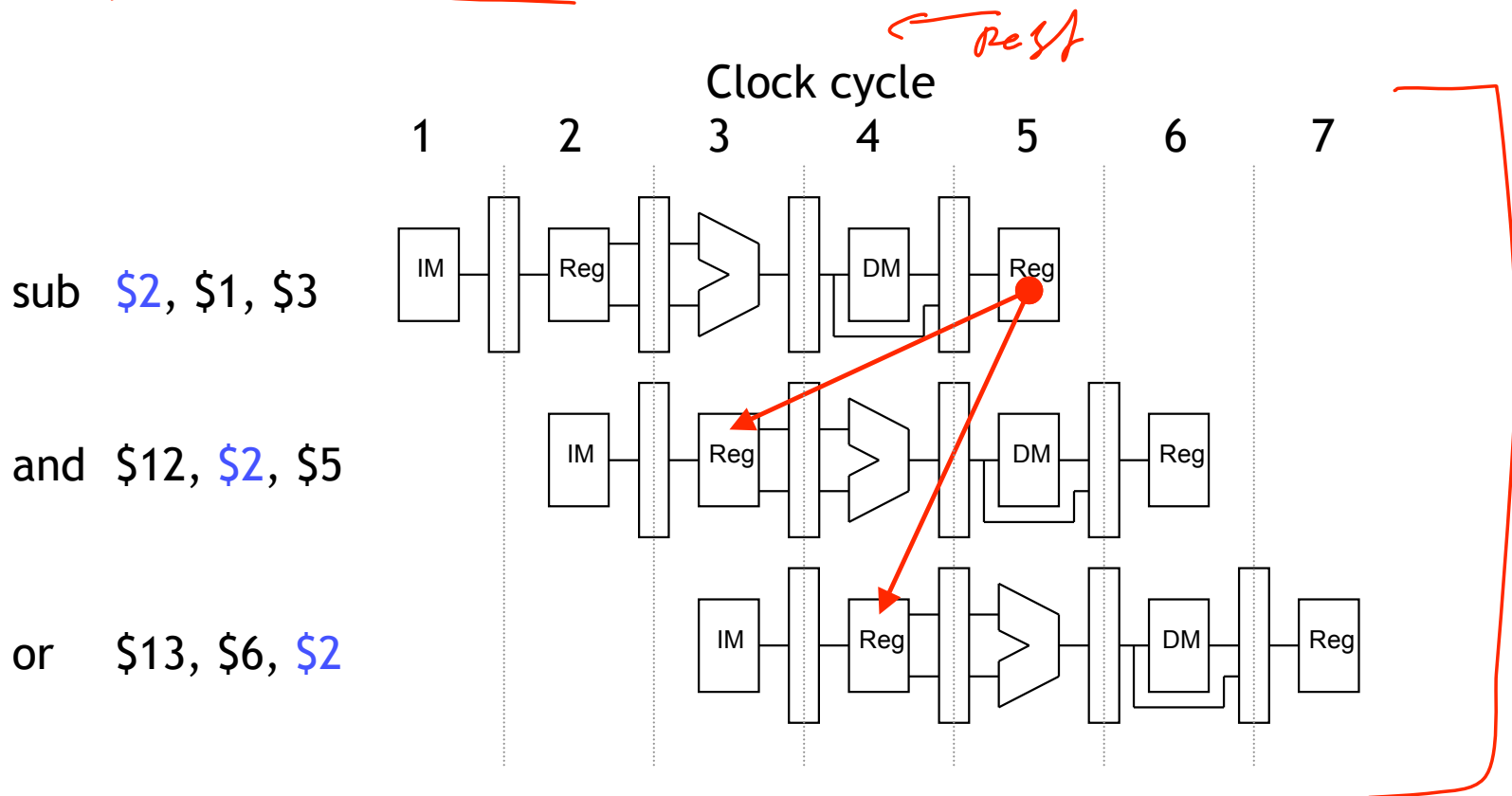


Stalls and flushes

- So far, we have discussed data hazards that can occur in pipelined CPUs if some instructions depend upon others that are still executing.
 - Many hazards can be resolved by forwarding data from the pipeline registers, instead of waiting for the writeback stage.
 - The pipeline continues running at full speed, with one instruction beginning on every clock cycle.
- Now, we'll see some real limitations of pipelining. ✓
 - Forwarding may not work for data hazards from load instructions.
 - Branches affect the instruction fetch for the next clock cycle.
- In both of these cases we may need to slow down, or stall, the pipeline.

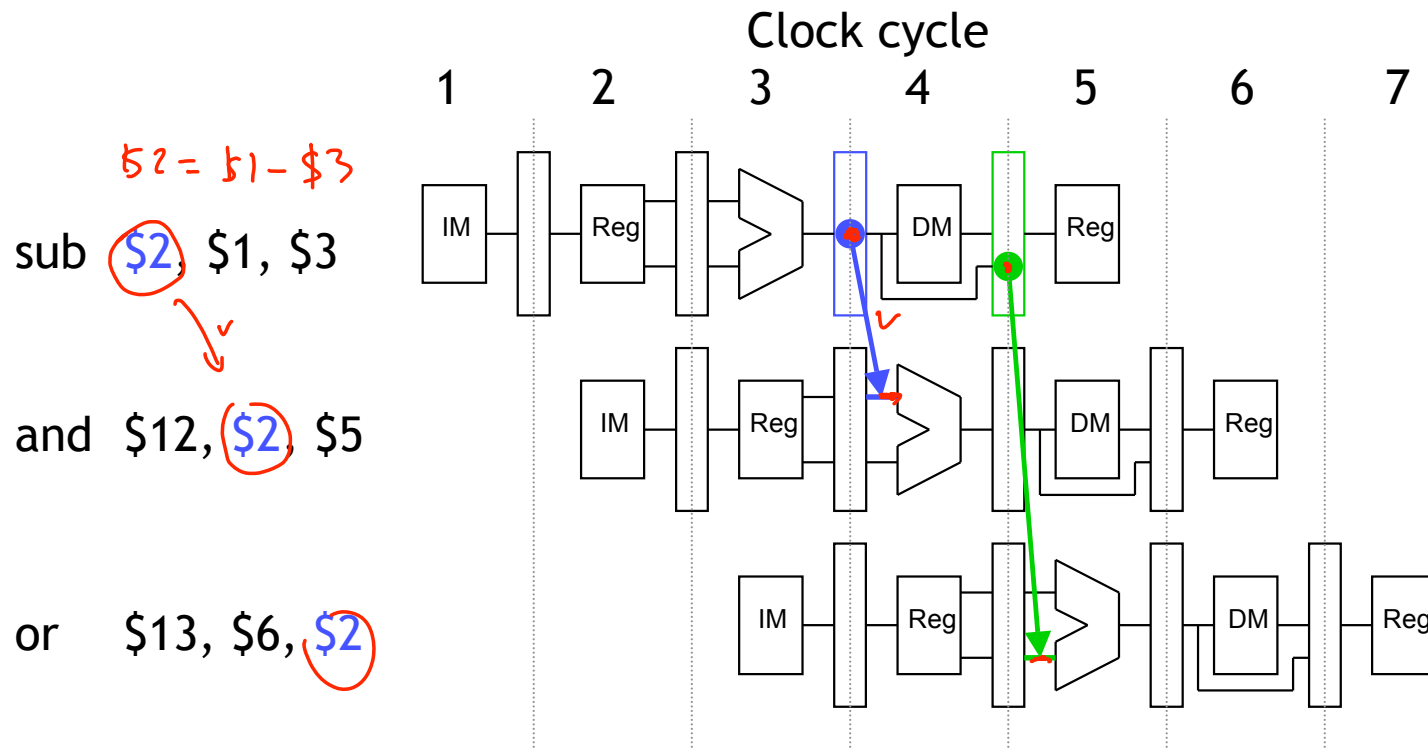
Data hazard review

- A data hazard arises if one instruction needs data that isn't ready yet.
 - Below, the AND and OR both need to read register \$2.
 - But \$2 isn't updated by SUB until the fifth clock cycle.
- Dependency arrows that point backwards indicate hazards.



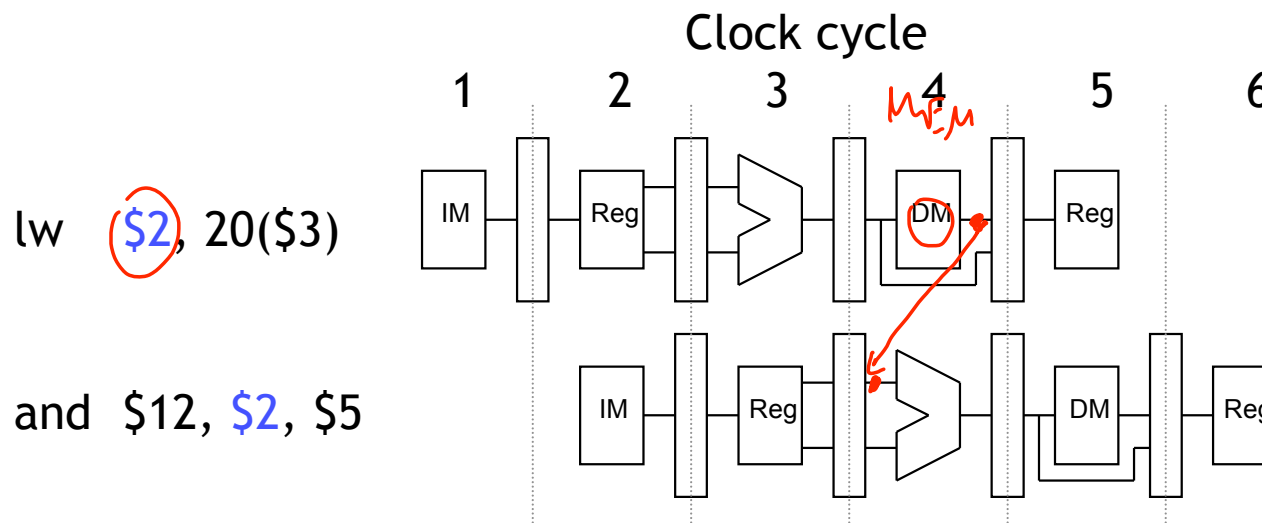
Forwarding

- The desired value (\$1 - \$3) has actually already been computed—it just hasn't been written to the registers yet.
- **Forwarding** allows other instructions to read ALU results directly from the pipeline registers, without going through the register file.



