

Optimizing Pipeline Hazards

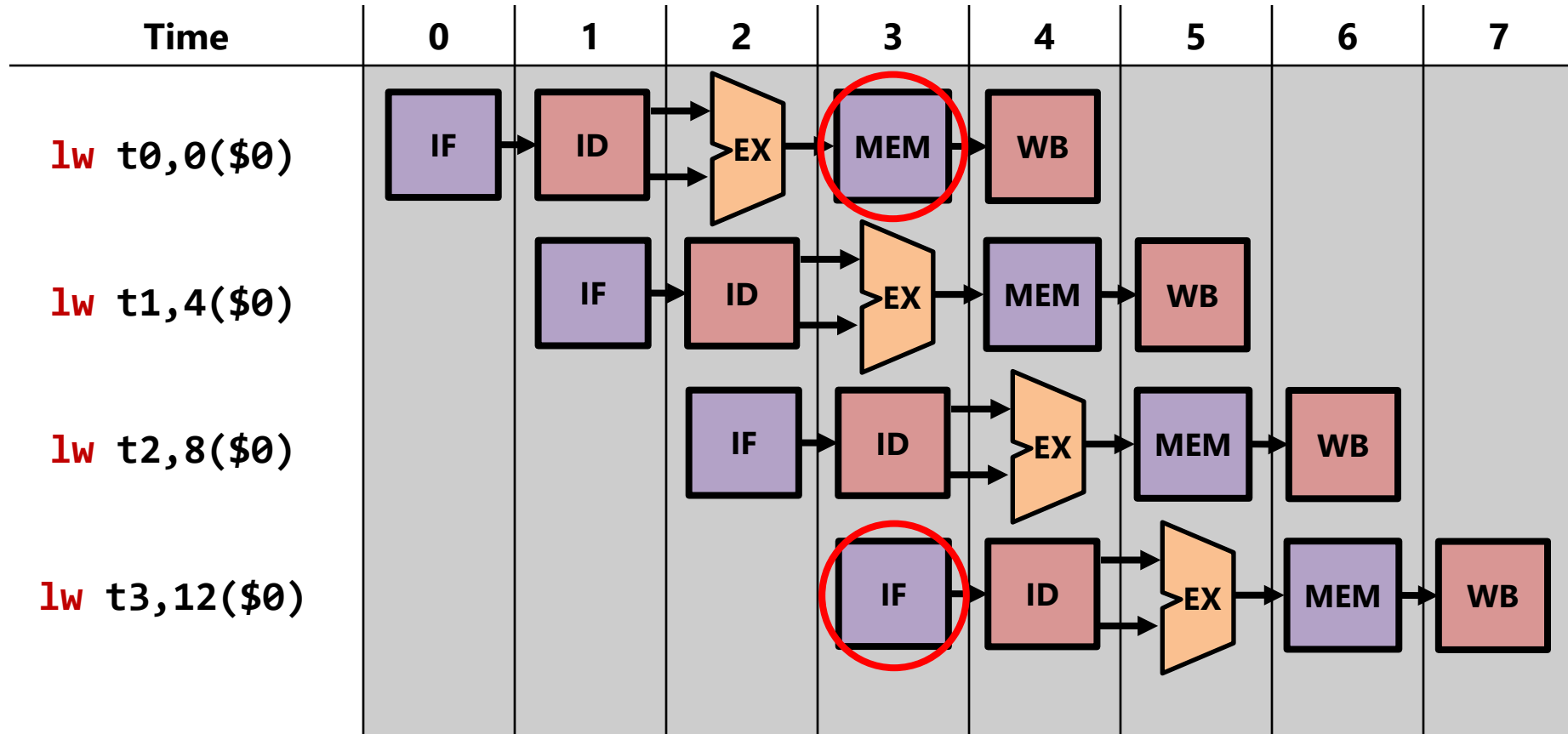
CS 1541

Wonsun Ahn

Solving Structural Hazards

Structural Hazard on Memory

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



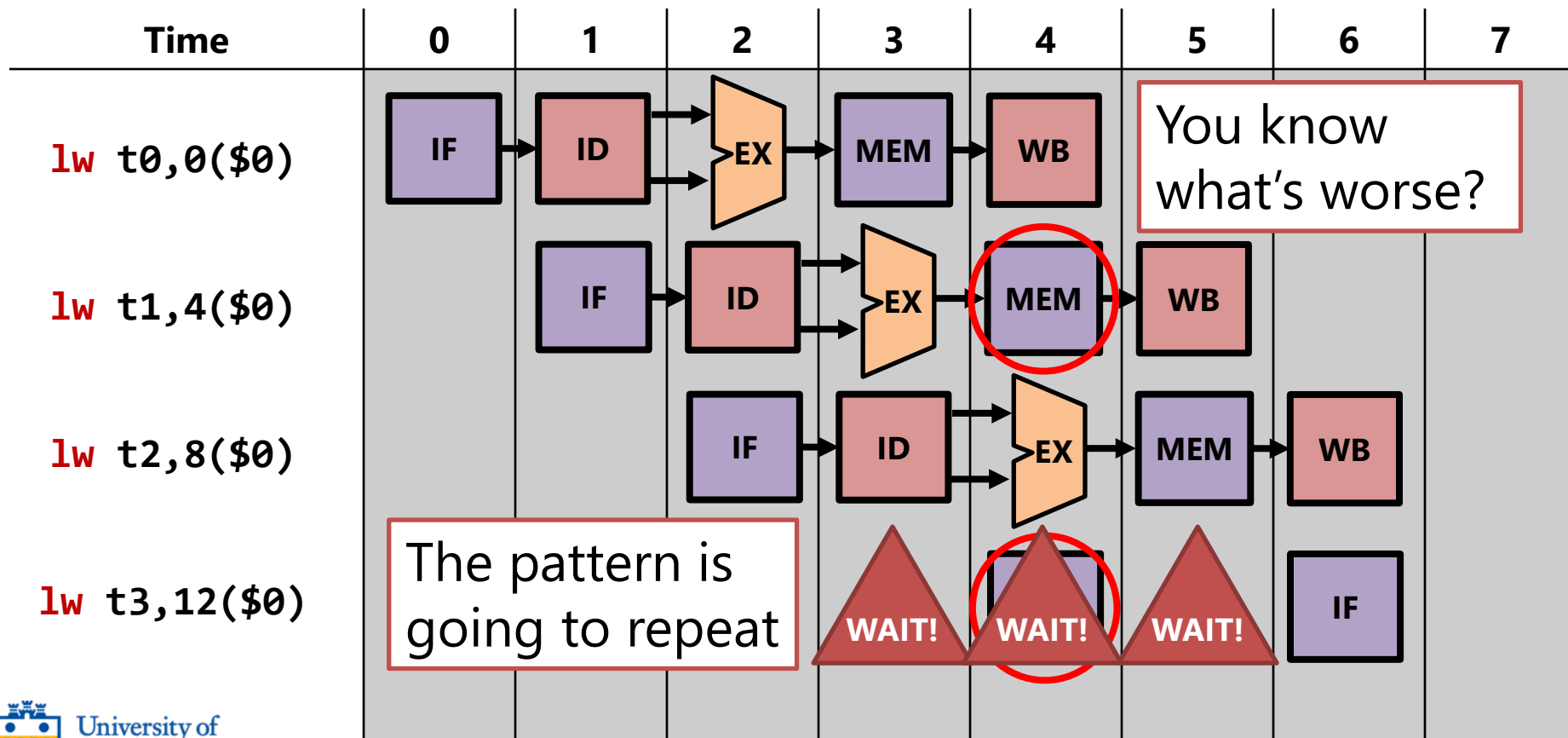
What could we do??

- Two people need to use **one** sink at the same time
 - Well, in this case, it's memory but same idea



We can do something similar!

- One option is to **wait** (a.k.a. **stall**).



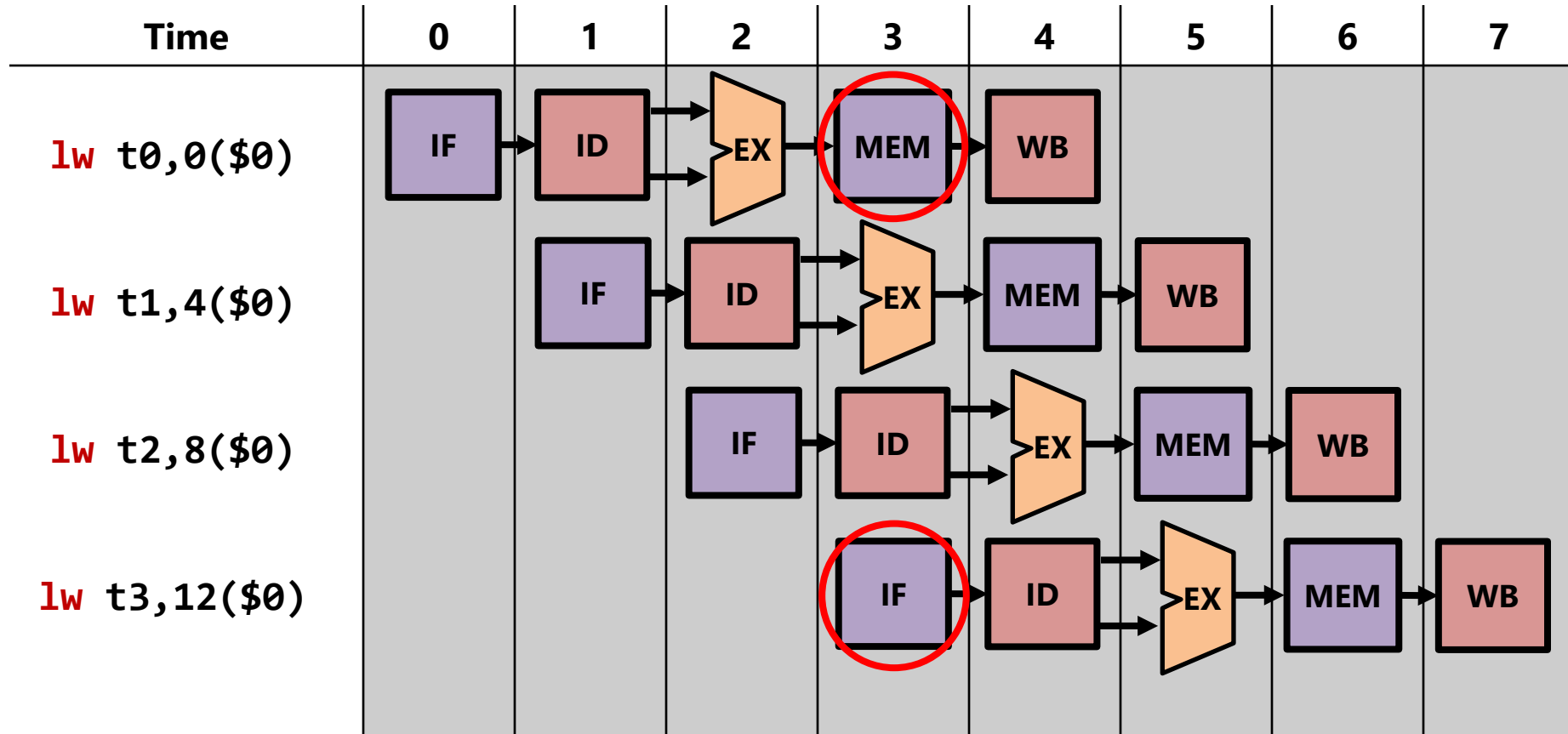
Or we could throw in more hardware!

