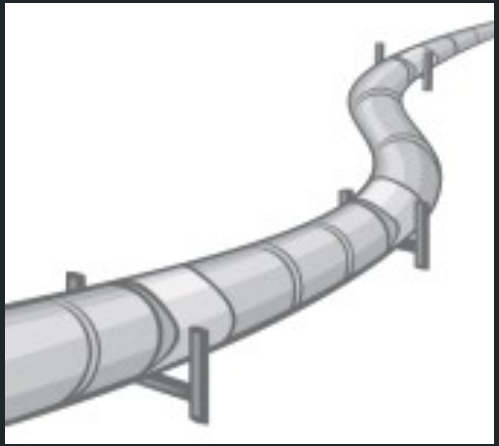
Processor Pipelining

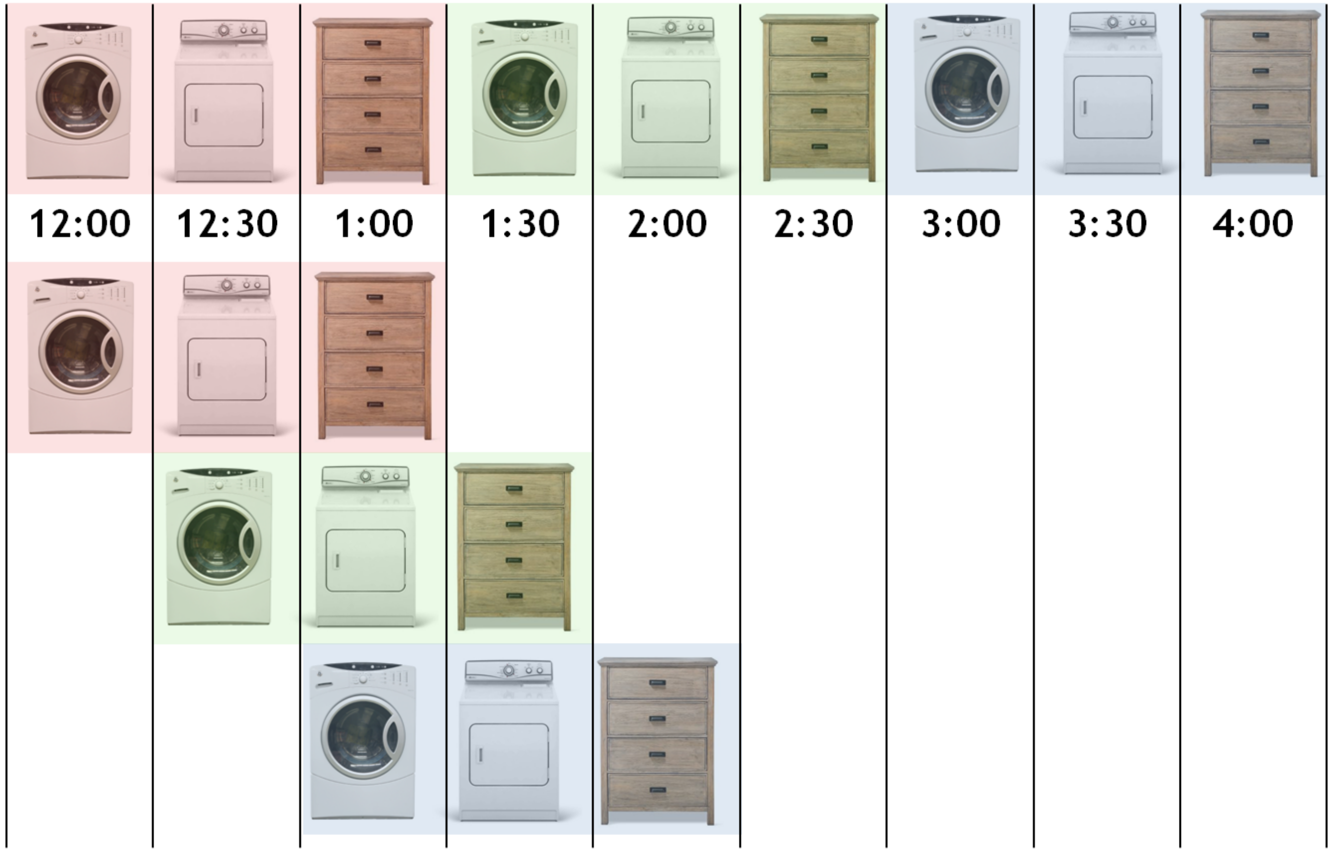
CS 1541
Wonsun Ahn

Pipelining Basics



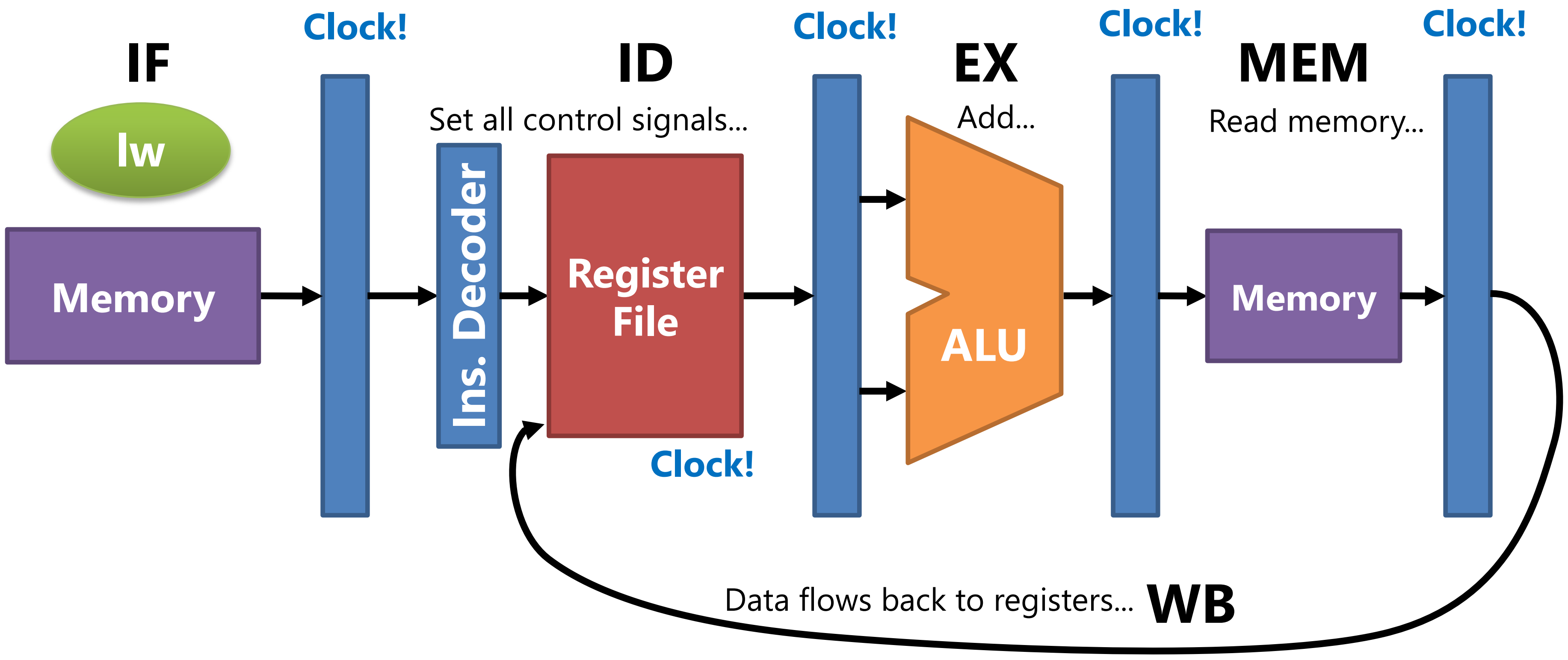
Improving Washer / Dryer / Closet Utilization

- If you work on loads of laundry one by one, you only get ~33% utilization
- If you form an “assembly line”, you achieve ~100% utilization!



