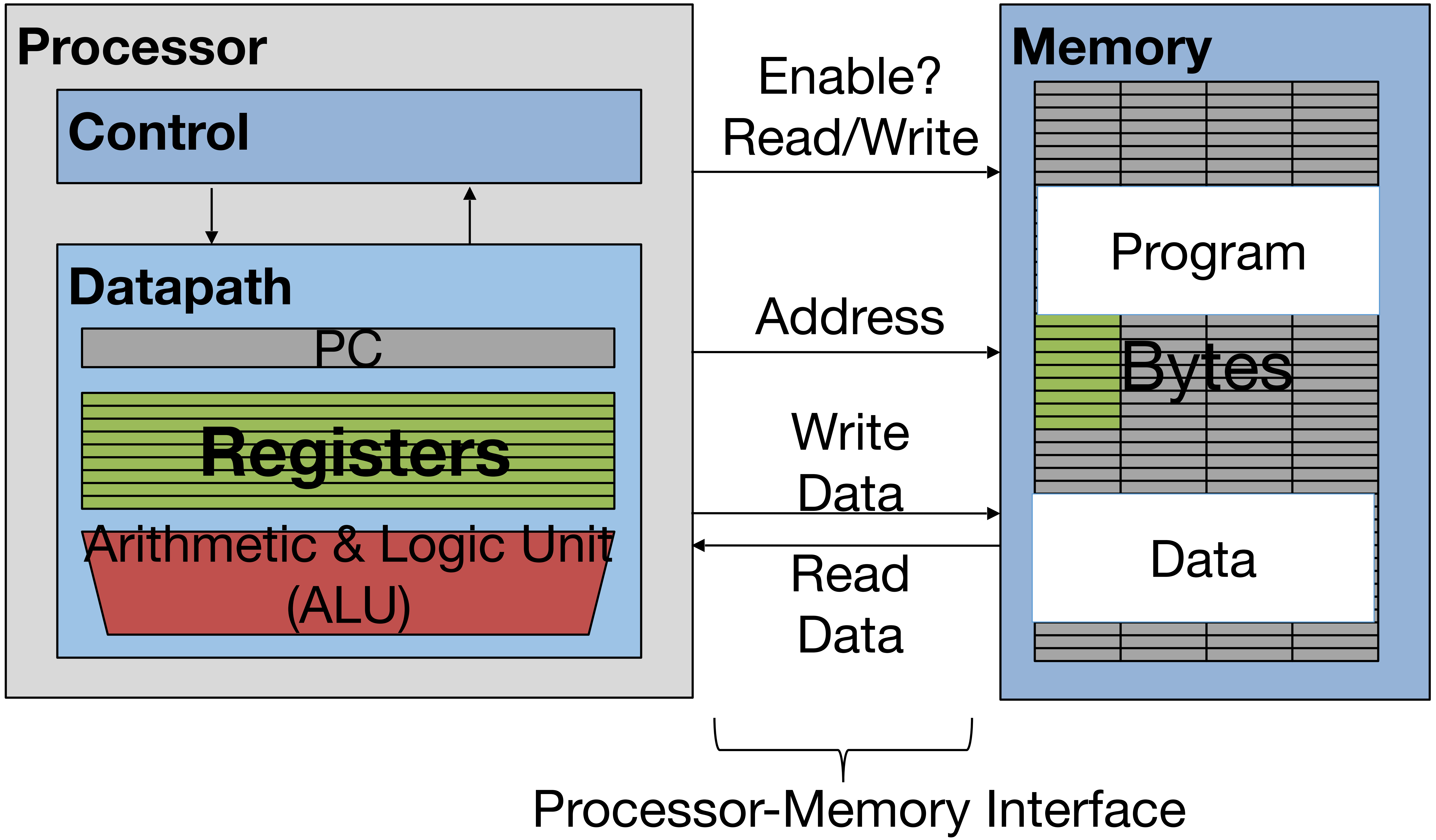
CS61c Fall 2021
Lecture 14
Pipelining RISC-V

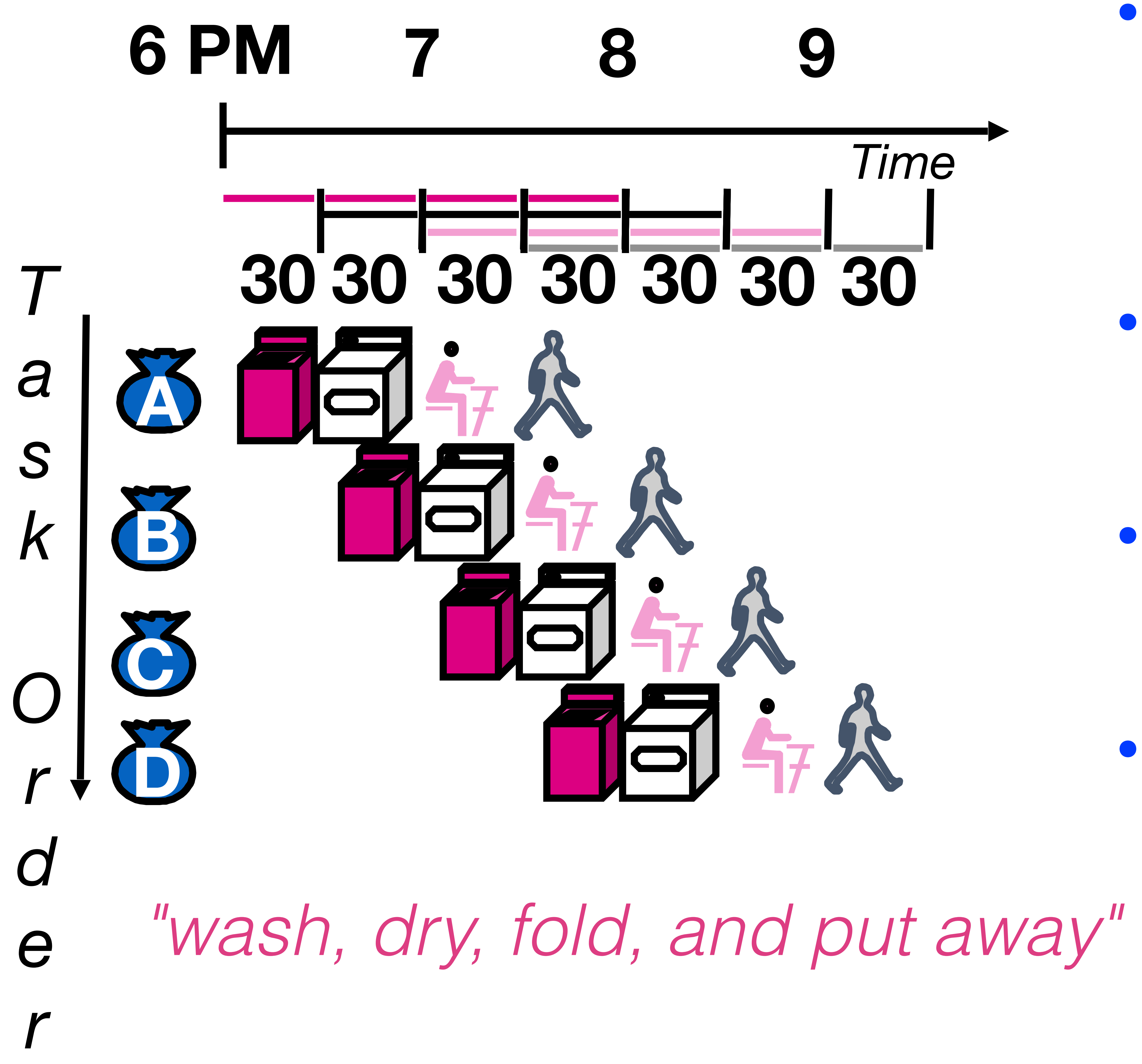
Review

- Controller
  - Tells universal datapath how to execute each instruction
- Instruction timing
  - Set by instruction complexity, architecture, technology
  - Pipelining increases clock frequency, “instructions per second”
    - But does not reduce time to complete instruction
- Performance measures
  - Different measures depending on objective
    - Response time
    - Jobs / second
    - Energy Efficiency (joules/operation, joules/instruction)

Processor


Processor
Control
Datapath
PC
Registers
Arithmetic & Logic Unit (ALU)
Enable?
Read/Write
Address
Write Data
Read Data
Memory
Program
Bytes
Data
Processor-Memory Interface

Pipelining Overview (Review)



- Pipelining doesn't help ***latency*** of single task, it helps ***throughput*** of entire workload
- Multiple tasks operating simultaneously using different resources
- Potential speedup = Number pipe stages
- Time to "fill" pipeline and time to "drain" it reduces speedup: 2.3X v. 4X in this example
  - With lots of laundry, approaches 4X

Agenda

- **RISC-V Pipeline**
- Pipeline Control
- Hazards
  - Structural
  - Data
    - R-type instructions
    - Load
  - Control
- Superscalar processors

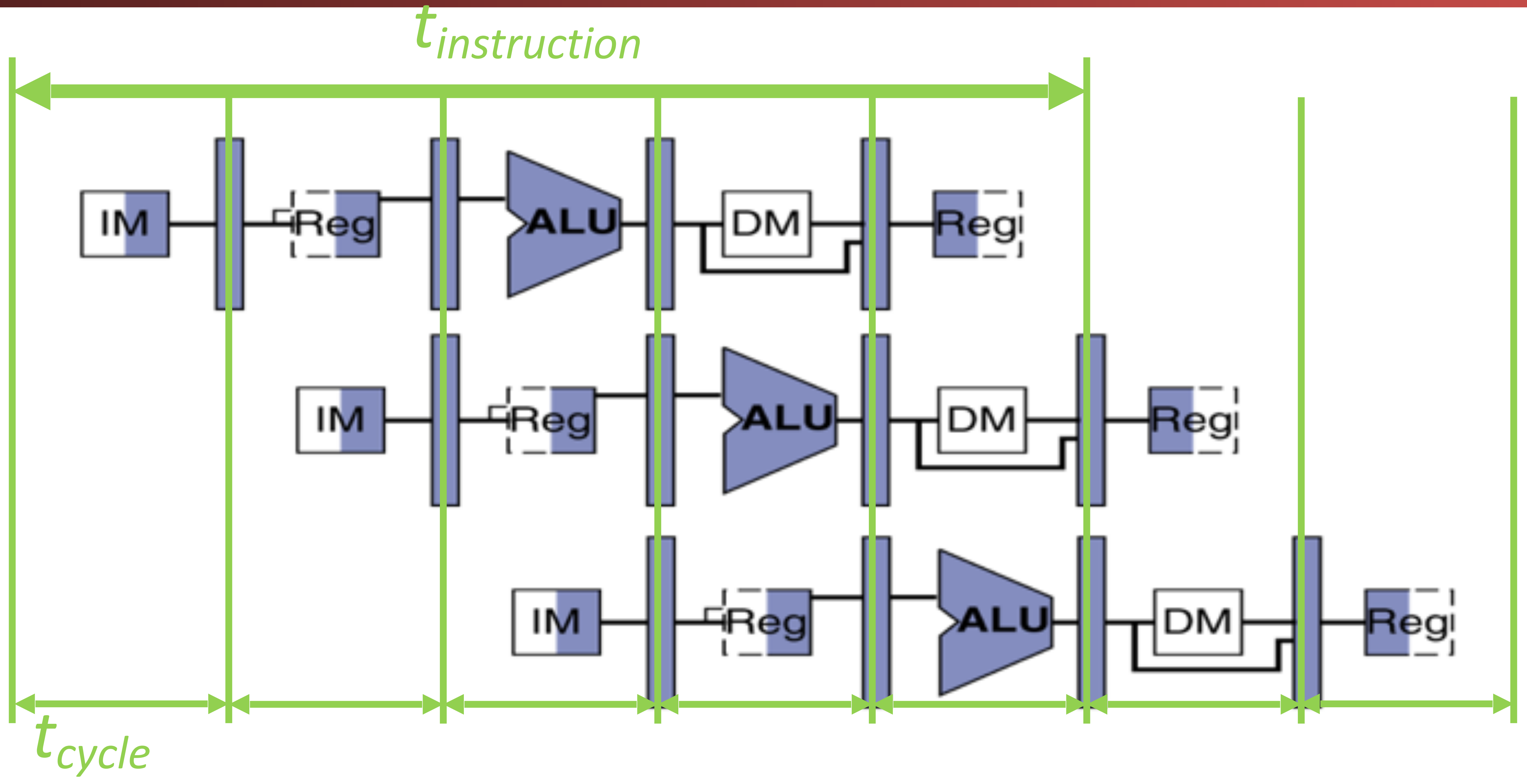
Recap: Pipelining with RISC-V

instruction sequence

add t0, t1, t2

or t3, t4, t5

sll t6, t0, t3



	Single Cycle	Pipelining
Timing	t_{step} = 100 … 200 ps	t_{cycle} = 200 ps
	Register access only 100 ps	All cycles same length
Instruction time, $t_{instruction}$	= t_{cycle} = 800 ps	1000 ps
Clock rate, f_s	1/800 ps = 1.25 GHz	1/200 ps = 5 GHz
Relative speed	1 x	4 x