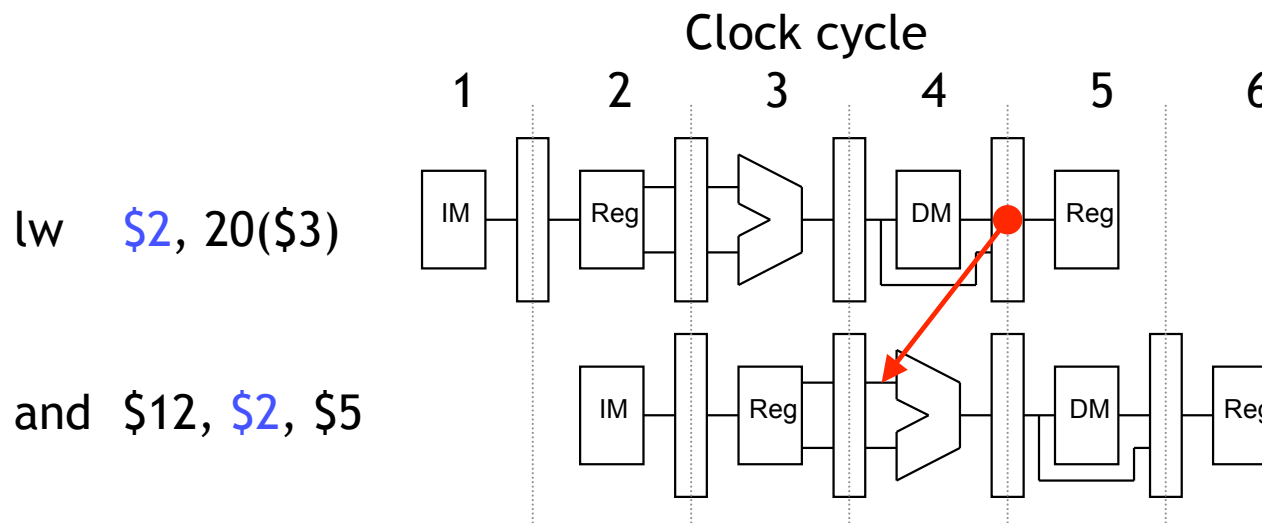
What about loads?

- Imagine if the first instruction in the example was LW instead of SUB.
 - How does this change the data hazard?



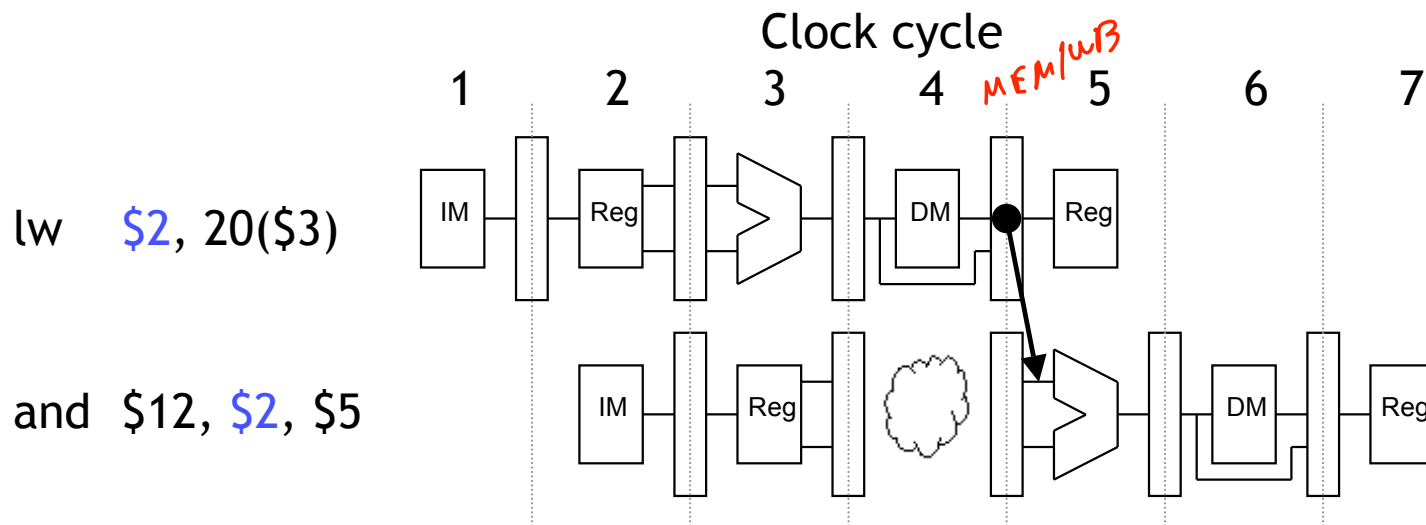
What about loads?

- Imagine if the first instruction in the example was LW instead of SUB.
 - The load data doesn't come from memory until the *end* of cycle 4.
 - But the AND needs that value at the *beginning* of the same cycle!
- This is a “true” data hazard—the data is not available when we need it.



Stalling

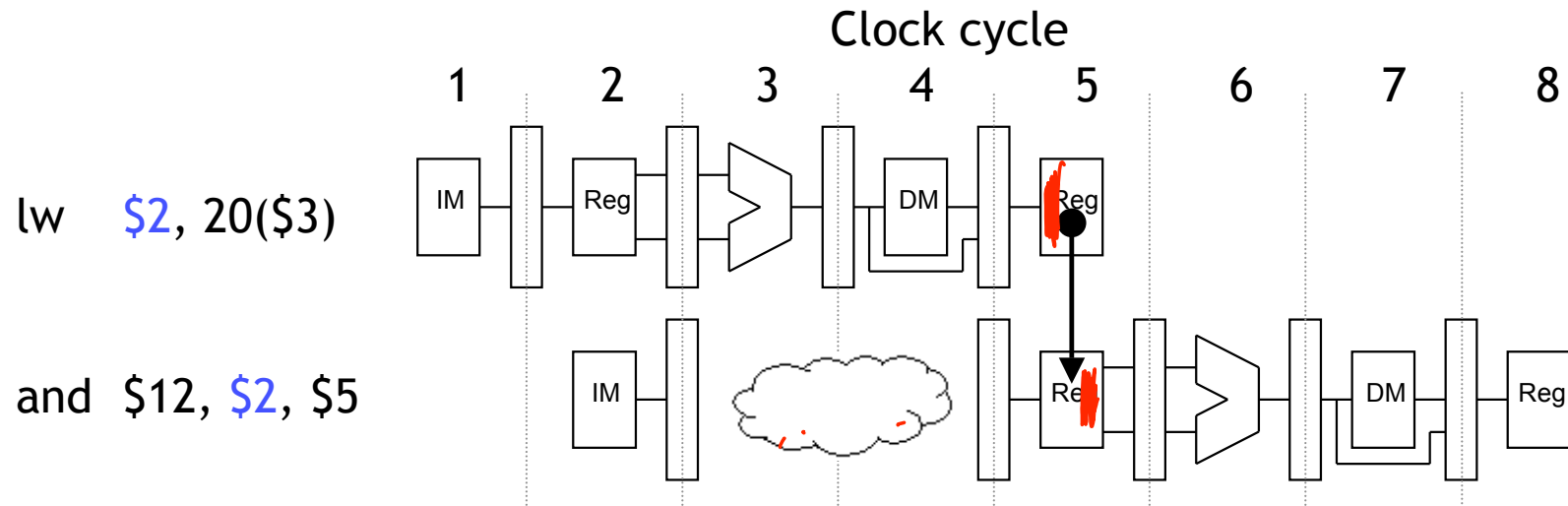
- The easiest solution is to stall the pipeline.
- We could delay the AND instruction by introducing a one-cycle delay into the pipeline, sometimes called a bubble.



- Notice that we're still using forwarding in cycle 5, to get data from the MEM/WB pipeline register to the ALU.

