Lecture 13

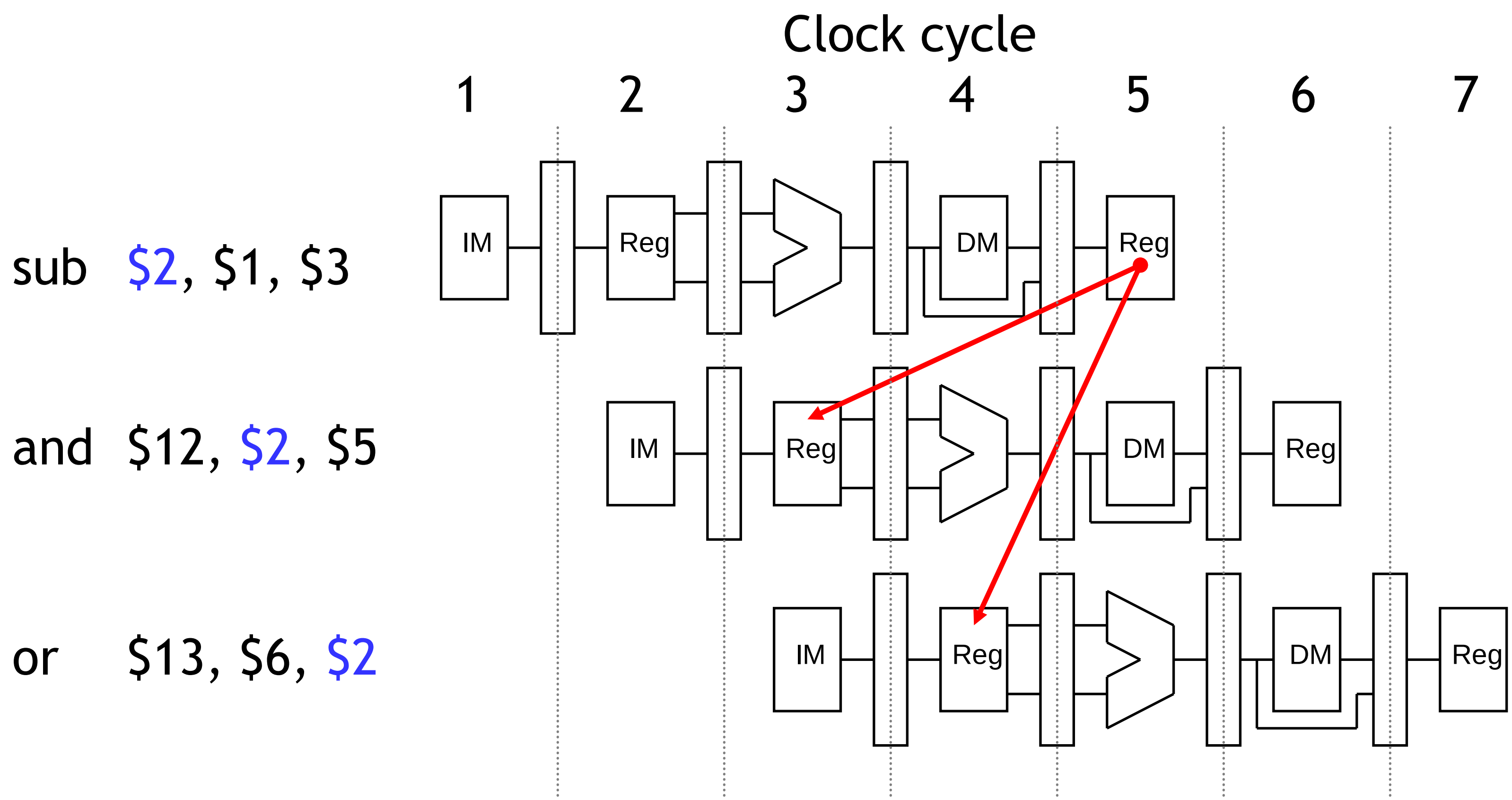
- Today's lecture:
  - What about load followed by use?
  - What about branches?
  - Crystal ball

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.