- For less commonly used CPU resources, stalling can work fine
- But memory (and some other things) is used **CONSTANTLY**
- How do the bathrooms solve this problem?
 - Throw in lots of sinks!
 - In other words, throw more hardware at the problem!
- Memory's a resource with a lot of **contention**
 - So have two memories, one for instructions, and one for data!
 - Not literally but CPUs have separate **instruction** and **data caches**



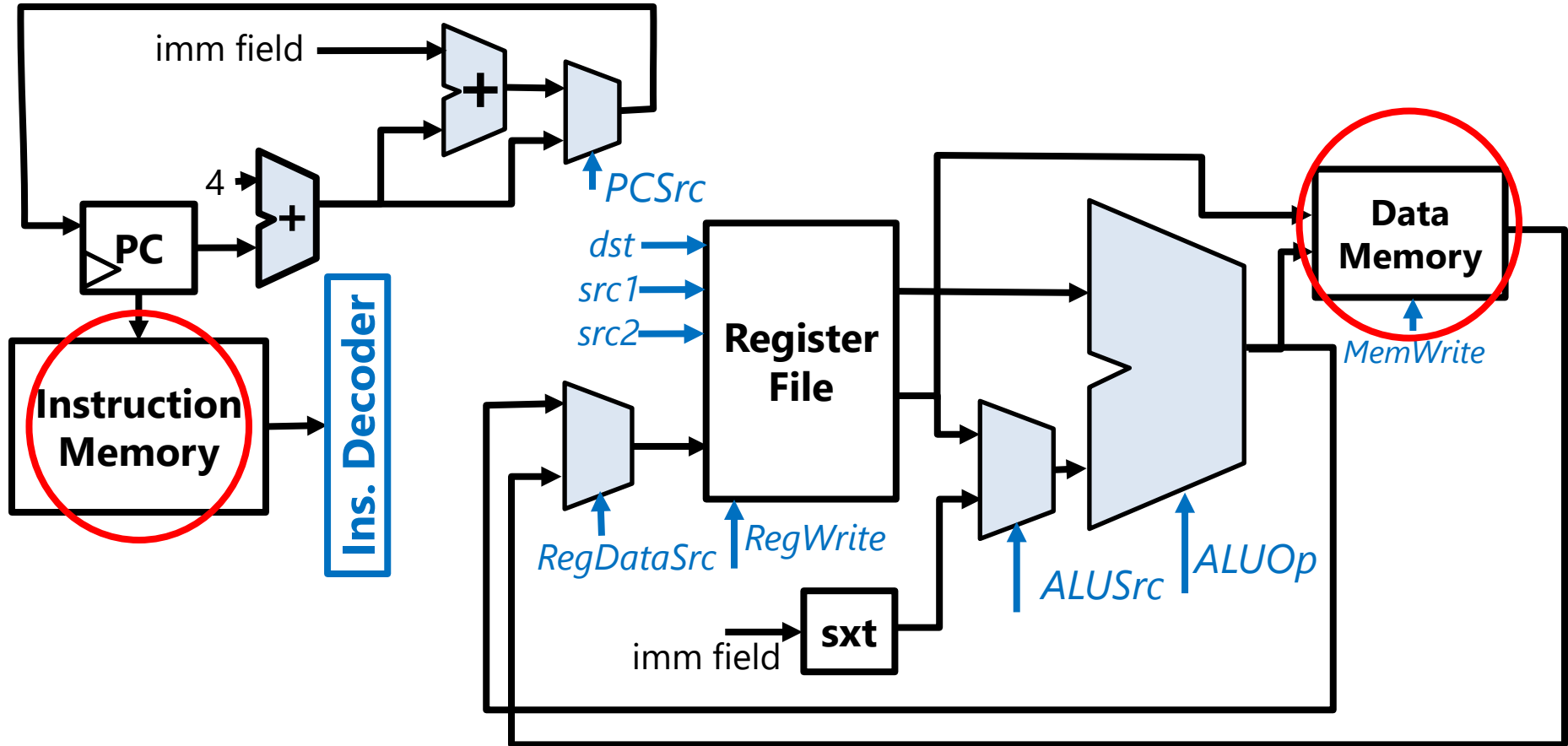
Structural Hazard removed with two Memories

- With separate i-cache and d-cache, MEM and IF can work in parallel



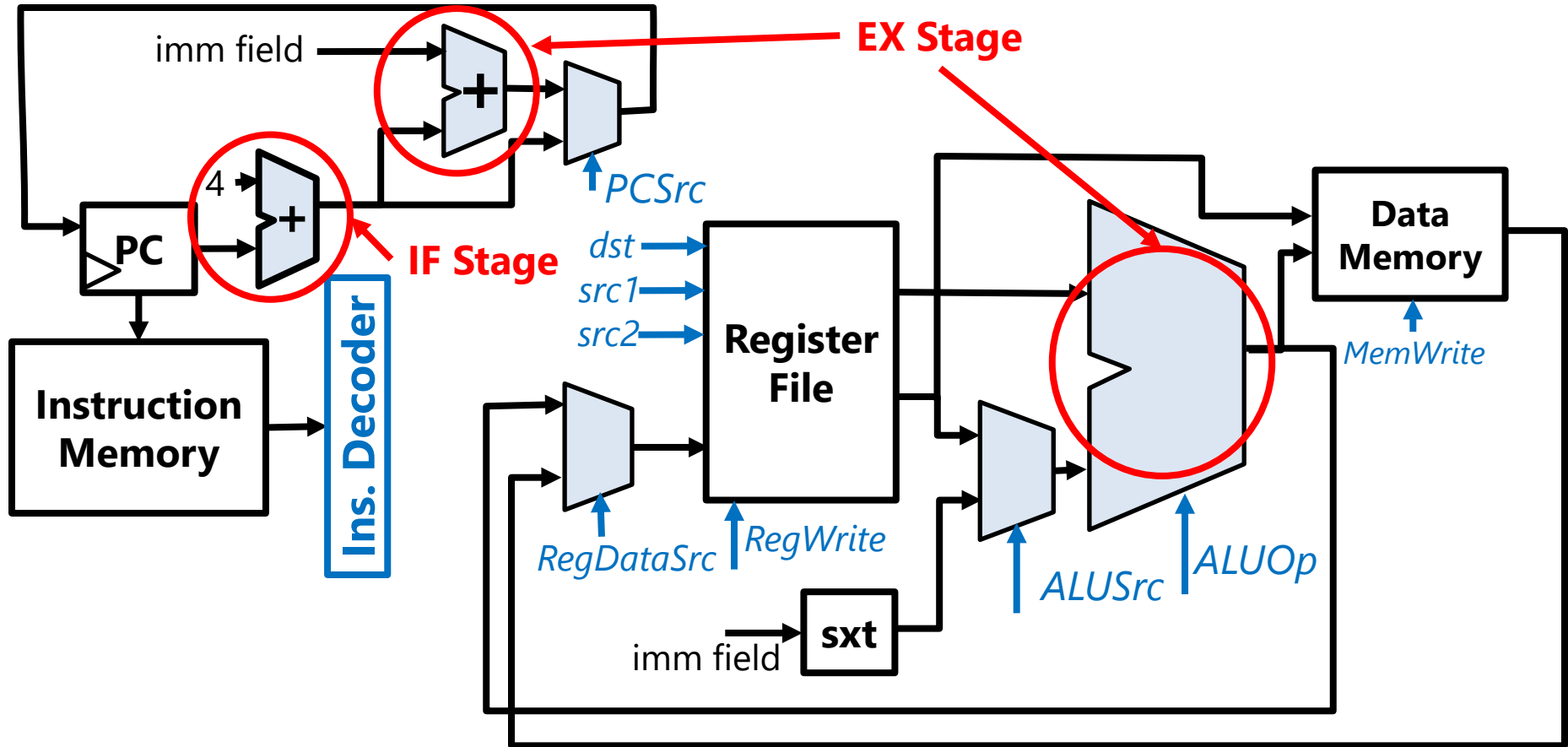
Structural Hazard removed with two Memories

- But is that the only hardware duplication going on here?



Structural Hazards removed with Multiple Adders

- Why do we need 3 adders? To avoid stalls due to contention on ALU!

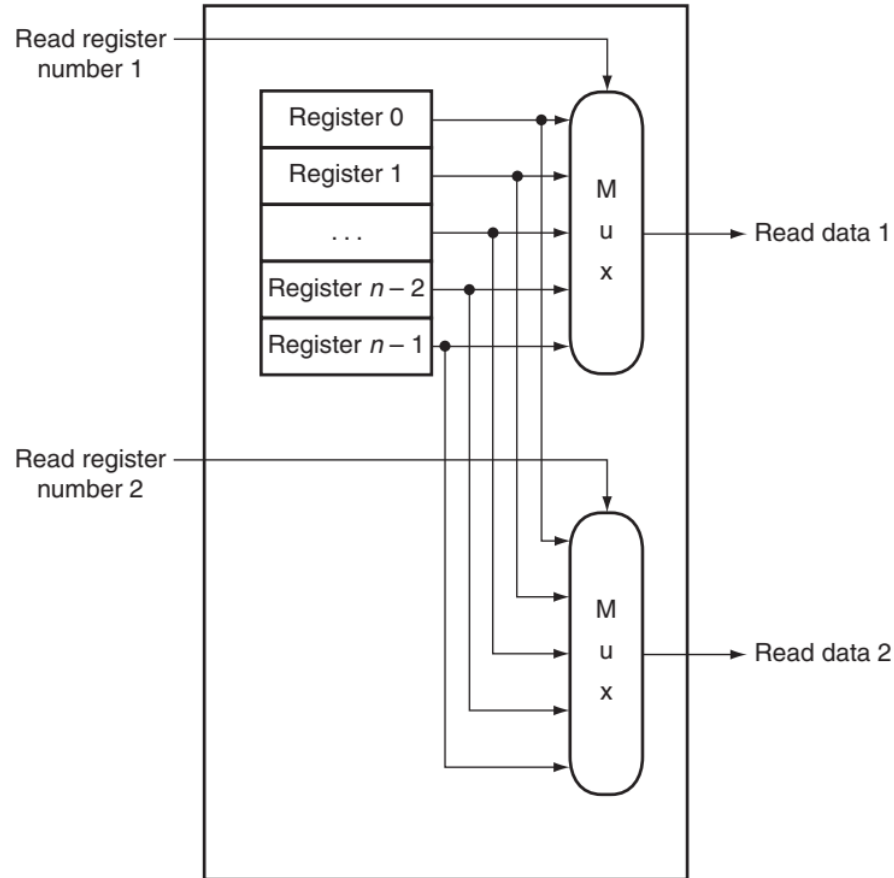


Solving Structural Hazards

- There are mainly two ways to throw more hardware at the problem
 1. Duplicate contentious resource
 - One memory cannot sustain MEM + IF stage at same cycle
→ Duplicate into one instruction memory, one data memory
 - One ALU cannot sustain IF + EX stage at same cycle
→ Duplicate into one ALU and two simple adders
 2. Add ports to a single shared memory resource
 - **Port:** Circuitry that allows either read or write access to memory
 - If current number of ports cannot sustain rate of access per cycle
→ Add more ports to memory structure for simultaneous access