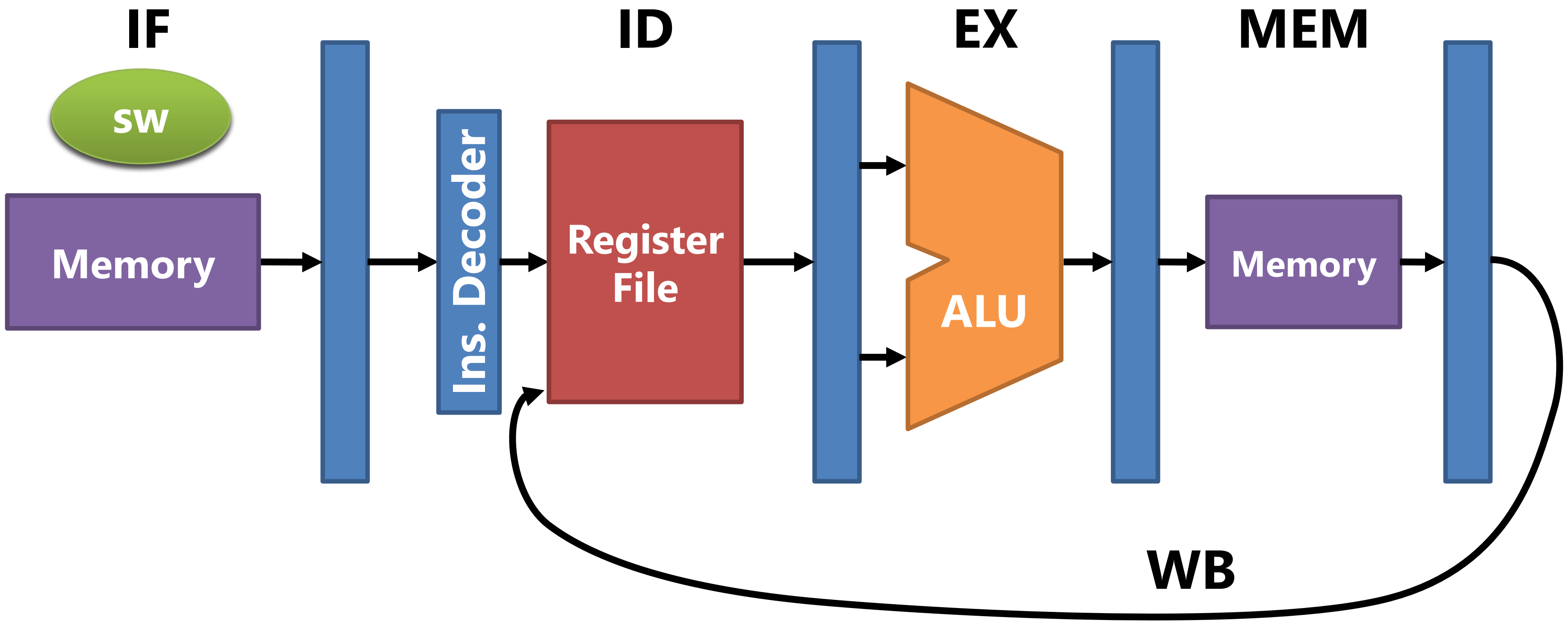
Multi-cycle instruction execution

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



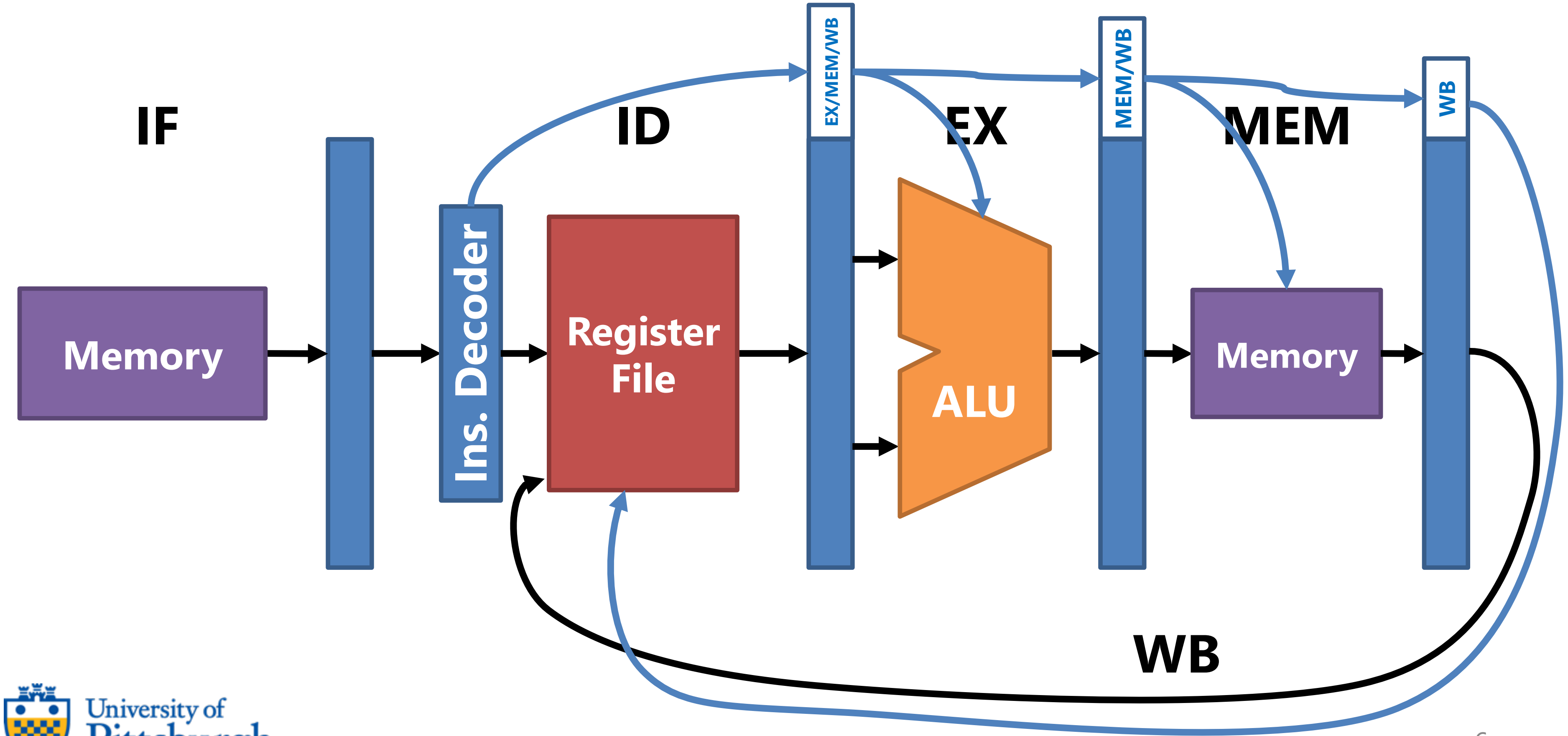
Pipelined instruction execution

- Pipelining allows one instruction to be fetched each cycle!



