Optimizing Pipeline Hazards

CS 1541 Wonsun Ahn

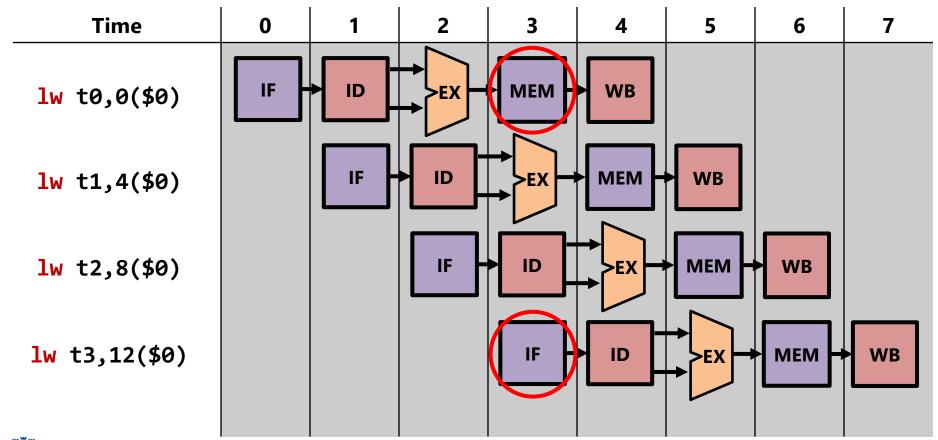


Solving Structural Hazards



Structural Hazard on Memory

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





What could we do??

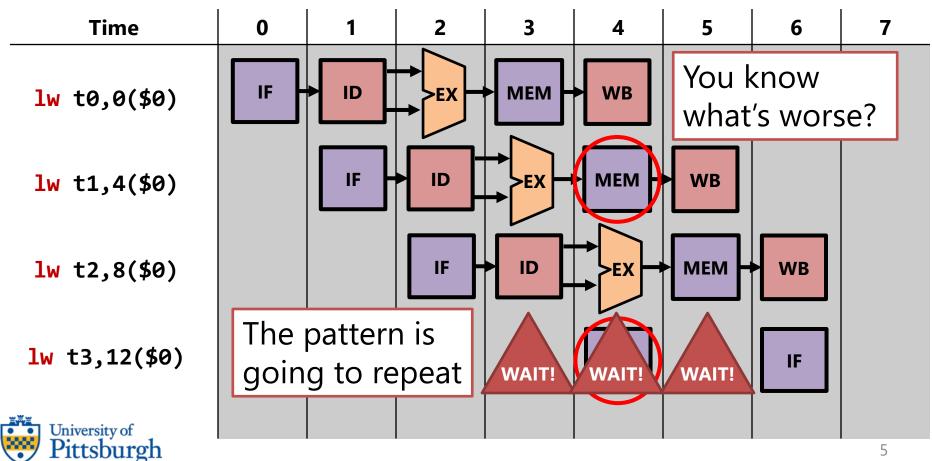
Two people need to use **one** sink at the same time
Well, in this case, it's memory but same idea





We can do something similar!

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



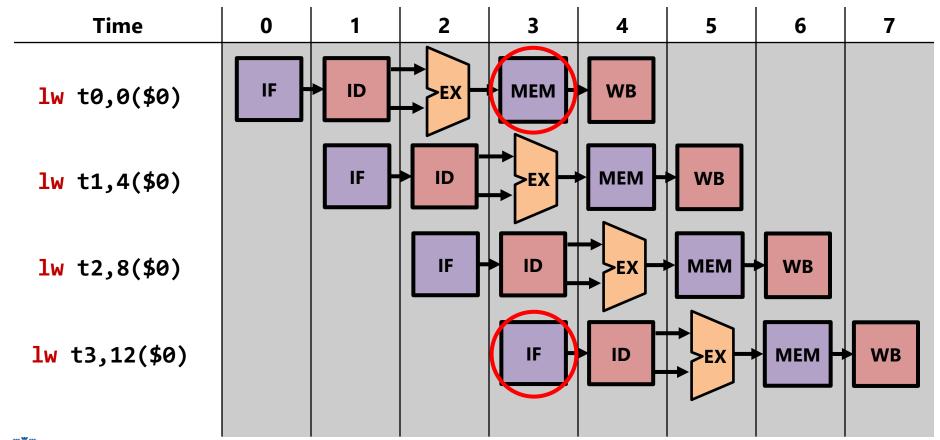
Or we could throw in more hardware!