RISC-V Pipeline

instruction sequence

add t0, t1, t2

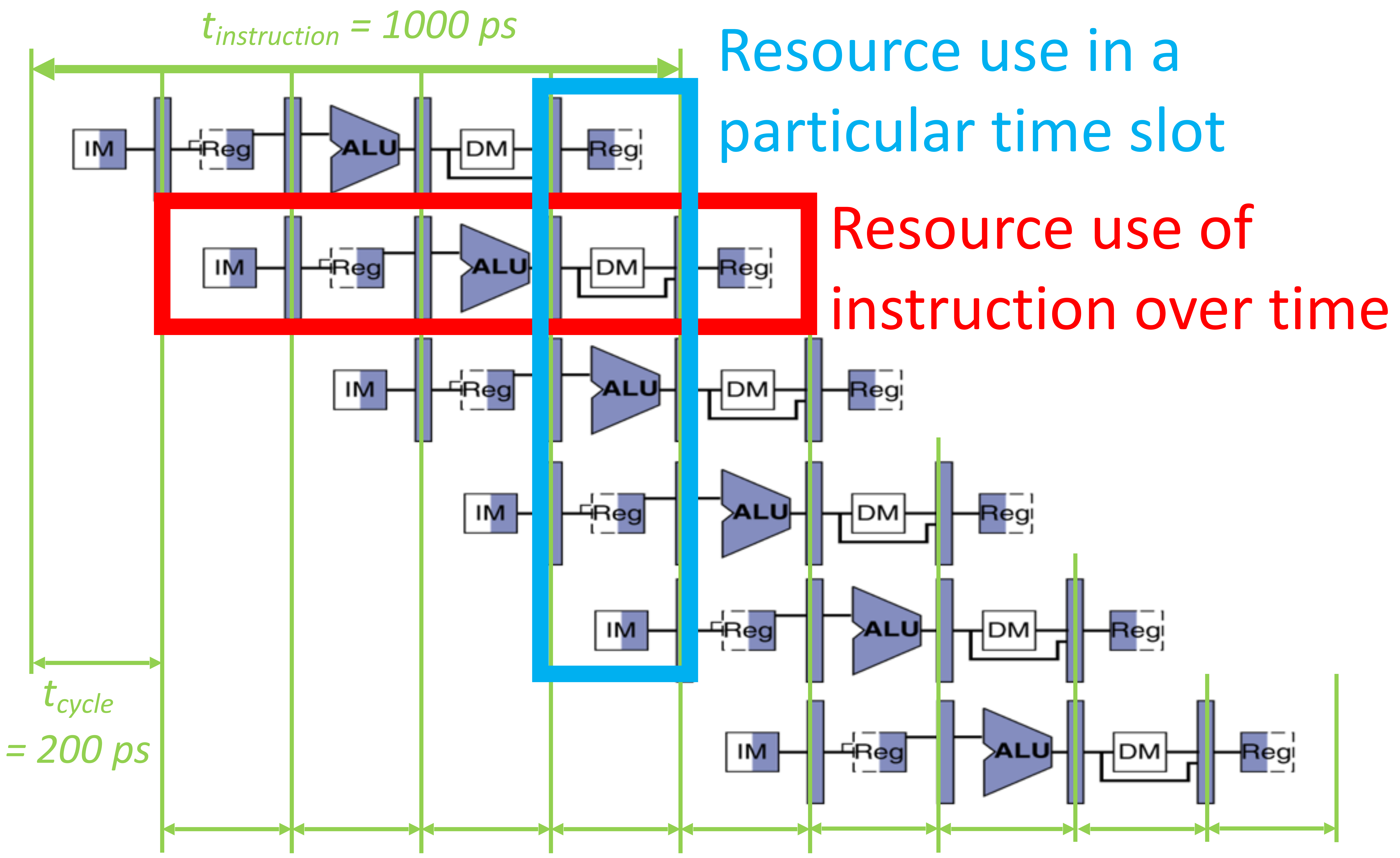
or t3, t4, t5

slt t6, t0, t3

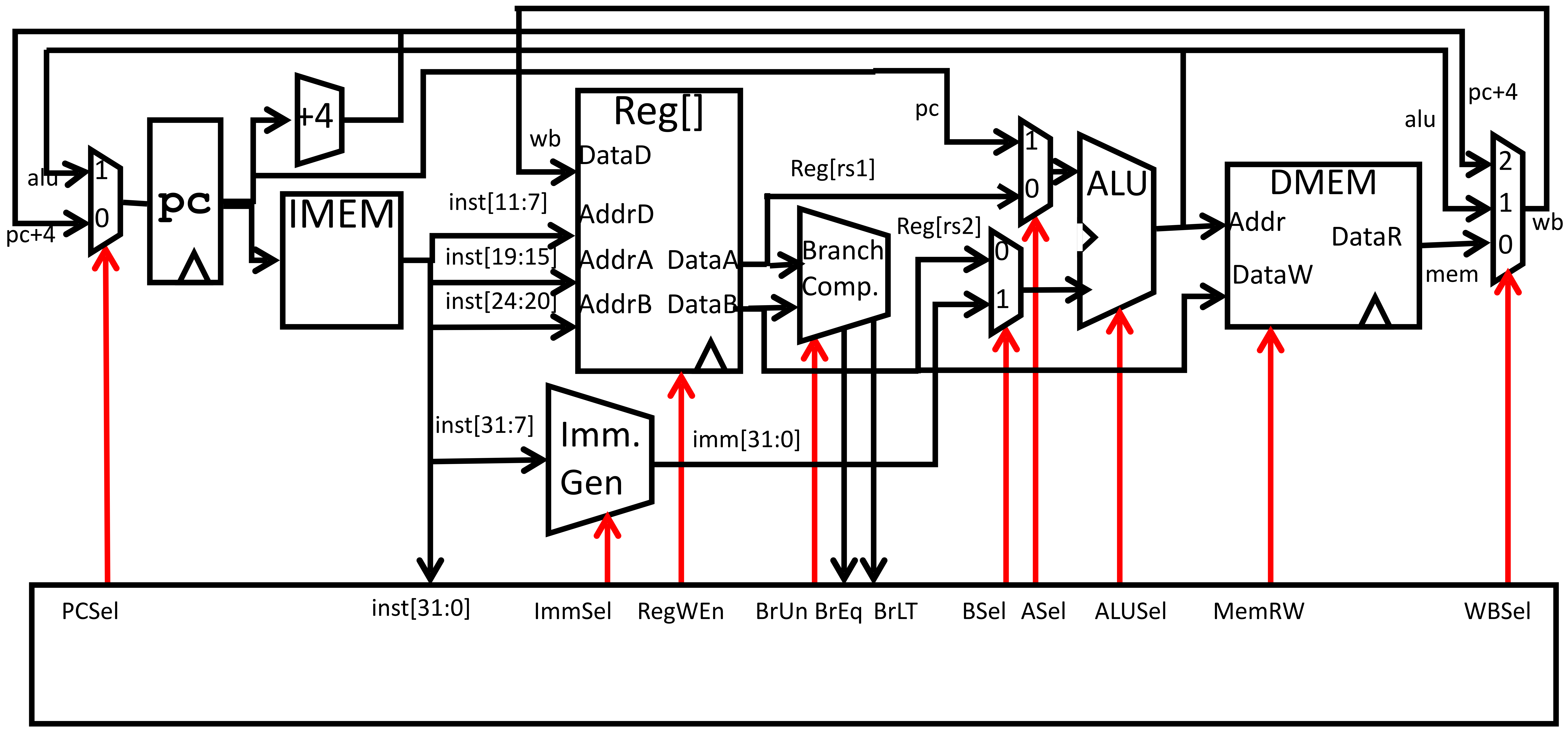
sw t0, 4(t3)

lw t0, 8(t3)

addi t2, t2, 1


$t_{instruction}$ = 1000 ps
Resource use in a particular time slot
Resource use of instruction over time
t_{cycle} = 200 ps
IM
Reg
ALU
DM

Single-Cycle RISC-V RV32I Datapath



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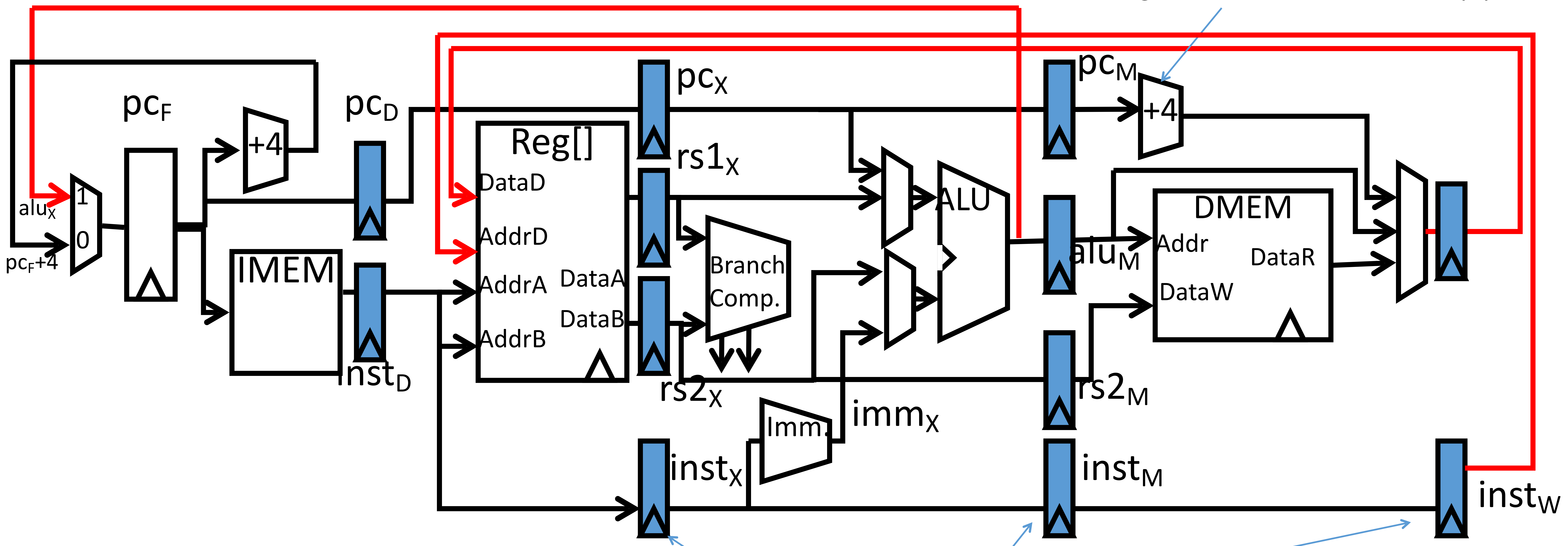
Pipelining RISC-V RV32I Datapath

alu
pc+4
1
0
pc
+4
IMEM
wb
Reg[]
DataD
inst[11:7]
AddrD
inst[19:15]
AddrA
DataA
inst[24:20]
AddrB
DataB
inst[31:7]
Imm.
Gen
imm[31:0]
pc
Reg[rs1]
Reg[rs2]
Branch
Comp.
ALU
DMEM
Addr
DataR
DataW
alu
pc+4
2
mem
wb
Instruction Fetch
(F)
Instruction Decode/
Register Read
(D)
ALU Execute
(X)
Memory Access
(M)
Write Back
(W)

Pipelined RISC-V RV32I Datapath

Recalculate PC+4 in M stage to avoid sending both PC and PC+4 down pipeline



Must pipeline instruction along with data, so control operates correctly in each stage

Each stage operates on different instruction

lw t0, 8(t3)
sw t0, 4(t3)
slt t6, t0, t3
or t3, t4, t5
add t0, t1, t2
pcF
+4
pcD
pcX
rs1X
pcM
+4
aluX
1
0
pcF+4
IMEM
instD
Reg[]
DataD
AddrD
AddrA
DataA
AddrB
DataB
rs2X
Branch Comp.
Imm.
immX
instX
ALU
aluM
DMEM
Addr
DataR
DataW
rs2M
instM
instW

