

CPU Pipelining

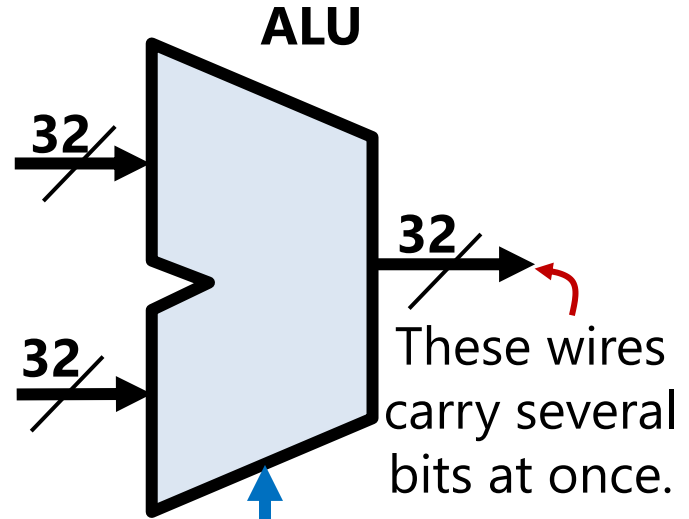
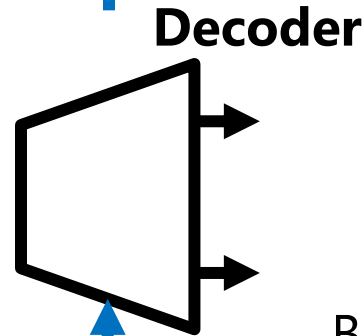
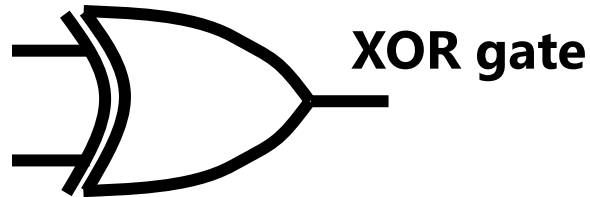
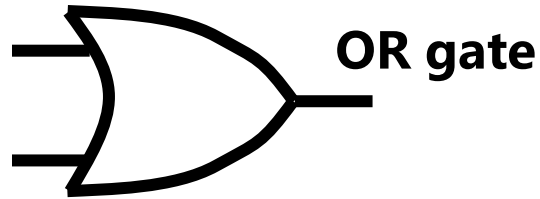
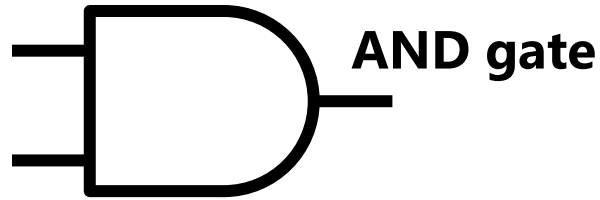
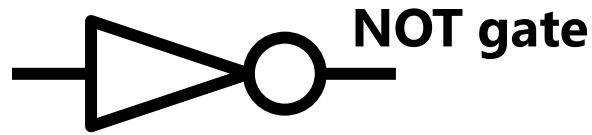
CS/COE 1541 (Fall 2020)
Wonsun Ahn

Clocking Review

Stuff you learned in CS 447

Logic components

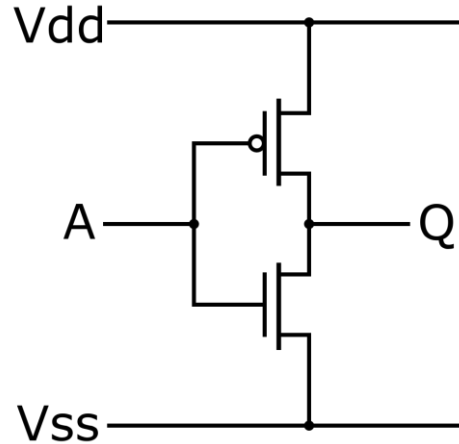
- Do you remember what all these do?



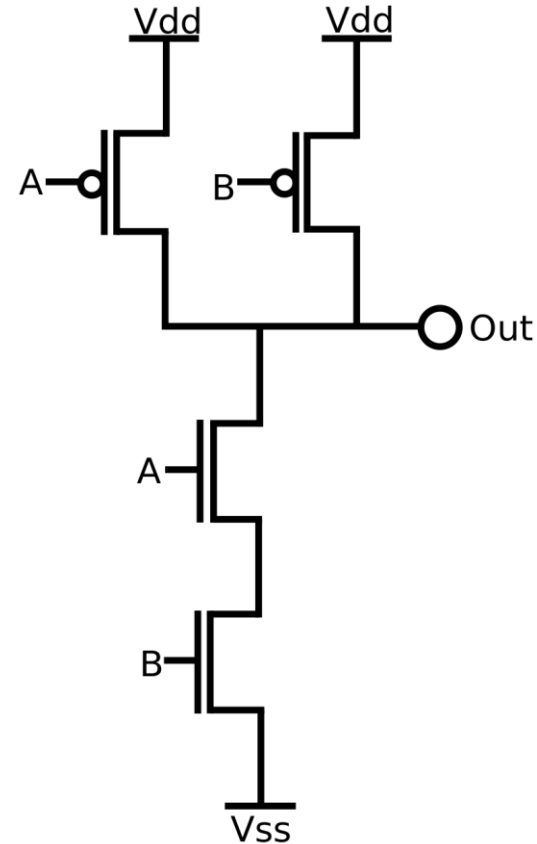
Blue wires are control signals.

Gates are made of transistors (of course)

- NOT gate

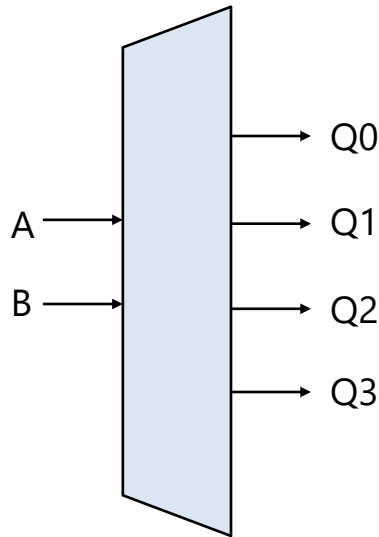


- NAND gate



Uses of a Decoder

- Translates a set of input signals to a bunch of output signals.
 - E.g. a binary decoder:



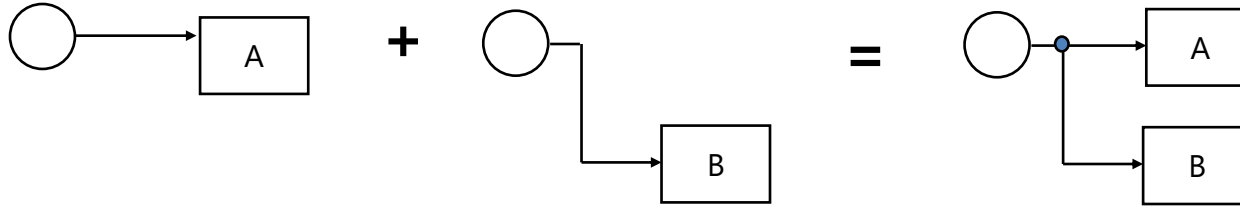
Truth Table for Decoder

A	B	Q0	Q1	Q2	Q3
0	0	1	0	0	0
0	1	0	1	0	0
1	0	0	0	1	0
1	1	0	0	0	1

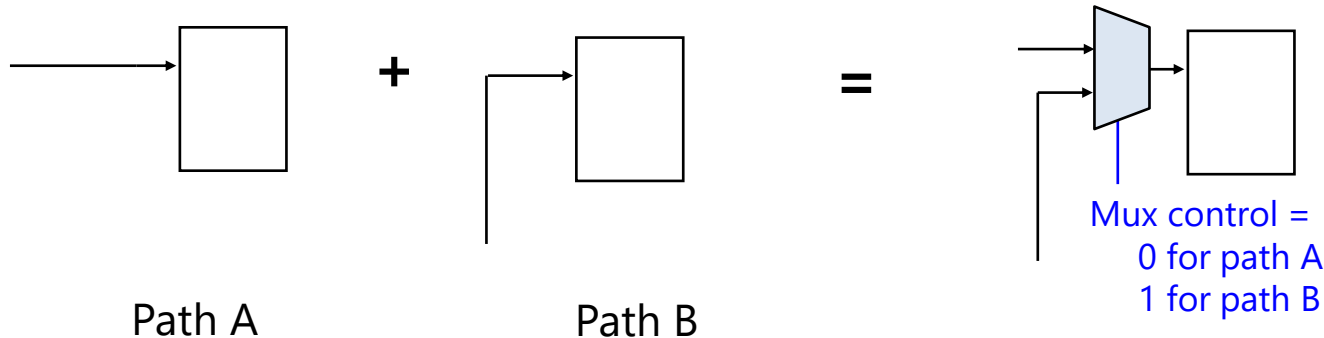
- You can come up with any truth table and make a decoder for it!