- 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?
 - o Throw in lots of sinks!
 - o 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

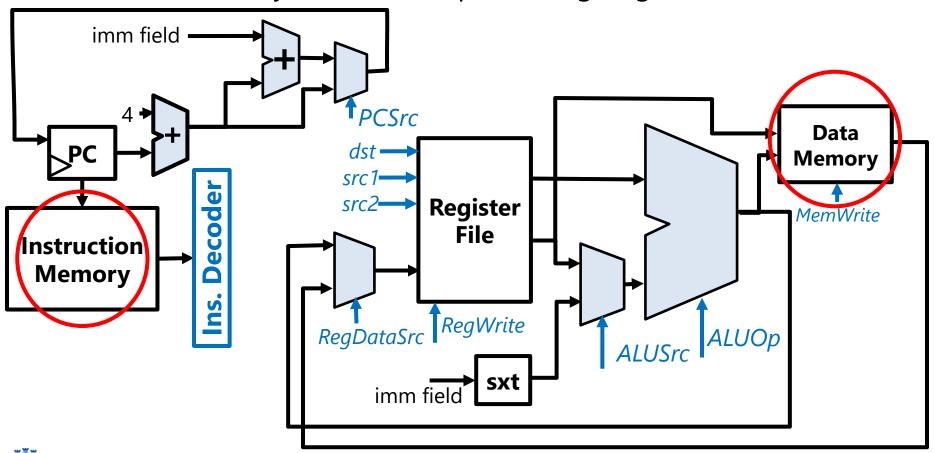




Structural Hazard removed with two Memories

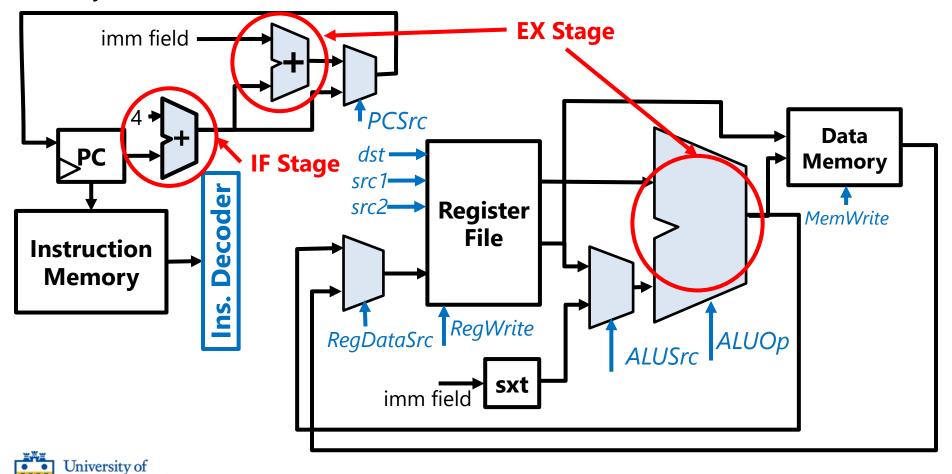
But is that the only hardware duplication going on here?

University of Pittsburgh



Structural Hazards removed with Multiple Adders

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



Pittsburgh

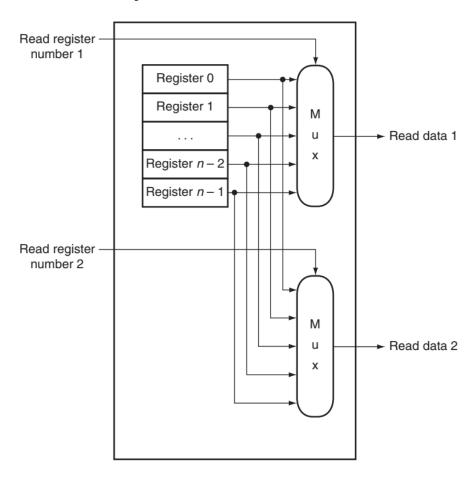
Solving Structural Hazards

- 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
 - o **Port**: Circuitry that allows either read or write access to memory
 - o 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