Pipeline registers separate stages, hold data for each instruction in flight

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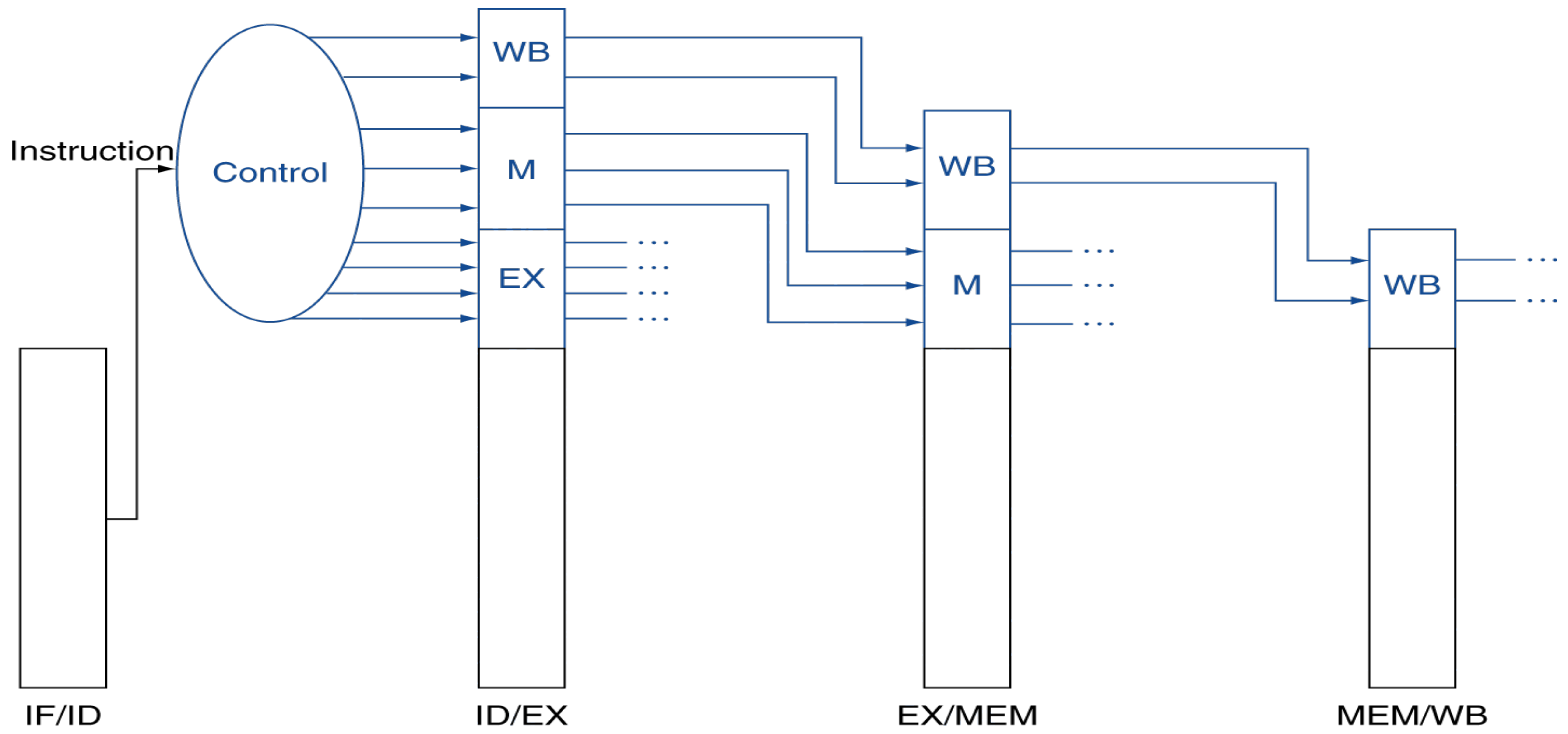
- RISC-V Pipeline
- **Pipeline Control**
- Hazards
  - Structural
  - Data
    - R-type instructions
    - Load
  - Control
- Superscalar processors

Pipelined Control

- Control signals derived from instruction
  - As in single-cycle implementation
  - Information is stored in pipeline registers for use by later stages



Question:

$$\frac{time}{program} = \frac{instructions}{program} \cdot \underbrace{\frac{cycles}{instruction} \cdot \frac{time}{cycle}}_{\text{1 / throughput}}$$

Pipelining the single-cycle processor can increase processor performance by:

	Instructions /program	**Cycles/ instruction**	**Time/cycle**
A	decrease	decrease	same
B	same	increase	decrease
C	same	same	decrease
D	increase	decrease	increase

Hazards Ahead

Agenda

- RISC-V Pipeline
- Pipeline Control
- Hazards
  - **Structural**
  - Data
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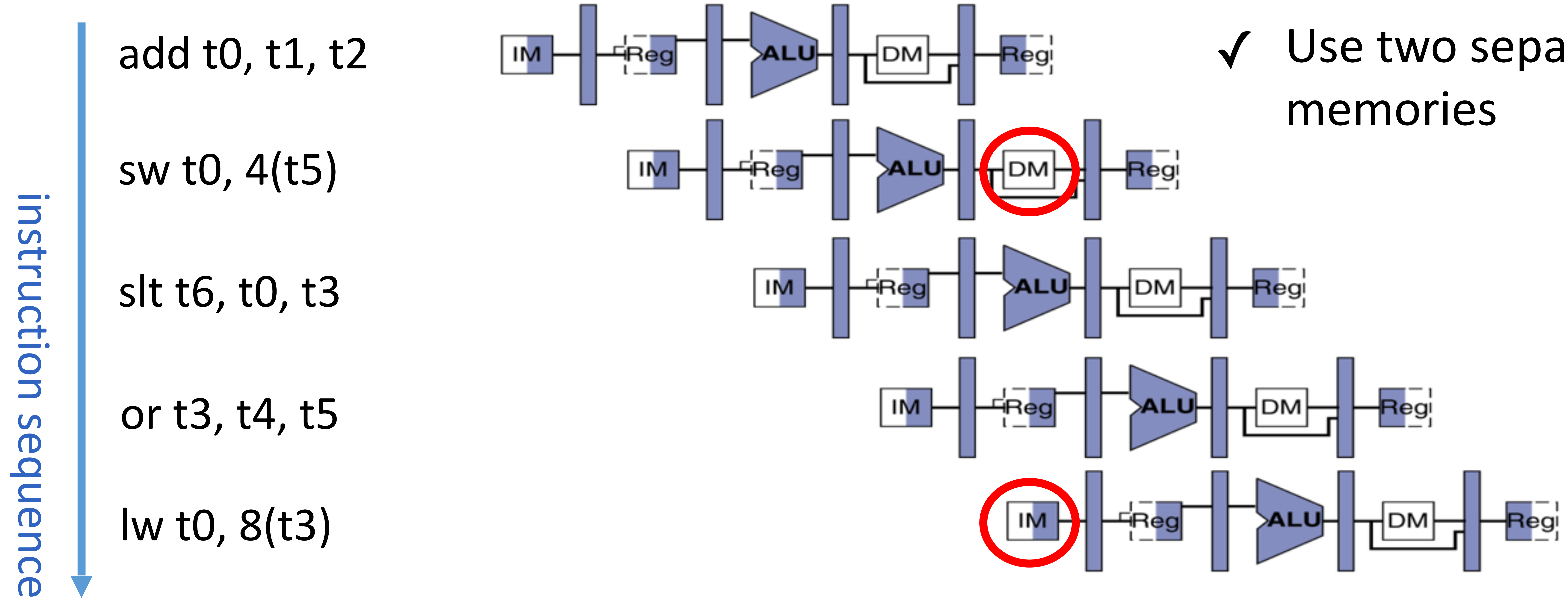
Structural Hazard

- **Problem:** Two or more instructions in the pipeline compete for access to a single physical resource
- **Solution 1:** Instructions take turns to use resource, some instructions have to stall
- **Solution 2:** Add more hardware to machine
  - *Can always solve a structural hazard by adding more hardware*

Regfile Structural Hazards

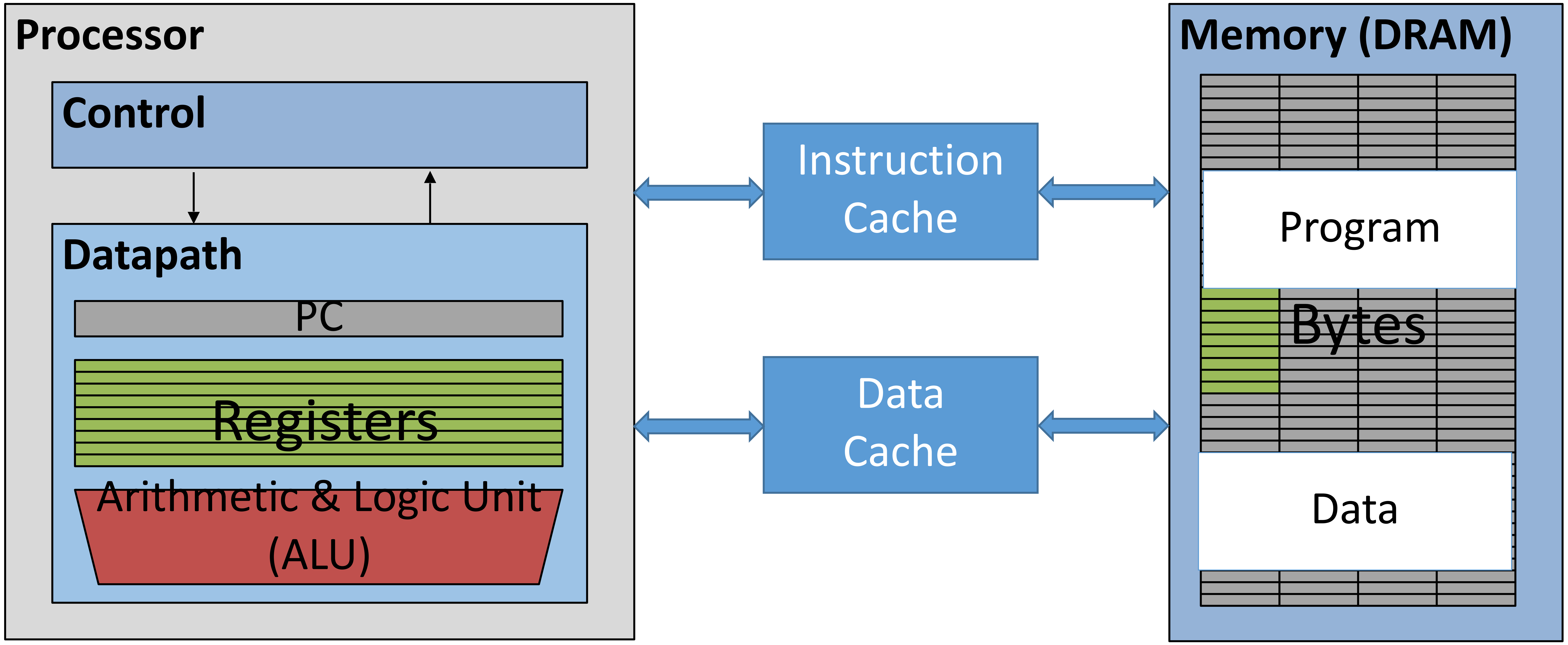
- Each instruction:
  - can read up to two operands in decode stage
  - can write one value in writeback stage
  - *therefore two different instructions might be accessing the register file on the same cycle!*
- Avoid structural hazard by having separate “ports”
  - two independent read ports and one independent write port
- *Reads from one instruction and writes from another can happen simultaneously*

Structural Hazard: Memory Access



- Instruction and data memory used simultaneously
  - ✓ Use two separate memories

Instruction and Data Caches



Caches: relatively small and fast "buffer" memories

Structural Hazards – Summary

- Conflict for use of a resource
- In RISC-V pipeline with a single memory
  - Load/store requires data access
  - Without separate memories, instruction fetch would have to stall for that cycle
    - All other operations in pipeline would have to wait
- Pipelined datapaths require separate instruction/data memories
  - Or at least separate instruction/data ***caches***
- Multi-ported register file
- RISC ISAs (including RISC-V) designed to avoid structural hazards
  - e.g. at most one memory access/instruction
  - limited operands per instruction