Uses of a Multiplexer

- No problem in fanning out one signal to two points

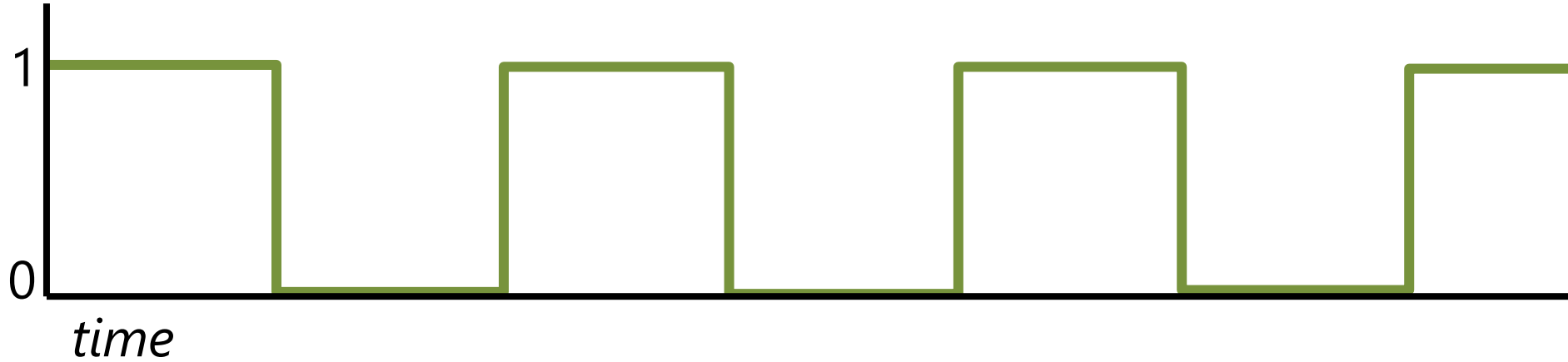


- Cannot connect two signals to one point
 - Must use a multiplexer to *select* between the two



The clock signal

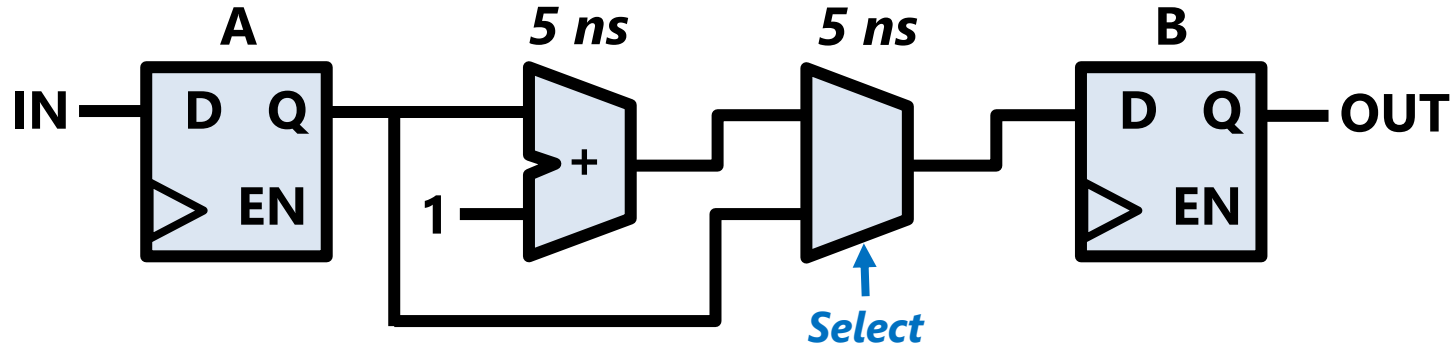
- The clock is a signal that alternates regularly between 0 and 1:



- Bits are latched on to registers and flip-flops on rising edges
- In between rising edges, bits propagate through the logic circuit
 - Composed of ALUs, muxes, decoders, etc.
 - **Propagation delay**: amount of time it takes from input to output

Critical Path

- **Critical path**: path in a circuit that has longest propagation delay
 - Determines the overall clock speed.



- The ALU and the multiplexer both have a 5 ns delay
- How fast can we clock this circuit?
 - Is it $1 / 5 \text{ ns}$ ($5 \times 10^{-9} \text{ s}$) = 200 MHz?
 - Or is it $1 / 10 \text{ ns}$ ($10 \times 10^{-9} \text{ s}$) = 100 MHz? ✓

MIPS Review

Stuff you learned in CS 447

The MIPS ISA - Registers

- MIPS has 32 32-bit registers, with the following usage conventions
 - But really, all are general purpose registers (nothing special about them)

Name	Register number	Usage
\$zero	0	the constant value 0 (can't be written)
\$at	1	assembler temporary
\$v0-\$v1	2-3	values for results and expression evaluation
\$a0-\$a3	4-7	function arguments
\$t0-\$t7	8-15	unsaved temporaries
\$s0-\$s7	16-23	saved temporaries (like program variables)
\$t8-\$t9	24-25	more unsaved temporaries
\$k0-\$k1	26-27	reserved for OS kernel
\$gp	28	global pointer
\$sp	29	stack pointer
\$fp	30	frame pointer
\$ra	31	return address

The MIPS ISA - Memory

- MIPS is a **RISC (reduced instruction set computer)** architecture
- It is also a **load-store** architecture
 - **All** memory accesses performed by load and store instructions
- Memory is a giant array of 2^{32} bytes

Addr	Data
0	0x3F
1	0x00
2	0x2A
3	0x08
4	0x47
5	0xF4
6	0x26
7	0xB9
...	...

Addr	Data
0	0x3F00
2	0x2A08
4	0x47F4
6	0x26B9
...	...

Addr	Data
0	0x3F002A08
4	0x47F426B9
...	...

- The same memory viewed as bytes, 16-bit halfwords, and 32-bit words (using big-endian)
- All addresses are **aligned** (multiples of data size)

The MIPS ISA - Memory

- Loads move data *from* memory *into* the registers.

lw **\$t0**, **8(\$s4)**

This is the address, and it means "the value of \$s4 + 8."

t0	0x0000BEEF
s4	0x00000004

Registers

- Stores move data *from* the registers *into* memory.

sw **\$t0**, **12(\$s4)**

\$t0 is the SOURCE!

lw

sw

$\$s4 + 8$

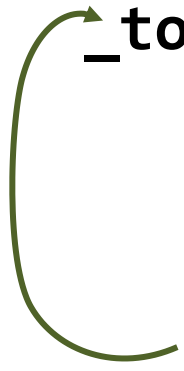
$\$s4 + 12$

0	0x3F002A08
4	0x47F426B9
8	0x00000000
12	0x0000BEEF
16	0x0000BEEF
...	...

Memory

The MIPS ISA – Flow control

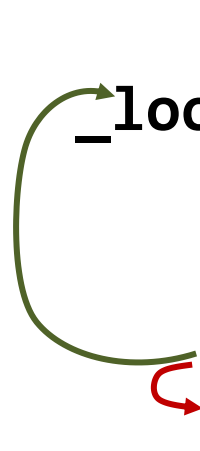
- Jump and branch instructions change the flow of execution.



```
_top:
# ....
# Lots o' code
# ....
j _top
```

j : jumps *unconditionally*

- jumps to **_top**



```
li    $s0, 10
_loop:
# ....
addi  $s0, $s0, -1
bne   $s0, $zero, _loop
jr    $ra
```

bne : jumps *conditionally*

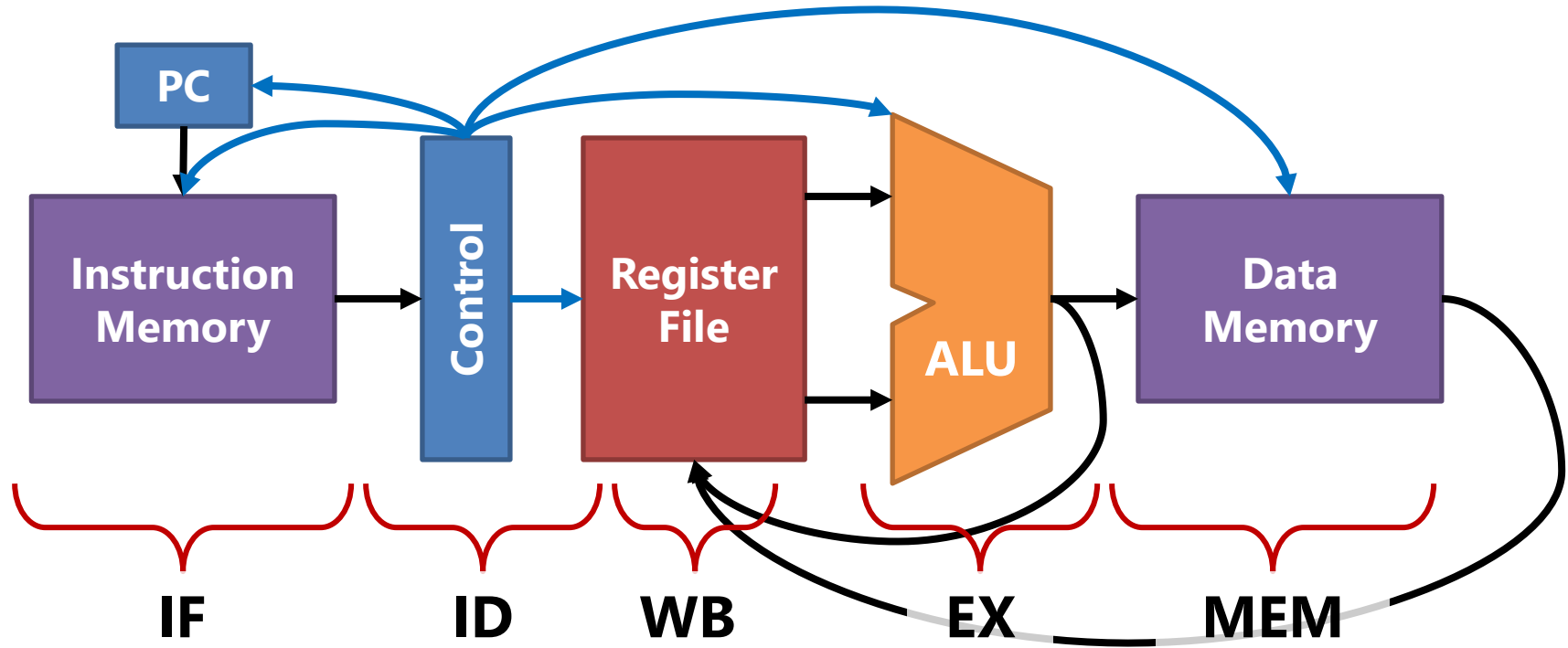
If **\$s0** != **\$zero**, jumps to **_loop**