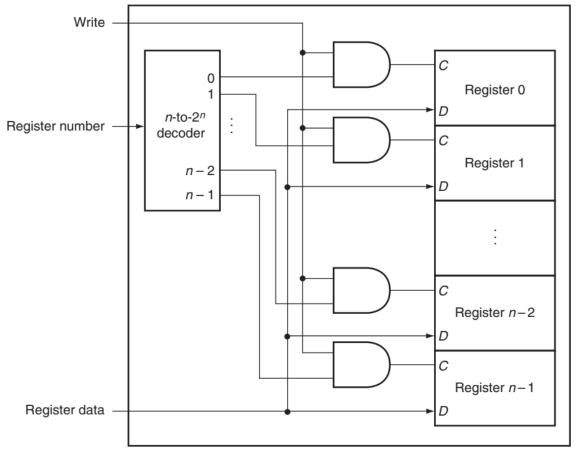
• By adding more MUXes, you can add even more read ports





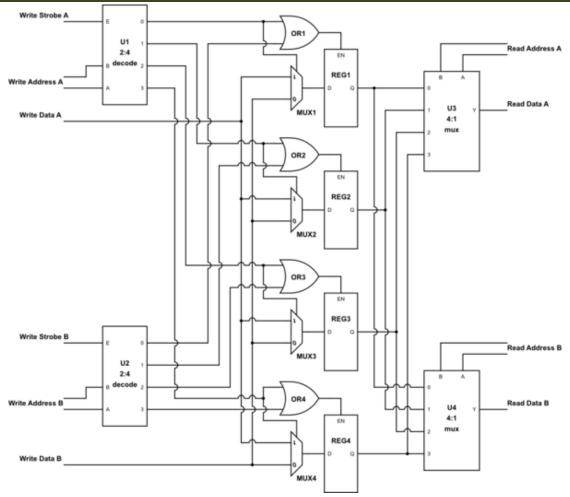
One Register Write Port

• 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
 - o 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

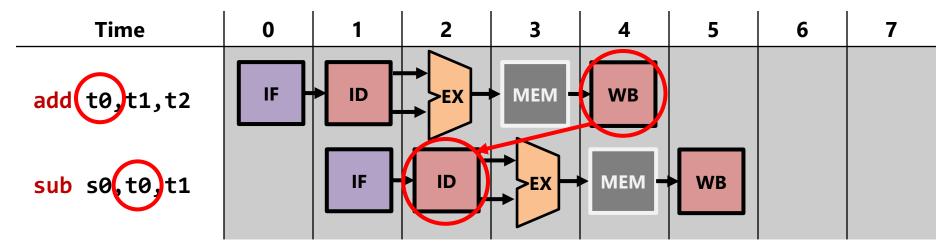


Solving Data Hazards



Data Hazards

An instruction depends on the output of a previous one.

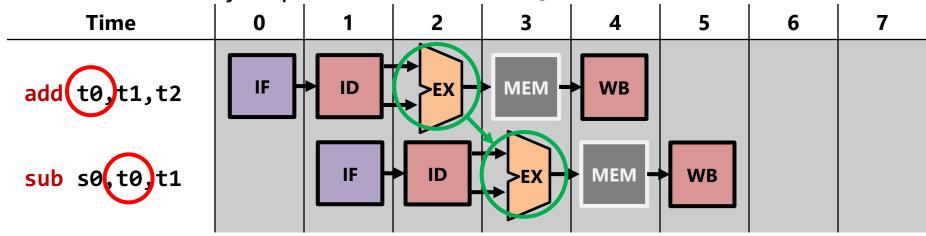


- When does **add** finish computing its sum?
- Well then... why not just use the sum when we need it?



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.