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        - **R-type instructions**
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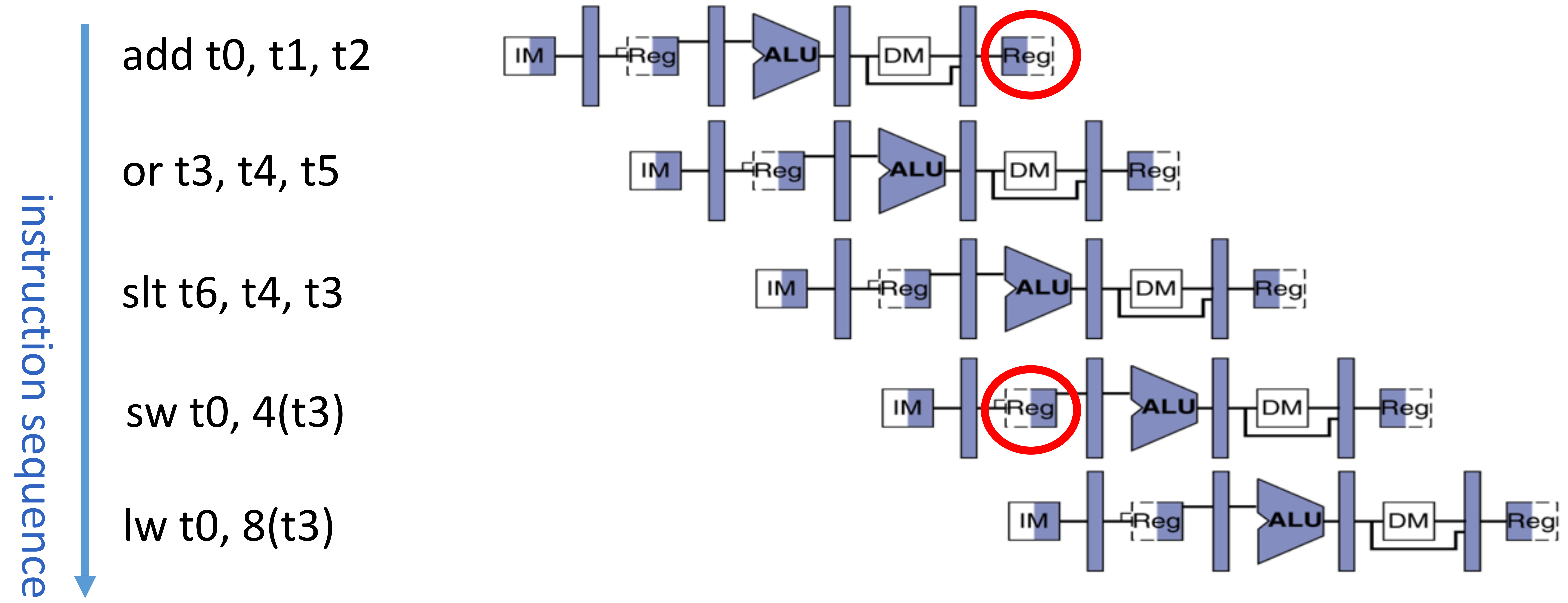
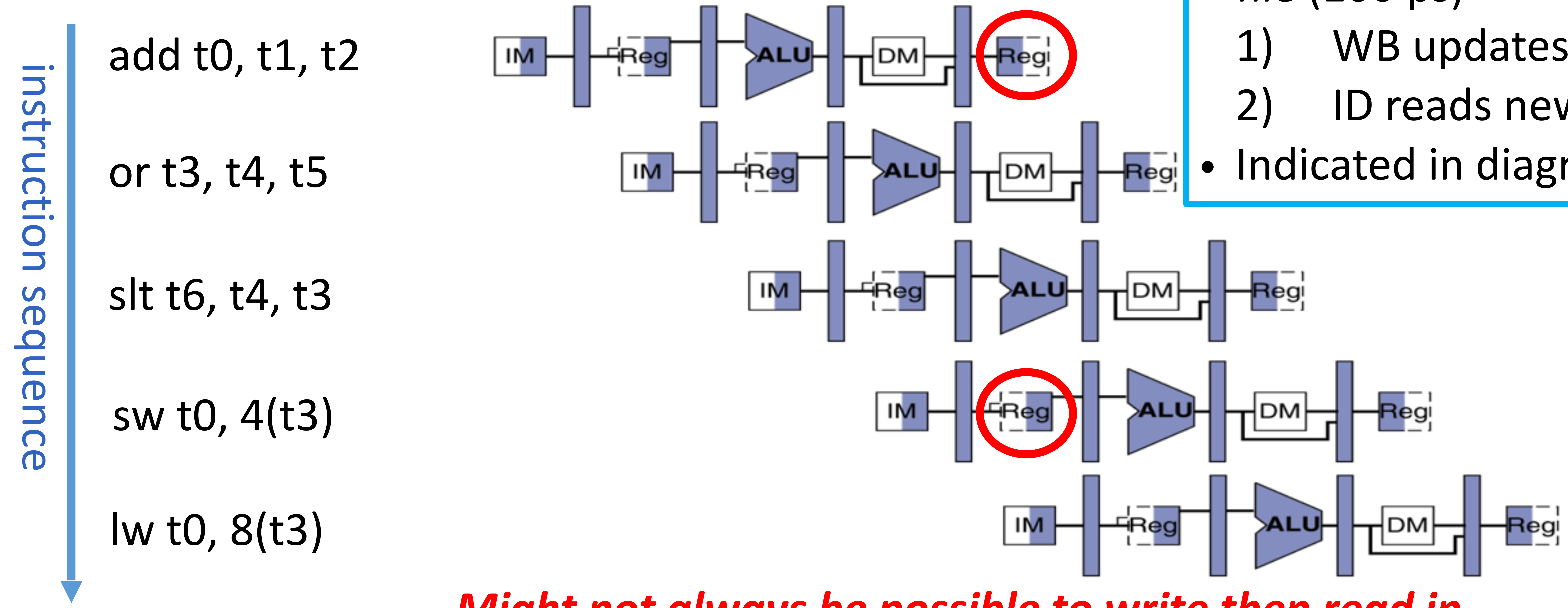
Data Hazard: Register Access

- Separate ports, but what if write to same value as read?
- Does **`sw`** in the example fetch the old or new value?



Register Access Policy

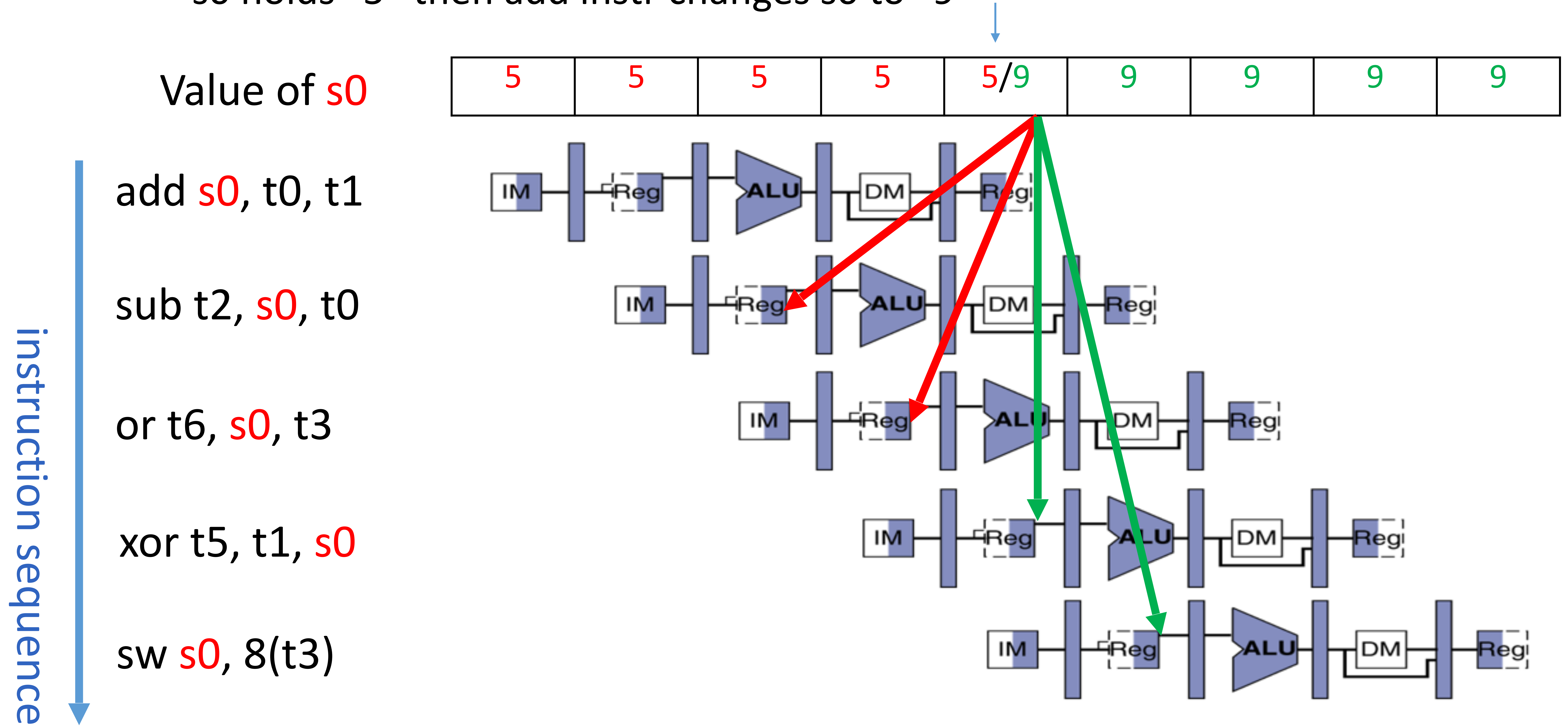
- Exploit high speed of register file (100 ps)
  1) WB updates value
  2) ID reads new value
- Indicated in diagram by shading



Might not always be possible to write then read in same cycle, especially in high-frequency designs.

Data Hazard: ALU Result

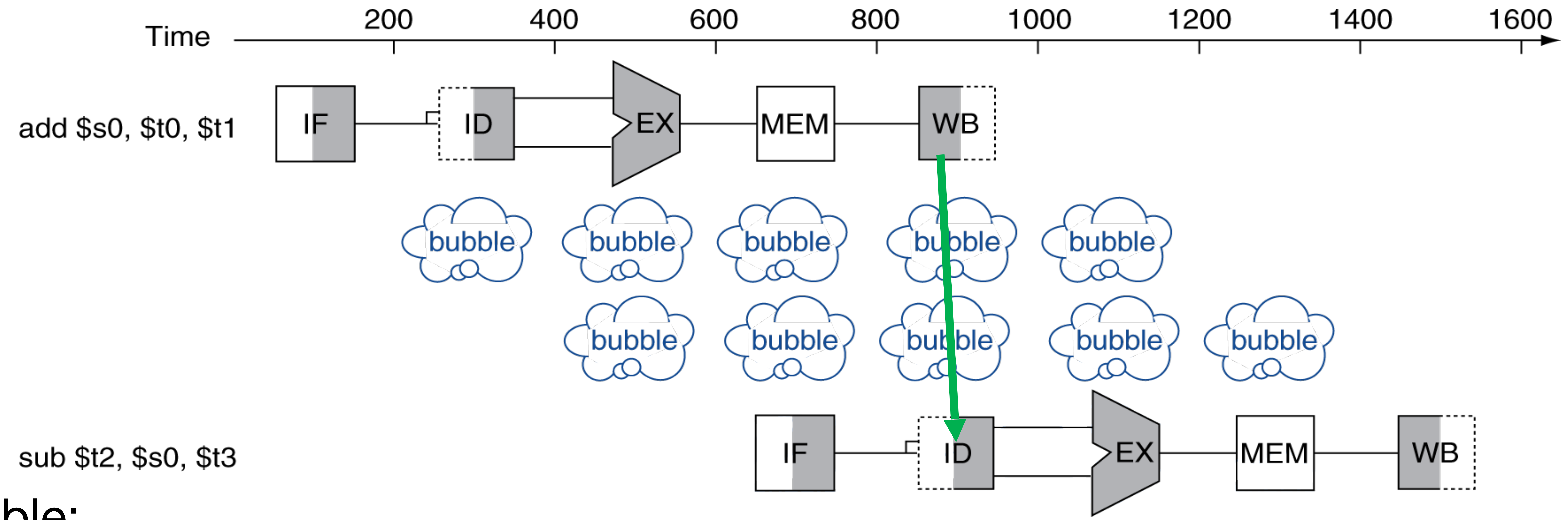
s0 holds "5" then add instr changes s0 to "9"



Without some fix, **sub** and **or** will calculate wrong result!

Solution 1: Stalling

- Problem: Instruction depends on result from previous instruction
  - add s0, t0, t1
    sub t2, s0, t3



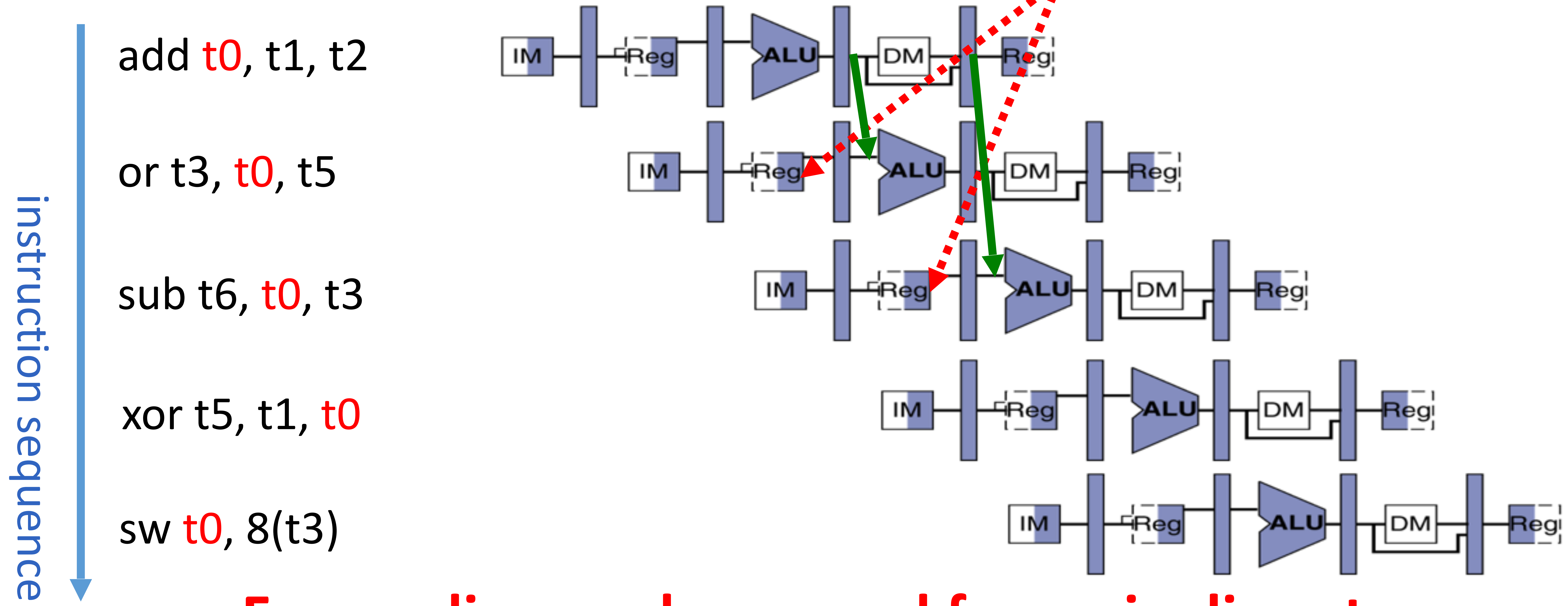
- Bubble:
  - stall the dependent instruction
  - effectively NOP: affected pipeline stages do “nothing”