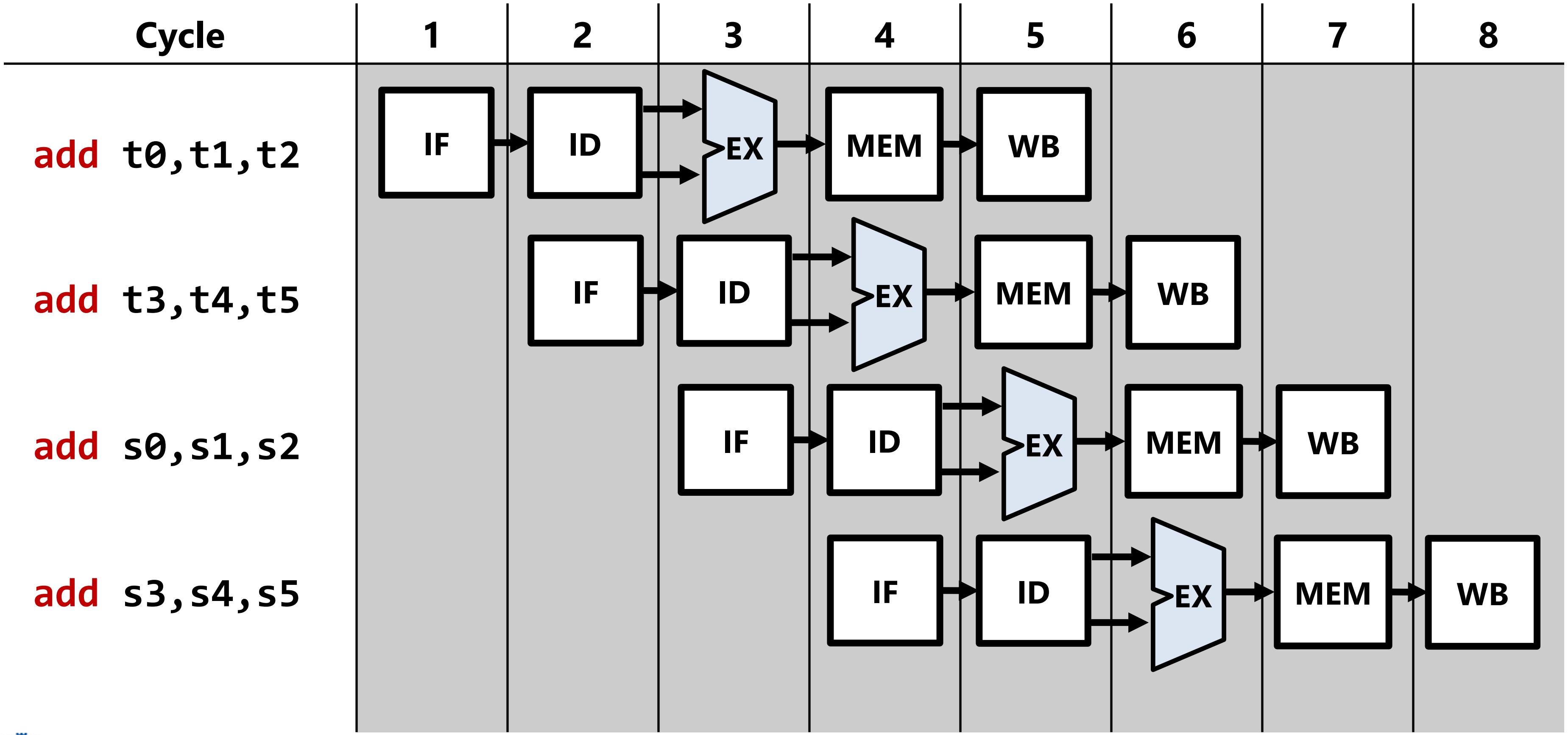
How about the control signals?

- A new instruction is decoded at every cycle!
- Control signals must be passed along with the data at each stage



Pipelining Timeline

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



A Pipelined Implementation is even Faster!

- Now every instruction takes the same number of cycles
  - **lw** takes 5 cycles: IF/ID/EX/MEM/WB
  - **add** takes 5 cycles: IF/ID/EX/---/WB
  - **sw** takes 5 cycles: IF/ID/EX/MEM/---

- If each stage takes *1 ns* each:

Q) Given 100 instructions, the average instruction execution time is?

A) (*5 ns* + *99 ns*) / 100 = *1.04 ns*

- A ~**5X** speed up from single cycle!

Pipelined vs. Multi-cycle vs. Single-cycle

- What happened to the three components of performance?

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

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*

Pipeline Hazards

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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

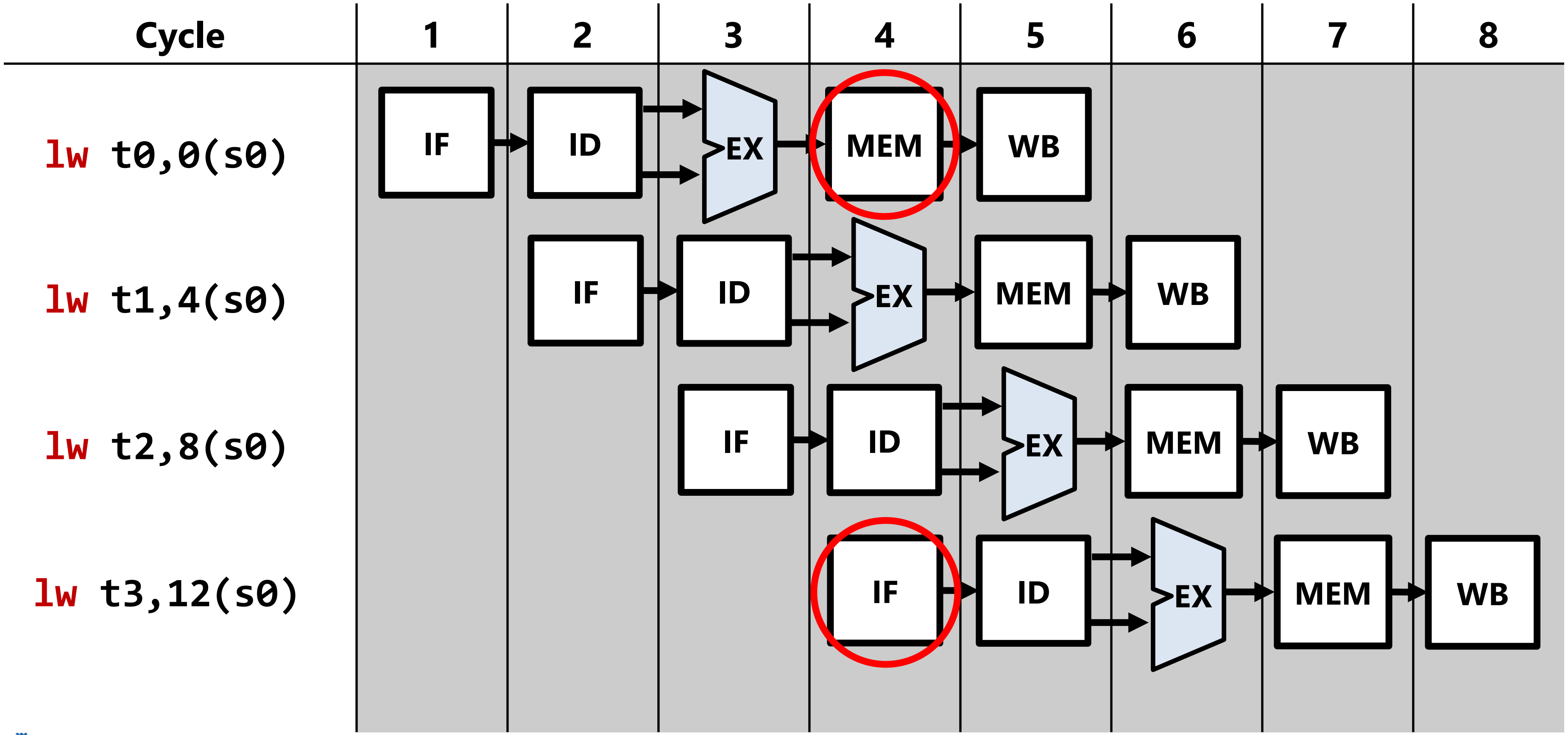
- ***Pipeline Hazard***
    - When the next instruction cannot execute in the following cycle
    - Hazards introduce ***bubbles*** (delays) into the pipeline timeline