Stalling and forwarding

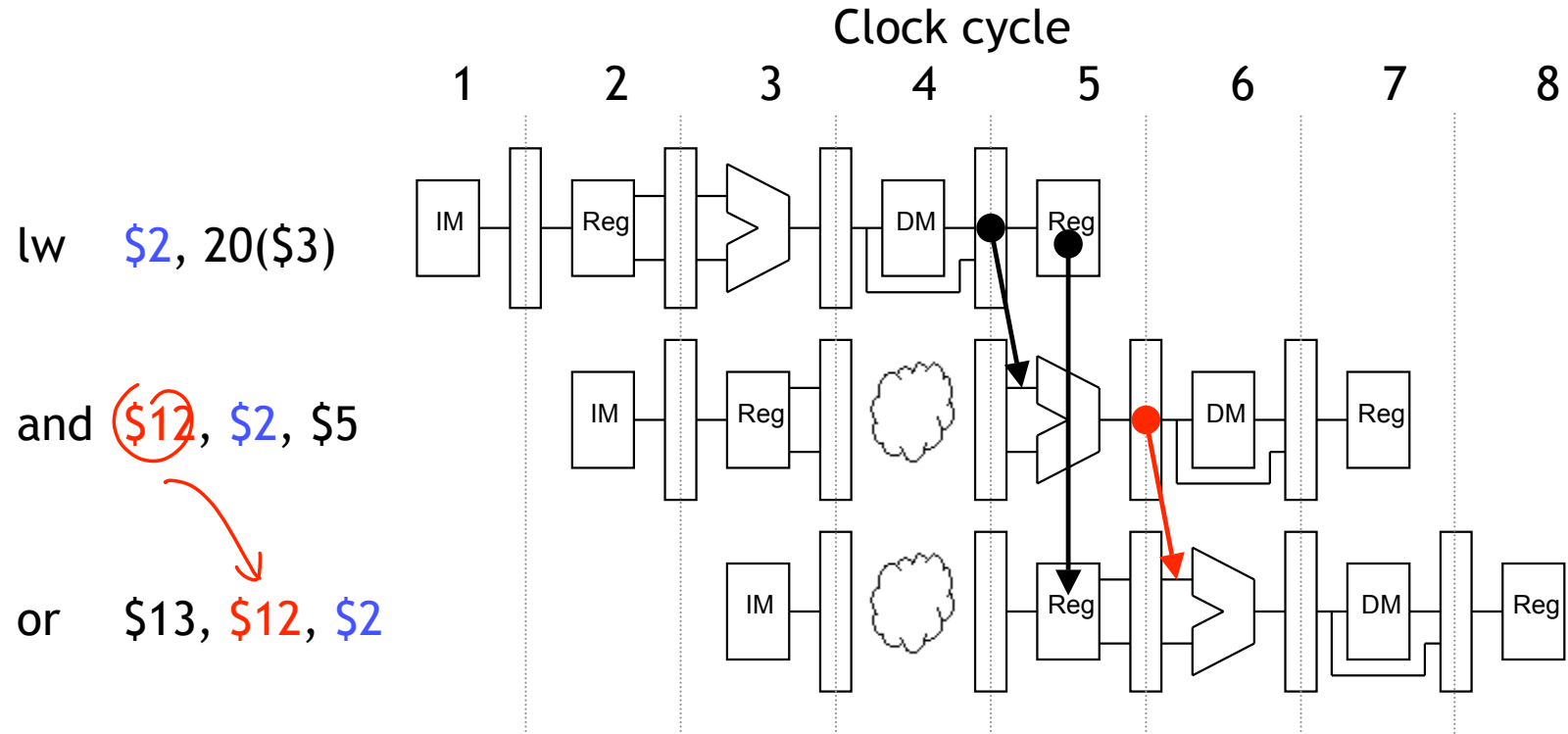
- Without forwarding, we'd have to stall for two cycles to wait for the LW instruction's writeback stage.



- In general, you can always stall to avoid hazards—but dependencies are very common in real code, and stalling often can reduce performance by a significant amount.

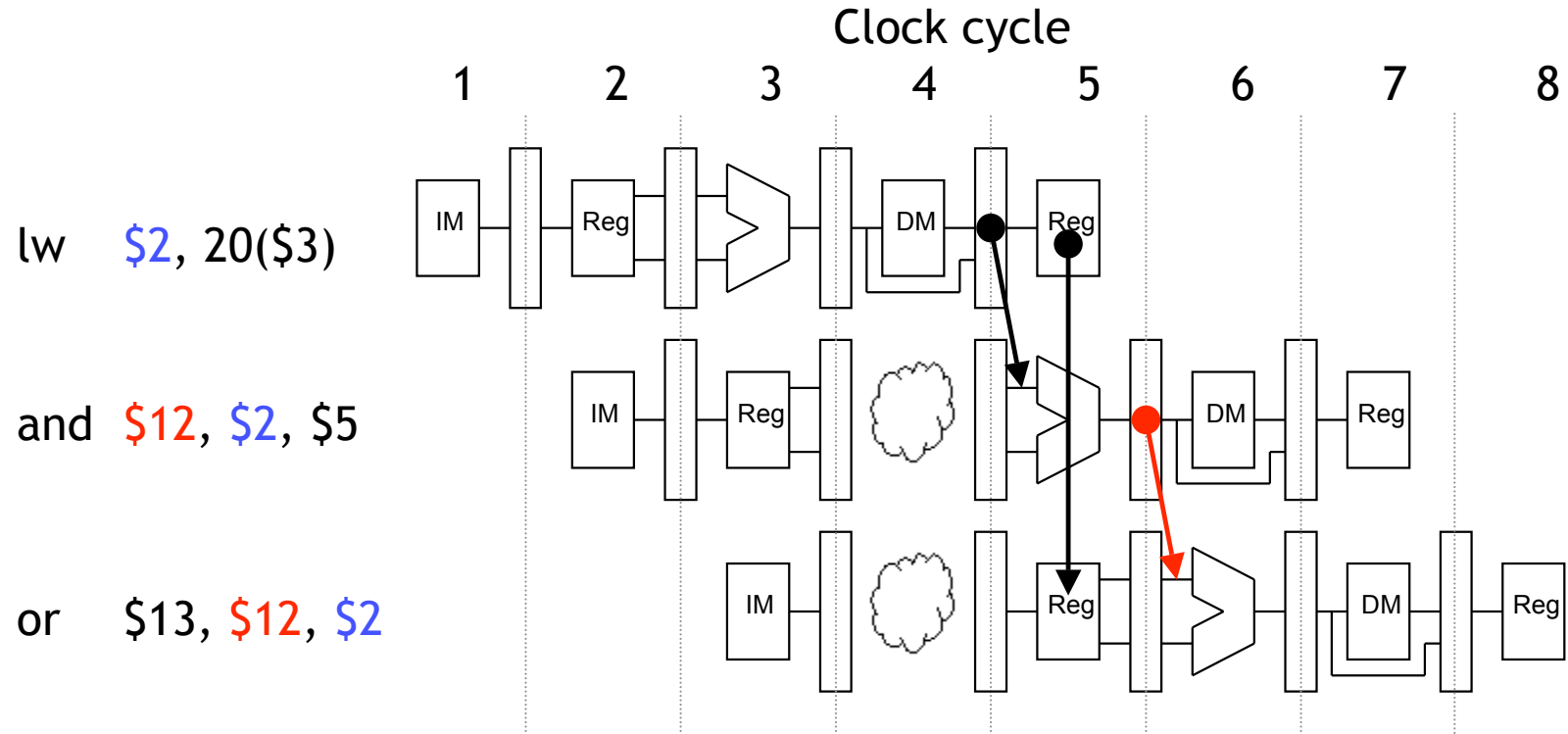
Stalling delays the entire pipeline

- If we delay the second instruction, we'll have to delay the third one too.
 - Why?



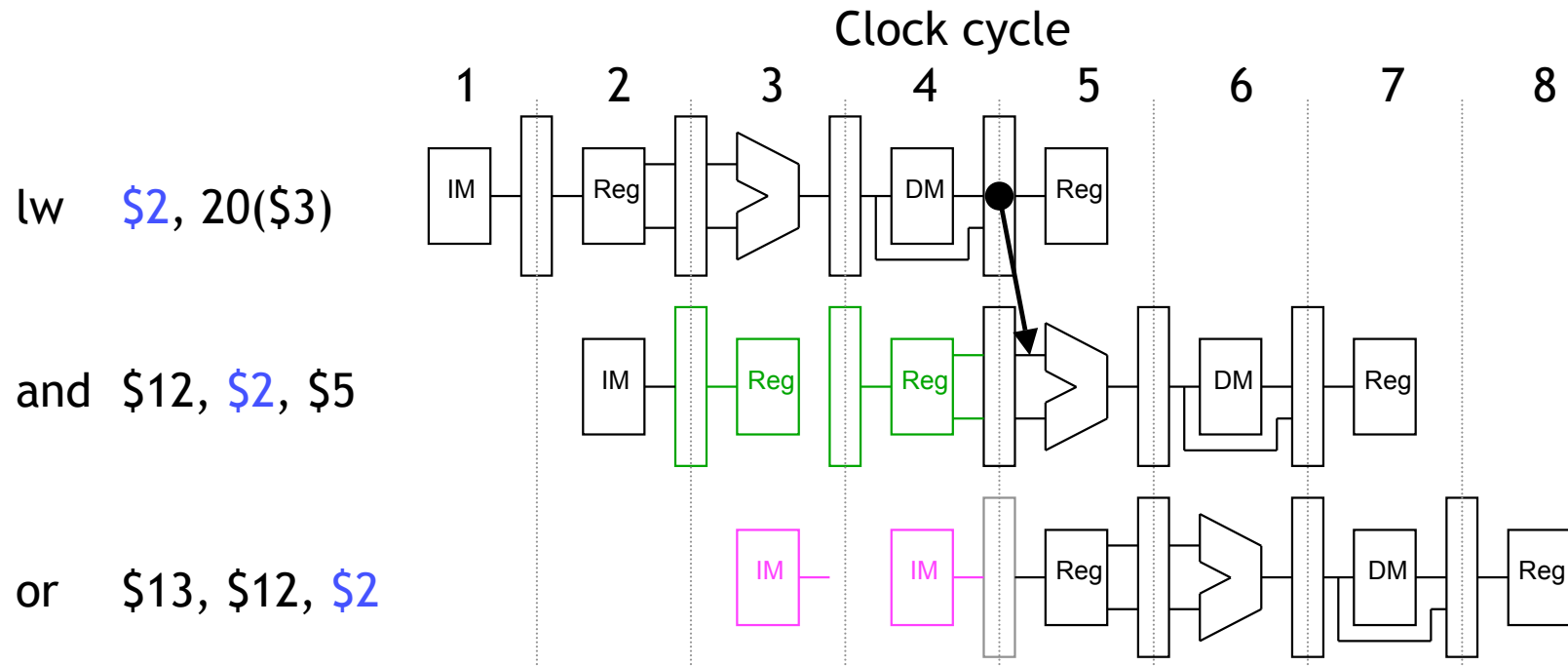
Stalling delays the entire pipeline

- If we delay the second instruction, we'll have to delay the third one too.
 - This is necessary to make forwarding work between AND and OR.
 - It also prevents problems such as two instructions trying to write to the same register in the same cycle.