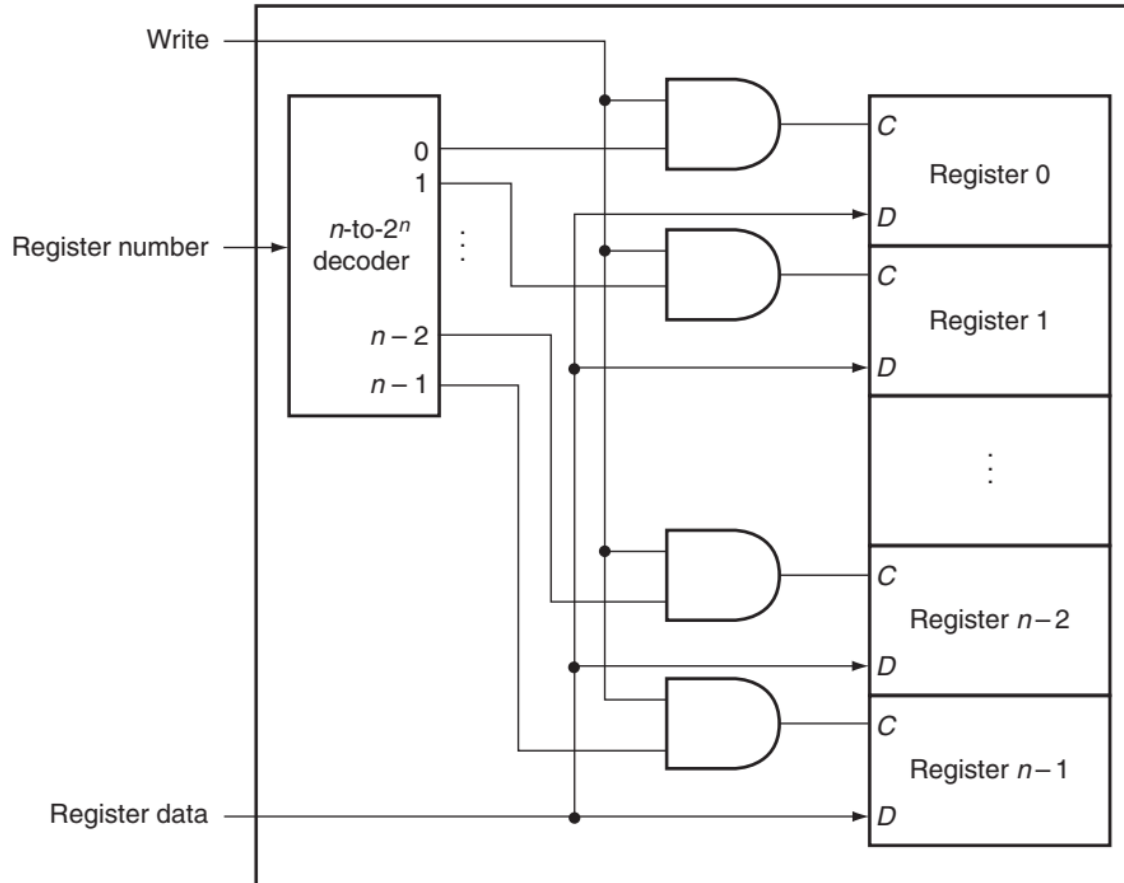
Two Register Read Ports

- By adding more MUXes, you can add even more read ports

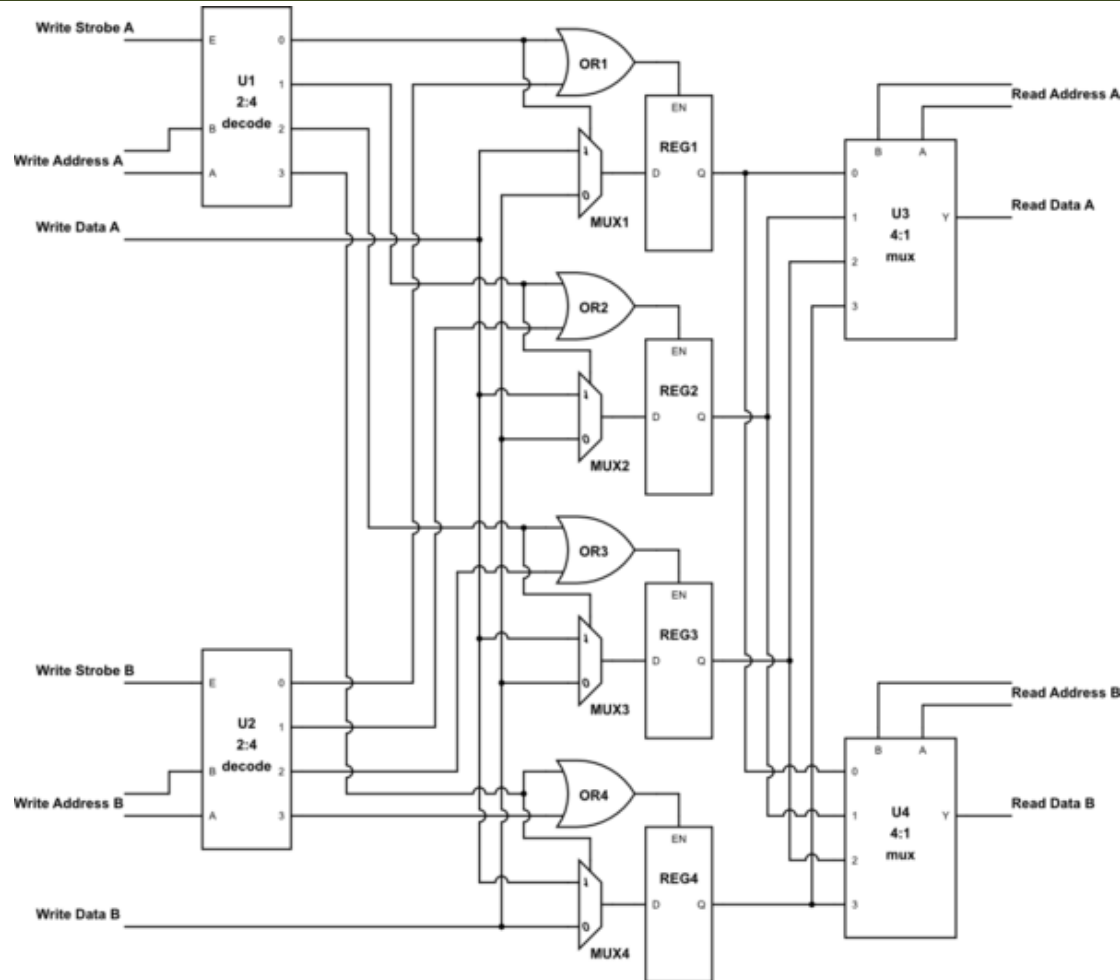


One Register Write Port

- By adding more decoders, you can add more write ports



Two Register Write + Two Register Read Ports



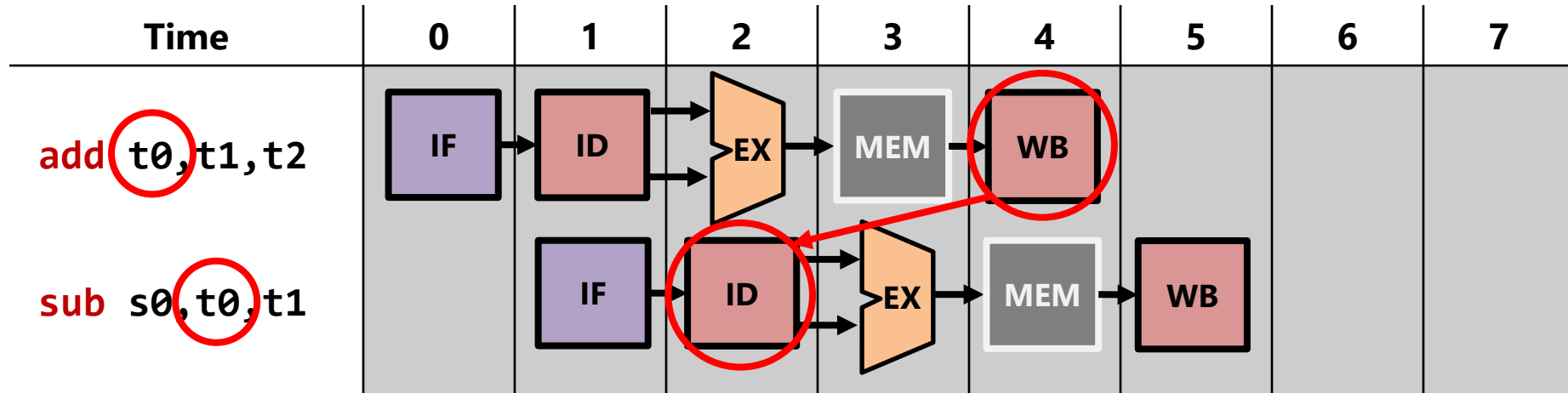
Two read ports and one write port is the minimum

- 2 read ports for 2 source registers, 1 write port for dest register
 - Enough to sustain one ID and one WB stage per cycle
 - Enough to sustain $CPI = 1$ (or in other words $IPC = 1$)
- But what if we want an $IPC > 1$? (a.k.a superscalar processor)
 - Must sustain more than one ID / WB stage per cycle
 - Need more register read ports and write ports!
 - Not only registers, (cache) memory would need more ports too!
 - Muxes, decoders increase critical path (lowers **frequency**)
 - Extra circuitry consumes more **power**
- We'll talk more about this when we discuss superscalars

Solving Data Hazards

Data Hazards

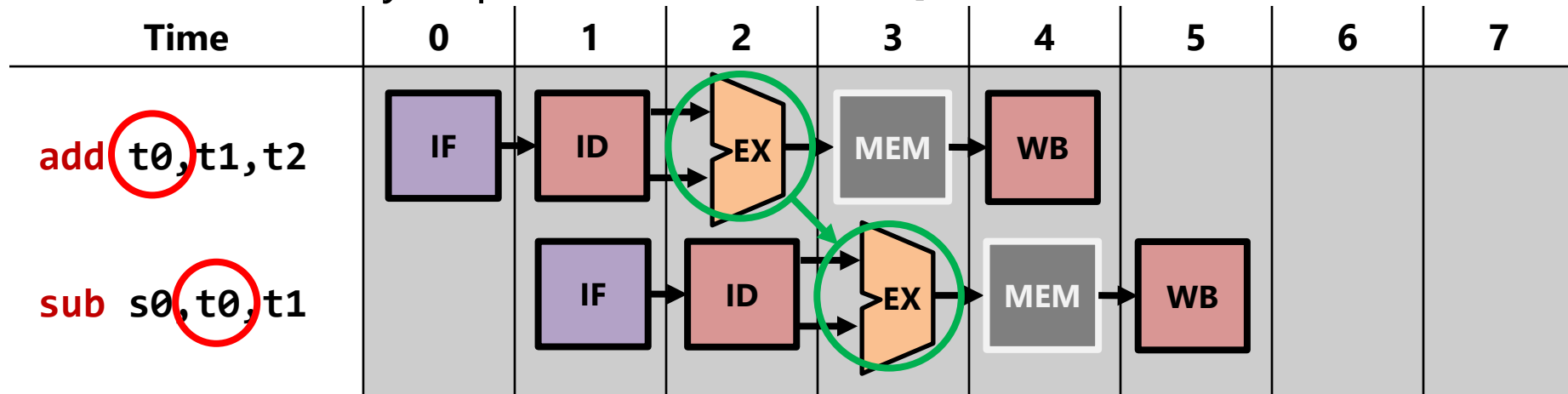
- An instruction depends on the output of a previous one.



- When does **add** finish computing its sum?
- Well then... why not just *use the sum when we need it*?