If **\$s0** == **\$zero**, continues to **jr \$ra**

Phases of instruction execution

- In most architectures, there are five phases:
 1. **IF** (Instruction Fetch) – get next instruction from memory
 2. **ID** (Instruction Decode) – figure out what instruction it is
 3. **EX** (Execute – ALU) – do any arithmetic
 4. **MEM** (Memory) – read or write data from/to memory
 5. **WB** (Register Writeback) – write any results to the registers
- Sometimes these phases are chopped into smaller stages

A simple single-cycle implementation



- An instruction goes through IF/ID/EX/MEM/WB in one cycle

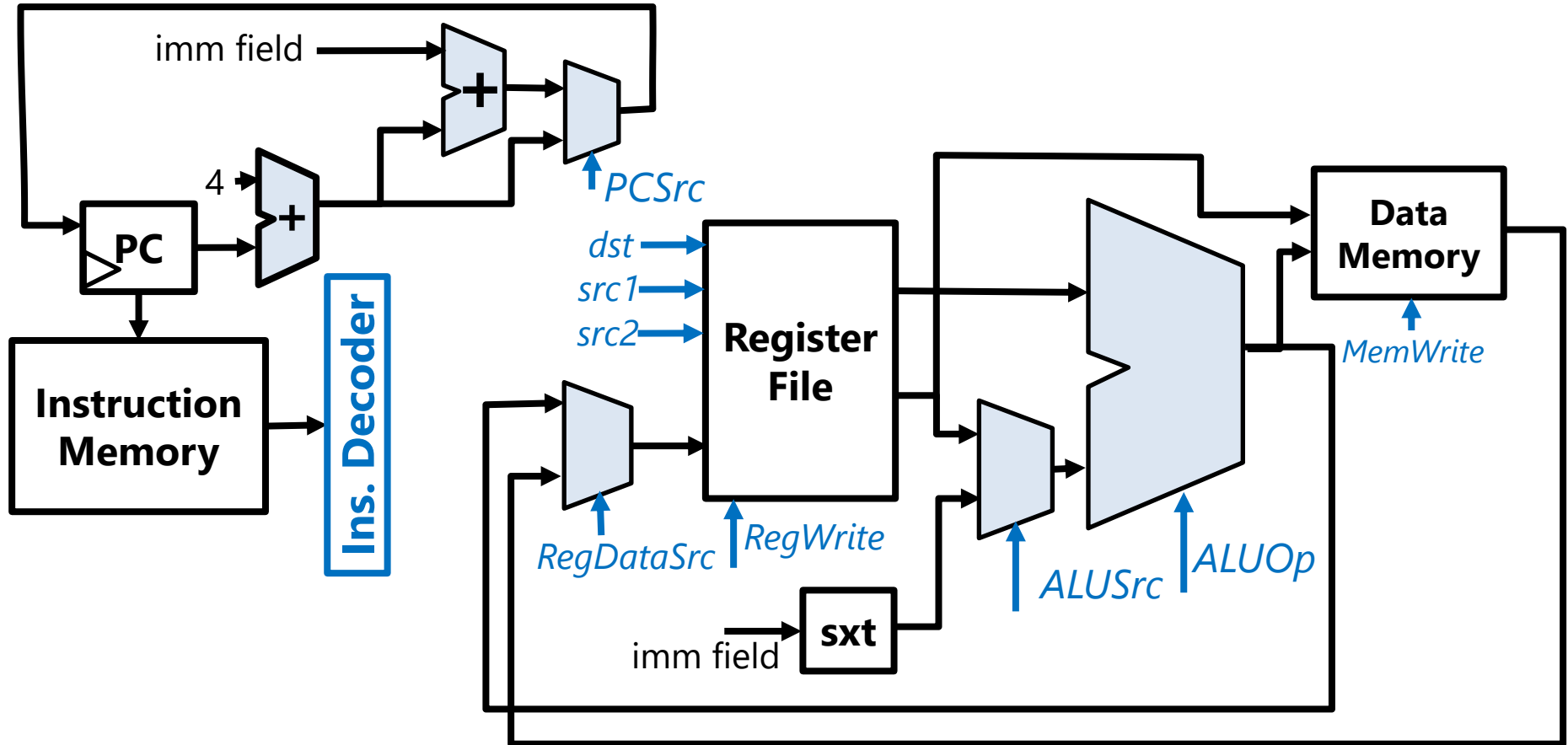
"Minimal MIPS"

It's a "subset" of MIPS

- For pedagogical (teaching) purposes
- Contains only a minimal number of instructions:
 - **lw, sw, add, sub, and, or, slt, beq, and j**
 - Other instructions in MIPS are variations on these anyway
- Let's review the Minimal MIPS CPU focusing on the control signals
 - Again, these control signals are decoded from the instruction