Implementing stalls

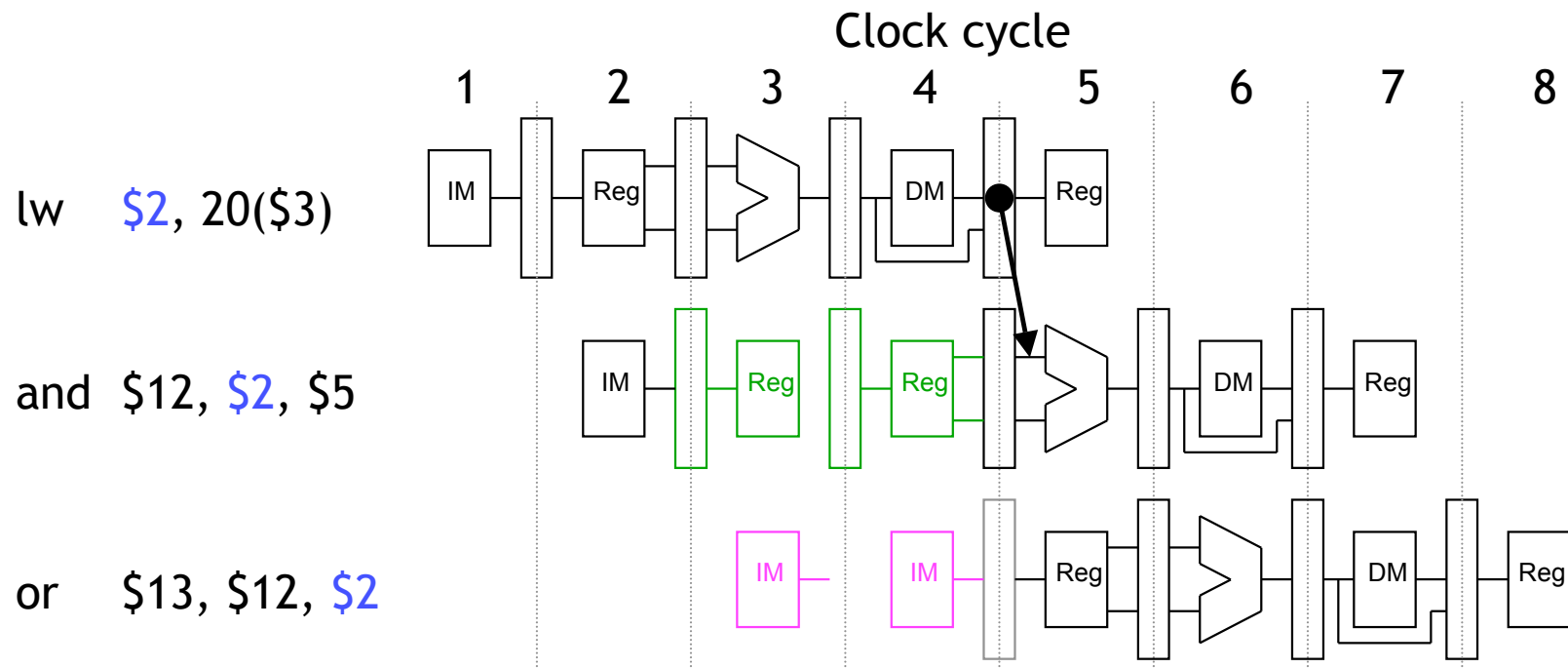
- One way to implement a stall is to force the two instructions after LW to pause and remain in their ID and IF stages for one extra cycle.



- This is easily accomplished.
 - Don't update the PC, so the current IF stage is repeated.
 - Don't update the IF/ID register, so the ID stage is also repeated.

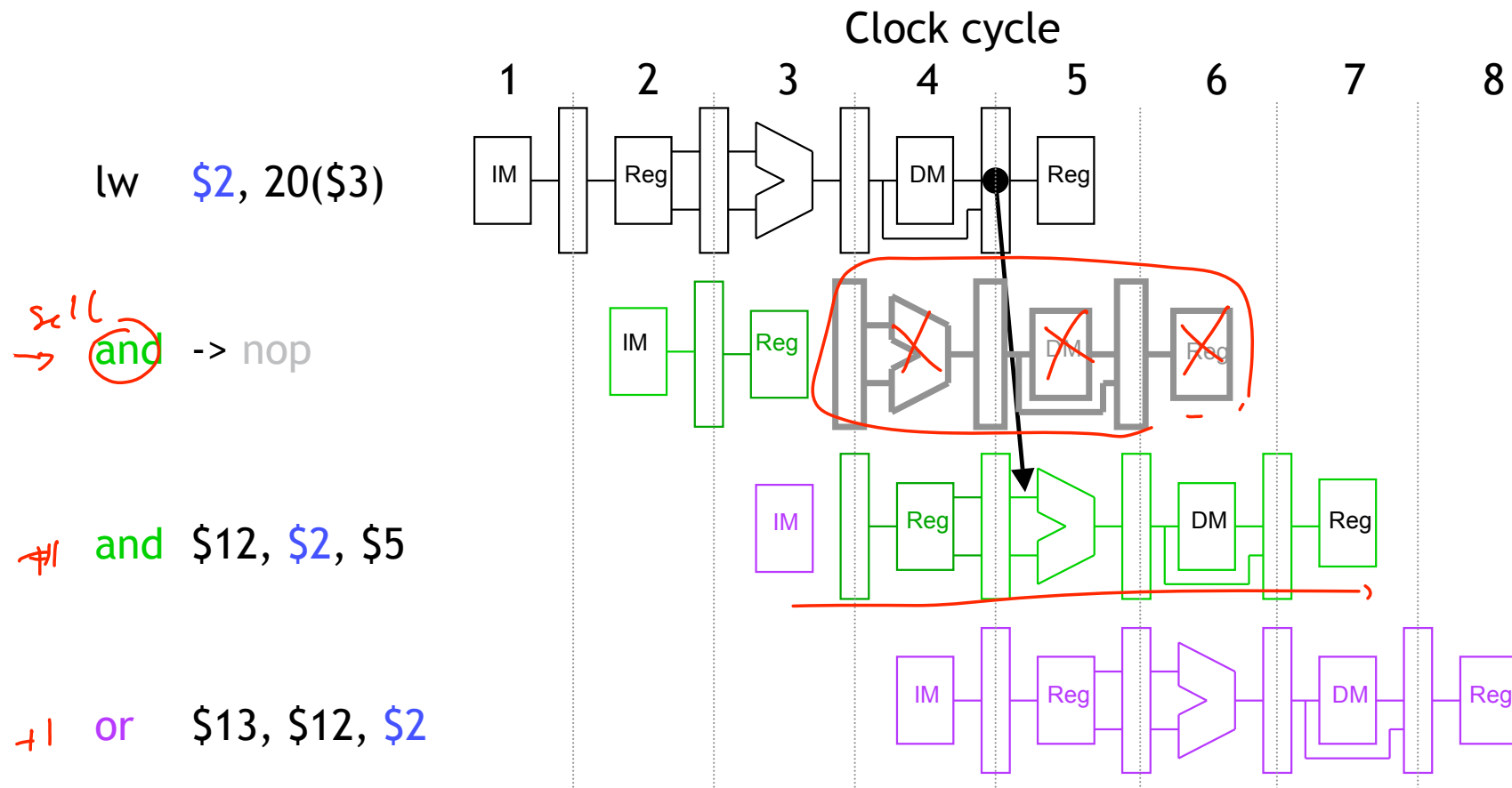
What about EXE, MEM, WB

- But what about the ALU during cycle 4, the data memory in cycle 5, and the register file write in cycle 6?



- Those units aren't used in those cycles because of the stall, so we can set the EX, MEM and WB control signals to all 0s.

Stall = Nop conversion



- The effect of a load stall is to insert an empty or **nop** instruction into the pipeline

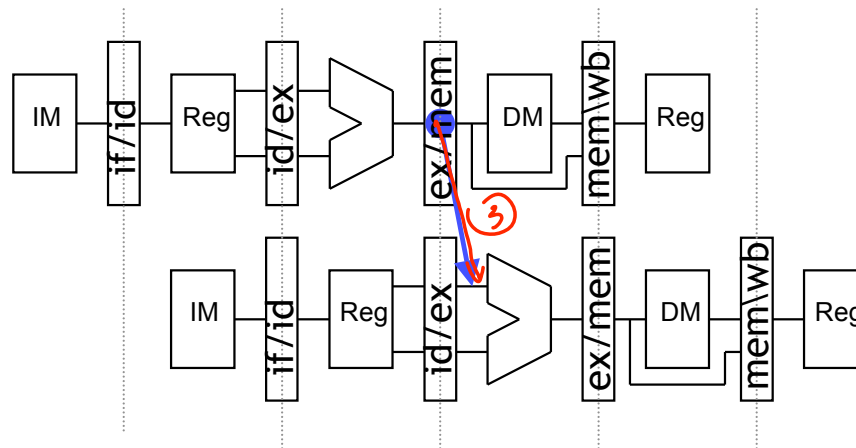
Detecting stalls

- Detecting stall is much like detecting data hazards.