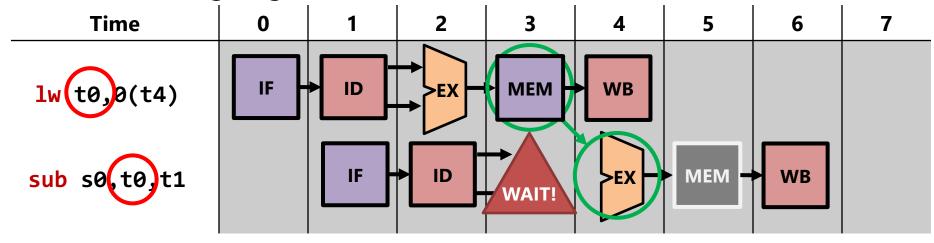


- This handles one kind of data forwarding...
- Where else can data come from and be written into registers?
 - Memory!



Data Forwarding from Memory

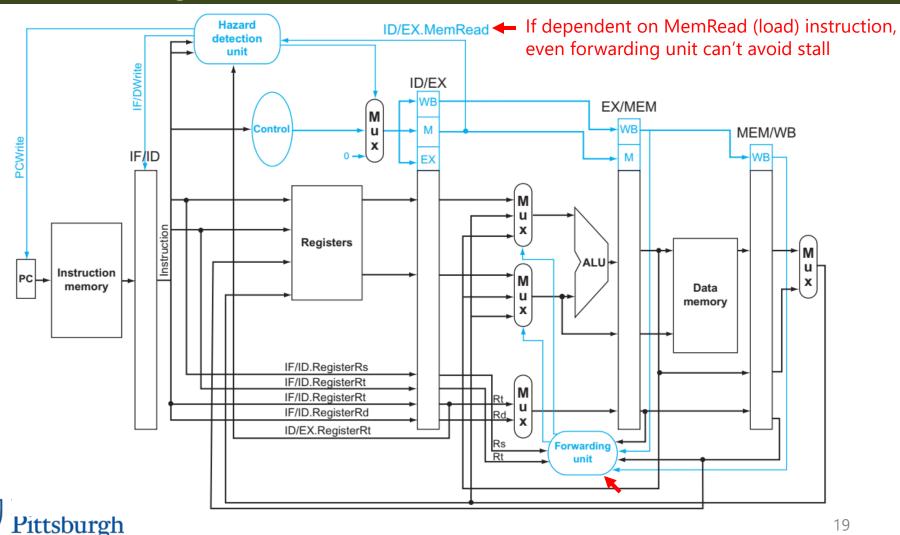
- Well memory accesses happen a cycle later...
- What are we going to have to do?



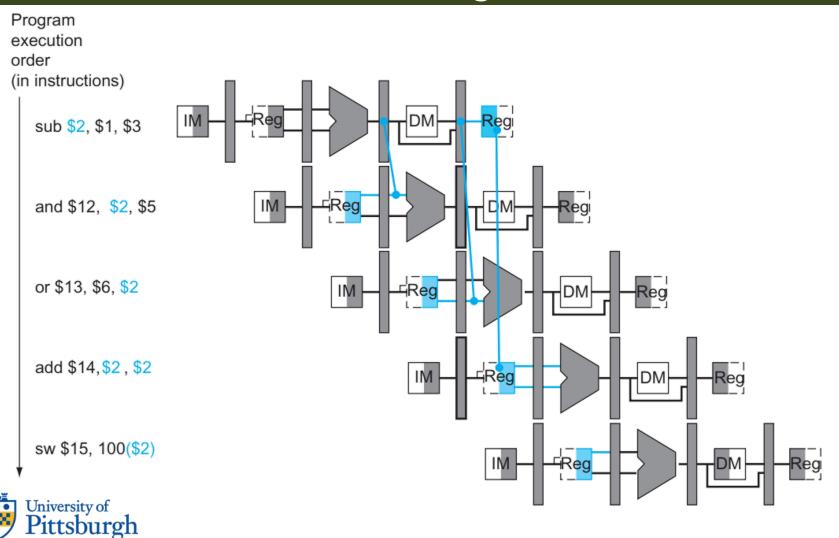
This kind of stall is unavoidable in our current pipeline



Forwarding Unit and Use-after-load-hazard



ALU --- ALU Data Forwarding removes all stalls



MEM ALU forwarding must stall on immediate use

Program execution order (in instructions)

lw \$2, 20(\$1)