Stalls and Performance

- Stalls reduce performance
  - But stalls might be required to get correct results
- Compiler could try to arrange code to avoid hazards and stalls
  - Requires knowledge of the pipeline structure

Solution 2: Forwarding

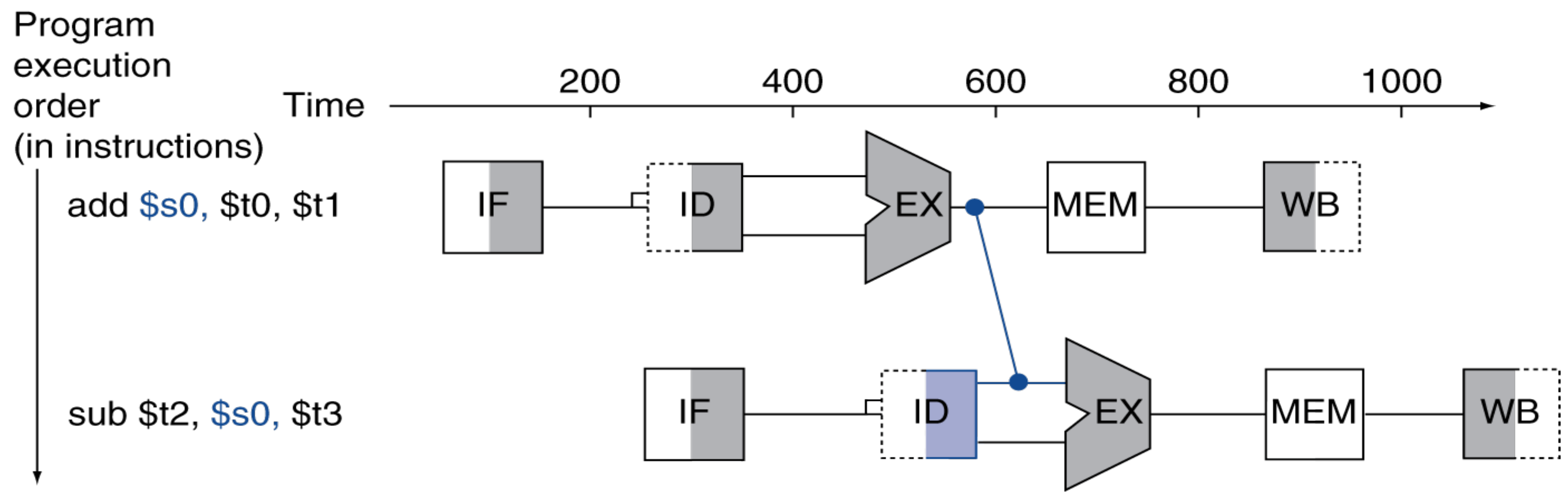
Value of t0	5	5	5	5	5/9	9	9	9	9



Forwarding: grab operand from pipeline stage, rather than register file

Forwarding (aka Bypassing)

- Access result before it is stored in a register
- Requires extra connections in the datapath



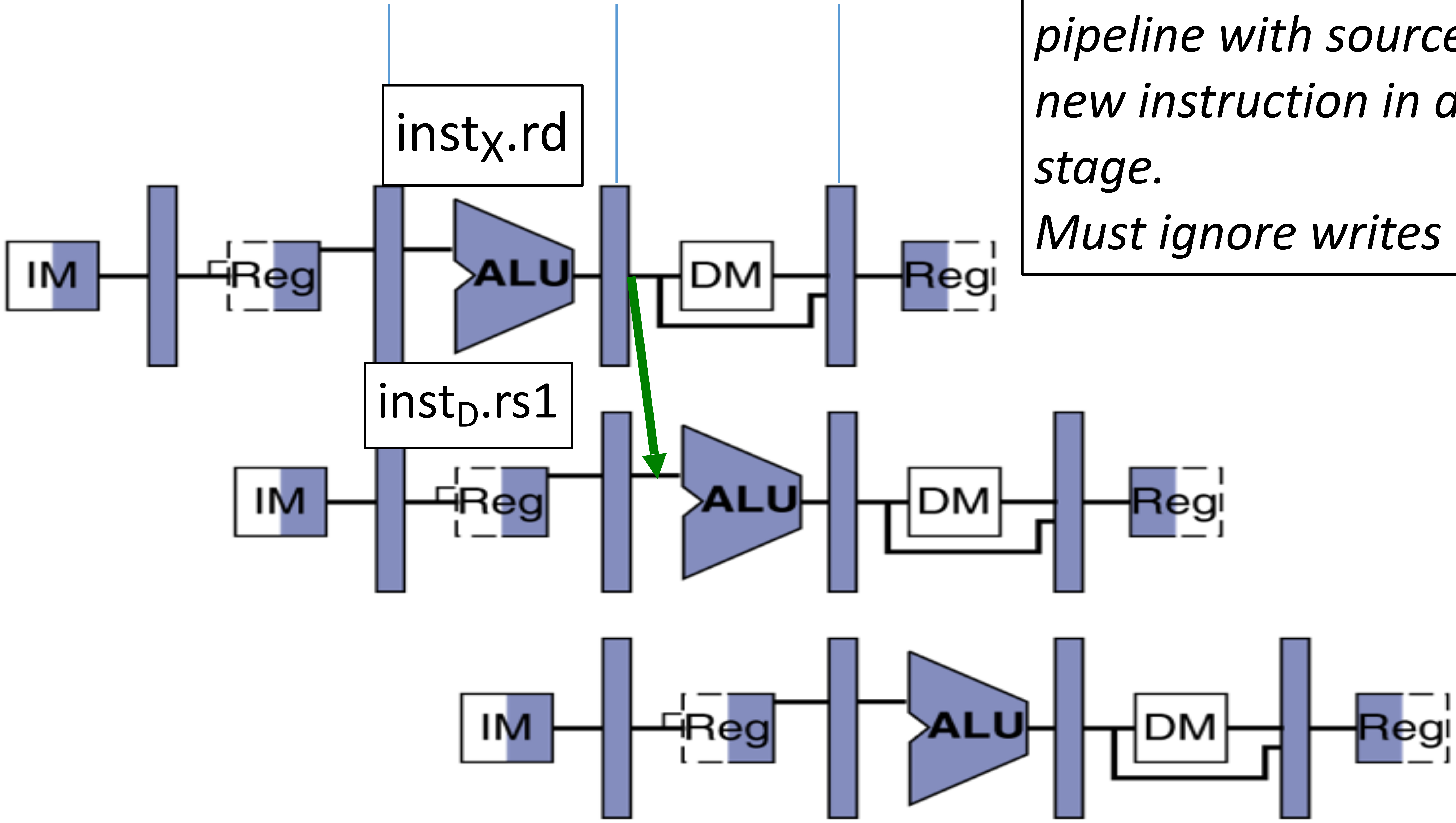
1) Detect Need for Forwarding (example)

Compare destination of older instructions in pipeline with sources of new instruction in decode stage.
Must ignore writes to x0!