- Recall the format of hazard detection equations:

older if (EX/MEM.RegWrite = 1 ^① *newer*
 and EX/MEM.RegisterRd = ID/EX.RegisterRs ^②
 then Bypass Rs from EX/MEM stage latch ^③

older sub ^① \$2, \$1, \$3
newer and \$12, \$2, \$5 ^②

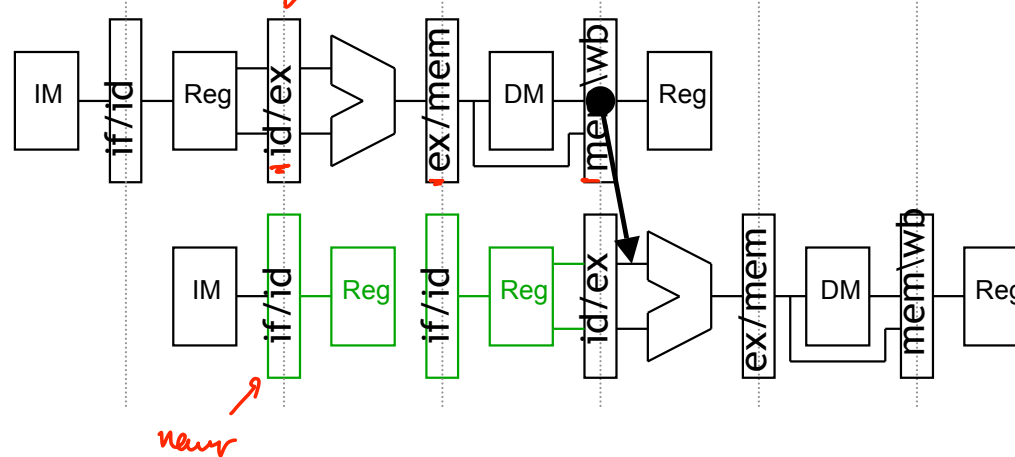


Detecting Stalls, cont.

- When should stalls be detected?

① lw \$2, 20(\$3)

② and \$12, \$2, \$5



- What is the stall condition?

if (ID/EX.MEM READ &&
 ((ID/EX.RS == IF/ID.RS) &&
 (ID/EX.RT == IF/ID.RT))

then stall

① is always
 2's source is
 = 1's dest.

Detecting stalls

- We can detect a load hazard between the current instruction in its ID stage and the previous instruction in the EX stage just like we detected data hazards.
- A hazard occurs if the previous instruction was LW...

$ID/EX.MemRead = 1$

...and the LW destination is one of the current source registers.

$ID/EX.RegisterRt = IF/ID.RegisterRs$

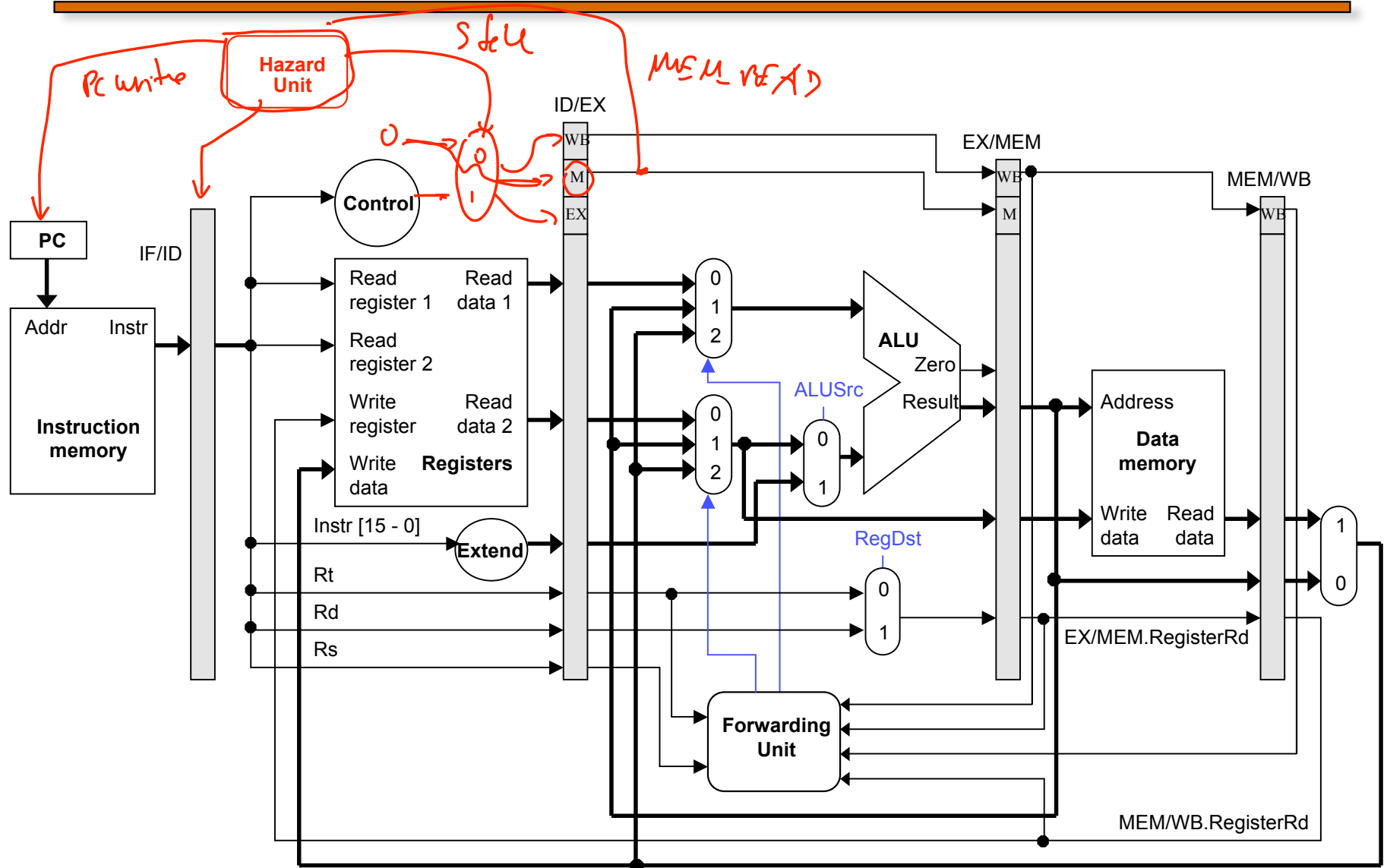
or

$ID/EX.RegisterRt = IF/ID.RegisterRt$

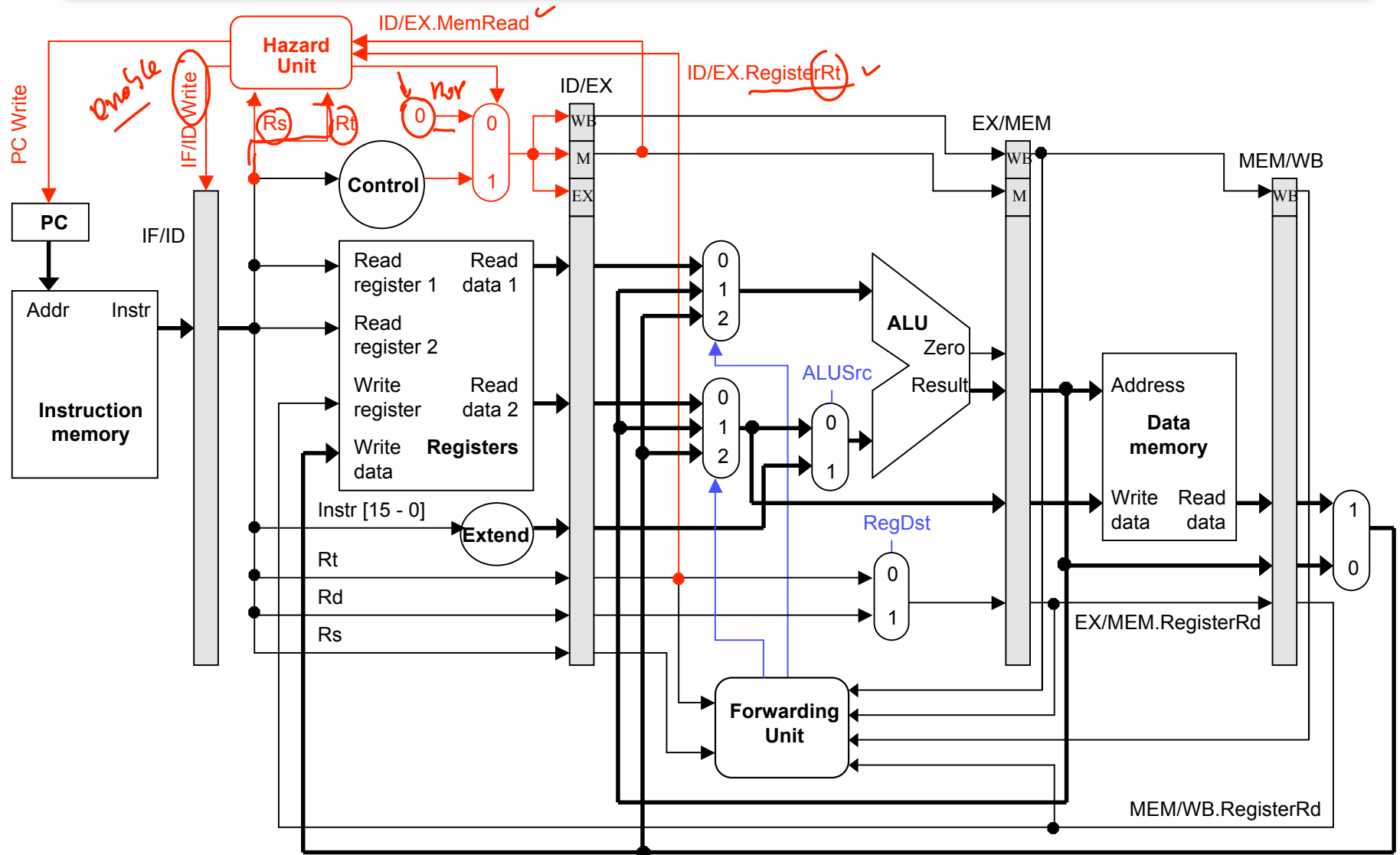
- The complete test for stalling is the conjunction of these two conditions.