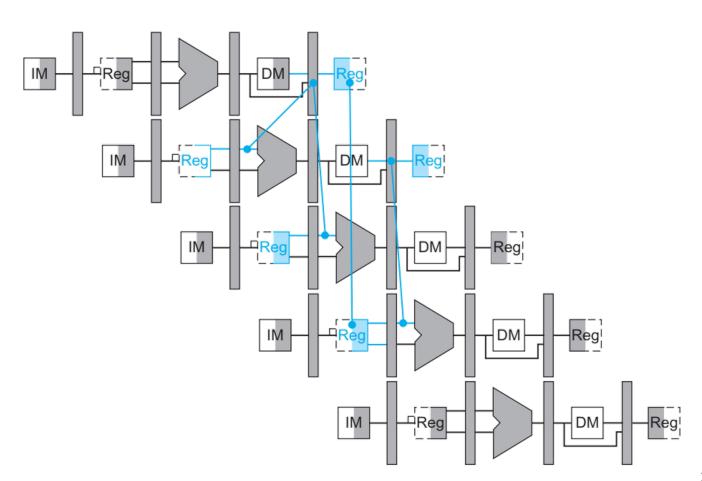
and \$4, \$2, \$5

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

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

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





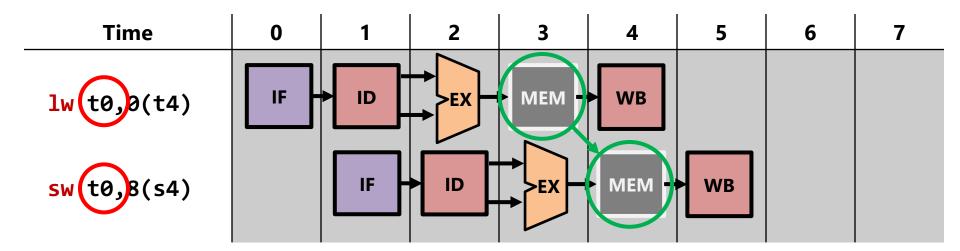
MEM → ALU forwarding with bubble

Program execution order (in instructions) lw \$2, 20(\$1) bubble IM and becomes nop and \$4, \$2, \$5 Reg or \$8, \$2, \$6 add \$9, \$4, \$2



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





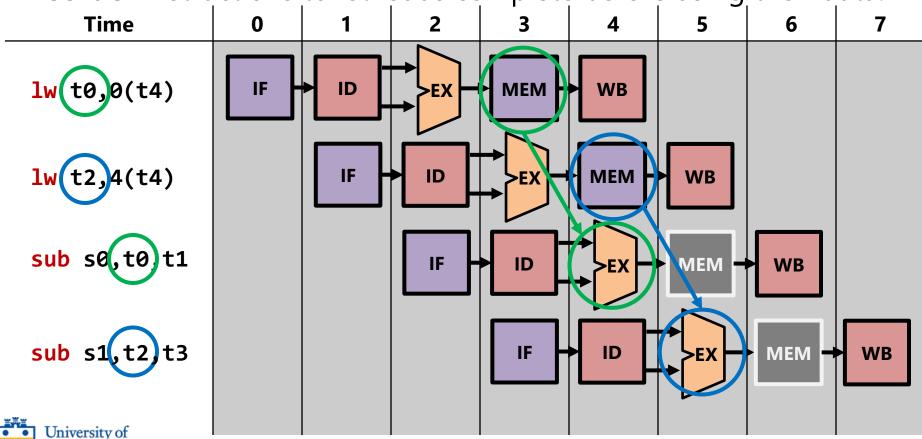
Data Hazard removed through Compiler Reordering

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

| redider 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 | | | | | | | | |
| University of | | | | | | | | |

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
 - o 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:

```
1w(t0), 0(t4)
```

SW S0, **8(t0)** We want to reorder to remove the data hazard.

lw t2,4(t4) 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
 - o It's easy to figure out data dependencies, even memory ones
 - At runtime, addresses of 8(t0) and 4(t4) are easily calculated
- But at runtime it uses lots of power for the data analysis
 - o ... which again causes problems with the **Power Wall**
 - But more on this later