- 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

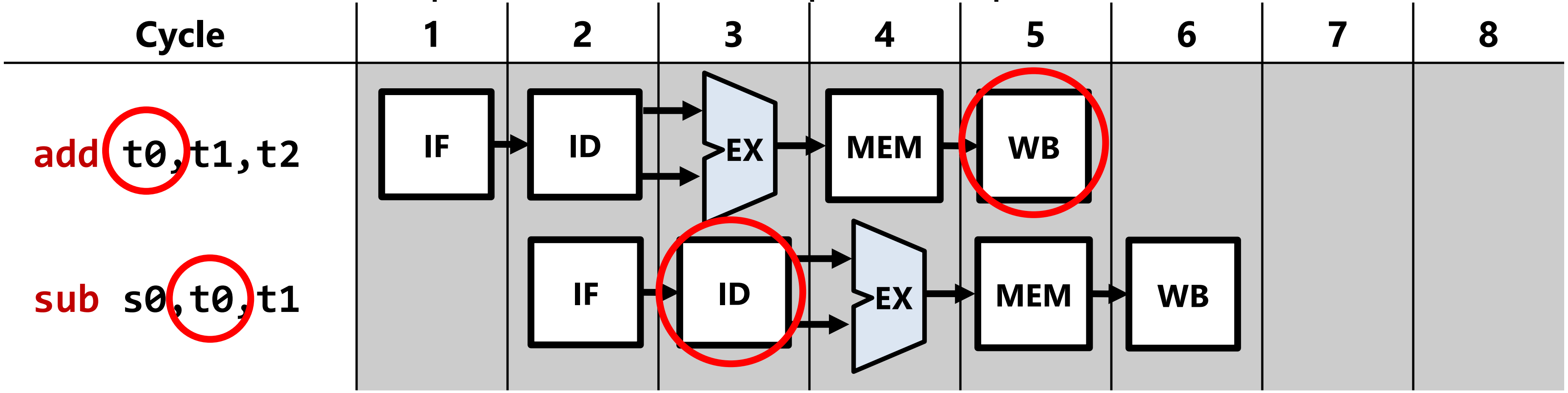
Structural Hazards

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



Data Hazards

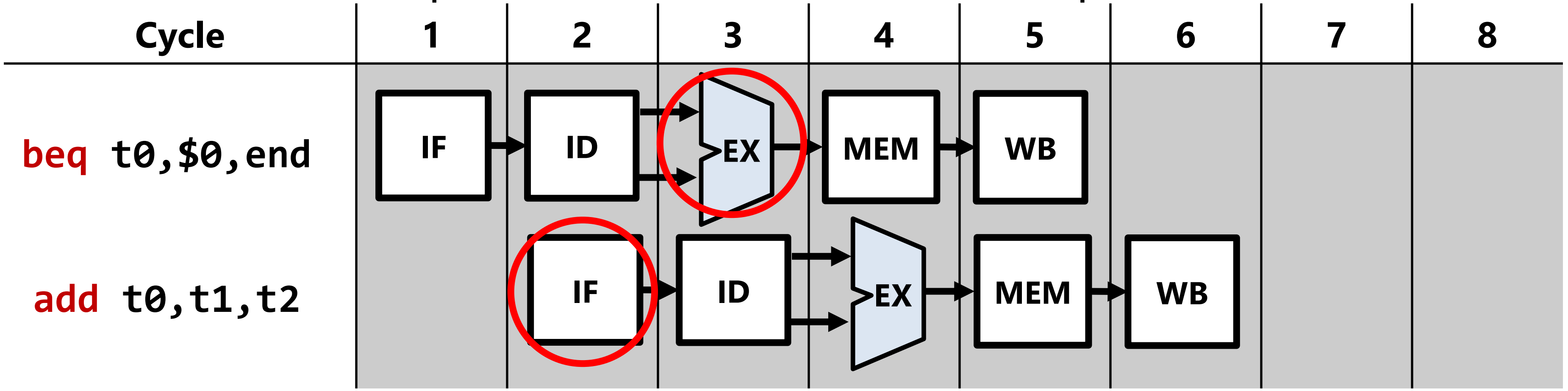
- An instruction depends on the output of a previous one.



- **sub** reads in **`t0`** before **add** has had a chance to write it back!

Control Hazards

- An instruction depends on branch outcome of previous instruction.



- **add** (PC+4) is fetched before **beq** branch outcome is known!

Dealing with Hazards

- Pipeline must be controlled so that hazards don't cause malfunction

- Who is in charge of that? You have a choice.

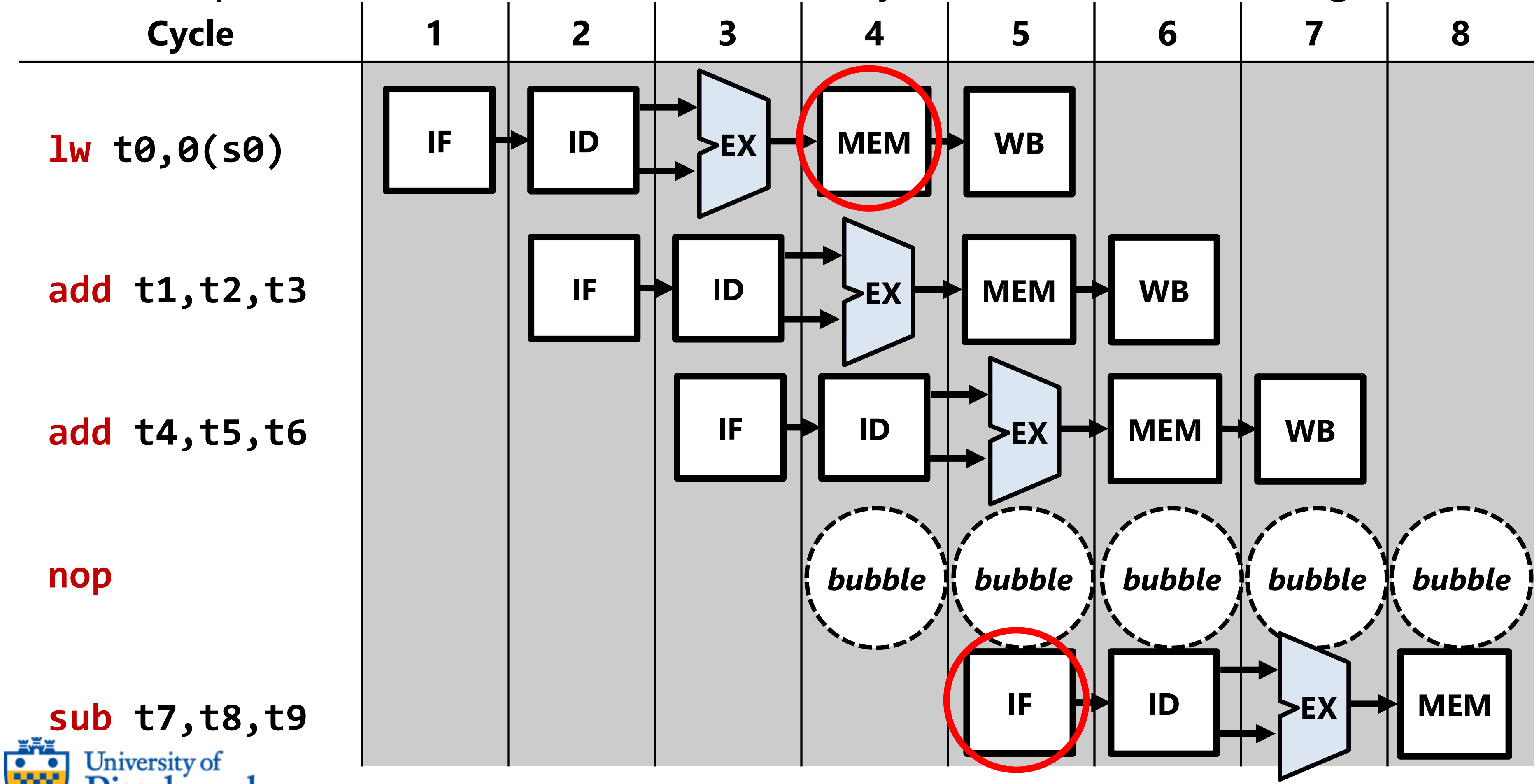
1. Compiler can avoid hazards by inserting nops
   - Insert nops where compiler thinks a hazard would happen
   - Nops flow through the pipeline not doing any work

2. CPU can internally avoid hazards using a ***hazard detection unit***
   - If structural/data hazard, pipeline ***stalled*** until resolved
   - If control hazard, pipeline ***flushed*** of wrong path instructions