if ($ID/EX.MemRead = 1$ and
 ($ID/EX.RegisterRt = IF/ID.RegisterRs$ or
 $ID/EX.RegisterRt = IF/ID.RegisterRt$))
then stall

Adding hazard detection to the CPU



Adding hazard detection to the CPU

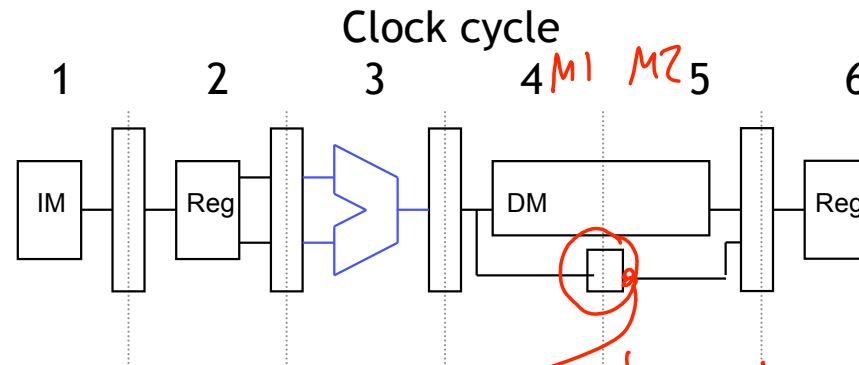


The hazard detection unit

- The hazard detection unit's inputs are as follows.
 - **IF/ID.RegisterRs** and **IF/ID.RegisterRt**, the source registers for the current instruction.
 - **ID/EX.MemRead** and **ID/EX.RegisterRt**, to determine if the previous instruction is LW and, if so, which register it will write to.
- By inspecting these values, the detection unit generates three outputs.
 - Two new control signals **PCWrite** and **IF/ID Write**, which determine whether the pipeline stalls or continues.
 - A **mux select** for a new multiplexer, which forces control signals for the current EX and future MEM/WB stages to 0 in case of a stall.

Generalizing Forwarding/Stalling

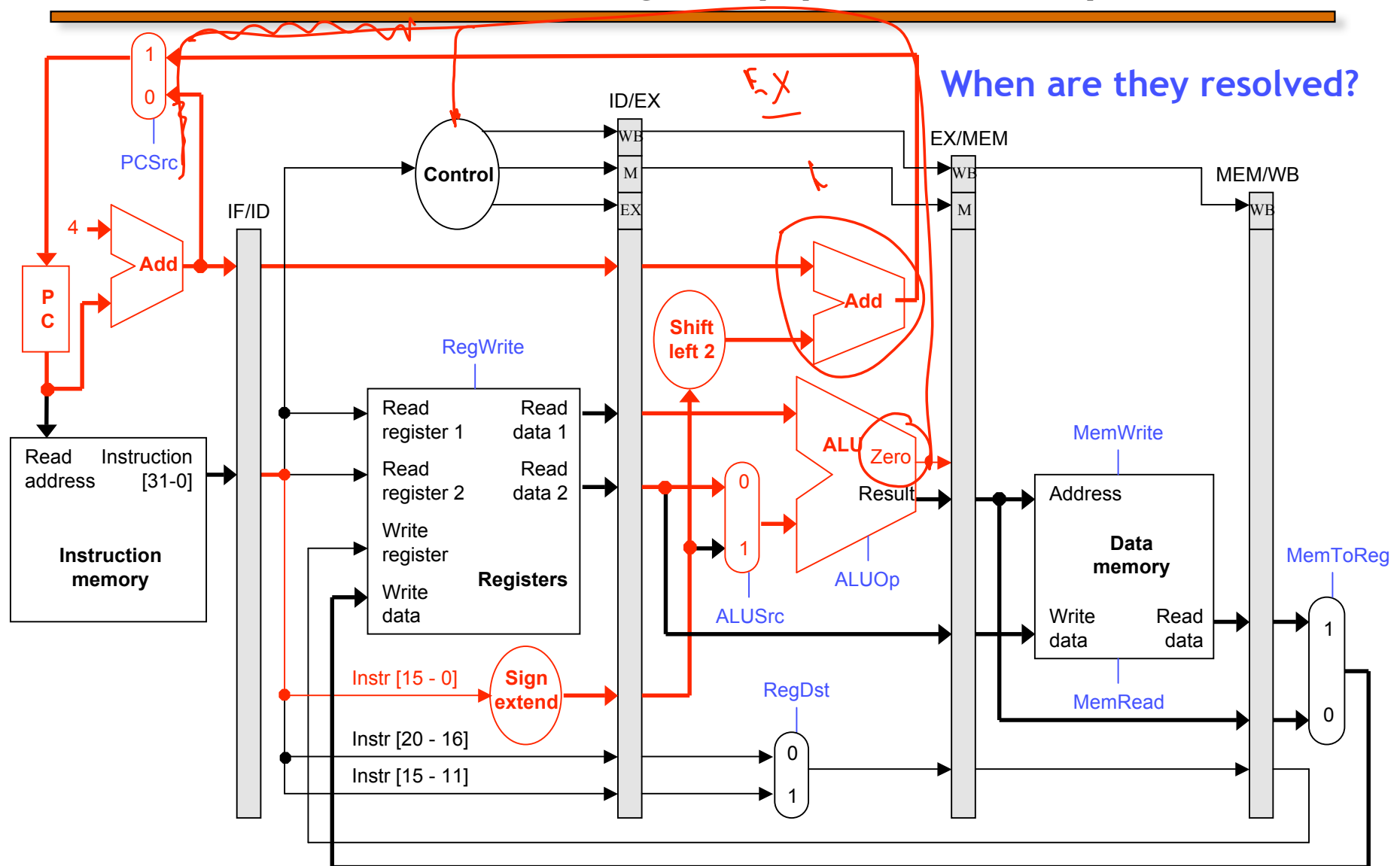
- What if data memory access was so slow, we wanted to pipeline it over 2 cycles?



- How many bypass inputs would the muxes in EXE have? *also enable mem*
- Which instructions in the following require stalling and/or bypassing? *feeding*

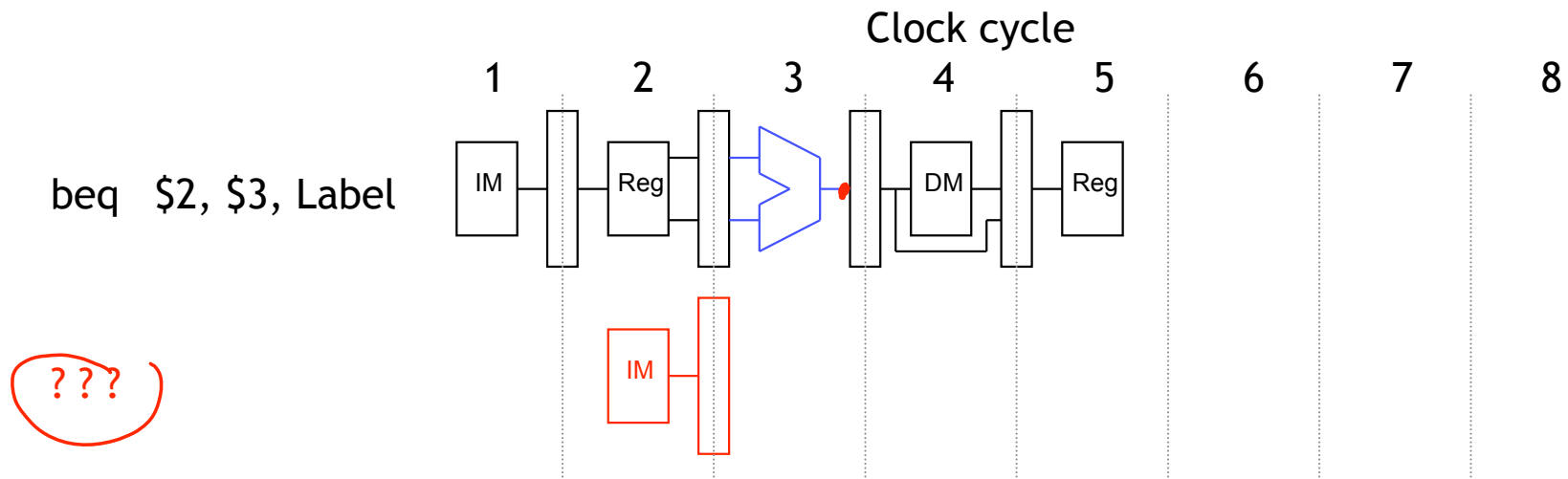
lw r13, 0(r11)
add r7, r8, r9
add r15, r7, r13