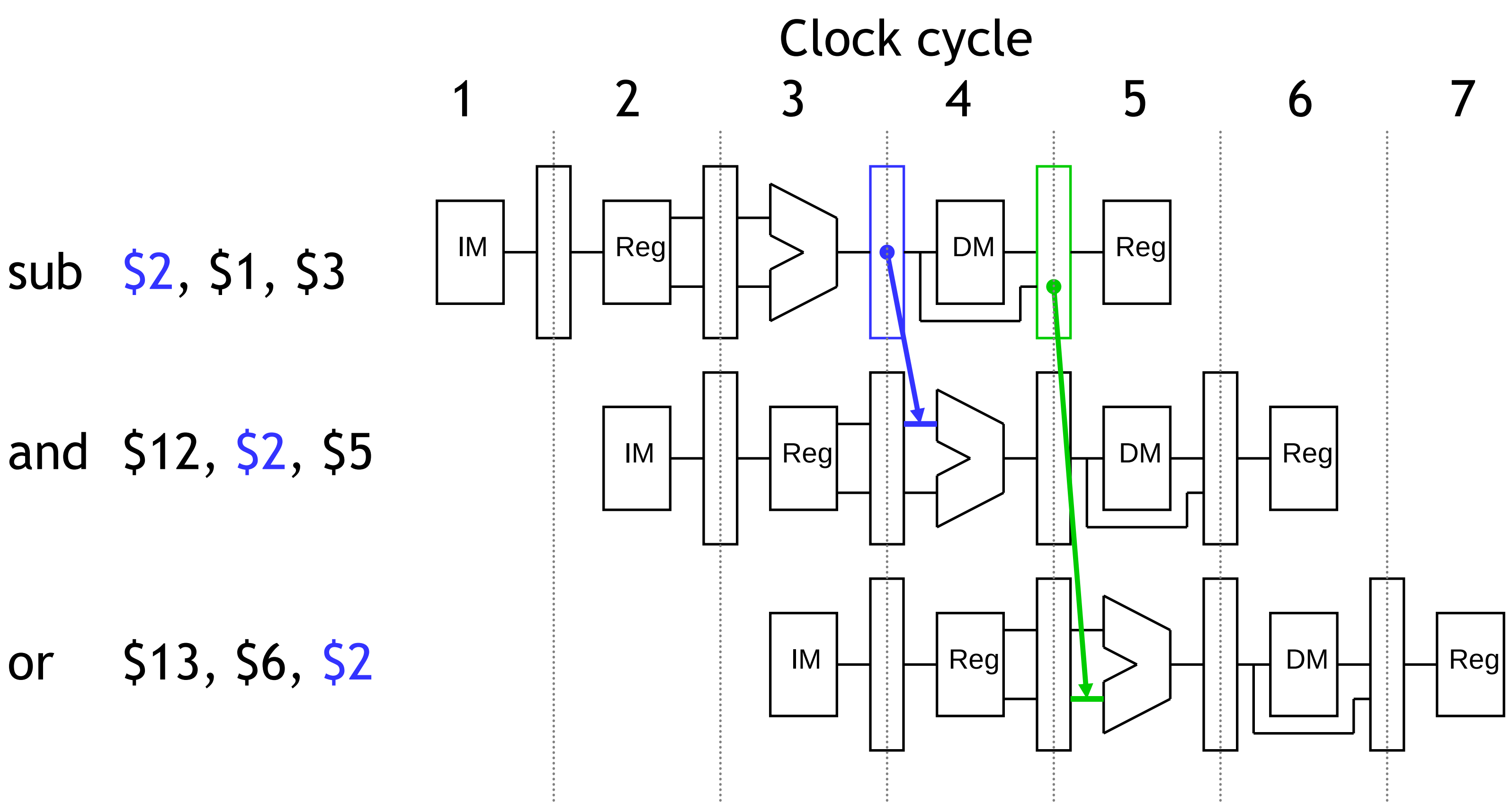
Data hazard review

- 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.