Solution 1: Data Forwarding

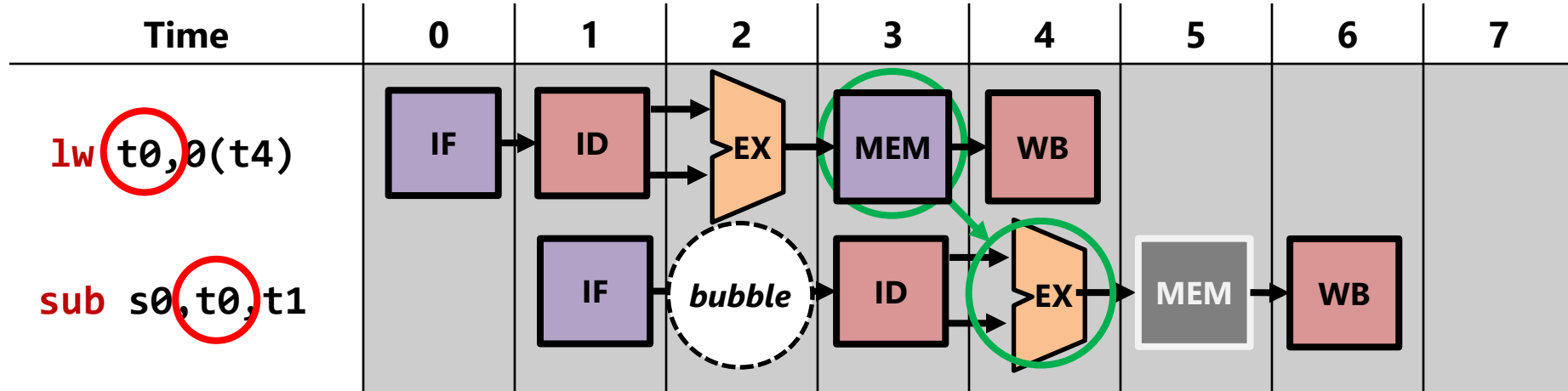
- Since we've pipelined control signals, we can check if instructions in the pipeline depend on each other (see if registers match).
- If we detect any dependencies, we can **forward** the needed data.



- This handles one kind of data forwarding...
- Where else can data come from and be written into registers?
 - Memory!

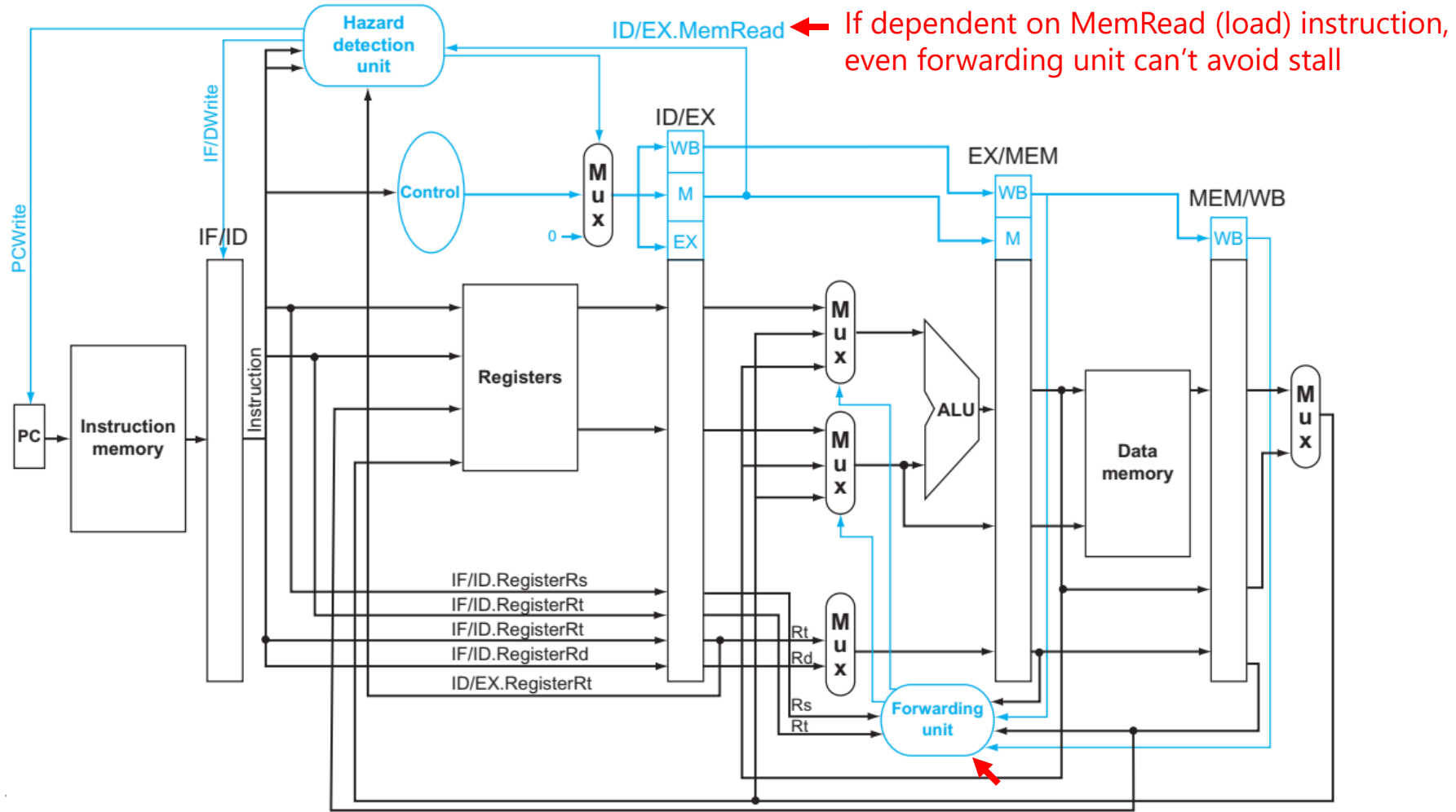
Data Forwarding from Memory

- Well memory accesses happen a cycle later...
- What are we going to have to do?



- This kind of stall is unavoidable in our current pipeline

Forwarding Unit and Use-after-load-hazard



ALU → ALU Data Forwarding removes all stalls

Program
execution
order
(in instructions)

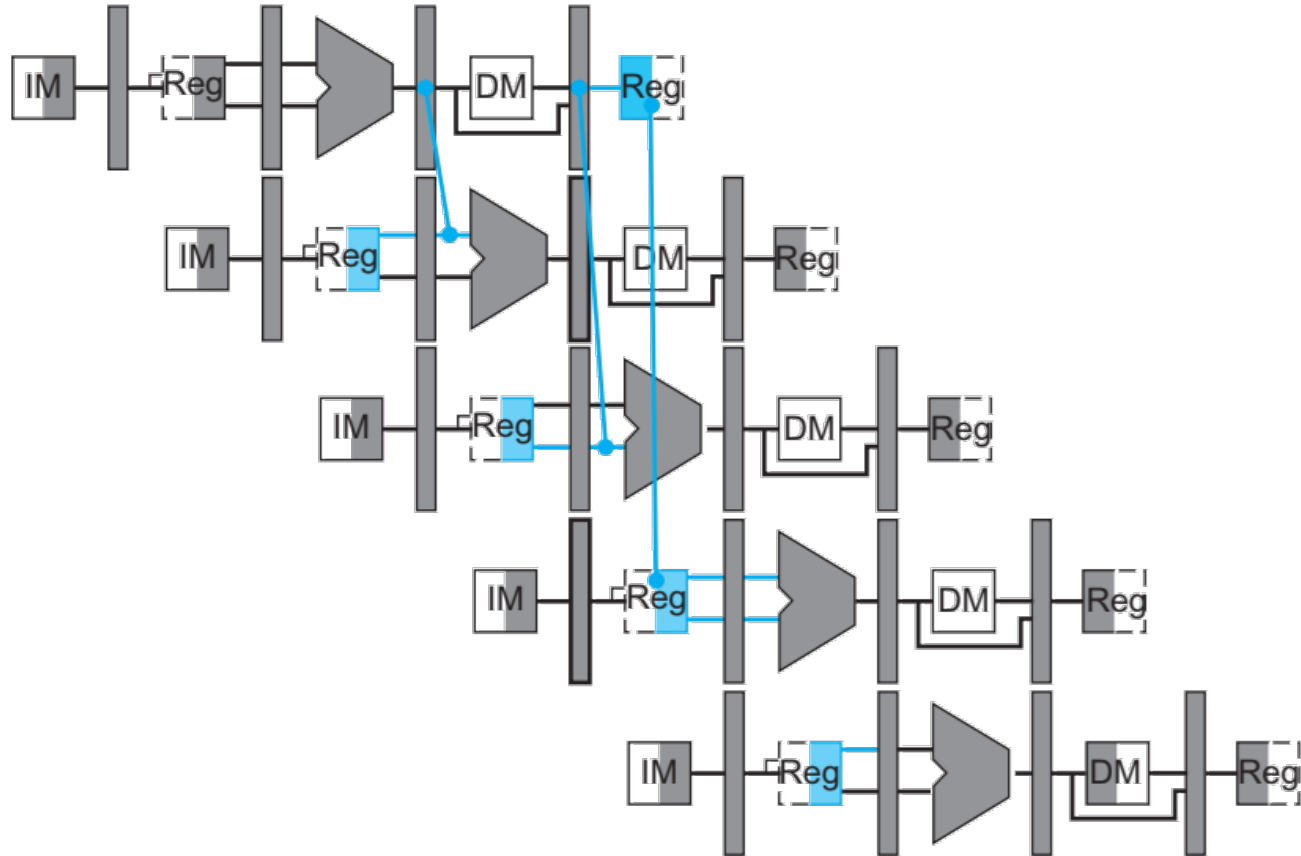
sub \$2, \$1, \$3

and \$12, \$2, \$5

or \$13, \$6, \$2

add \$14, \$2, \$2

sw \$15, 100(\$2)



MEM → ALU forwarding must stall on immediate use

Program
execution
order
(in instructions)

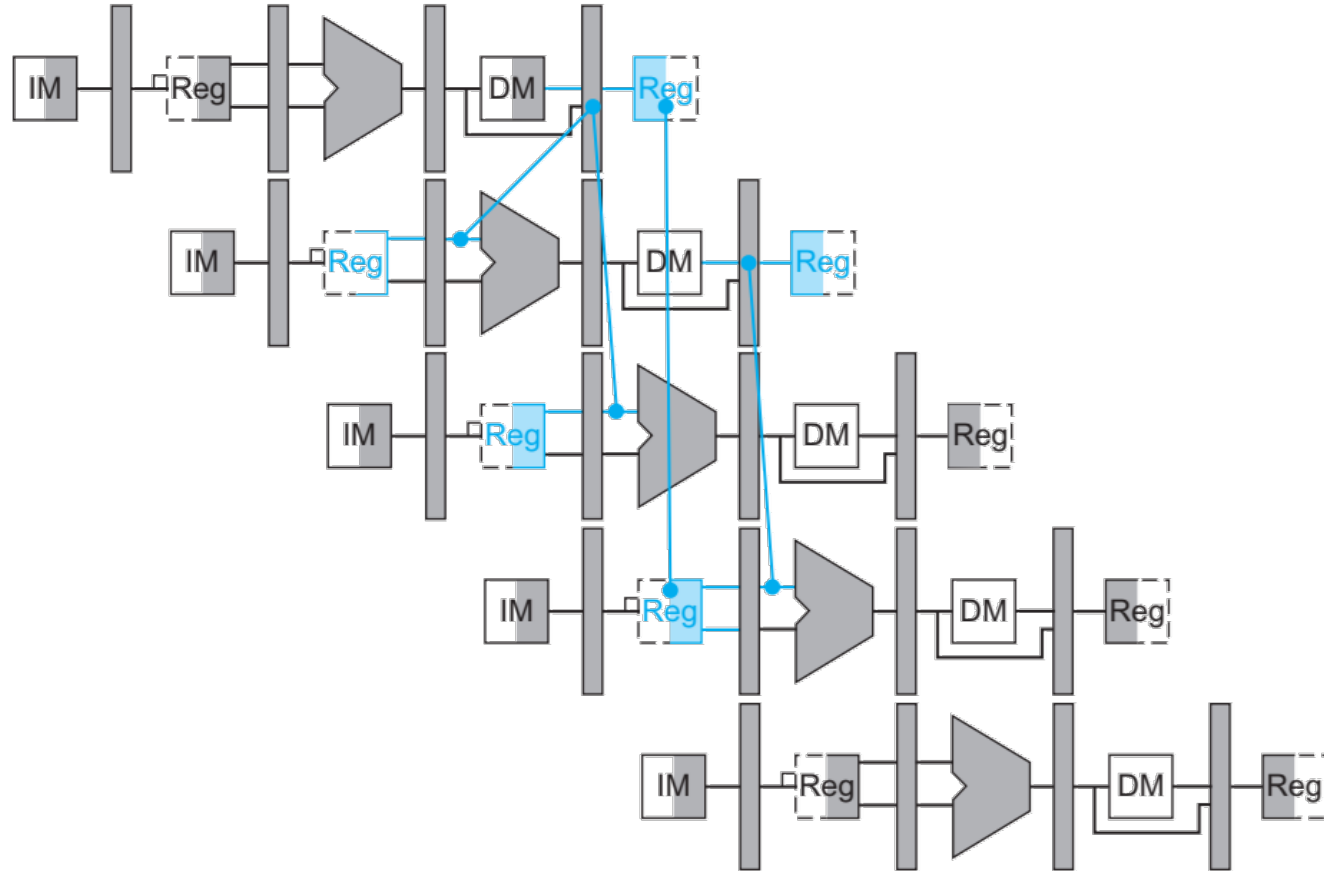
lw \$2, 20(\$1)