The Minimal MIPS single-cycle CPU

- A more detailed view of the 5-phase implementation

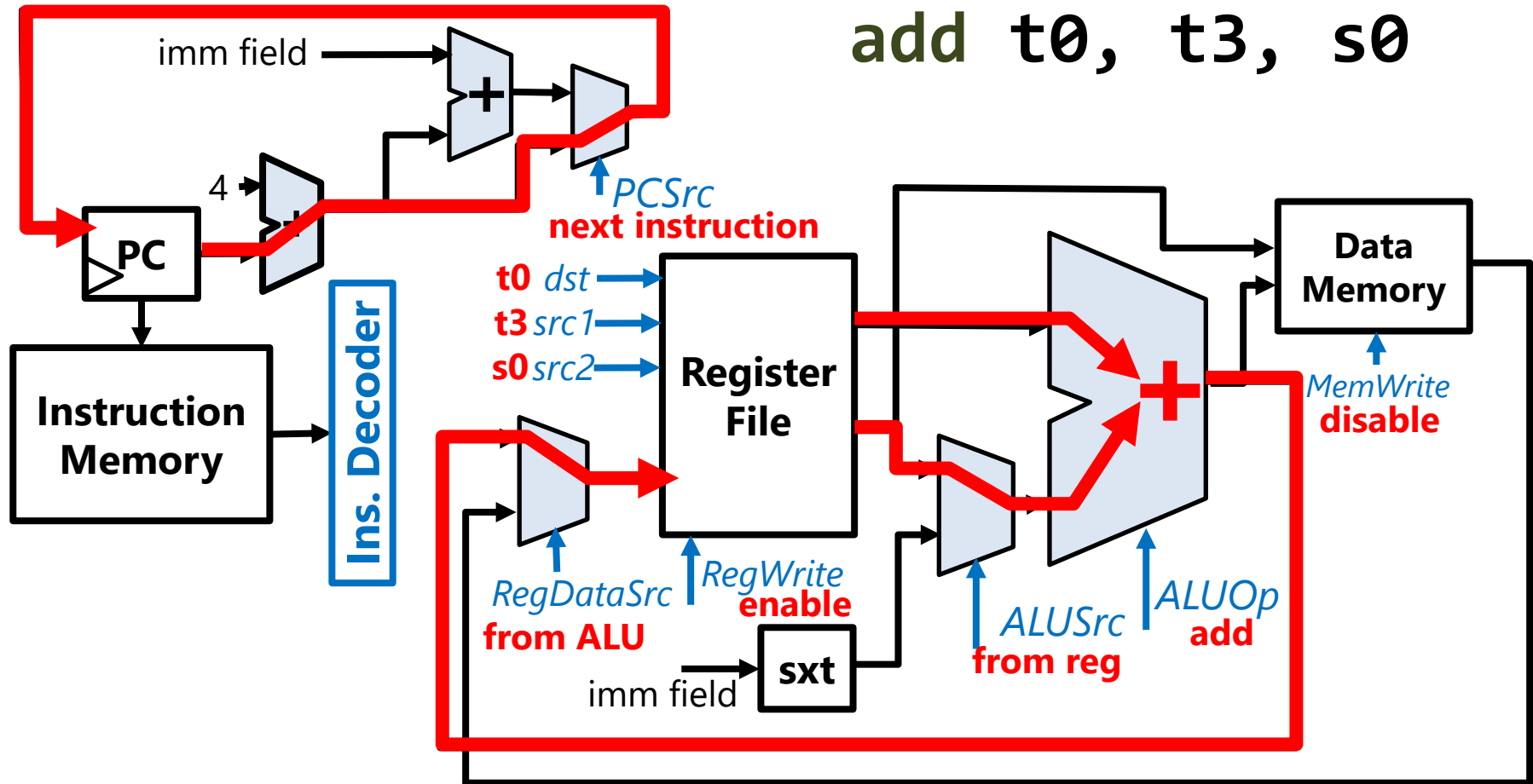


Control signals

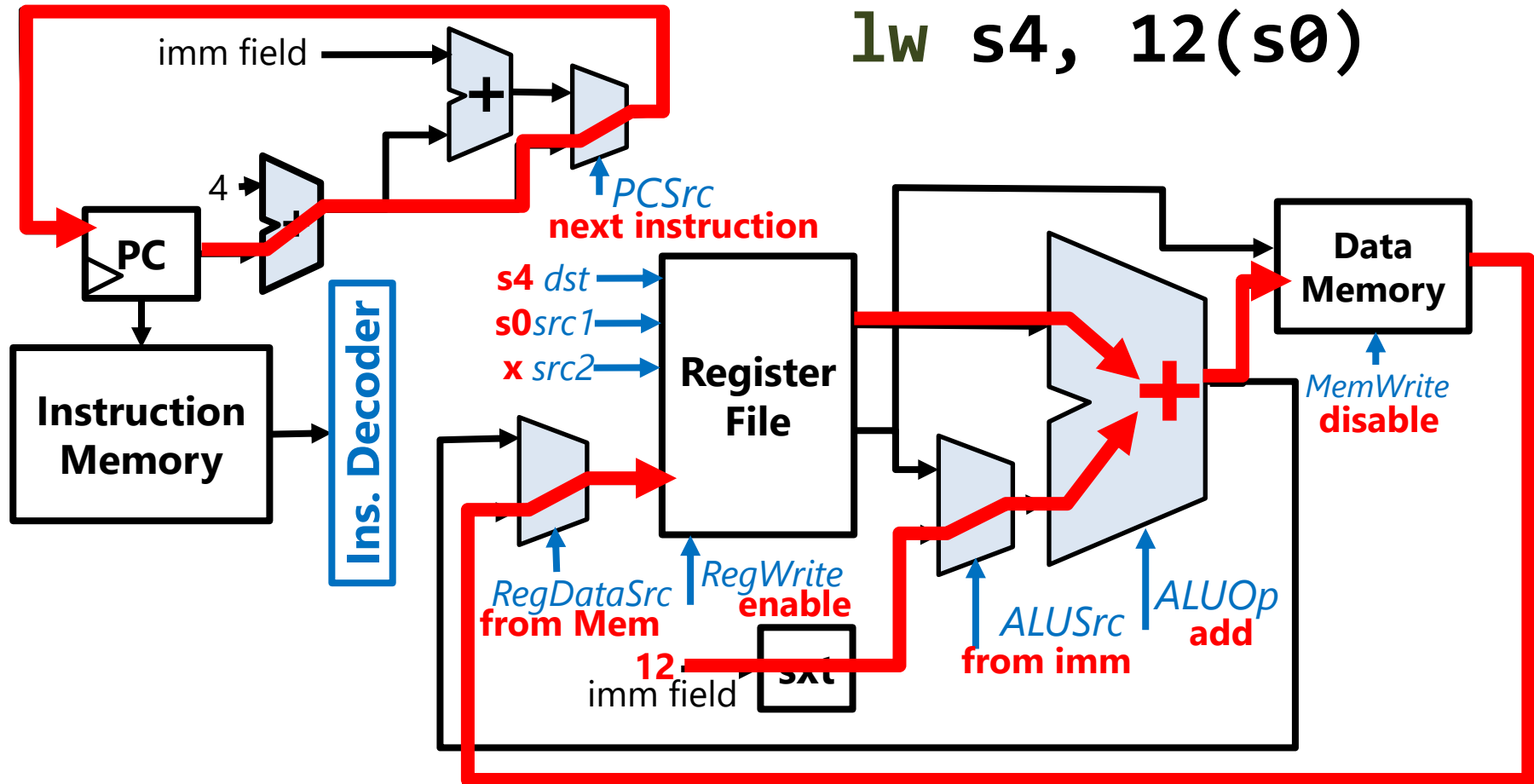
- Registers
 - **RegDataSrc**: controls source of a register write (ALU / memory)
 - **RegWrite**: enables a write to the register file
 - **src1, src2, dst**: the register number for each respective operand
- ALU
 - **ALUSrc**: whether second operand of ALU is a register / immediate
 - **ALUOp**: controls what the ALU will do (add, sub, and, or etc)
- Memory
 - **MemWrite**: enables a write to data memory
- PC
 - **PCSrc**: controls source of next PC ($PC + 4$ / $PC + 4 + imm$)

→ All these signals are decoded from the instruction!

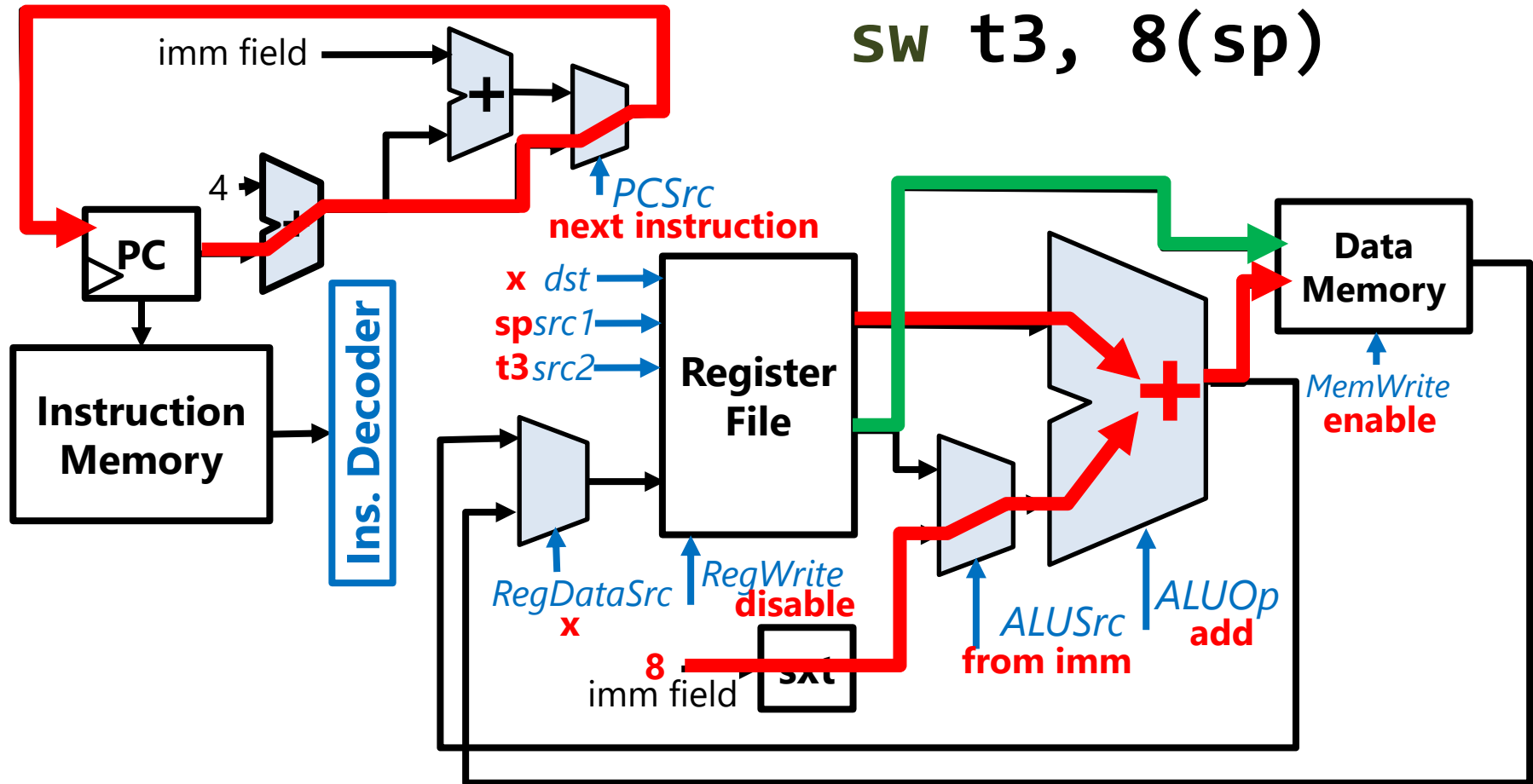
How an add/sub/and/or/slt work



How an lw works

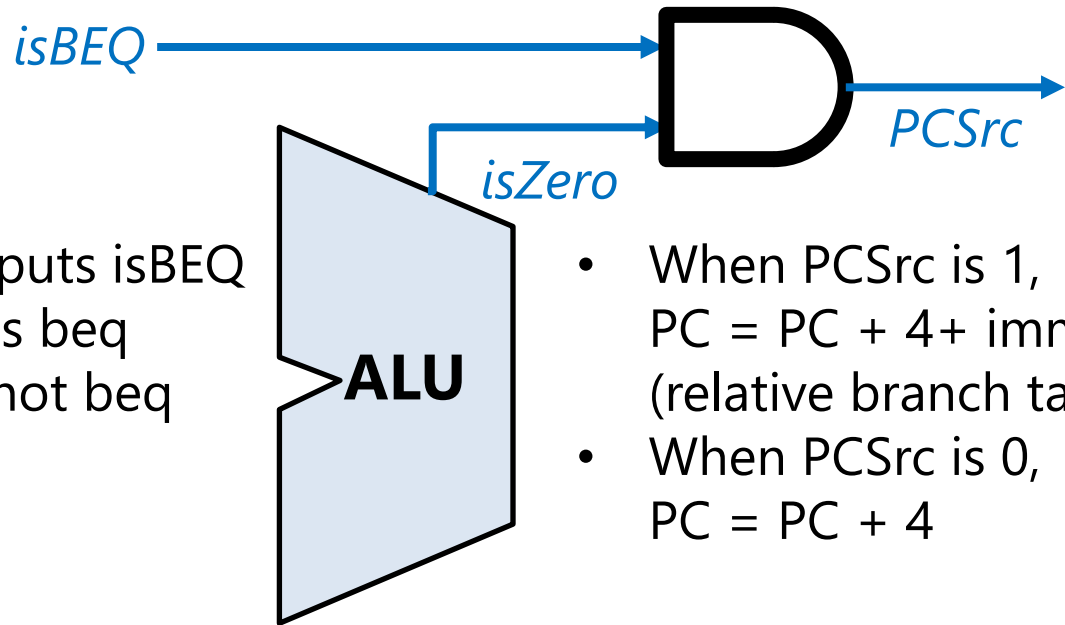


How an **sw** works



What about **beq**?

- Compares numbers by subtracting and see if result is 0
 - If result is 0, we set PCSrc to use the branch target.
 - Otherwise, we set PCSrc to $PC + 4$.