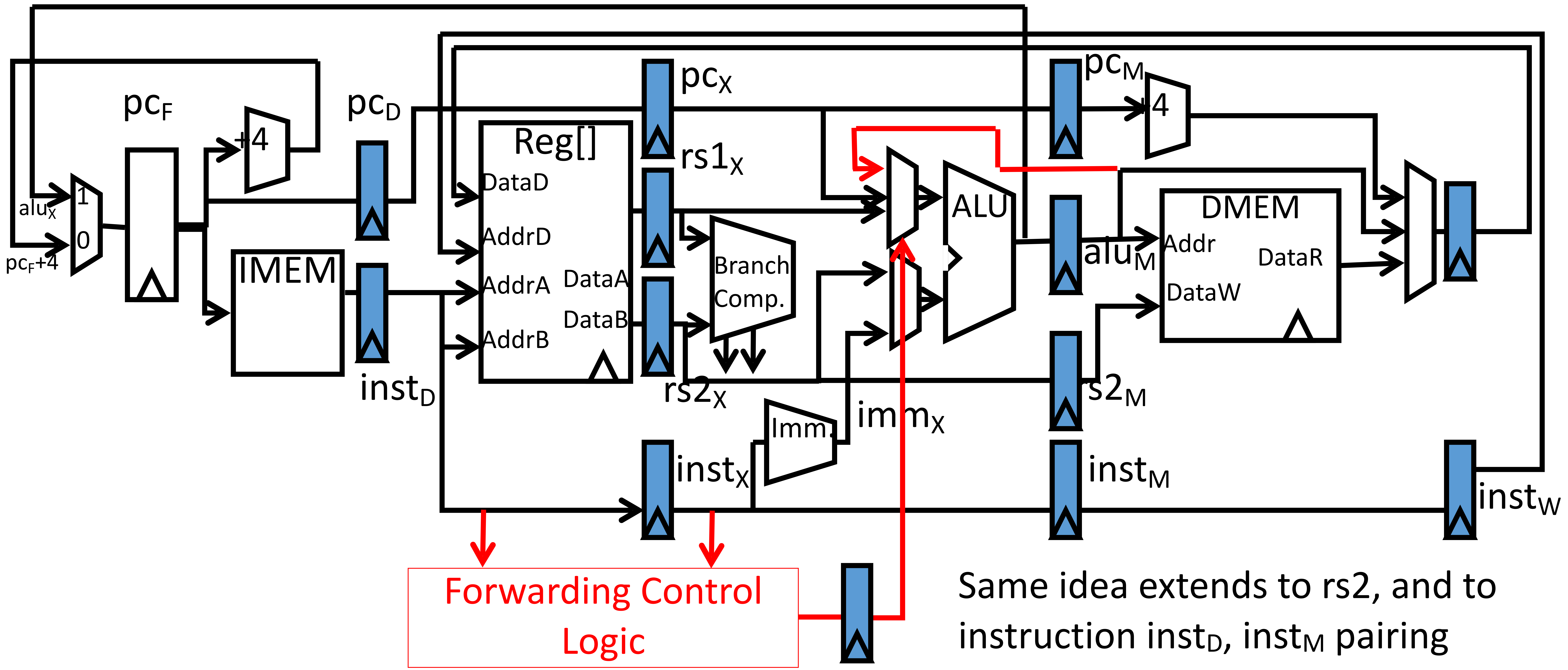
add t0, t1, t2

or t3, t0, t5

sub t6, t0, t3



Example Forwarding Path



Same idea extends to rs2, and to instruction $inst_D$, $inst_M$ pairing

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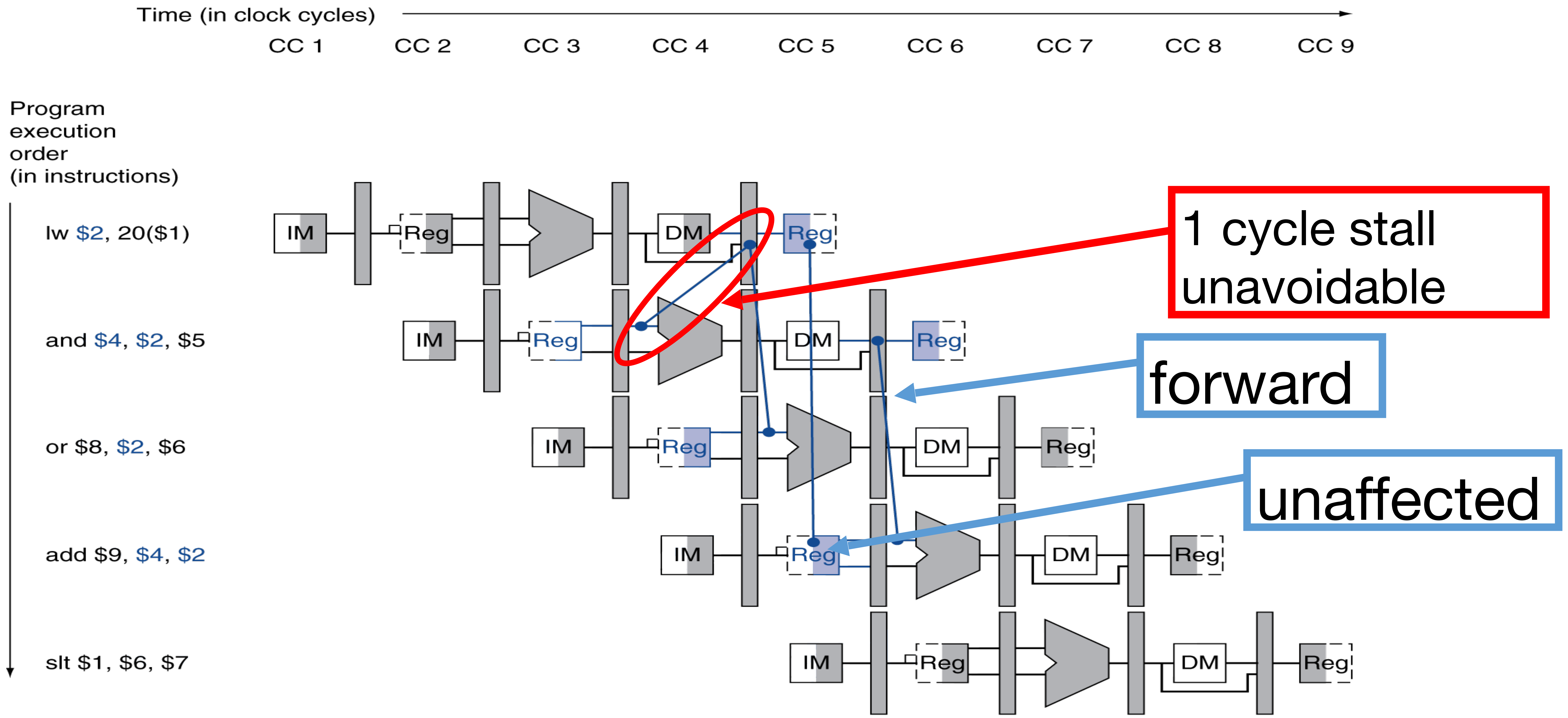
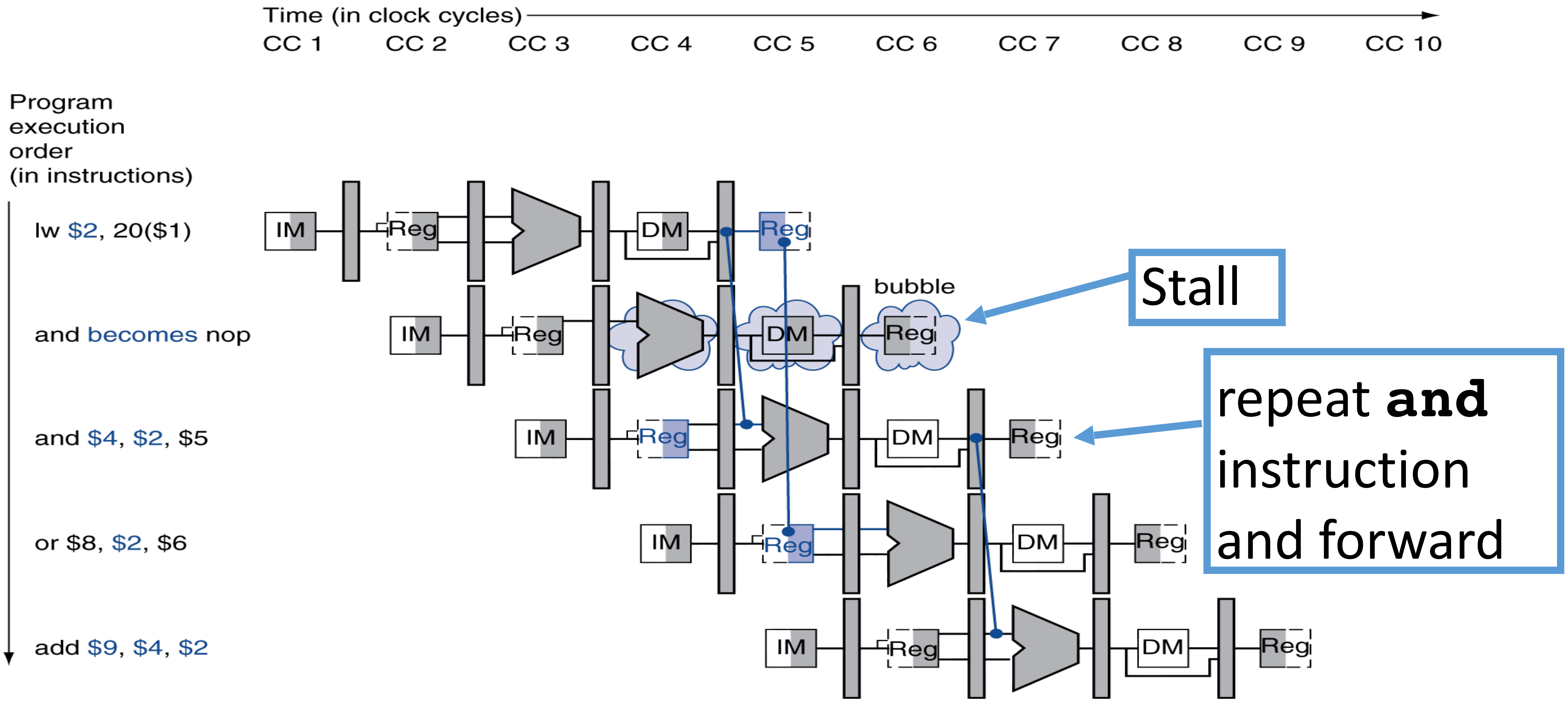
Load Data Hazard



Stall Pipeline

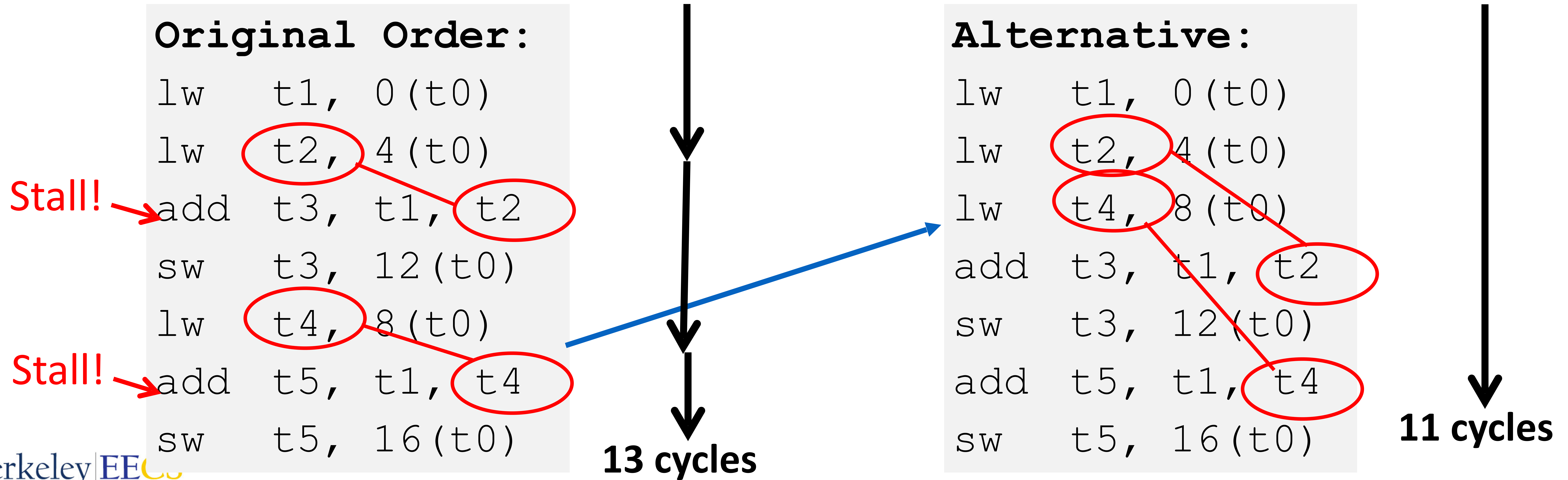


`lw` Data Hazard

- Slot after a load is called a *load delay slot*
  - If that instruction uses the result of the load, then the hardware will stall for one cycle
  - Equivalent to inserting an explicit **`nop`** in the slot
    - except the latter uses more code space
  - Performance loss!
- Idea:
  - Put unrelated instruction into load delay slot
  - No performance loss!

Code Scheduling to Avoid Stalls

- Reorder code to avoid use of load result in the next instruction!
- RISC-V code for `D=A+B; E=A+C;`



```
Original Order:
lw   t1, 0(t0)
lw   t2, 4(t0)
add  t3, t1, t2
sw   t3, 12(t0)
lw   t4, 8(t0)
add  t5, t1, t4
sw   t5, 16(t0)
```

```
Alternative:
lw   t1, 0(t0)
lw   t2, 4(t0)
lw   t4, 8(t0)
add  t3, t1, t2
sw   t3, 12(t0)
add  t5, t1, t4
sw   t5, 16(t0)
```

Cat Break: From Thomas Thurston

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Control Hazards

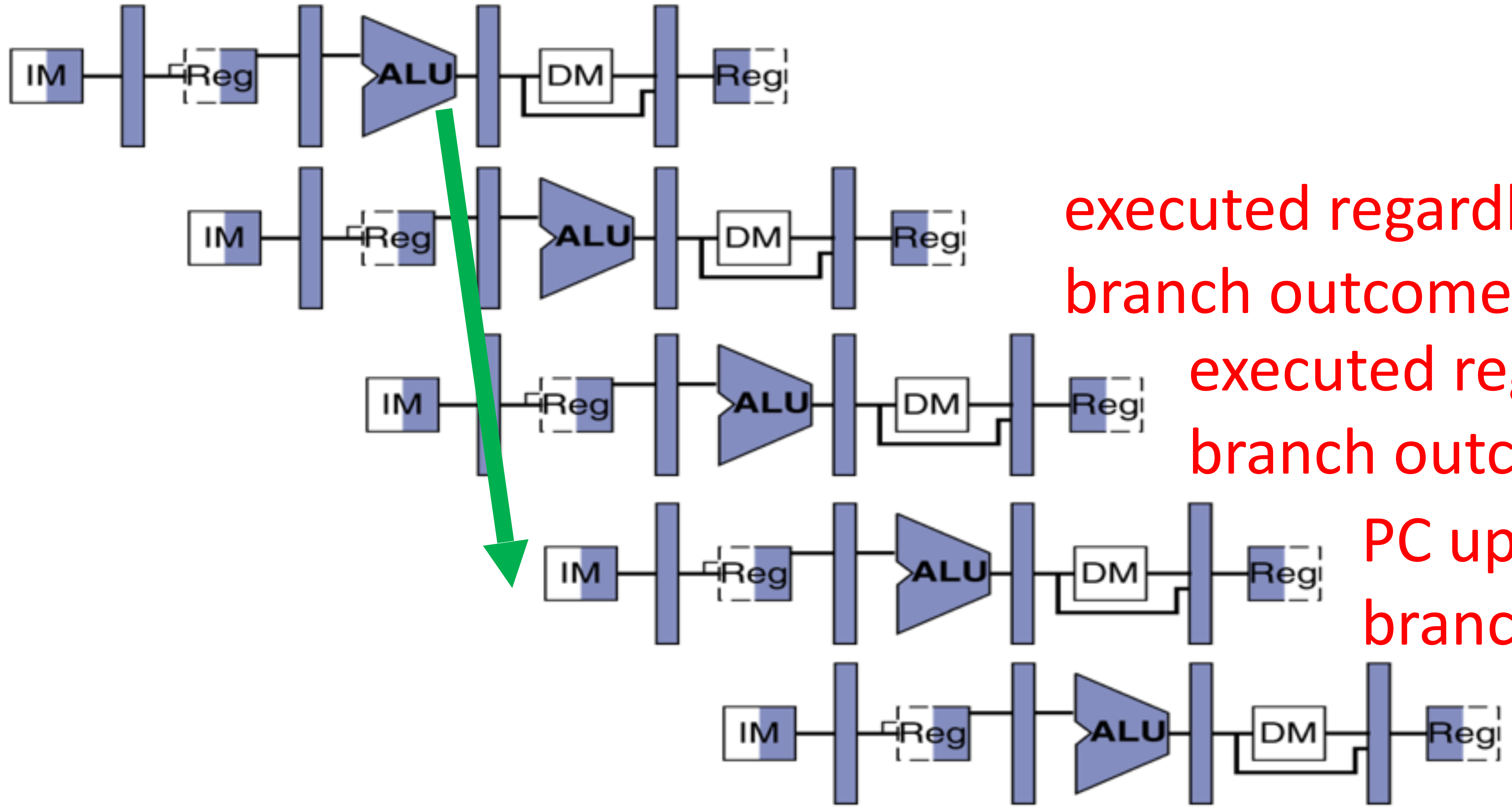
beq t0, t1, label

sub t2, s0, t5

or t6, s0, t3

xor t5, t1, s0

sw s0, 8(t3)



executed regardless of branch outcome!

executed regardless of branch outcome!!!