Branches in the original pipelined datapath



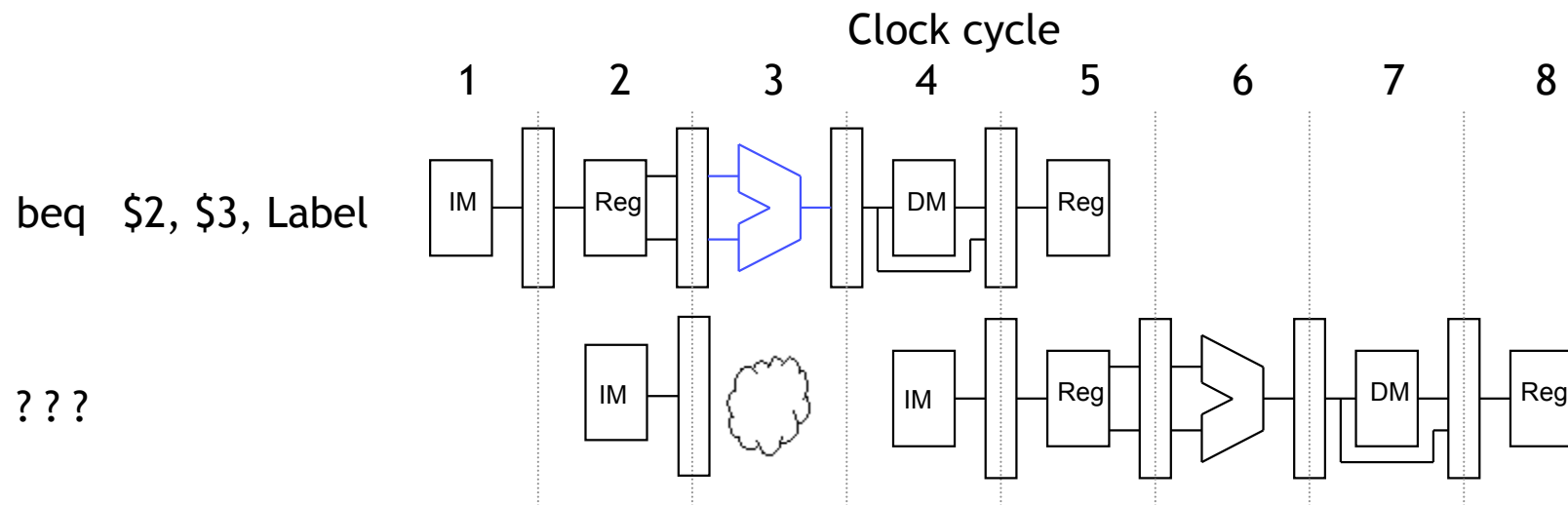
Branches

- Most of the work for a branch computation is done in the EX stage.
 - The branch target address is computed. ✓
 - The source registers are compared by the ALU, and the Zero flag is set or cleared accordingly. ✓
- Thus, the branch decision cannot be made until the end of the EX stage.
 - But we need to know which instruction to fetch next, in order to keep the pipeline running! –
 - This leads to what's called a control hazard.



Stalling is one solution

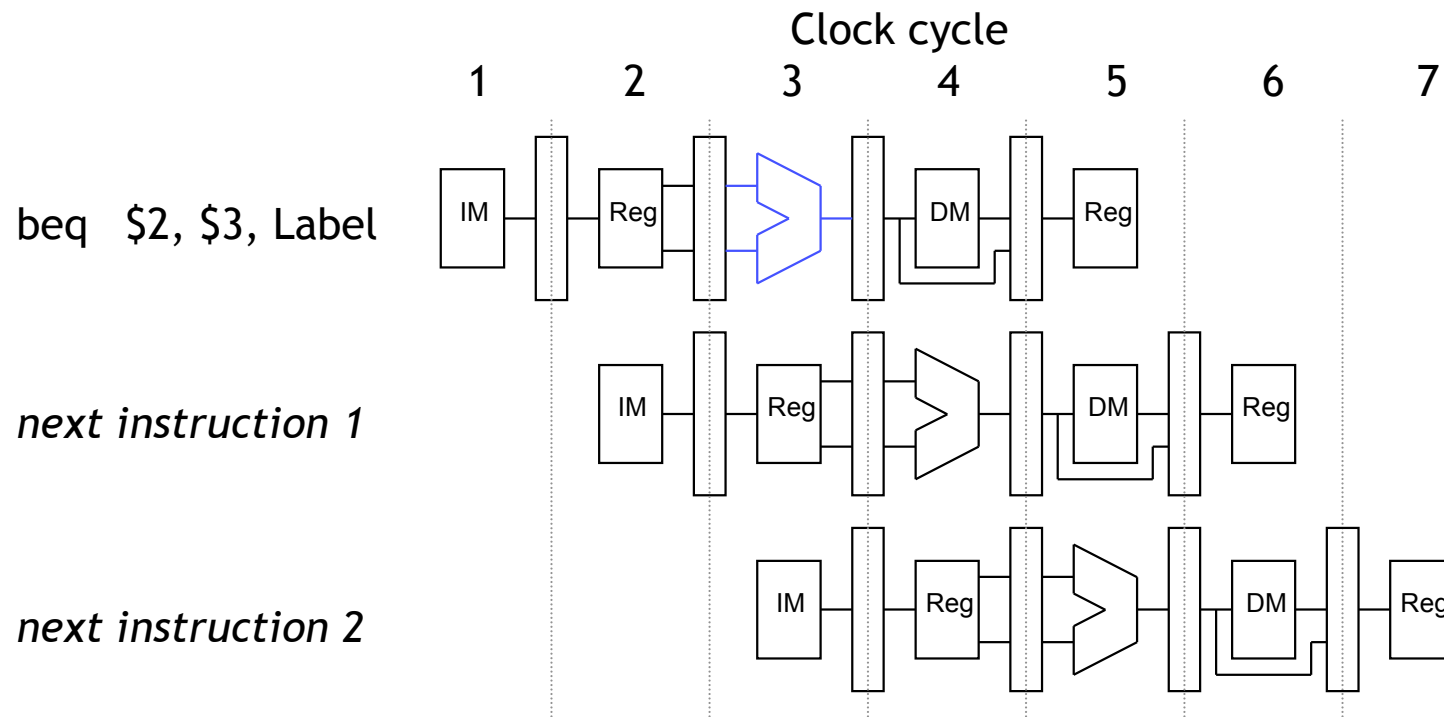
- Again, stalling is always one possible solution.



- Here we just stall until cycle 4, after we do make the branch decision.

Branch prediction

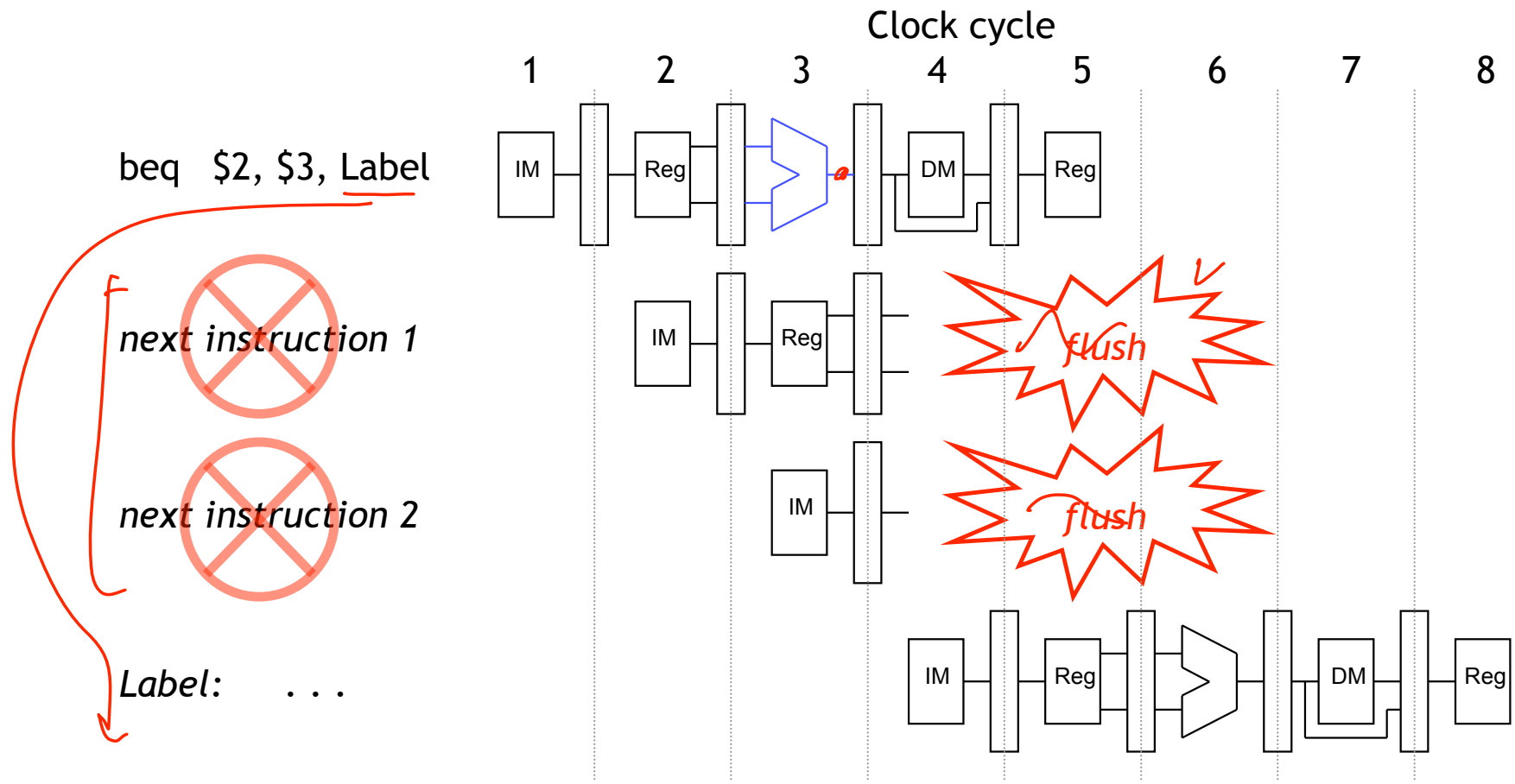
- Another approach is to guess whether or not the branch is taken.
 - In terms of hardware, it's easier to assume the branch is not taken.
 - This way we just increment the PC and continue execution, as for normal instructions.
- If we're correct, then there is no problem and the pipeline keeps going at full speed.



Label

Branch misprediction

- If our guess is wrong, then we would have already started executing two instructions incorrectly. We'll have to discard, or **flush**, those instructions and begin executing the right ones from the branch target address, Label.