- Instruction decoder outputs *isBEQ*
 - 1: When instruction is **beq**
 - 0: When instruction not **beq**

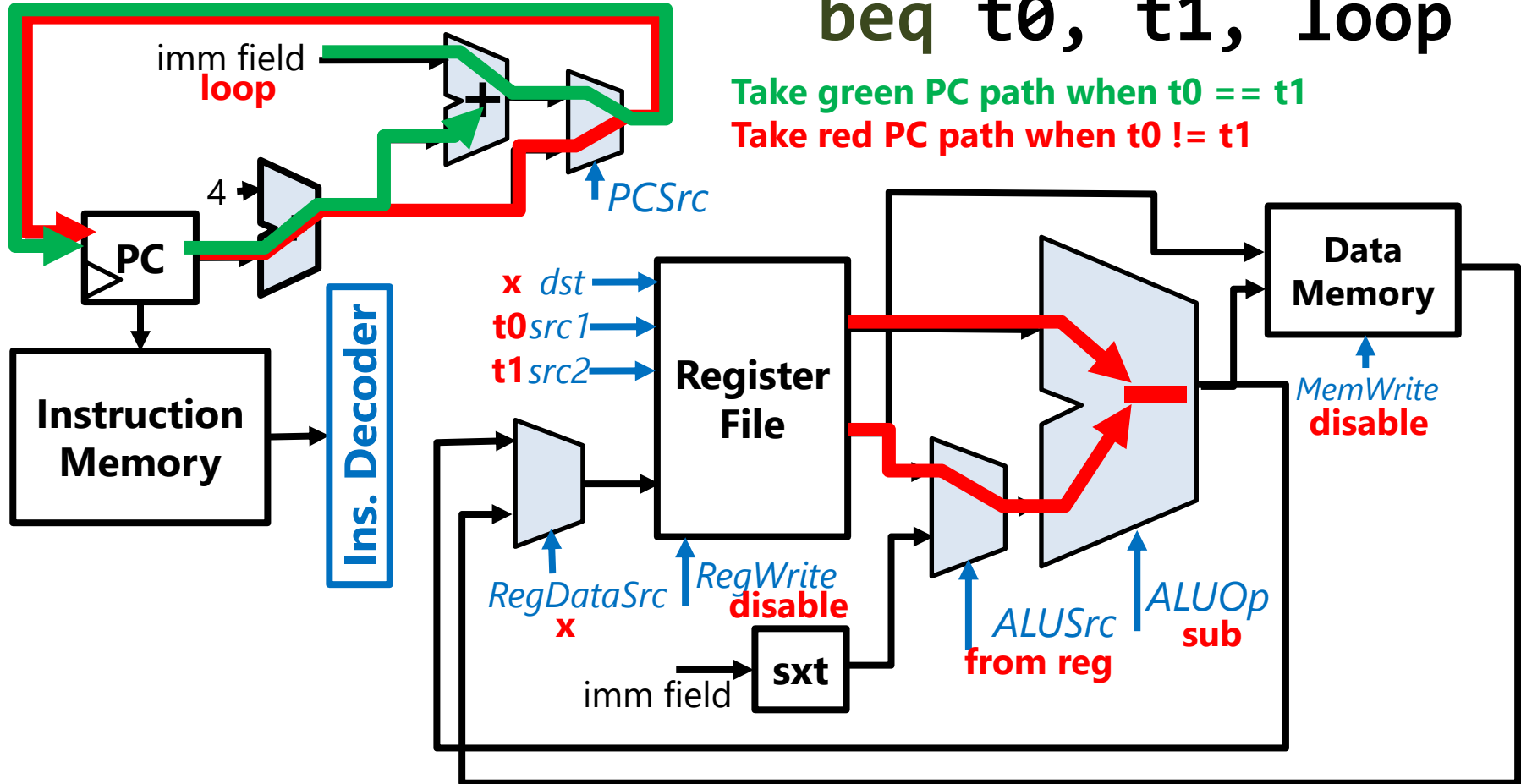
- When *PCSrc* is 1,
 $PC = PC + 4 + \text{imm}$
(relative branch target)
- When *PCSrc* is 0,
 $PC = PC + 4$

How a **beq** works

beq t0, t1, loop

Take green PC path when $t0 == t1$

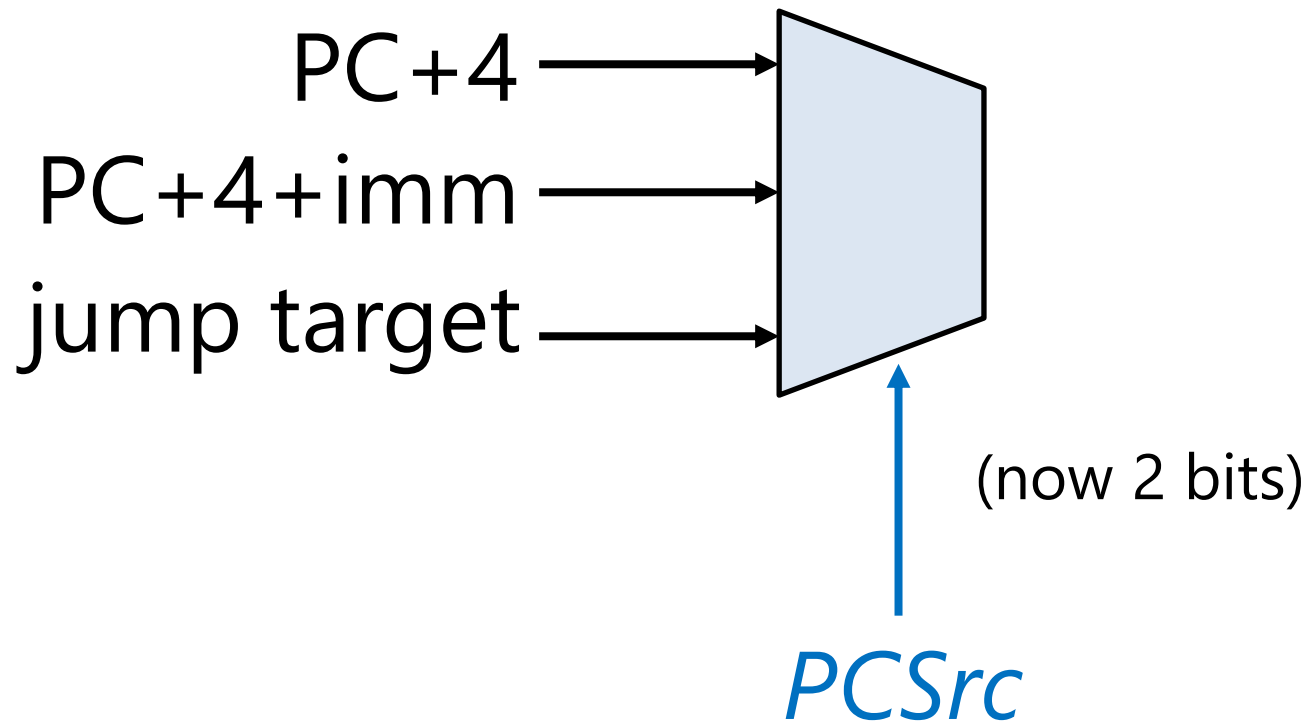
Take red PC path when $t0 \neq t1$



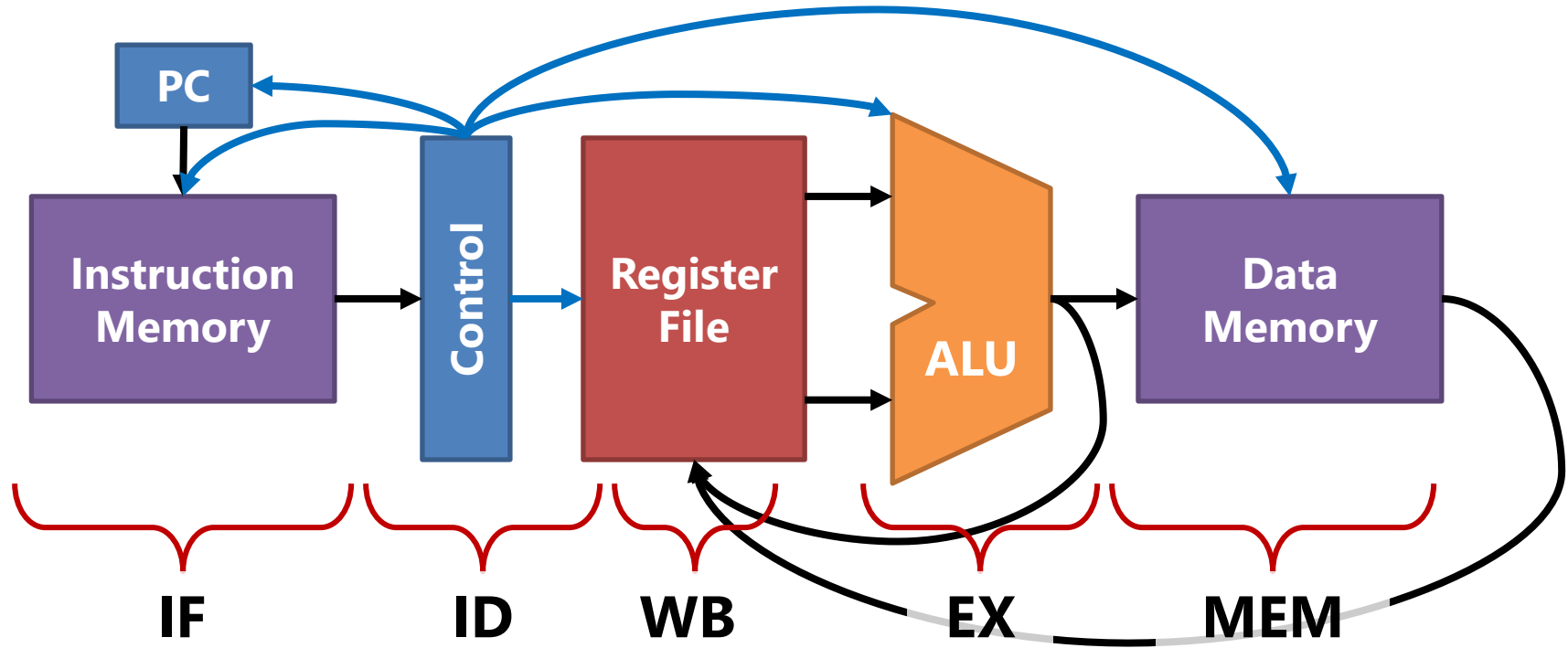
What about **j**?