PC updated reflecting branch outcome

Observation

- If branch not taken, then instructions fetched sequentially after branch are correct
- If branch or jump taken, then need to flush incorrect instructions from pipeline by converting to NOPs

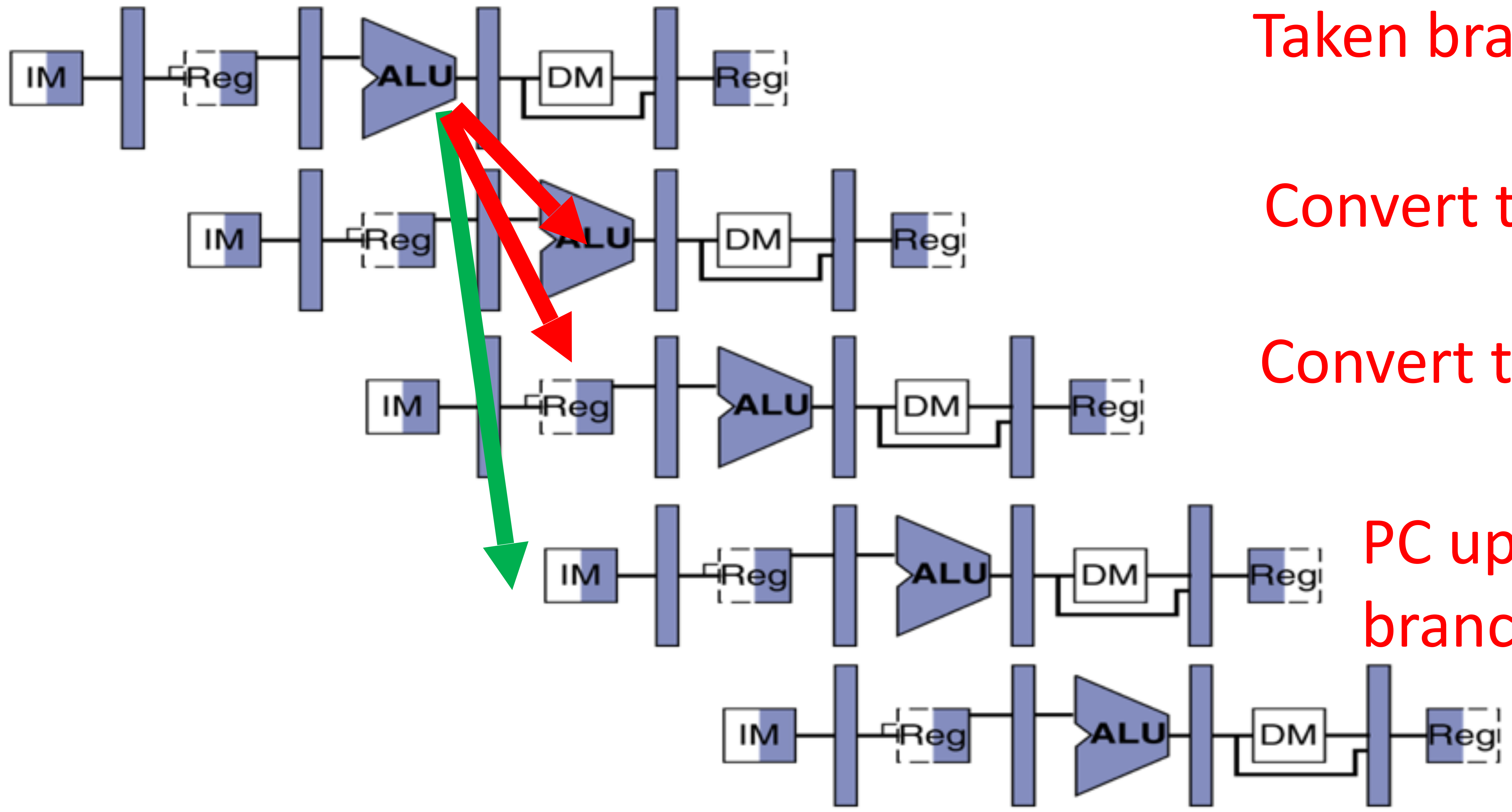
Kill Instructions after Branch if Taken

beq t0, t1, label

sub t2, s0, t5

or t6, s0, t3

label: xxxxxx



Taken branch

Convert to NOP

Convert to NOP

PC updated reflecting branch outcome

Reducing Branch Penalties

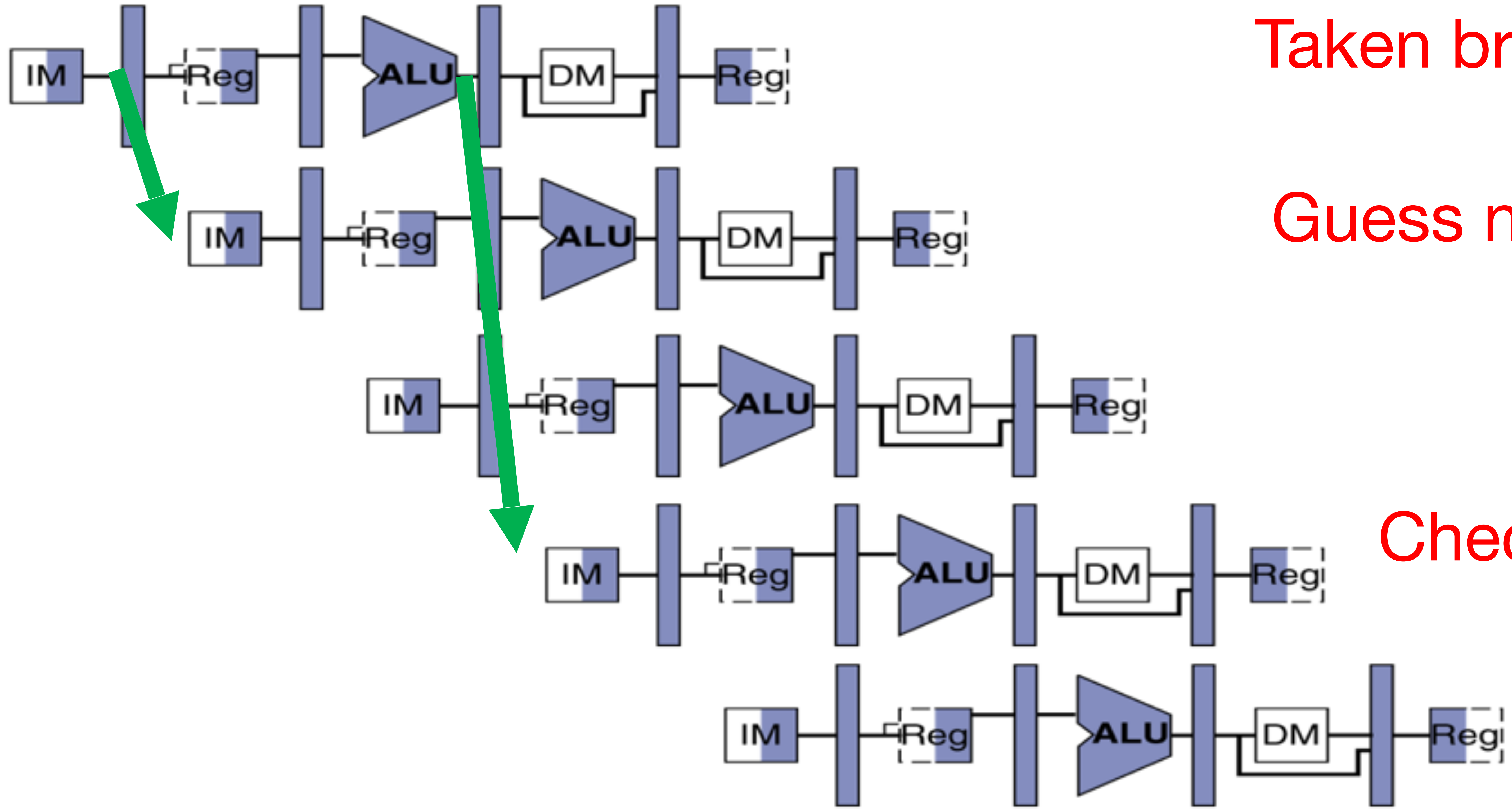
- Every taken branch in simple pipeline costs 2 dead cycles
- To improve performance, use “branch prediction” to guess which way branch will go earlier in pipeline
- Only flush pipeline if branch prediction was incorrect

Branch Prediction

beq t0, t1, label

label: …..

…..



Taken branch

Guess next PC!

Check guess correct

Implementing Branch Prediction...

- This is a CS152 topic, but some ideas:
  - Branch prediction is critical for performance on deeper pipelines/superscalar as the "Misprediction penalty" is vastly higher
- Keep a branch prediction buffer/cache: Small memory addressed by the lowest bits of **`PC`**
  - During instruction decode, if branch: Look up whether branch was taken last time?
    - If yes, compute **`PC + offset`** and fetch that (or store actual branch target address from last time)
    - If no, stick with **`PC + 4`**
  - If branch hasn't been seen before
    - Assume forward branches are not taken, backward branches are taken
  - Update state on predictor with results of branch when it is finally calculated

More on the Branch Predictor...

- What to do on the first time you see a branch?
  - RISC-V: Assume forward is not-taken, backwards will be taken
    - Forward == IF statement, backwards == loop
  - Compiler can then use this as a hint when structuring code
- Jumps are never mispredicted.... But JALR can be!
  - Maintain a similar cache for JALR instructions
  - One for **`JALR RA RX`**
    - Used to predict object-oriented function calls
  - One for **`JALR X0 RA`** as a stack
    - Used to handle function returns

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- **Superscalar processors**

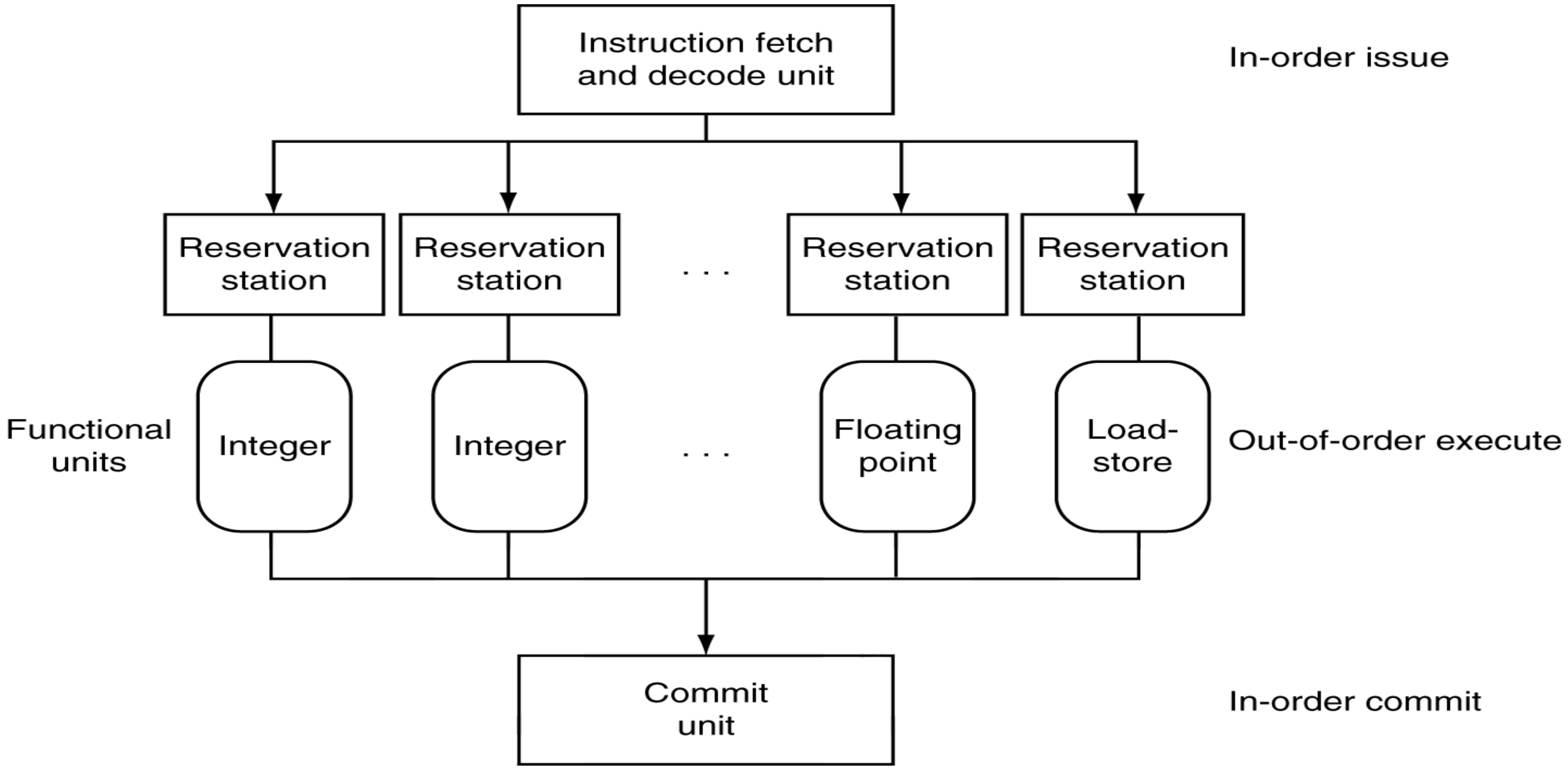
Increasing Single Processor Core Performance