and \$4, \$2, \$5

or \$8, \$2, \$6

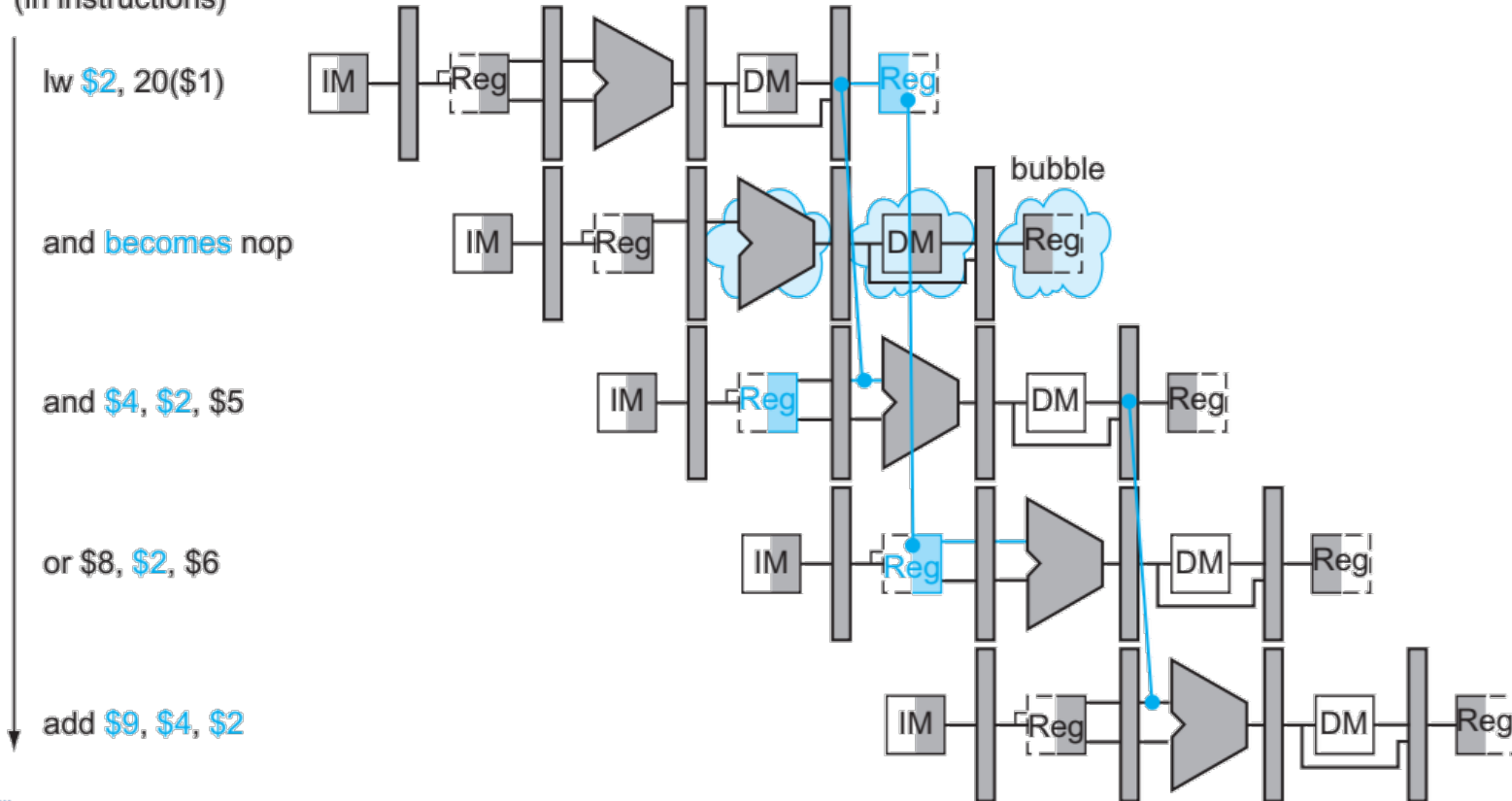
add \$9, \$4, \$2

slt \$1, \$6, \$7



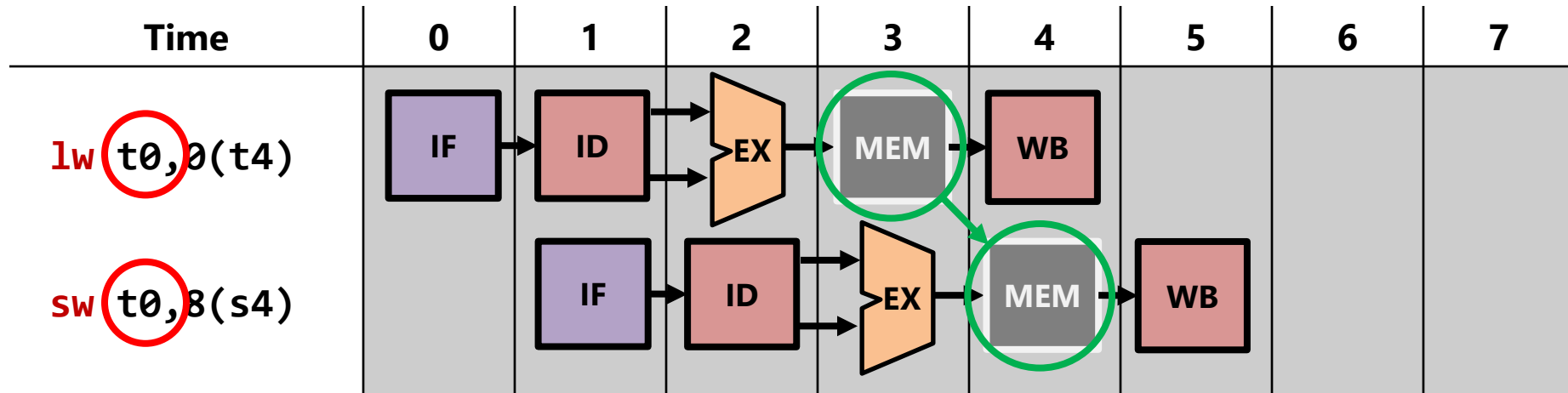
MEM → ALU forwarding with bubble

Program
execution
order
(in instructions)



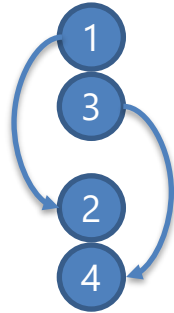
How about MEM → MEM forwarding?

- Will this work with our current processor design?



Solution 2: Avoid stalls by reordering

- Let's say the following is your morning routine (*approx. 1 hour*)
 1. Have laundry running in washing machine (*30 minutes*)
 2. Dump laundry into basket
 3. Have tea boiling in the pot (*30 minutes*)
 4. Pour tea into cup
- Can you make this shorter? Yes! (*approx. 30 minutes*)
 1. Have laundry running in washing machine (*30 minutes*)
 3. Have tea boiling in the pot (*while machine is running*)
 2. Dump laundry into basket
 4. Pour tea into cup
- Instructions can be **reordered** for a better schedule
 - As long as it doesn't break data dependencies



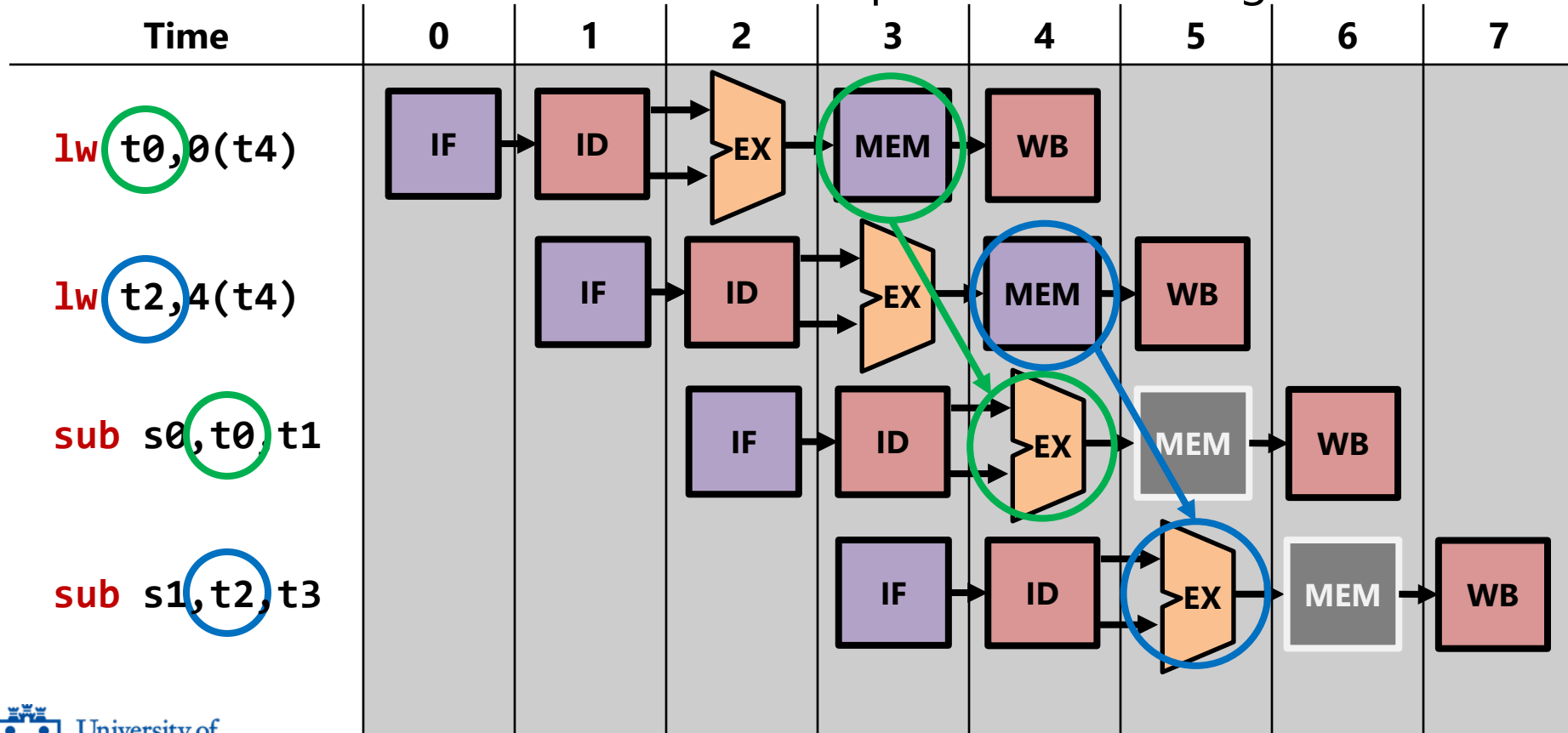
Data Hazard removed through Compiler Reordering

- If the **compiler** has knowledge of how the pipeline works, it can **reorder** instructions to let loads complete before using their data.