- We have to add another input to the PCSrc mux.

j **top**



A Single-cycle Implementation is not Optimal



- Why? Since the **longest** critical path must be chosen for cycle time
 - And there is a wide variation among different instructions

A Single-cycle Implementation is not Optimal

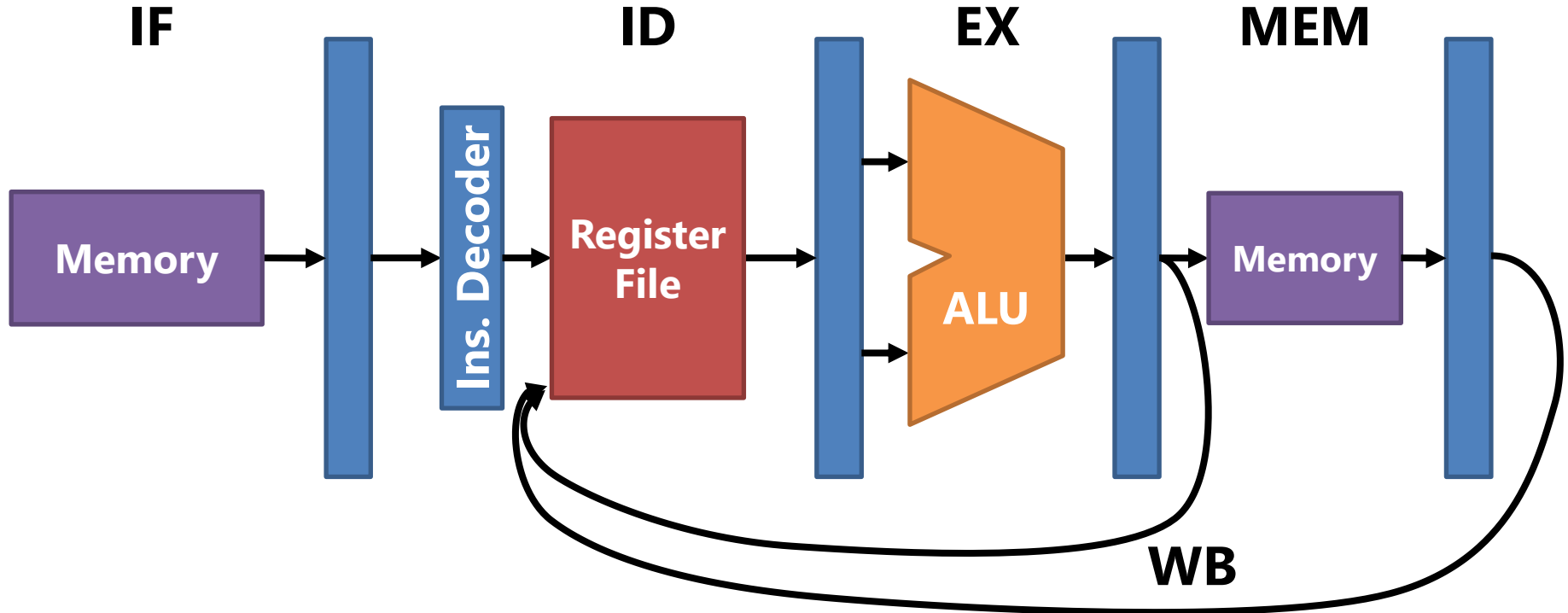
- In our CPU, the **lw** instruction has the longest critical path
 - Must go through all 5 stages: IF/ID/EX/MEM/WB
 - Whereas **add** goes through just 4 stages: IF/ID/EX/WB
- If each phase takes *1 ns* each, cycle time must be *5 ns*:
 - Because it needs to be able to handle **lw**, which takes *5 ns*
 - **add** also takes *5 ns* when it could have been done in *4 ns*

Q) If **lw** is 1% and **add** is 99% of instruction mix,
what is the average instruction execution time?

A) Still *5 ns*! Even if add is 99% of instructions!

A Multi-cycle Implementation

- It takes one cycle for each phase through the use of internal latches



A Multi-cycle Implementation is Faster!

- Now each instruction takes different number of cycles to complete
 - **lw** takes 5 cycles: IF/ID/EX/MEM/WB
 - **add** takes 4 cycles: IF/ID/EX/WB
- If each phase takes *1 ns* each as before:
 - **lw** takes *5 ns* and **add** takes *4 ns*

Q) If **lw** is 1% and **add** is 99% of instruction mix, what is the average instruction execution time?

A) $0.01 * 5 \text{ ns} + 0.99 * 4 \text{ ns} = 4.01 \text{ ns}$ (25% faster than single cycle)

** Caveat: there is some delay due to the added latches but net win*

And we can do even better!

- Did you notice?
 - When an instruction is on a particular phase (e.g. IF) ...
 - ... other phases (ID/EX/MEM/WB) are not doing any work!
- Our CPU is getting chronically ***underutilized***!
 - If CPU is a factory, 80% (4/5) of the workers are idling!
- Car factories create an assembly line to solve this problem
 - No need to wait until a car is finished before starting on next one
 - Our CPU is going to use a ***pipeline*** (similar concept)

Pipelining Basics

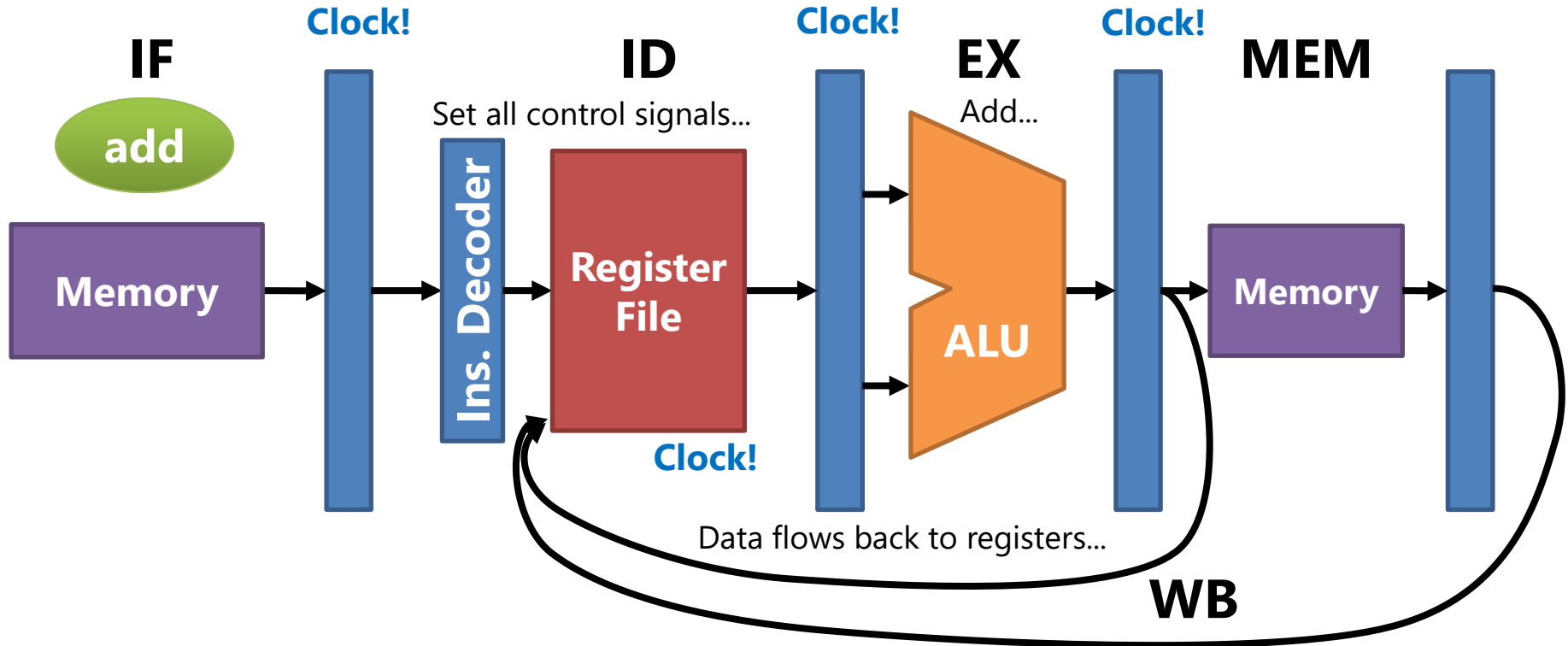
Improving Washer / Dryer / Closet Utilization

- If washer works on next load immediately after passing on to dryer
→ Washer gets higher utilization → Improves overall throughput!



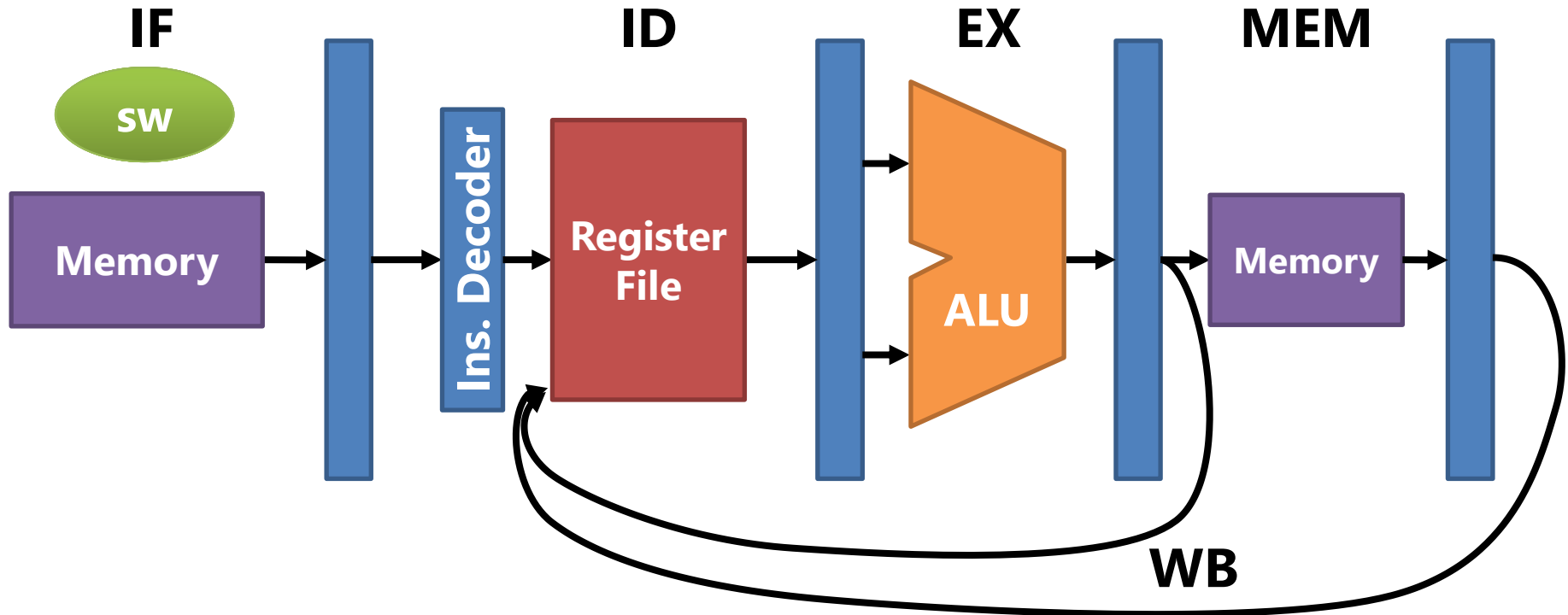
Multi-cycle instruction execution

- Let's watch how an instruction flows through the datapath.