Solving Control Hazards



Loops

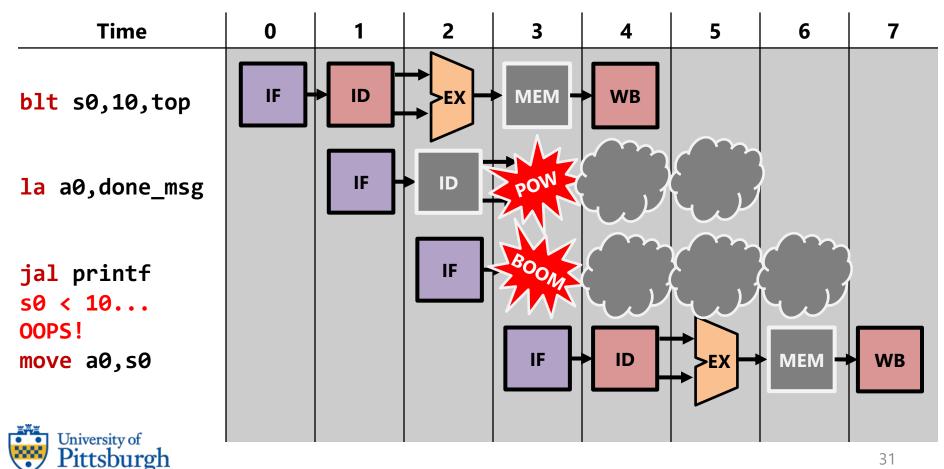
Loops happen all the time in programs.

```
for(s0 = 0 .. 10)
                                 li
                                       s0, 0
    print(s0);
                            top:
                                 move a0, s0
printf("done");
                                 jal
                                       print
                                 addi s0, s0, 1
                                 blt s0, 10, top
 How often does this
 blt instruction go to
top? How often does
                                       a0, done_msg
                                 la
it go to the following
                                       printf
                                 jal
   la instruction?
```



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 ∝ frequency of branches
 - o If we have a tight loop, branches happen every few instructions
 - Typically, branches account for 15~20% of all instructions
- **Penalty** from one flush ∝ 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
 - $\circ \alpha$: fraction of branch instructions in the instruction mix
 - \circ π : probability a branch is actually taken
 - K: penalty per pipeline flush

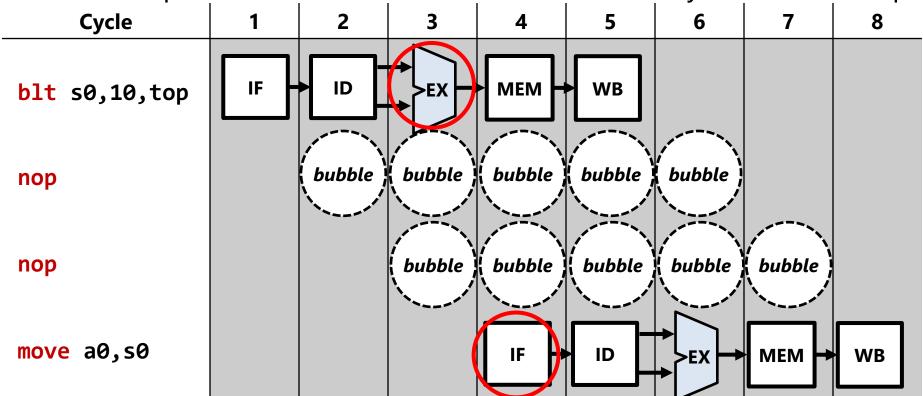
Example: If 20% of instructions are branches and the probability that a branch is taken is 50%, and pipeline flush penalty 7 cycles, then: $CPI = CPI_{nch} + 0.2 * 0.5 * 7 = CPI_{nch} + 0.7$ cycles per instruction

- 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
 - $\circ \alpha$: 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: $CPI = CPI_{nch} + 0.2 * 7 = CPI_{nch} + 1.4$ 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
 - o 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

```
s0, 10, else
  blt
                                   s0, 10, else
                              addi t2, t2, 1
       # Delay slot
  nop
then:
                            then:
                              add
  add t0, t1, t0
                                   t0, t1, t0
       merge
                                   merge
                           else:
else:
       t1, t1, t0
                              add
  add
                                   t1, t1, t0
merge:
                           merge:
  addi t2, t2, 1
```

- The addi instruction is moved into delay slot
 - o It is not control dependent on the branch outcome of blt
 - It is not data dependent on registers to 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
 - Delays slots ended up being a hindrance
- Next idea please!