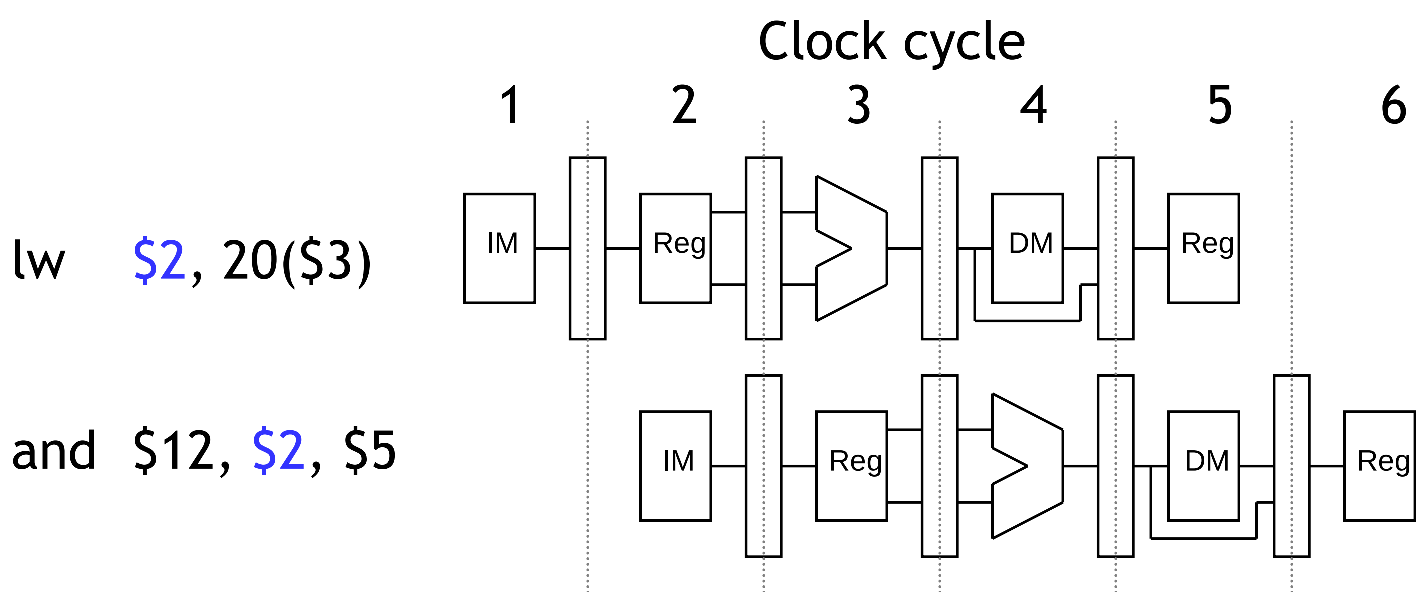
Forwarding

- 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.



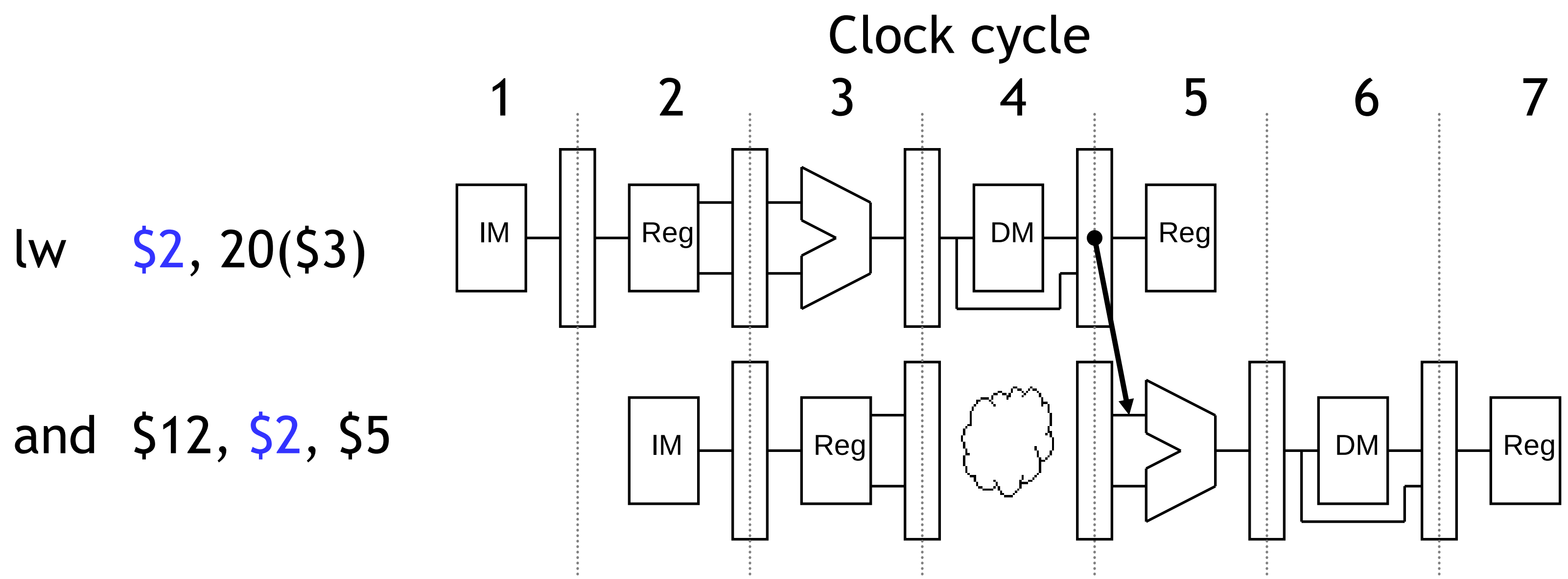
What about loads?