Dealing with Hazards Using Compiler Scheduling

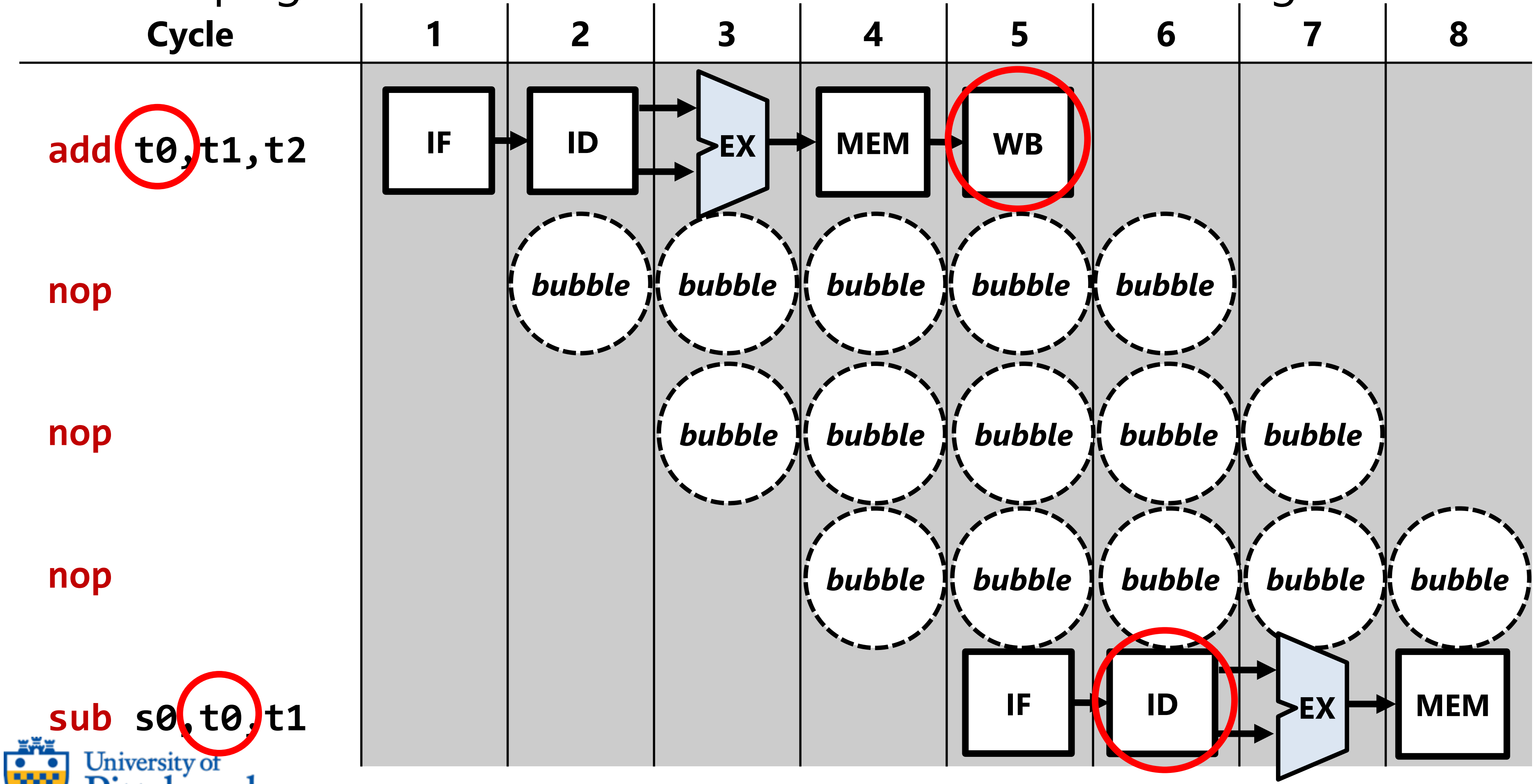
Compiler avoiding a structural hazard

- The nop avoids simultaneous access by the MEM and IF stages



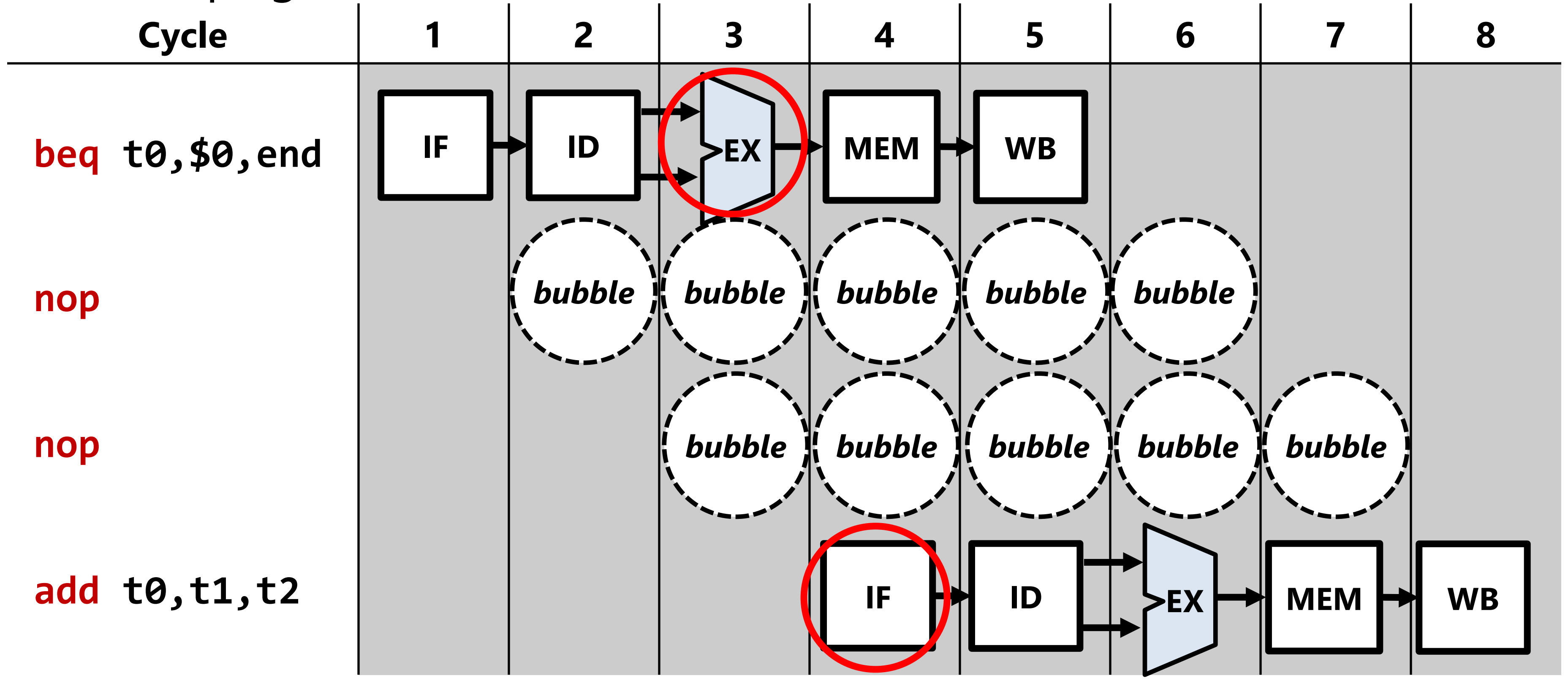
Compiler avoiding a data hazard

- The nops give time for **`t0`** to be written back before being read



Compiler avoiding a control hazard