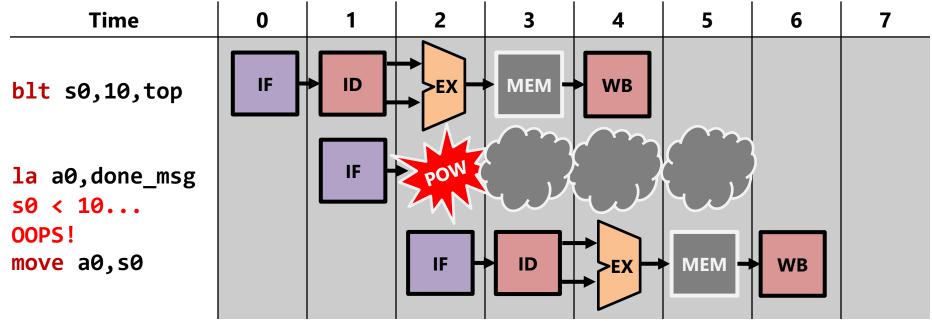


Solution 2: MORE SINKS! (a.k.a. hardware)



Do we reeeally need to compare at EX stage?

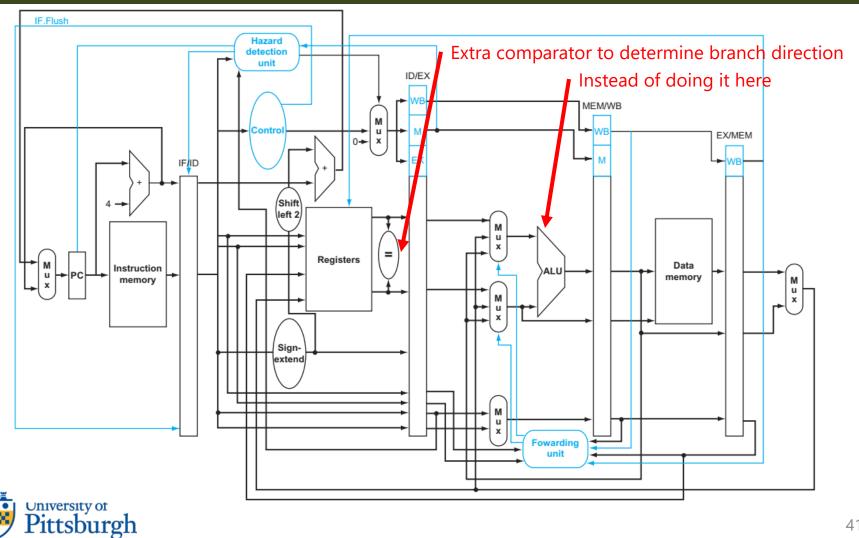
What if branch comparison was done at the ID stage, not EX stage?



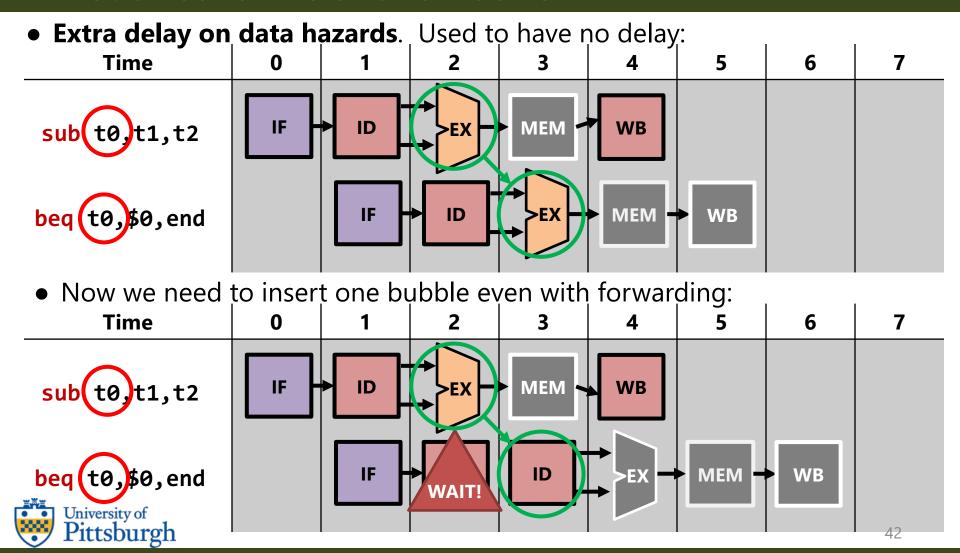
- Reduced penalty from 2 cycles → 1 cycle!
- But of course that means we need a comparator at the ID stage