Time	0	1	2	3	4	5	6	7
lw t0,0(t4)								
sub s0,t0,t1								
lw t2,4(t4)								
sub s1,t2,t3								

Data Hazard removed through Compiler Reordering

- If the **compiler** has knowledge of how the pipeline works, it can **reorder** instructions to let loads complete before using their data.



Limits of Static Scheduling

- Reordering done by the compiler is called ***static scheduling***
- Static scheduling is a powerful tool but is in some ways **limited**
 - Again, compiler must make assumptions about pipeline
 - Length of MEM stage is very hard to predict by the compiler
 - Remember the **Memory Wall**?
 - Data dependencies are hard to figure out by a compiler
 - When data is in registers, trivial to figure out
 - When data is in memory locations, more difficult. Given:

```
lw t0, 0(t4)
sw s0, 8(t0)
lw t2, 4(t4)
```

]
We want to reorder to remove the data hazard.
But what if 8(t0) and 4(t4) are the same addresses?
This involves *pointer analysis*, a notoriously difficult analysis!

Dynamic scheduling is another option

- **Dynamic scheduling** is scheduling done by the CPU
- It doesn't have the limitations of static scheduling
 - It doesn't have to predict memory latency
 - It can adapt as things unfold
 - It's easy to figure out data dependencies, even memory ones
 - At runtime, addresses of $8(t_0)$ and $4(t_4)$ are easily calculated
- But at runtime it uses lots of power for the data analysis
 - ... which again causes problems with the **Power Wall**
 - But more on this later

Solving Control Hazards

Loops

- Loops happen *all the time* in programs.

```
for(s0 = 0 .. 10)  
    print(s0);
```

```
printf("done");
```

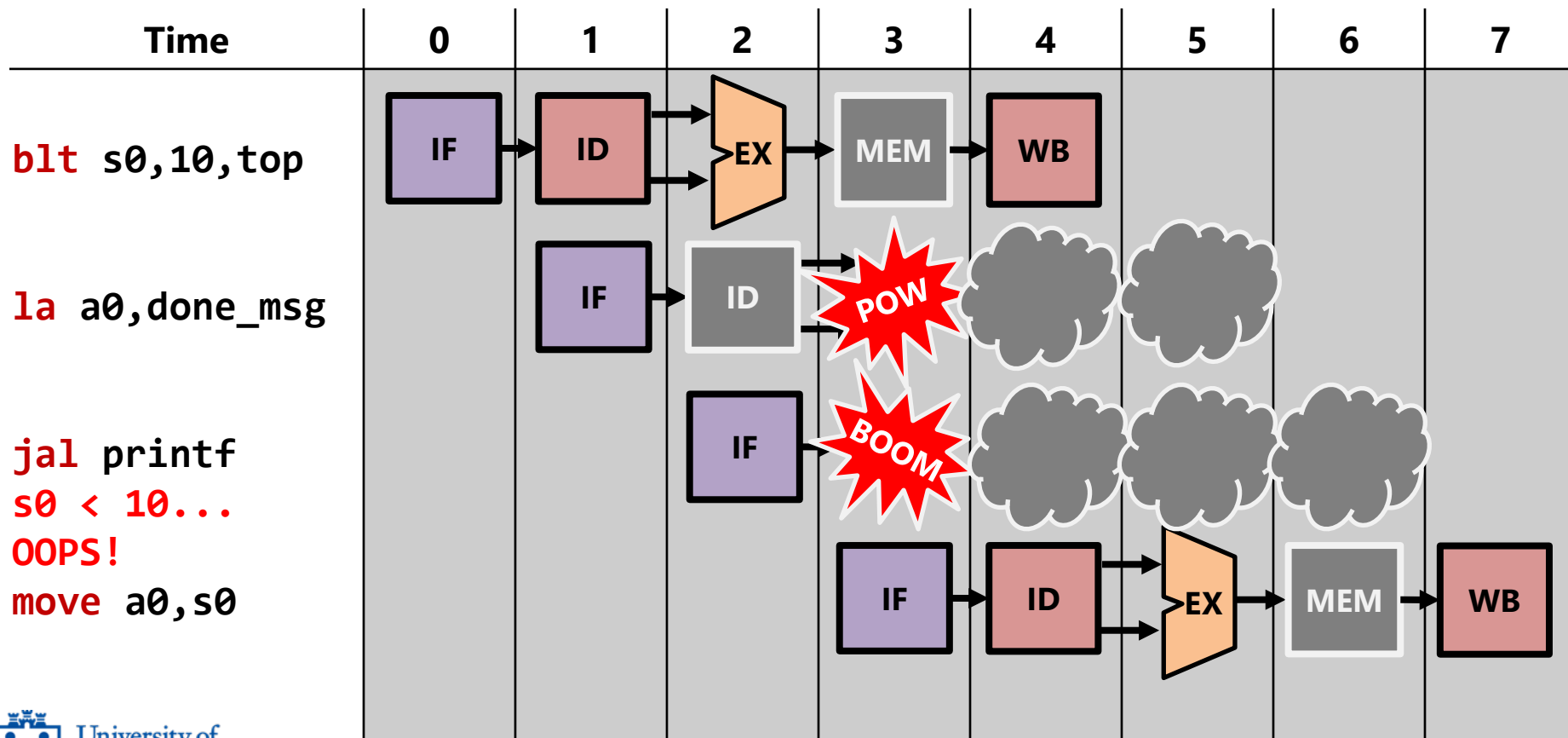
How often does this **blt** instruction go to **top**? How often does it go to the following **la** instruction?

```
li    s0, 0  
top:  
move  a0, s0  
jal   print  
addi  s0, s0, 1  
blt   s0, 10, top
```

```
la    a0, done_msg  
jal   printf
```

Pipeline Flushes at Every Loop Iteration

- The pipeline must be **flushed** every time the code loops back!



Performance Impact from Control Hazards

- **Frequency** of flushes \propto frequency of branches
 - If we have a tight loop, branches happen every few instructions
 - Typically, branches account for 15~20% of all instructions
- **Penalty** from one flush \propto depth of pipeline
 - Number of flushed instructions == distance from IF to EX
 - What if **3** IF stages, **4** ID stages, and **3** EX stages? Penalty == 10!
- Current architectures can have more than 20 stages!
 - May spend more time just flushing instructions than doing work!
 - Another reason why deep pipelines are problematic

Performance Impact from Control Hazards

- $CPI = CPI_{nch} + \alpha * \pi * K$
 - CPI_{nch} : CPI with no control hazard
 - α : fraction of branch instructions in the instruction mix
 - π : probability a branch is actually taken
 - K : penalty per pipeline flush

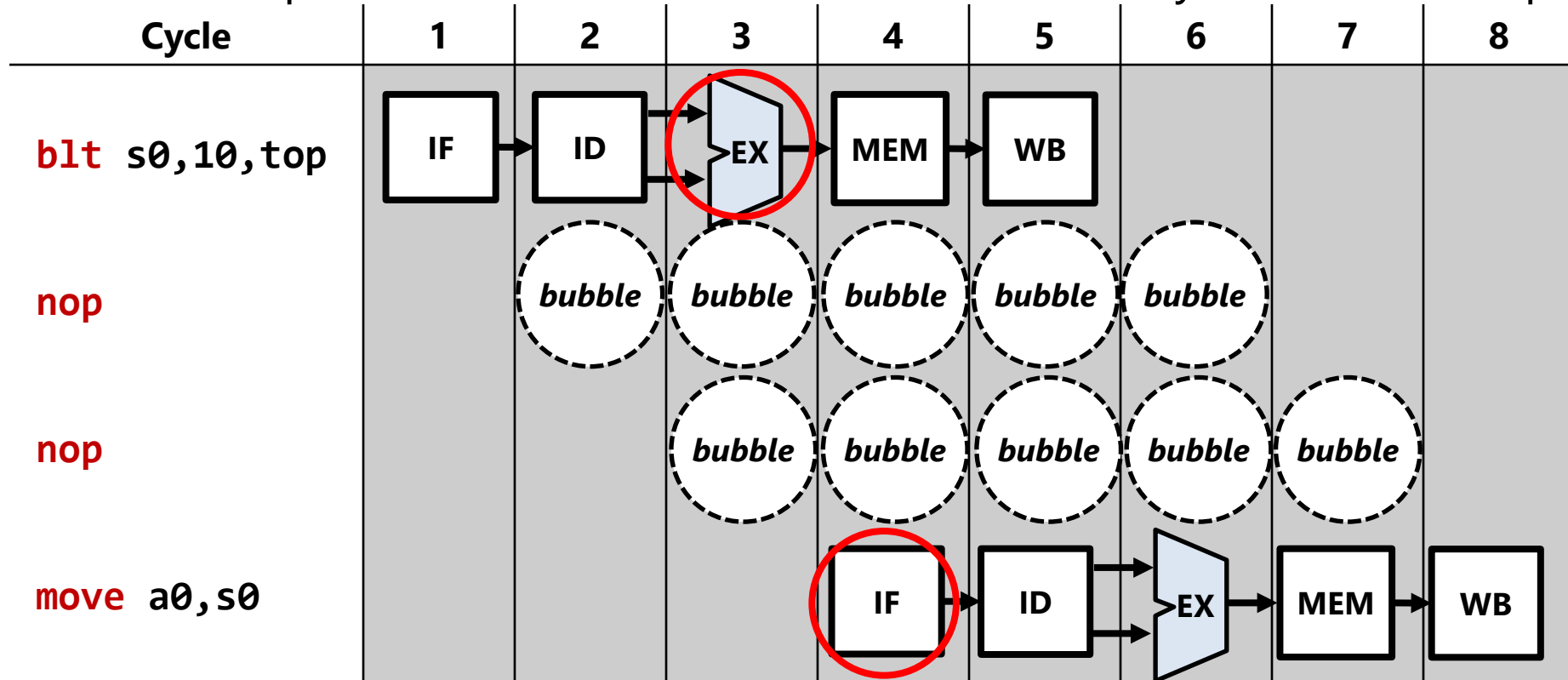
Example: If 20% of instructions are branches and the probability that a branch is taken is 50%, and pipeline flush penalty 7 cycles, then:

$$CPI = CPI_{nch} + 0.2 * 0.5 * 7 = CPI_{nch} + 0.7 \text{ cycles per instruction}$$

- What if we had a compiler insert no-ops, with no HDU?
 - It's even worse, as we will soon see.