- The nops give time for condition to resolve before instruction fetch



Dealing with Hazards Using Hardware Scheduling

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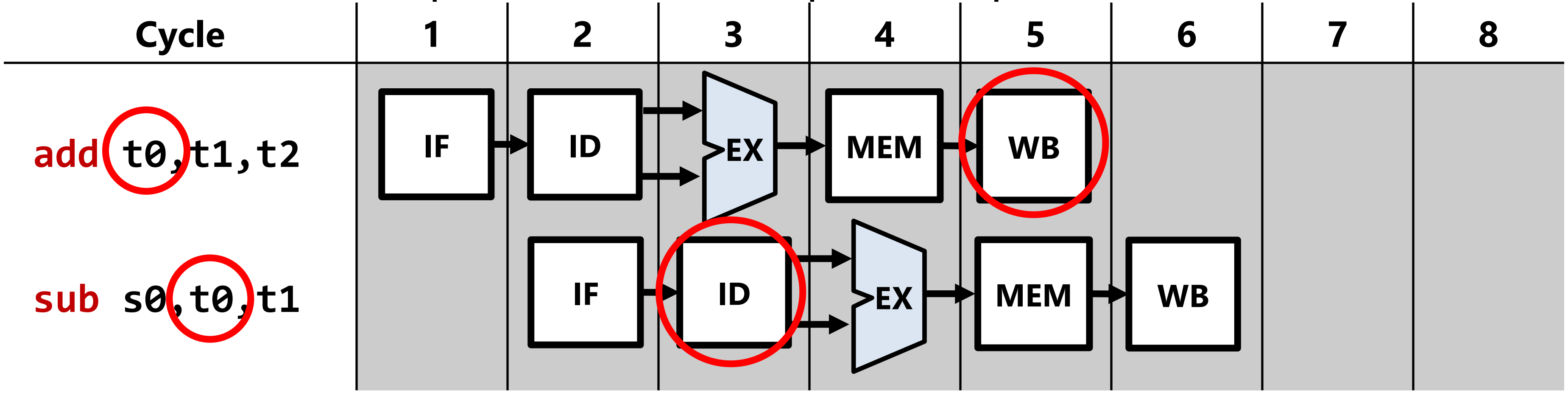
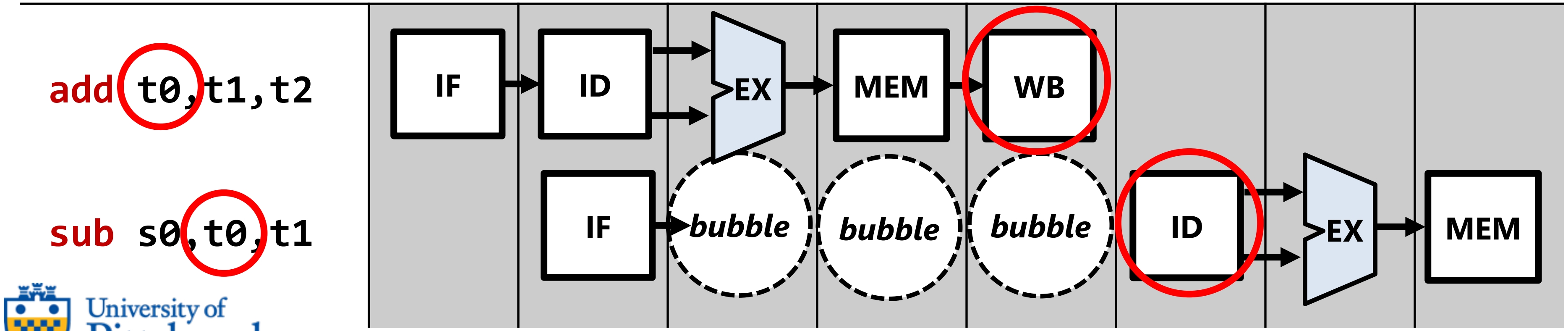
Hardware avoiding a data hazard

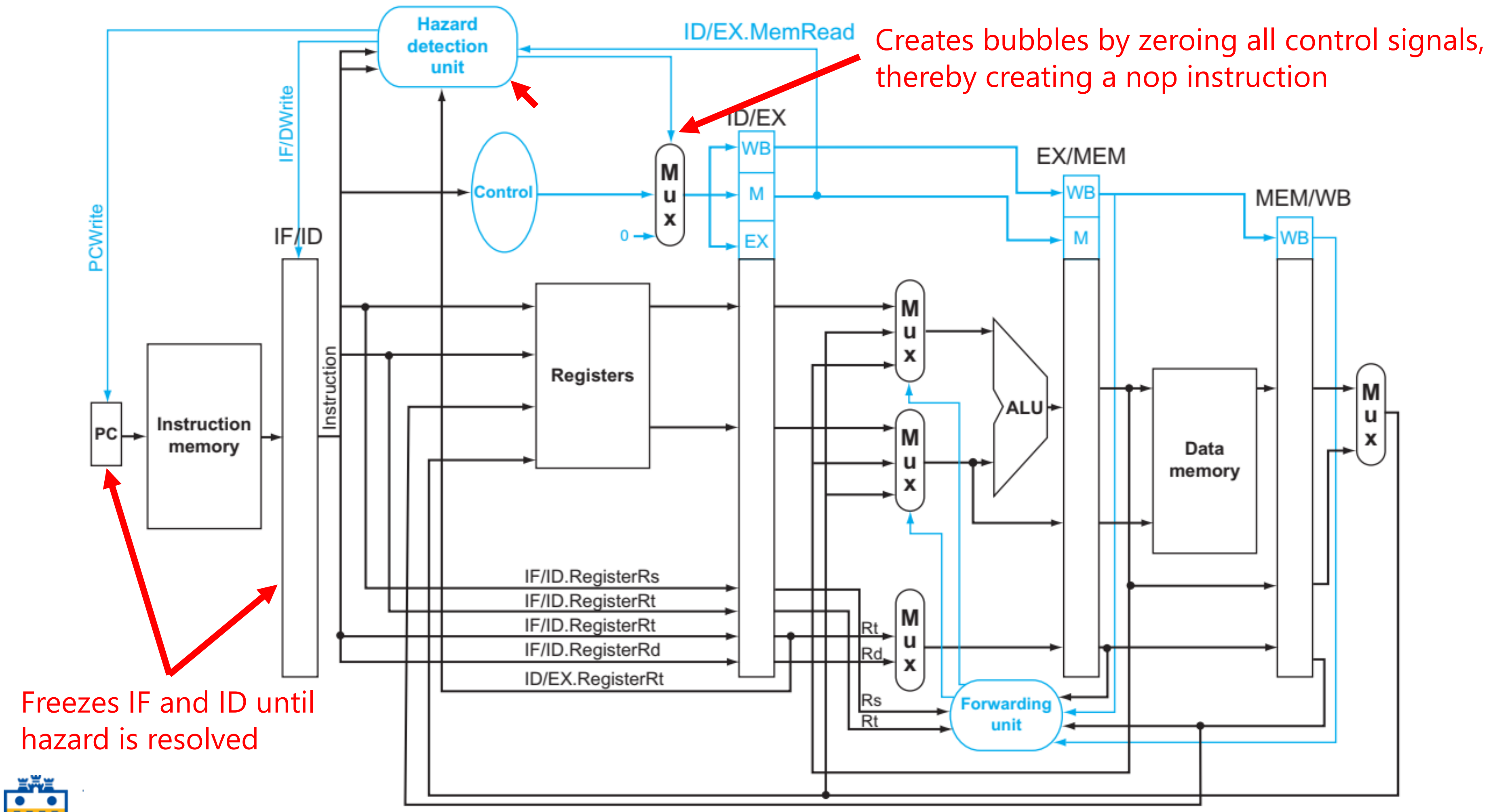
- An instruction depends on the output of a previous one.