1. Clock rate
   - Limited by technology and power dissipation
2. Pipelining
   - “Overlap” instruction execution
   - Deeper pipeline: 5 => 10 => 15 stages
     - Less work per stage → shorter clock cycle
     - But more potential for hazards (CPI > 1)
     - Depth limited by max clock rate and power dissipation
3. Multi-issue “superscalar” processor

Superscalar Processor

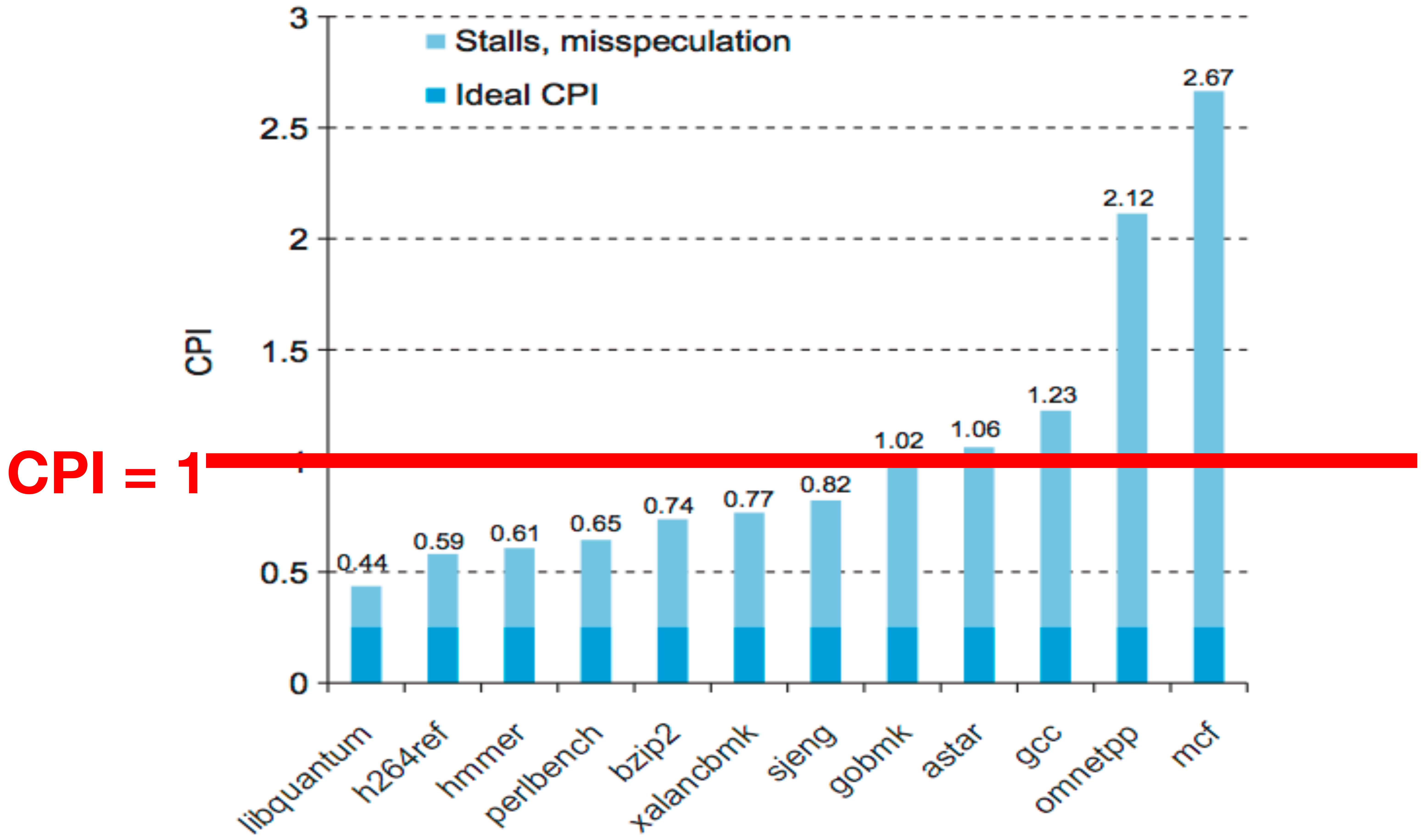
- Multiple issue "superscalar"
  - Replicate pipeline stages ⇒ multiple pipelines
  - Start multiple instructions per clock cycle
  - CPI < 1, so use Instructions Per Cycle (IPC)
  - E.g., 4GHz 4-way multiple-issue
    - 16 BIPS, peak CPI = 0.25, peak IPC = 4
  - Dependencies reduce this in practice
- "Out-of-Order" execution
  - Reorder instructions dynamically in hardware to reduce impact of hazards: EG, memory/cache misses
- CS152 discusses these techniques!

Out Of Order Superscalar Processor



P&H p. 340

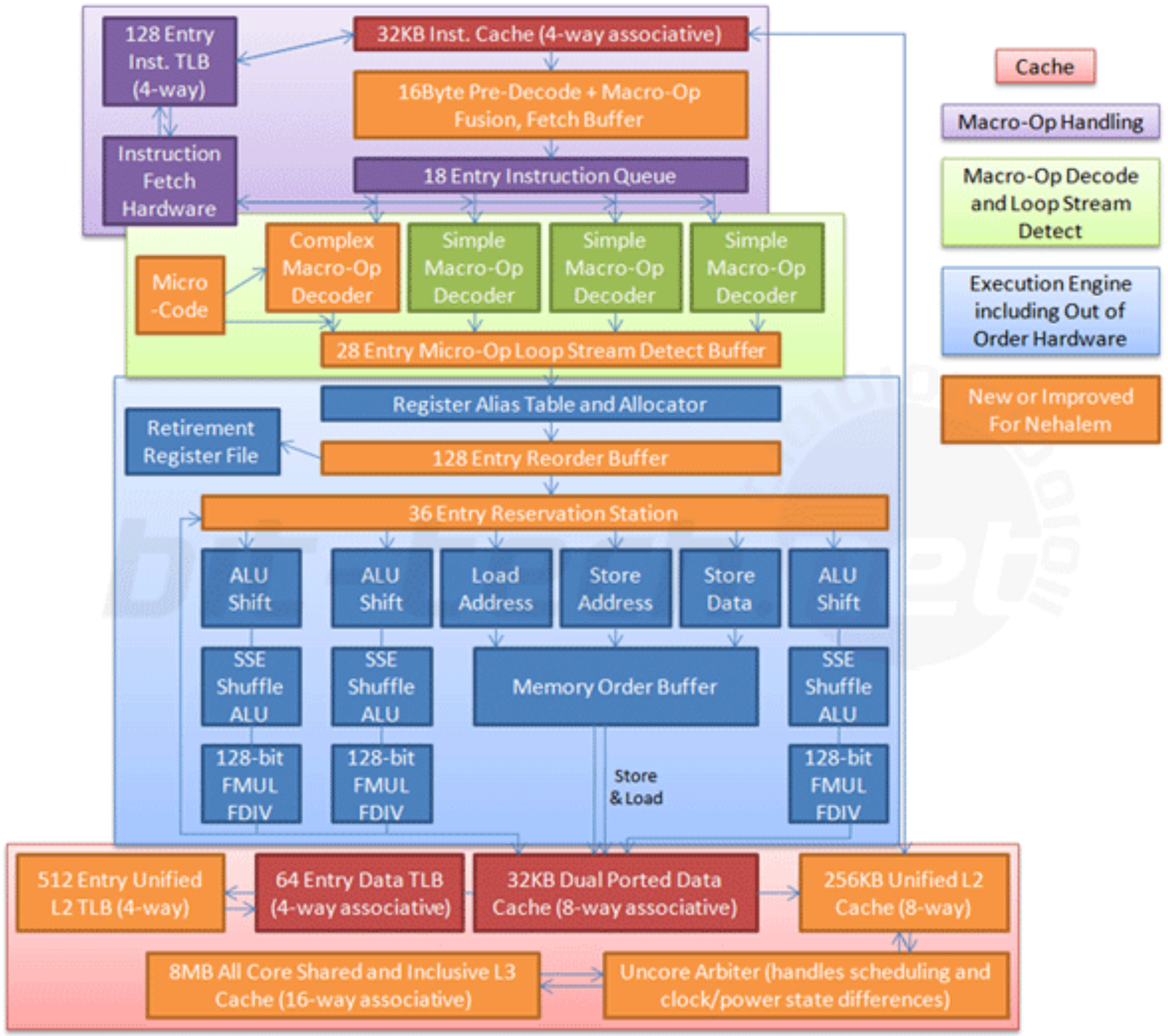
Benchmark: CPI of an older Intel Core i7



CPI of Intel Core i7 920 running SPEC2006 integer benchmarks.

And That Is A Beast...

- 6 separate functional units
  - 3x ALU
  - 3 for memory operations
- 20-24 stage pipeline
- Aggressive branch prediction and other optimizations
  - Massive out-of-order capability:
    Can reorder up to 128 micro-operation instructions!
- And yet it still barely averages a 1 on CPI!



128 Entry Inst. TLB (4-way)
32KB Inst. Cache (4-way associative)
16Byte Pre-Decode + Macro-Op Fusion, Fetch Buffer
Instruction Fetch Hardware
18 Entry Instruction Queue
Micro -Code
Complex Macro-Op Decoder
Simple Macro-Op Decoder
Simple Macro-Op Decoder
Simple Macro-Op Decoder
28 Entry Micro-Op Loop Stream Detect Buffer
Register Alias Table and Allocator
Retirement Register File
128 Entry Reorder Buffer
36 Entry Reservation Station
ALU Shift
ALU Shift
Load Address
Store Address
Store Data
ALU Shift
SSE Shuffle ALU
SSE Shuffle ALU
Memory Order Buffer
SSE Shuffle ALU
128-bit FMUL FDIV
128-bit FMUL FDIV
Store & Load
128-bit FMUL FDIV
512 Entry Unified L2 TLB (4-way)
64 Entry Data TLB (4-way associative)
32KB Dual Ported Data Cache (8-way associative)
256KB Unified L2 Cache (8-way)
8MB All Core Shared and Inclusive L3 Cache (16-way associative)
Uncore Arbiter (handles scheduling and clock/power state differences)
Cache
Macro-Op Handling
Macro-Op Decode and Loop Stream Detect
Execution Engine including Out of Order Hardware
New or Improved For Nehalem

And then Multicore...

- Don't just have one super-scaler processor core, have multiple ones!
- Past approach: Take your best single-core and replicate it...
  - Problem: Those superscalar beasts consume a huge amount of energy
- New approach: Big/Little
  - Some of your processor cores are the single-core beasts...
  - Some are a more energy-optimized design
    - Far less energy/instruction, but fewer instructions/second
  - When absolute performance isn't needed, run tasks on the energy-efficient cores
- Started in cellular phones but now desktop & laptop processors (Intel "Alder Lake", Apple M1) adopt this approach

Pipelining and ISA Design

- RISC-V ISA designed for pipelining
  - All instructions are 32-bits in the RV-32 ISA
    - Easy to fetch and decode in one cycle
      - Variant additions add 16b and 64b instructions,
        but can tell by looking at just the first bits what type it is
    - Versus x86: 1- to 15-byte instructions
      - Requires additional pipeline stages for decoding instructions
  - Few and regular instruction formats
    - Decode and read registers in one step
  - Load/store addressing
    - Calculate address in 3rd stage, access memory in 4th stage
  - Alignment of memory operands
    - Memory access takes only one cycle

And Apple M1

- The following is informed speculation...
  - But the M1 seems to have delivered an >25% performance boost over comparable x86s
- The M1 is ARM rather than Intel x86
  - Arm is best described as "Mostly-RISC"
  - 32 general purpose registers, a load/store architecture, and an easy instruction decoding
    - Probably reduces branch mispredict penalty by a couple of clock cycles
  - But a fair bit of ISA bloat
    - Patterson & Hennessy ARM edition uses a subset of the ISA
- Where is the performance from?
  - Wide decode: 8 instructions/cycle
    - Latest Intel is only 6
  - Monstrous L1 caches, flatter cache hierarchy
    - L1: 192/128kB vs Intel's 32/48kB ("Alder Lake")
  - Huge reordering: 630 deep out-of-order, 100+ memory loads/stores in process
  - Oh, and 32 general purpose registers to make the compiler happy!

In Conclusion

- Pipelining increases throughput by overlapping execution of multiple instructions
- All pipeline stages have same duration
  - Choose partition that accommodates this constraint
- Hazards potentially limit performance
  - Maximizing performance requires programmer/compiler assistance
- Superscalar processors use multiple execution units for additional instruction level parallelism
  - Performance benefit highly code dependent