Compiler avoiding the control hazard without HDU

- Since compiler does not know direction, must always insert two nops



Performance Impact without Hazard Detection Unit

- $CPI = CPI_{nch} + \alpha * K$
 - CPI_{nch} : CPI with no control hazard
 - α : fraction of branch instructions in the instruction mix
 - K : no-ops inserted after each branch

Example: If 20% of instructions are branches and the probability that a branch is taken is 50%, and branch resolution delay of 7 no-ops, then:

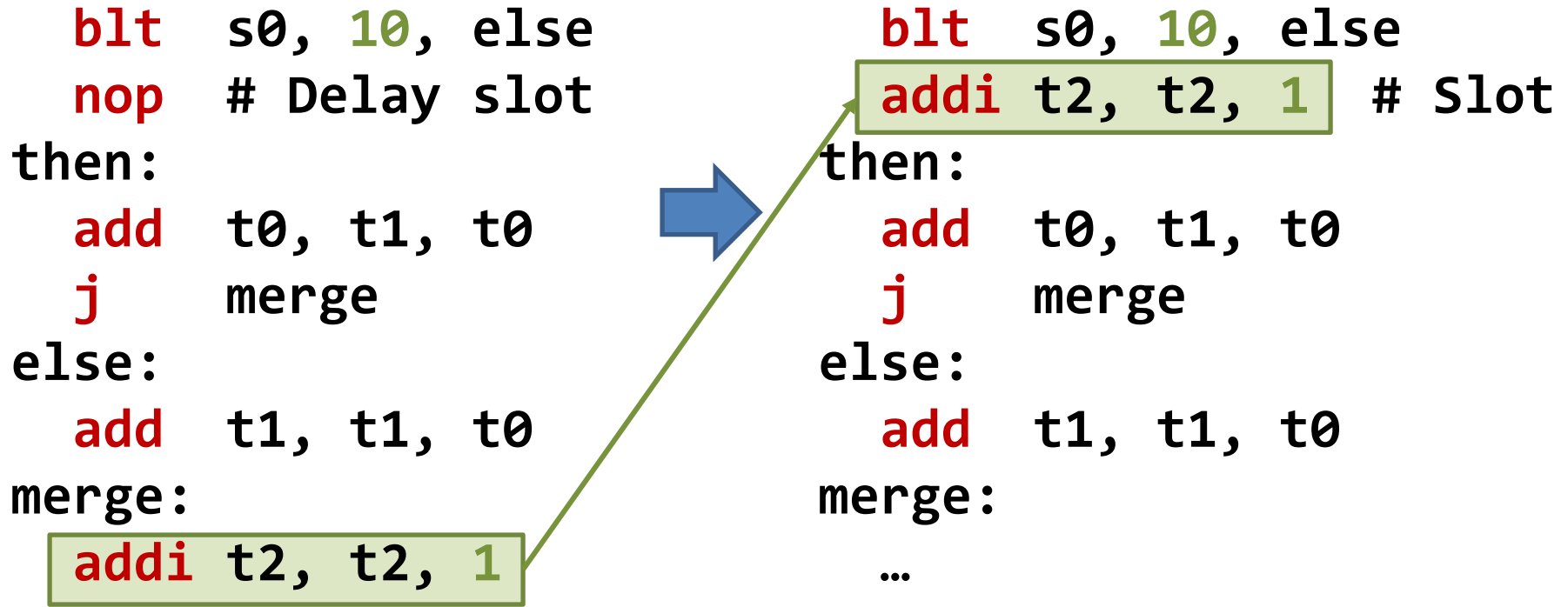
$$CPI = CPI_{nch} + 0.2 * 7 = CPI_{nch} + 1.4 \text{ cycles per instruction}$$

- Branch-taken rate is irrelevant - compiler always inserts two nops
- Is there a way to minimize the performance impact?

Solution 1: Delay Slots

- Idea: Do **static scheduling** to replace nops with useful work
 - Remember? Compiler did the same for nops due to data hazards.
- **Delay slot**: An instruction scheduling slot following a branch
 - Needs to execute while branch direction is getting resolved
 - Semantic: **executes regardless of branch direction**
 - ISA must be modified to support this branch semantic
 - Compiler must fill delay slot with control independent instruction
 - If not found, delay slot filled with nop instruction

Compiler static scheduling using delay slots



- The **addi** instruction is moved into delay slot
 - It is not control dependent on the branch outcome of **blt**
 - It is not data dependent on registers **t0** or **t1**

Delay slots are losing popularity

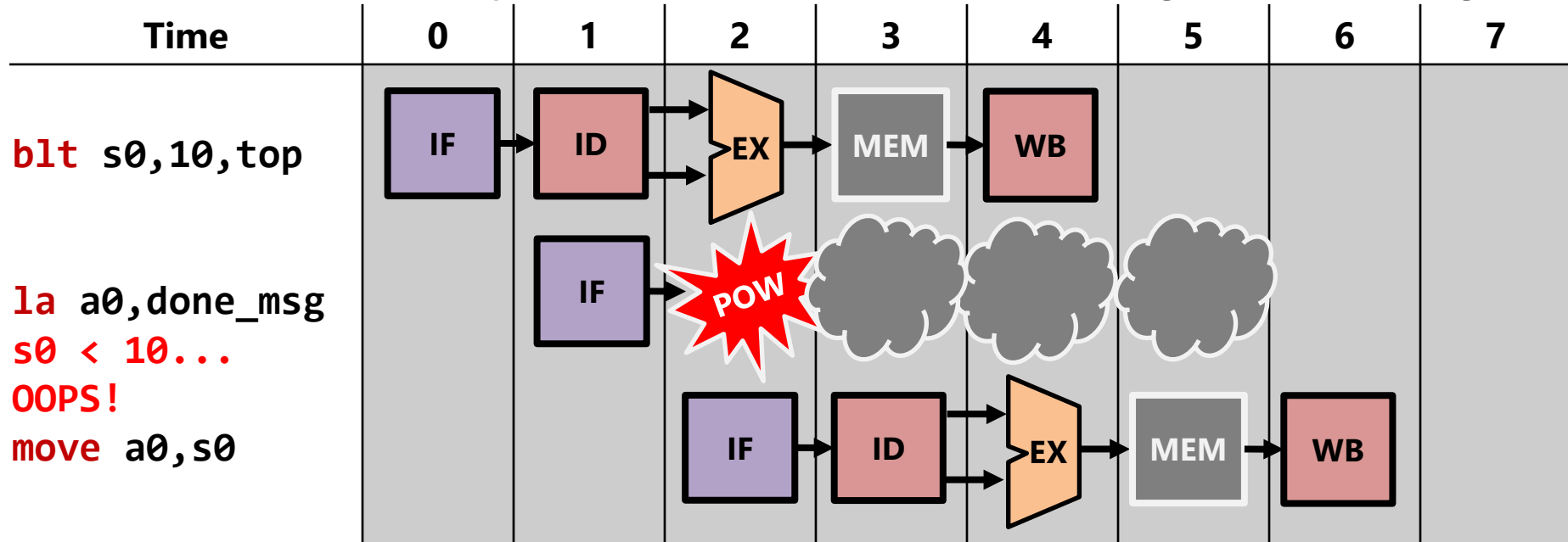
- Sounded like a good idea on paper but didn't work well in practice
 1. Turns out filling delay slots with the compiler is not always easy
 - Often data and control independent instructions don't exist
 2. Delay slots baked into the ISA were not future proof
 - Number of delay slots did not match new generation of CPUs
 - New generation of CPUs had fancier ways to avoid bubbles
 - Delay slots ended up being a hindrance
- Next idea please!

Solution 2: MORE SINKS! (a.k.a. hardware)



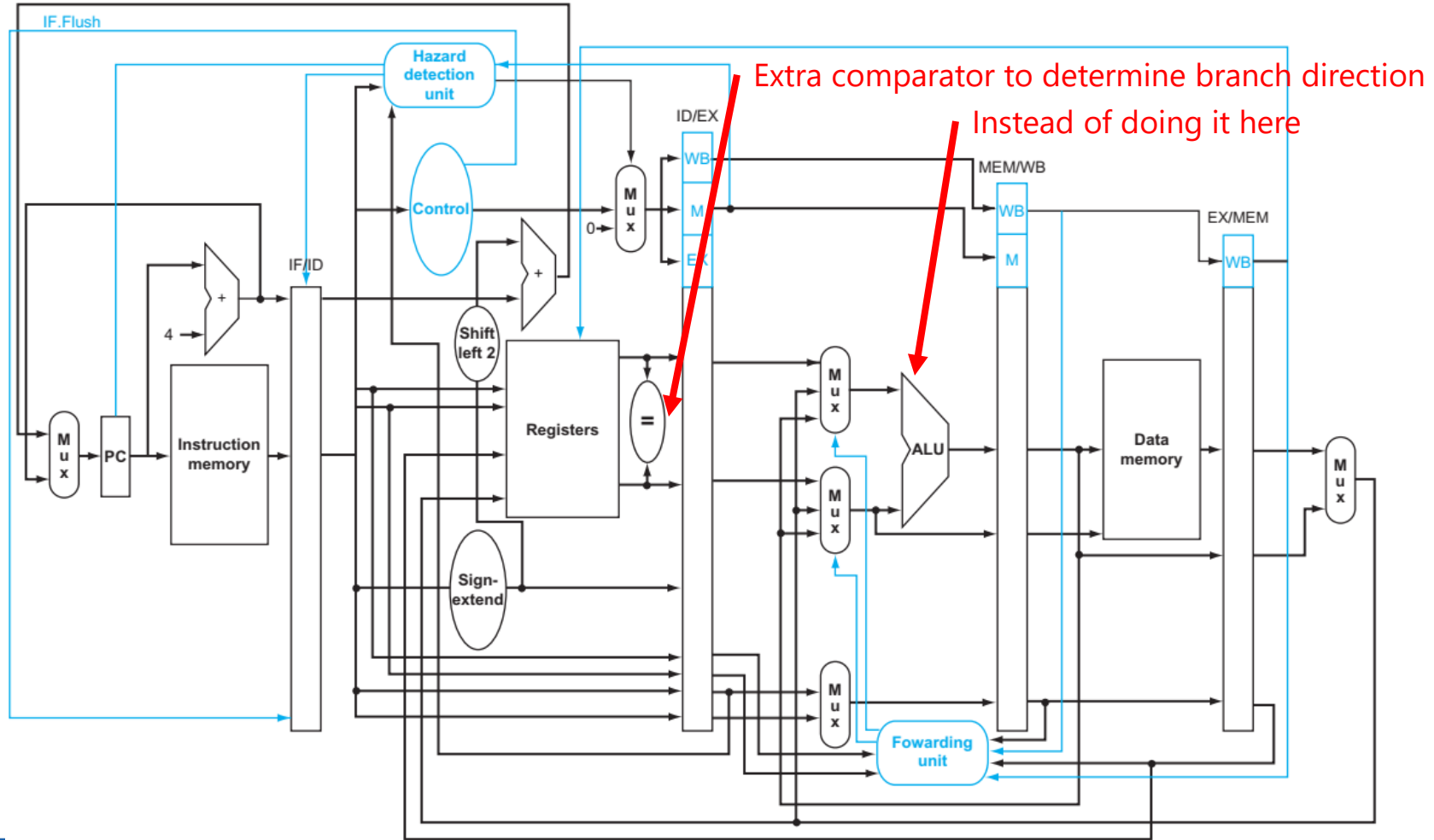
Do we *reeeally* need to compare at EX stage?

- What if branch comparison was done at the ID stage, not EX stage?