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

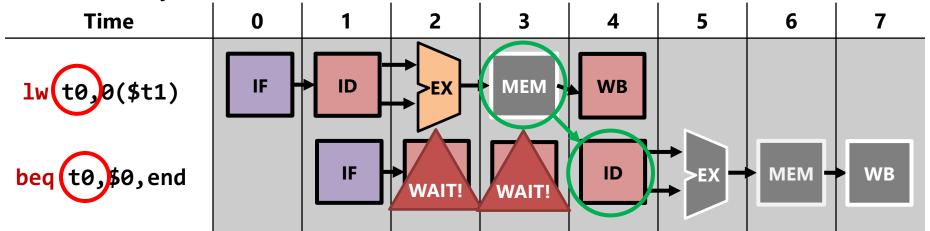


Not all sunshine and rainbows



Not all sunshine and rainbows

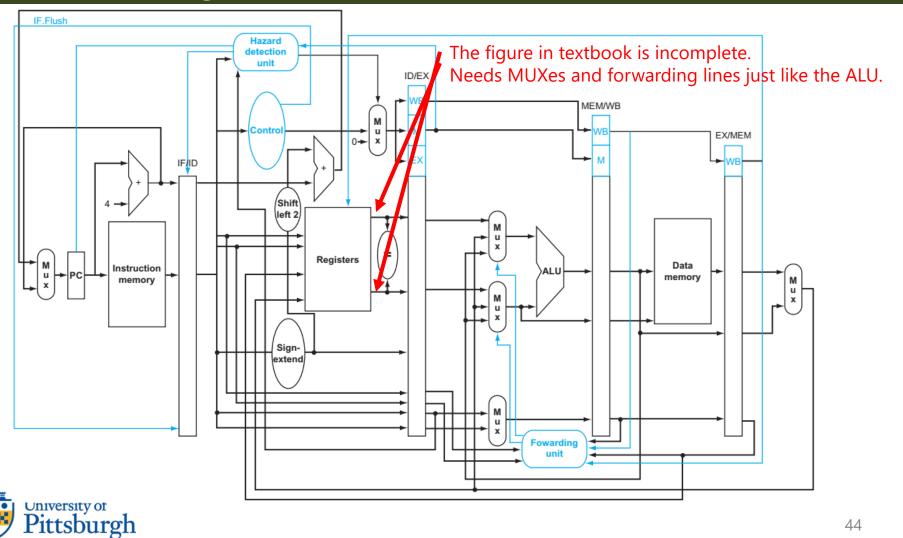
• Extra delay on data forwarded from **lw** also:



- 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

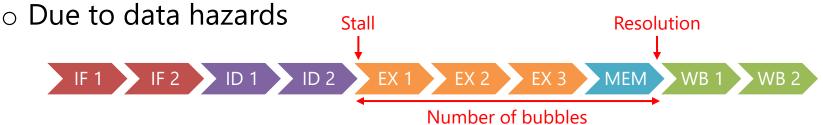


Limits of Pipelining

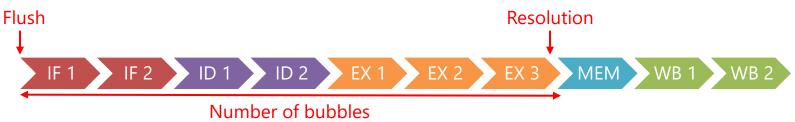


Increasing pipeline depth has diminishing returns

- 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)



- → Mitigated through instruction reordering (but Power Wall)
- Due to control hazards



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