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



Hazard Detection Unit (HDU)



Creates bubbles by zeroing all control signals, thereby creating a nop instruction

Freezes IF and ID until hazard is resolved

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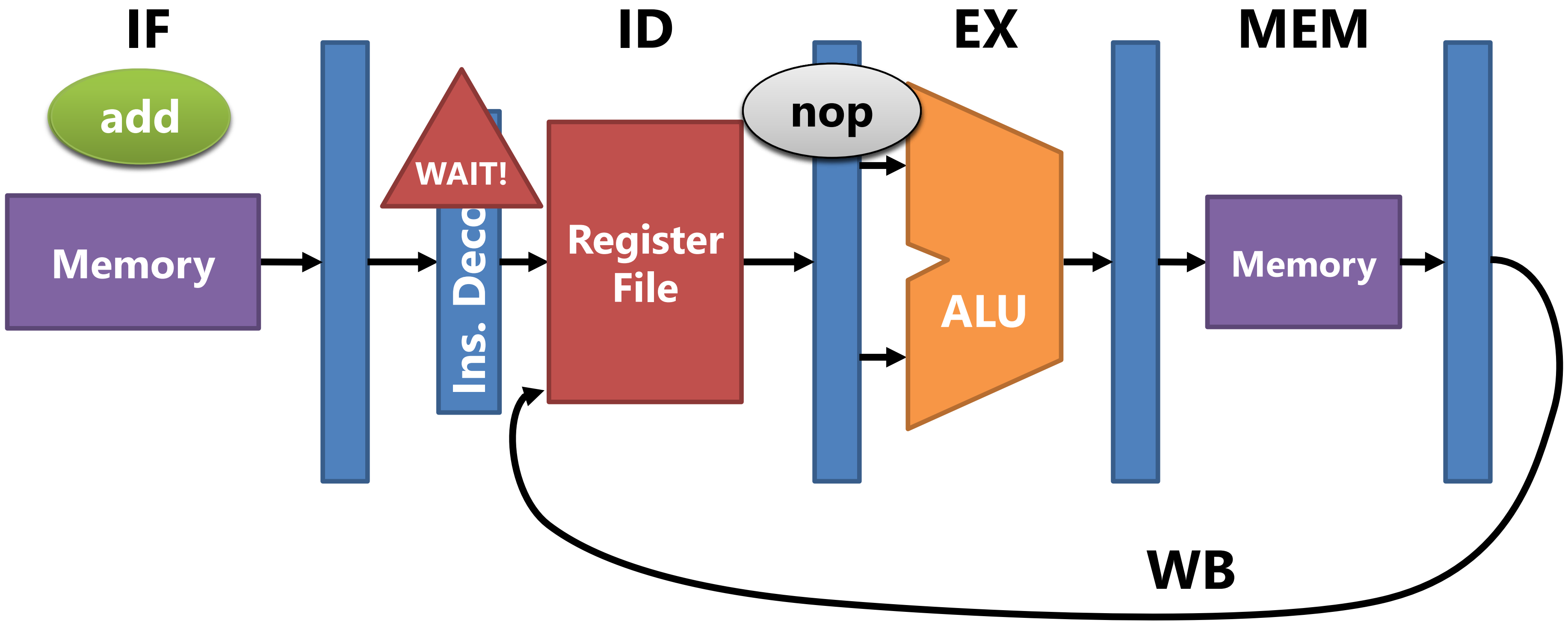
Hazard Detection Unit avoiding a data hazard

- Suppose we have an **add** that depends on an **lw**.



Structural / Data Hazards cause stalls

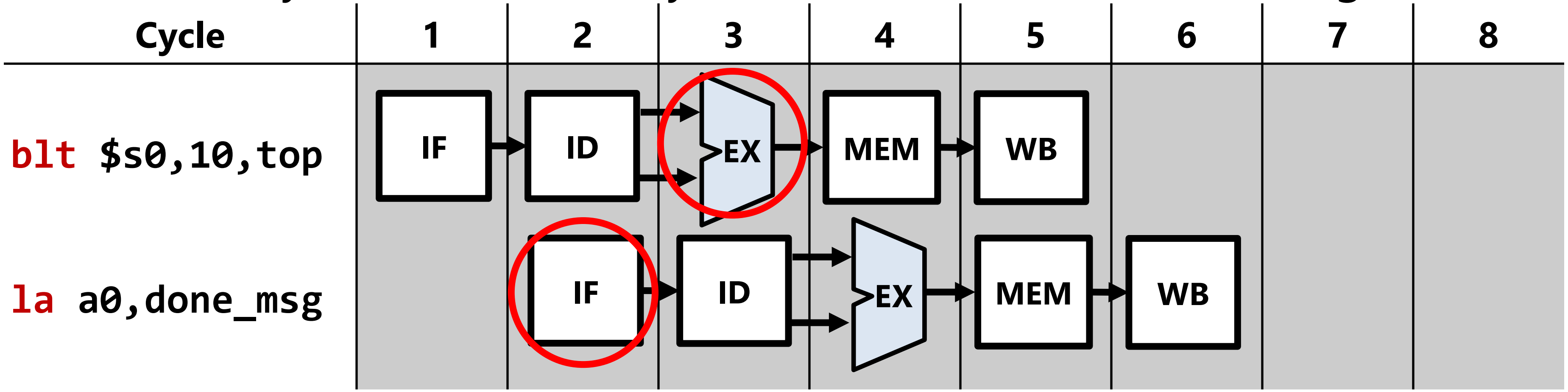
- If HDU detects a structural or data hazard, it does the following:
  - It **stops fetching instructions** (doesn't update the PC).
  - It **stops clocking the pipeline registers for the stalled stages.**
  - The stages after the stalled instructions **are filled with nops.**
    - Change control signals to 0 using the mux!
  - In this way, all following instructions will be stalled

- When structural or data hazard is resolved
  - HDU resumes instruction fetching and clocking of stalled stages

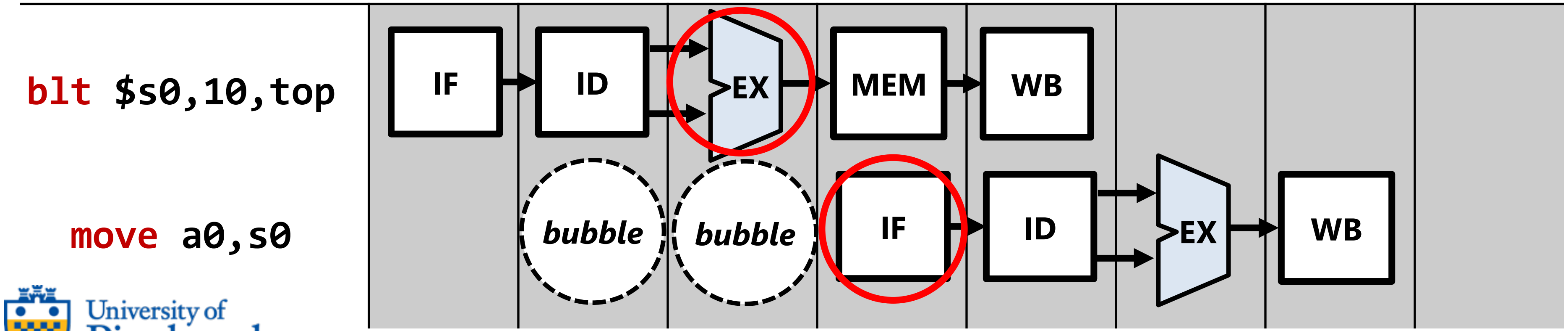
- But what about control hazards?
  - Instructions in wrong path are already in pipeline!
  - Need to ***flush*** these instructions

Hardware avoiding a control hazard

- You already fetched `la` but you later discover it's the wrong branch.



- HDU flushes instructions fetched while resolving branch.