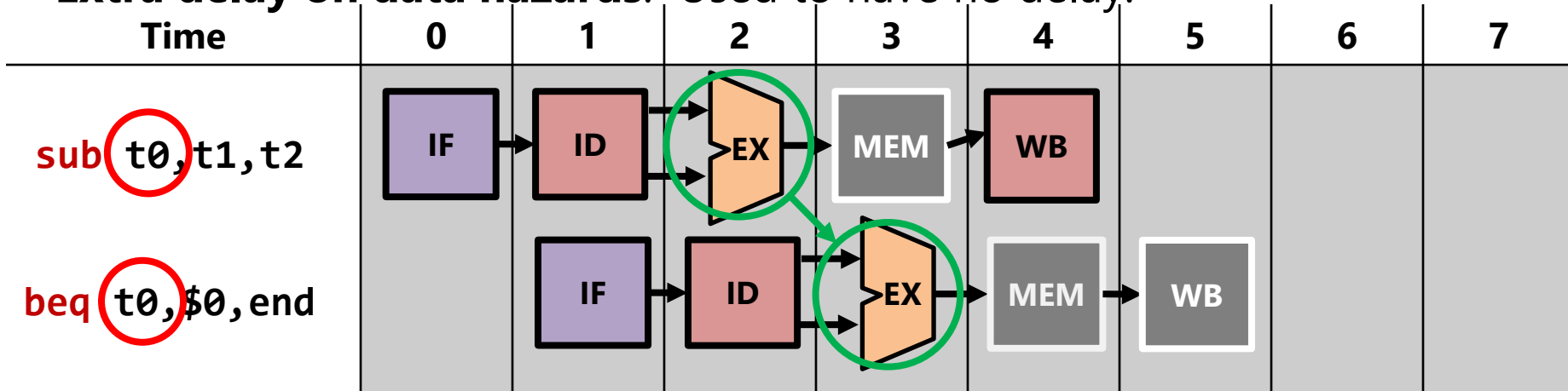
- Reduced penalty from 2 cycles → 1 cycle!
- But of course that means we need a comparator at the ID stage

Solution 2: MORE SINKS! (a.k.a. hardware)

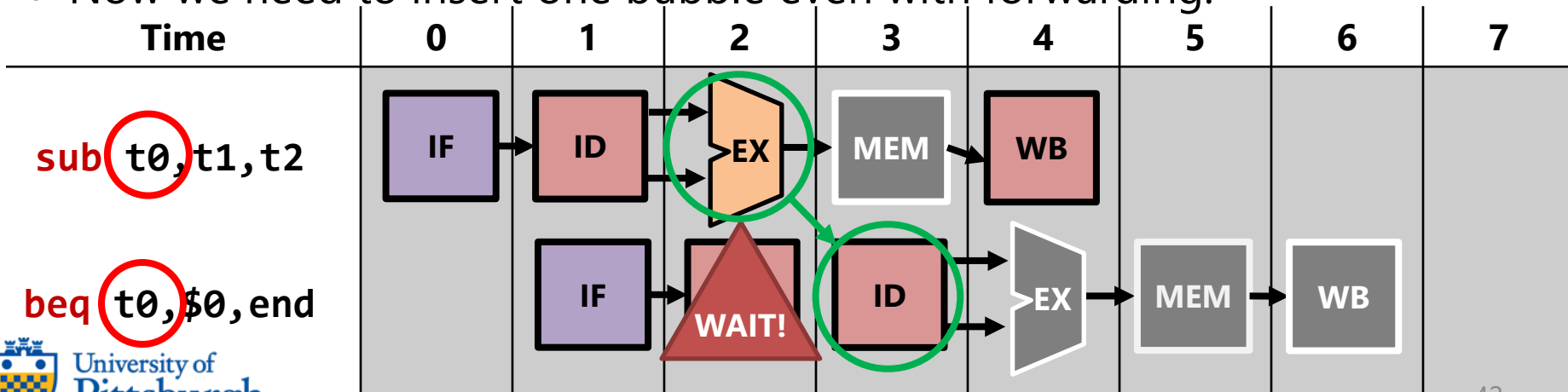


Not all sunshine and rainbows

- **Extra delay on data hazards.** Used to have no delay:

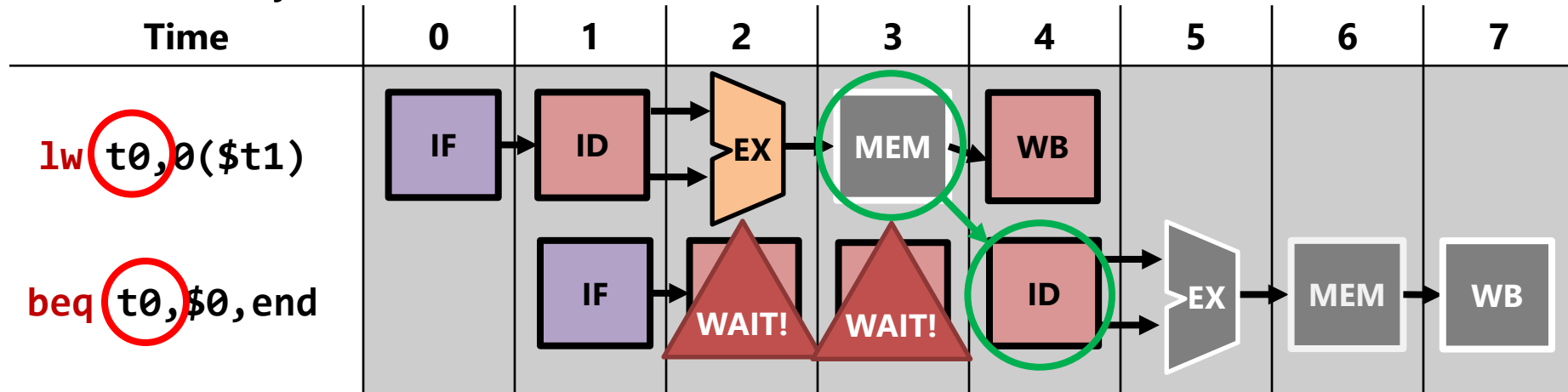


- Now we need to insert one bubble even with forwarding:



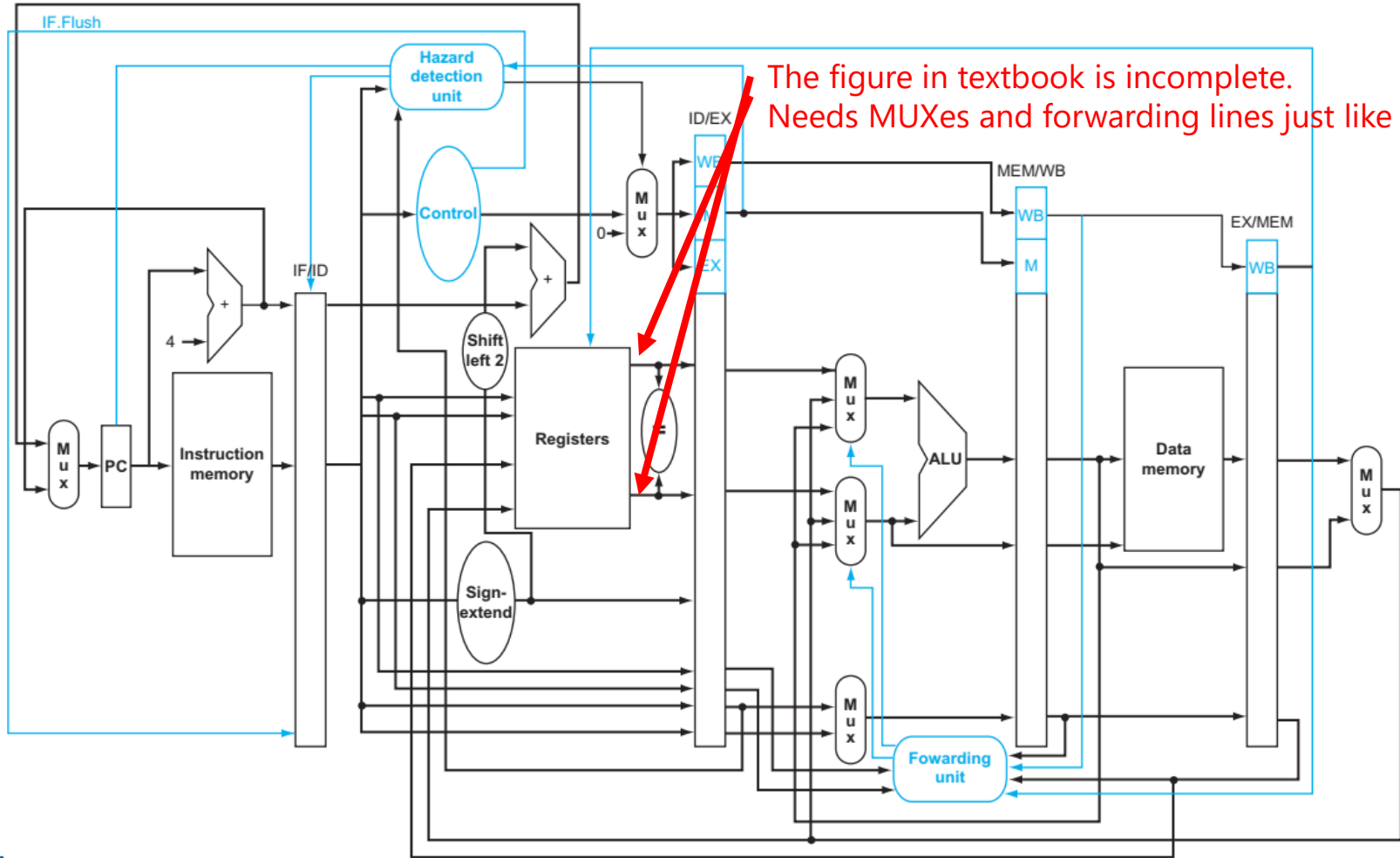
Not all sunshine and rainbows

- Extra delay on data forwarded from **lw** also:



- Now we must insert two bubbles instead of one!
- Not to mention we must now add **more forwarding paths**:
 - EX** → **ID**, **MEM** → **ID**
- We also need to add MUXes before our new comparator

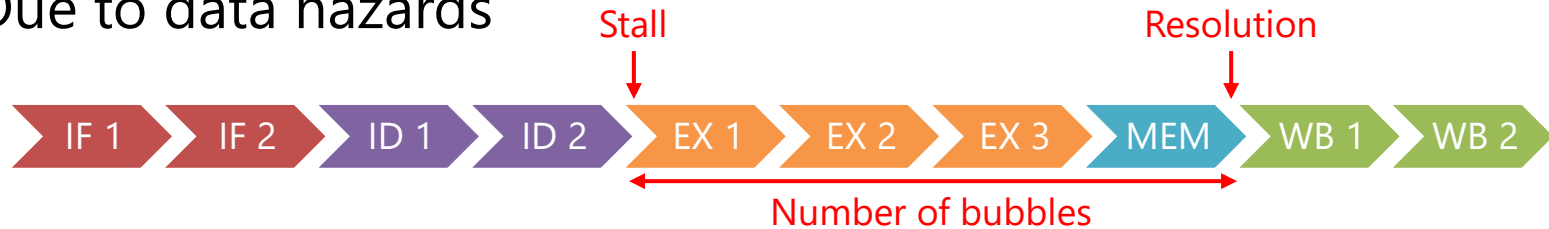
Textbook figure correction



Limits of Pipelining

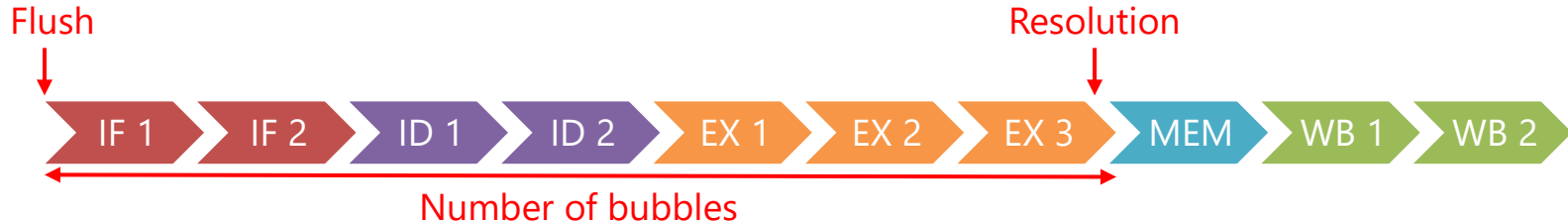
Increasing pipeline depth has diminishing returns

- In terms of clock frequency
 - Delay of pipeline latches becomes big portion of cycle time
 - Unbalanced stages (due to both design and manufacturing)
- In terms of utilization (CPI)
 - Due to data hazards



→ Mitigated through **instruction reordering** (but **Power Wall**)

- Due to control hazards



→ How do we mitigate this? Through **branch prediction**.