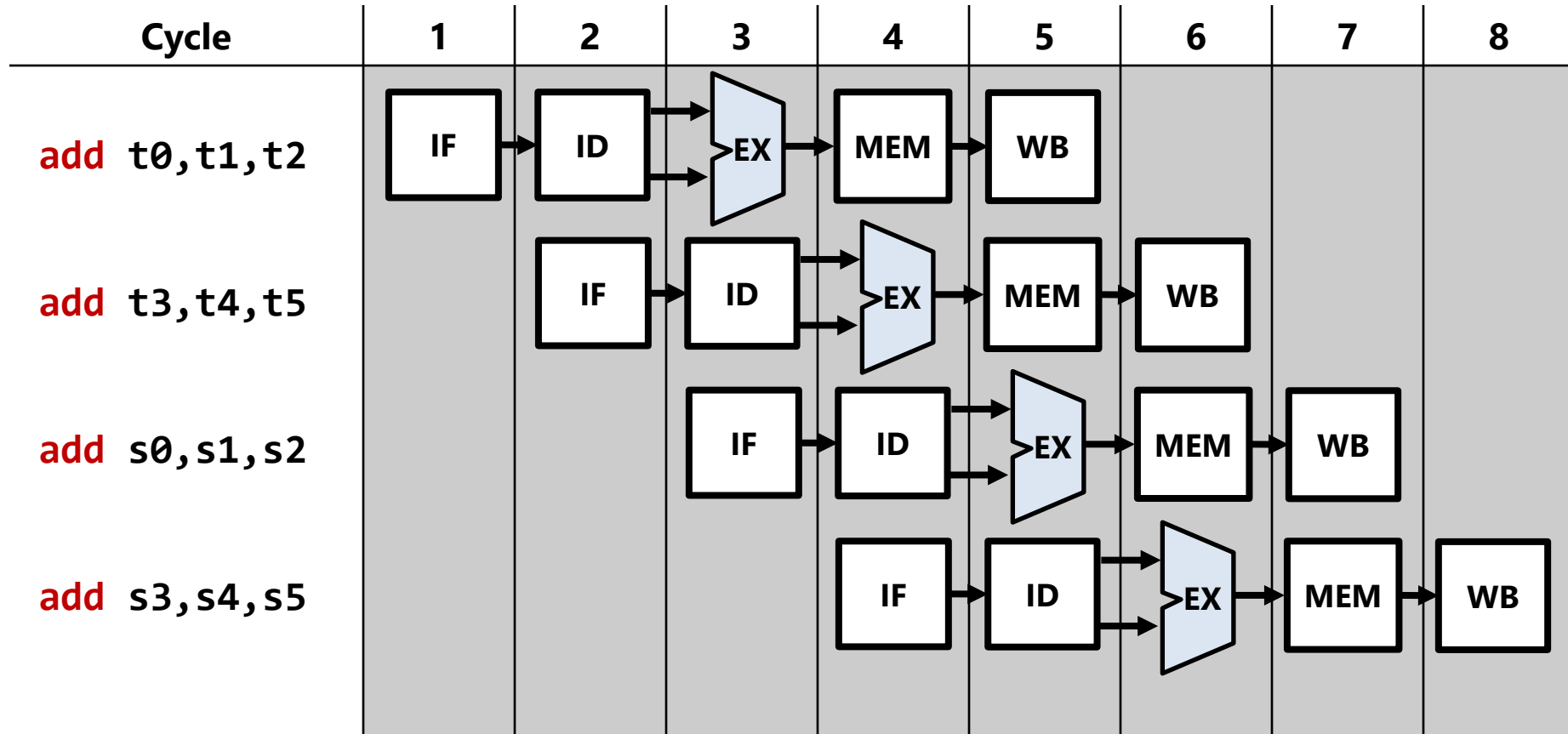
Pipelined instruction execution

- Pipelining is just an extension of that idea!



Pipelining Timeline

- This type of parallelism is called *pipelined parallelism*.



A Pipelined Implementation is even Faster!

- Again each instruction takes different number of cycles to complete
 - **lw** takes 5 cycles: IF/ID/EX/MEM/WB
 - **add** takes 4 cycles: IF/ID/EX/WB
- If each stage takes *1 ns* each:
 - **lw** takes *5 ns* and **add** takes *4 ns*

Q) The average instruction execution time (given 100 instructions)?

A) $(99 \text{ ns} + 5 \text{ ns}) / 100 = 1.04 \text{ ns}$

- Assuming last instruction is a **lw** (a 5-cycle instruction)
- A ~**5X** speed up from single cycle!

Pipelined vs. Multi-cycle vs. Single-cycle

- What happened to the three components of performance?

$$\frac{\text{instructions}}{\text{program}} \times \frac{\text{cycles}}{\text{instructions}} \times \frac{\text{seconds}}{\text{cycle}}$$

Architecture	Instructions	CPI	Cycle Time (1/F)
Single-cycle	Same	1	5 ns
Multi-cycle	Same	4~5	1 ns
Pipelined	Same	1	1 ns

- Compared to single-cycle, pipelining improves clock cycle time
 - Or in other words CPU **clock frequency**
 - The deeper the pipeline, the higher the frequency will be
- * *Caveat: latch delay and unbalanced stages can increase cycle time*
- * *Caveat: pipeline hazards and memory delay can increase CPI*

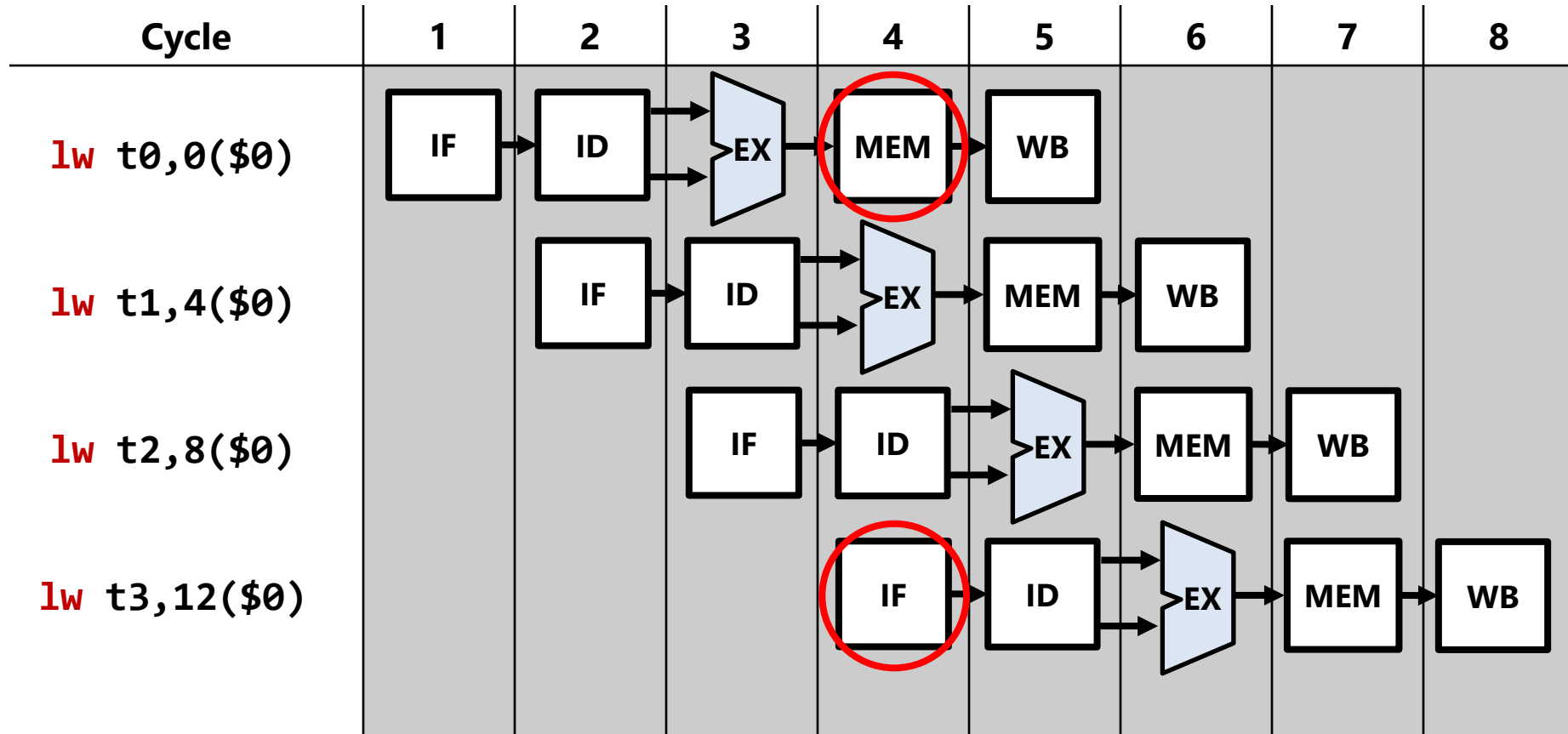
Pipeline Hazards

Pipeline Hazards

- For pipelined CPUs, we said CPI is practically 1
 - But that depends entirely on having the pipeline filled
 - In real life, there are **hazards** that prevent 100% utilization
- **Pipeline Hazard**
 - When the next instruction cannot execute in the following cycle
 - Hazards introduce “bubbles” into the pipeline timeline
- Architects have some tricks up their sleeves to avoid hazards
- But first let's briefly talk about the three types of hazards:
Structural hazard, Data hazard, Control Hazard