Control Hazard Example

- Supposed we had this for loop followed by printf("done"):

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

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

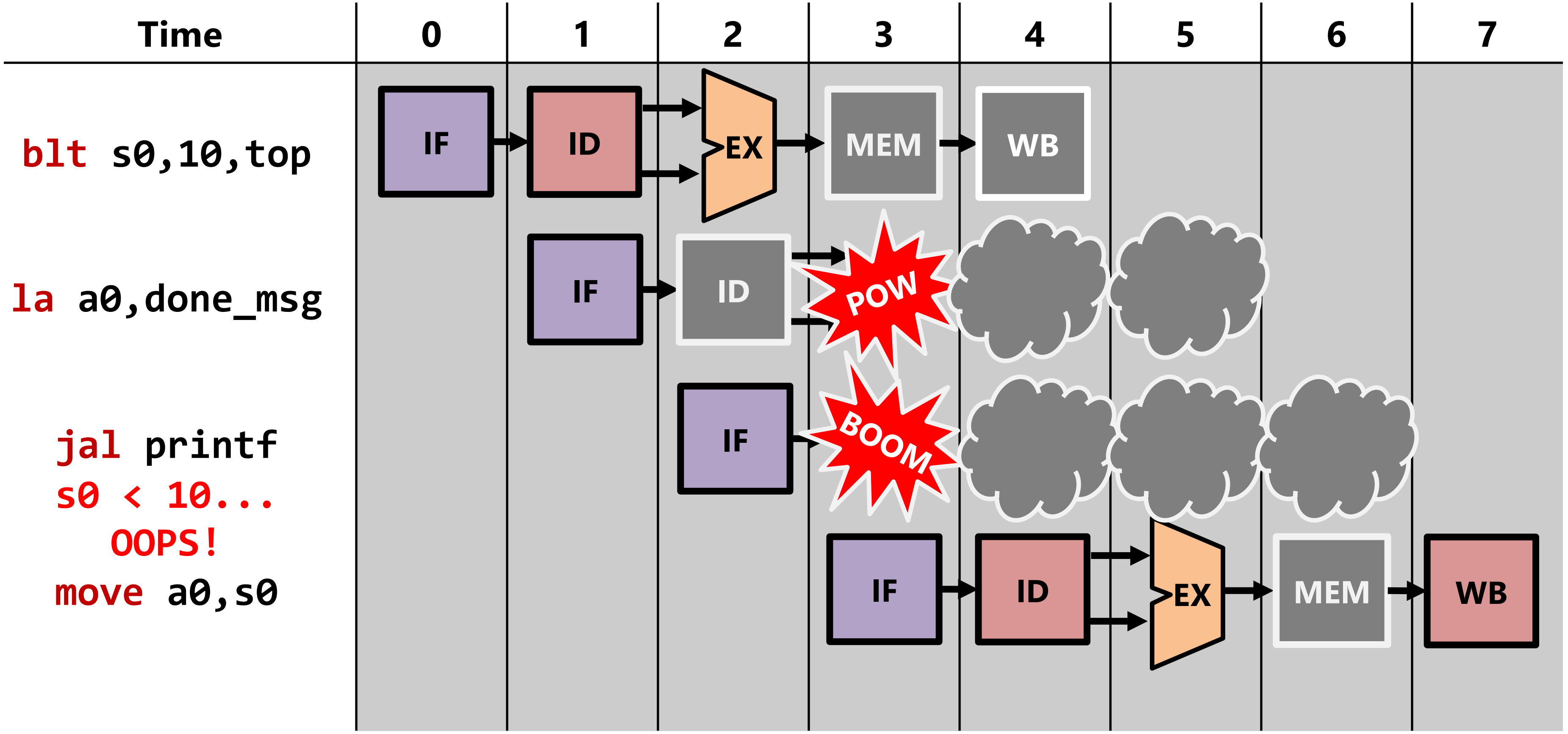
```
        li   s0, 0
top:
        move a0, s0
        jal  print
        addi s0, s0, 1
        blt  s0, 10, top
```

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

By the time `s0, 10` are compared at `blt` EX stage, the CPU would have already fetched `la` and `jal`!

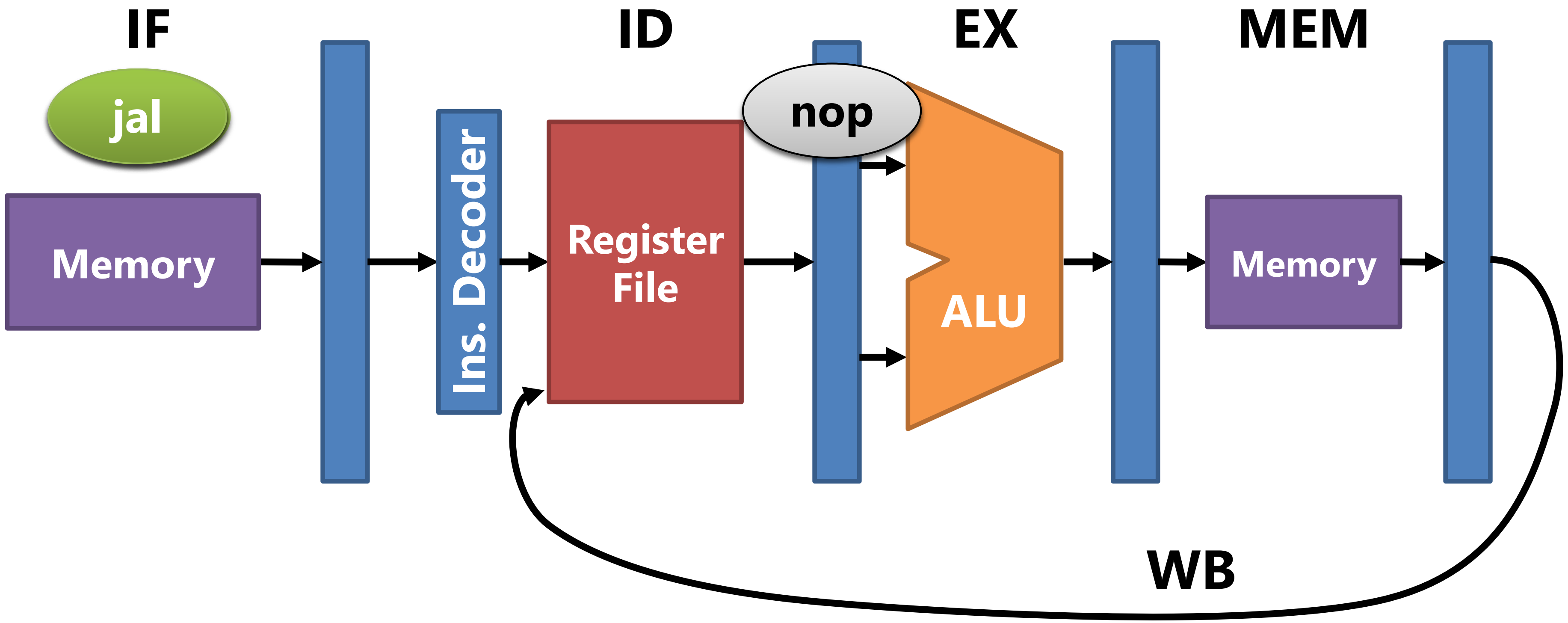
What's a flush?

- A pipeline flush removes all wrong path instructions from pipeline



Hazard Detection Unit avoiding a control hazard

- Let's watch the previous example.



Control Hazards cause flushes

- If a control hazard is detected due to a branch instruction:
  - Any "newer" instructions (those already in the pipeline) → transformed into **nops.**
  - Any "older" instructions (those that came BEFORE the branch) → left alone to finish executing as normal.

Dealing with Hazards Summary

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Compiler scheduling vs. Hardware scheduling

- Compiler scheduling **pro**: Energy-efficiency
  - Hazard Detection Unit can be very power hungry
    - A lot of long wires controlling remote parts of the CPU
    - Adds to the **Power Wall** problem

- Compiler scheduling **con**: Must make assumptions about pipeline
  - That means pipeline design must become part of ISA
    - Pipeline design tends to change drastically across generations
  - Length of MEM stage is hard to predict by the compiler
    - Until now we assumed MEM takes a uniform one cycle
    - But remember what we said about the **Memory Wall**?
    - Depending on whether access hits in cache: 1 ~ 100s of cycles

Performance penalty of pipeline stalls

- Remember the three components of performance:

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

Architecture	Instructions	CPI	Cycle Time (1/F)
Single-cycle	Same	1	5 ns
Ideal 5-stage pipeline	Same	1	1 ns
Pipeline w/ stalls	Same	> 1	1 ns

- Pipelining increases ***clock frequency*** proportionate to depth
- But stalls increase ***CPI*** (cycles per instruction)
  - If CPI of 2 → Only 2.5X speed up (instead of 5X)

- We'd like to avoid this penalty if possible!

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