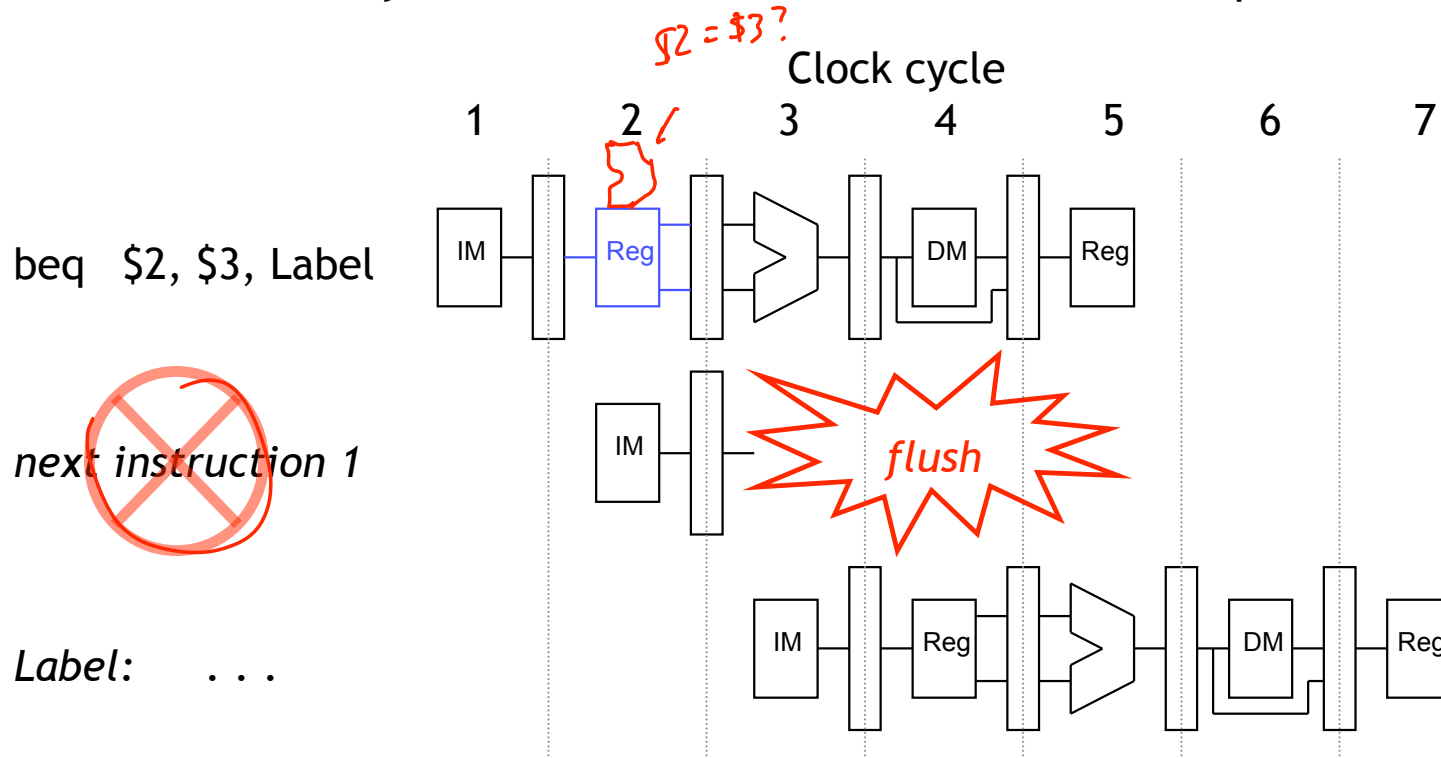


Performance gains and losses

- Overall, branch prediction is worth it.
 - Mispredicting a branch means that two clock cycles are wasted.
 - But if our predictions are even just occasionally correct, then this is preferable to stalling and wasting two cycles for every branch.
- All modern CPUs use branch prediction.
 - Accurate predictions are important for optimal performance.
 - Most CPUs predict branches dynamically—statistics are kept at run-time to determine the likelihood of a branch being taken.
- The pipeline structure also has a big impact on branch prediction.
 - A longer pipeline may require more instructions to be flushed for a misprediction, resulting in more wasted time and lower performance.
 - We must also be careful that instructions do not modify registers or memory before they get flushed.

Implementing branches

- We can actually decide the branch a little earlier, in ID instead of EX.
 - Our sample instruction set has only a BEQ.
 - We can add a small comparison circuit to the ID stage, after the source registers are read.
- Then we would only need to flush one instruction on a misprediction.

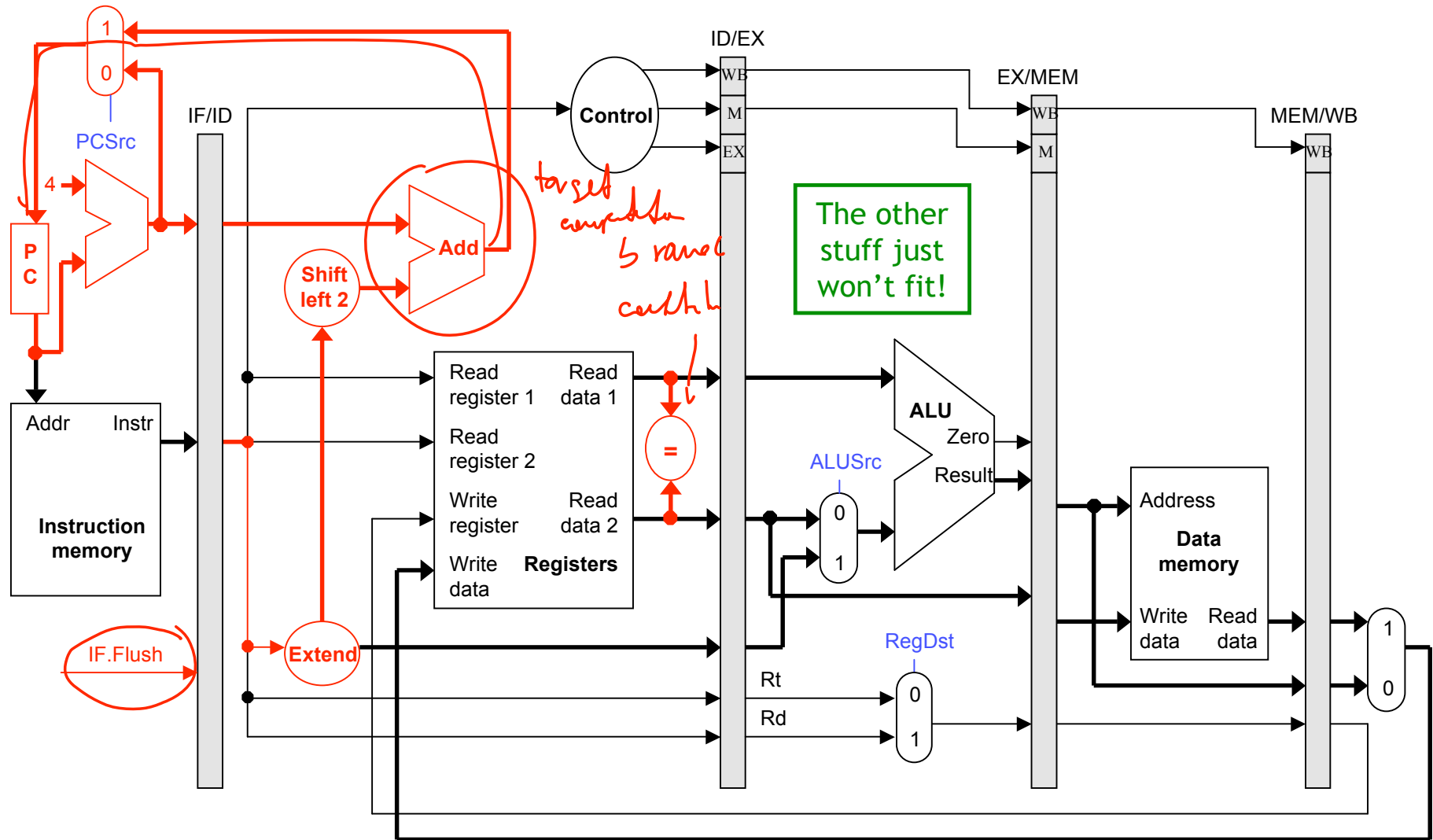


Implementing flushes

- We must flush one instruction (in its IF stage) if the previous instruction is BEQ and its two source registers are equal. *→ taken*
- We can flush an instruction from the IF stage by replacing it in the IF/ID pipeline register with a harmless nop instruction.
 - MIPS uses sll \$0, \$0, 0 as the nop instruction.
 - This happens to have a binary encoding of all 0s: 0000 0000.
- Flushing introduces a bubble into the pipeline, which represents the one-cycle delay in taking the branch.
- The IF.Flush control signal shown on the next page implements this idea, but no details are shown in the diagram.



Branching without forwarding and load stalls



Timing

- If no prediction:

IF ID EX MEM WB
IF IF ID EX MEM WB --- lost 1 cycle

- If prediction:

- If Correct ✓

IF ID EX MEM WB
IF ID EX MEM WB -- no cycle lost

- If Misprediction:

IF ID EX MEM WB
~~IF0~~ IF1 ID EX MEM WB --- 1 cycle lost

↑ *fake ID stage and prediction*

Summary

- Three kinds of hazards conspire to make pipelining difficult.
- **Structural hazards** result from not having enough hardware available to execute multiple instructions simultaneously.
 - These are avoided by adding more functional units (e.g., more adders or memories) or by redesigning the pipeline stages.
- **Data hazards** can occur when instructions need to access registers that haven't been updated yet.
 - Hazards from R-type instructions can be avoided with forwarding.
 - Loads can result in a “true” hazard, which must stall the pipeline.
- **Control hazards** arise when the CPU cannot determine which instruction to fetch next.
 - We can minimize delays by doing branch tests earlier in the pipeline.
 - We can also take a chance and predict the branch direction, to make the most of a bad situation.