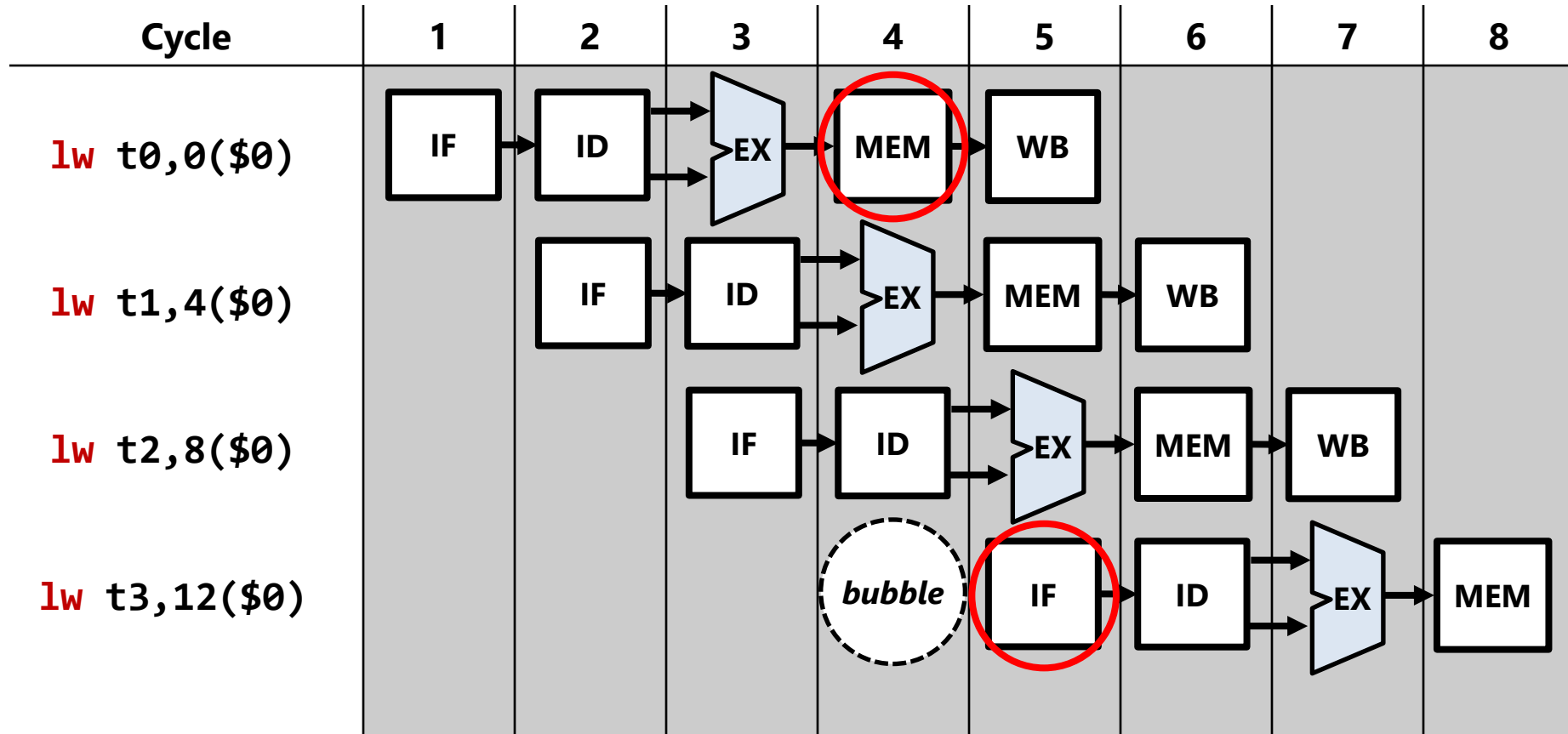
Structural hazards

- Two instructions need to use the same hardware at the same time.



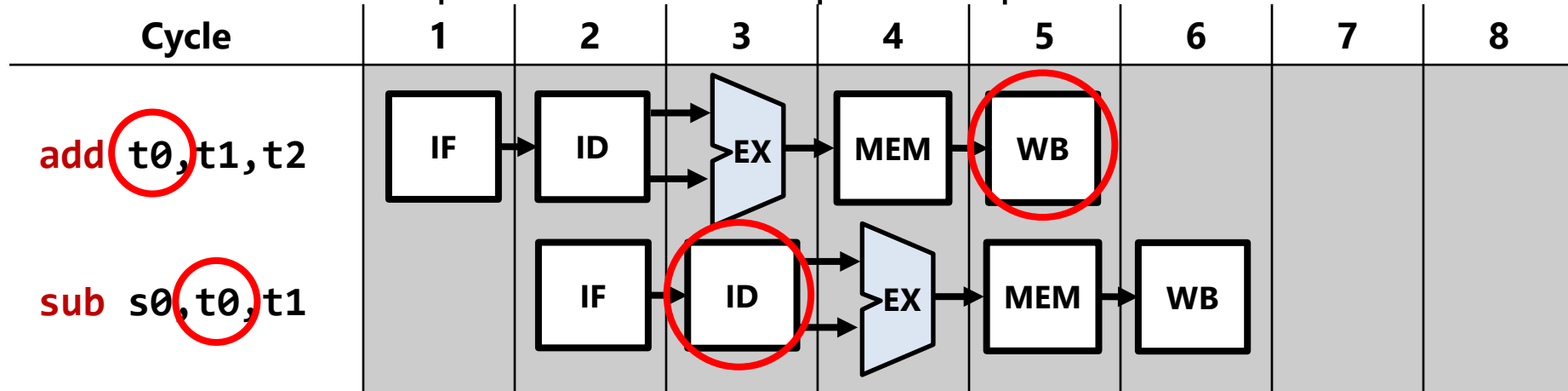
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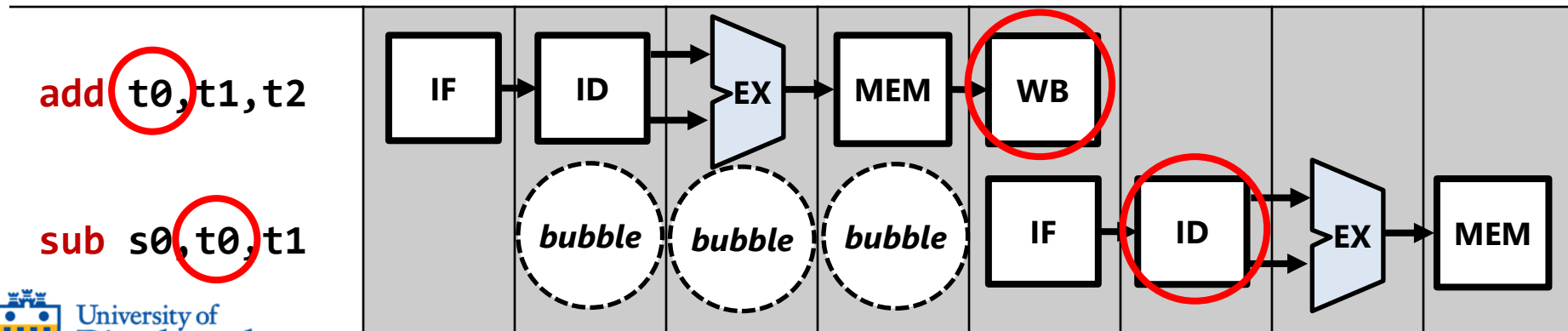


Data hazards

- An instruction depends on the output of a previous one.

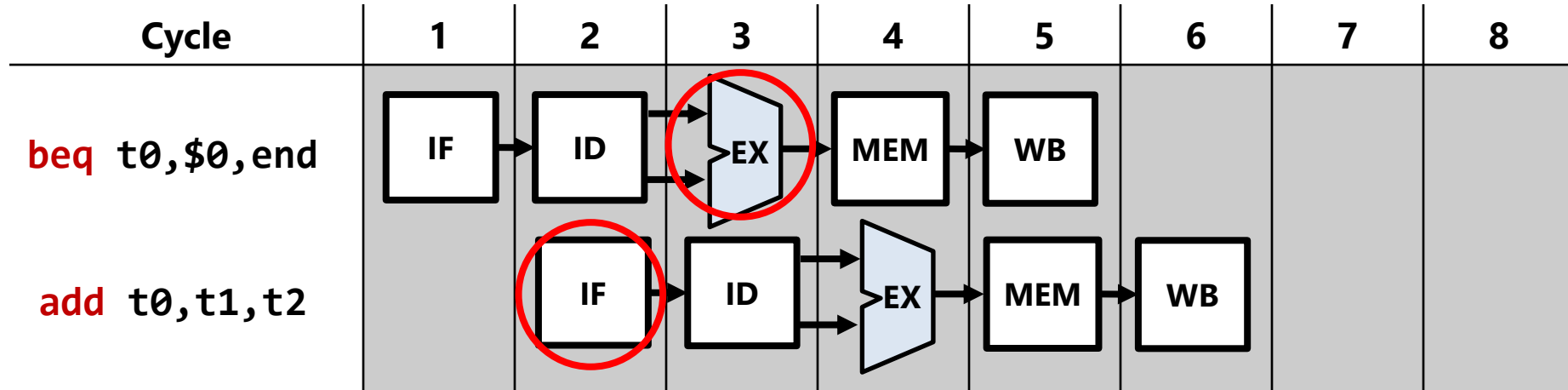


- sub** must wait until **add**'s WB phase is over before doing its ID phase



Control hazards

- You don't know the outcome of a conditional branch.



- add** must wait until **beq**'s EX phase is over before its IF phase