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



Stalling

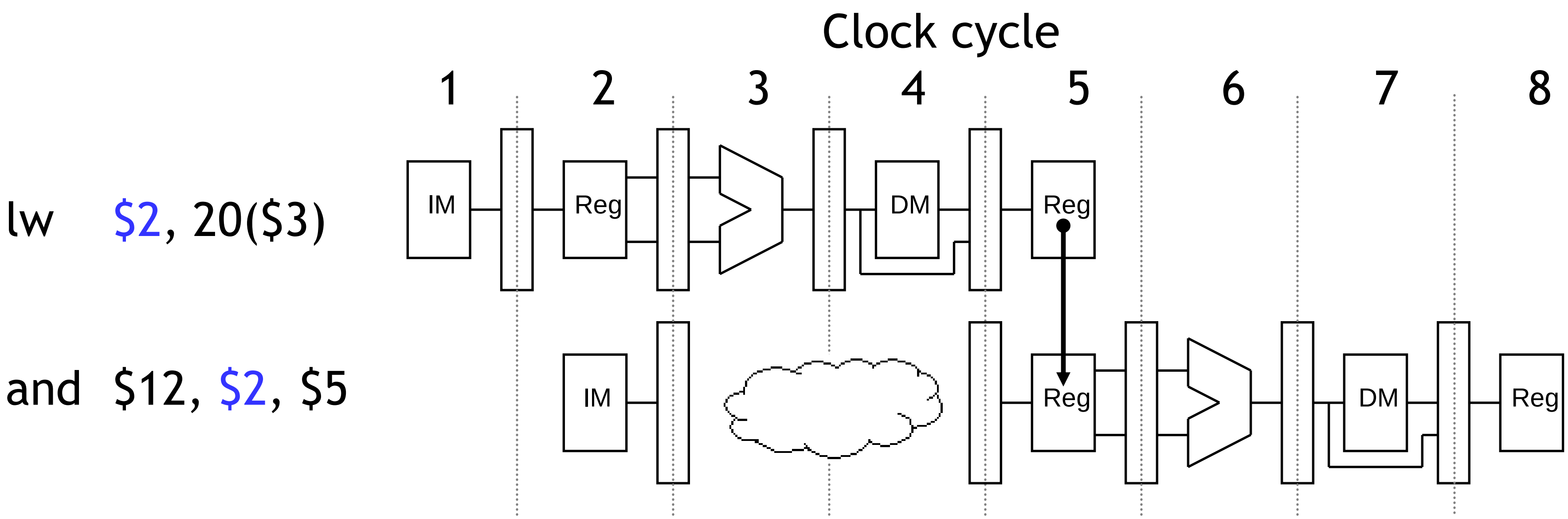
- The easiest solution is to stall the pipeline.
- We could delay the AND instruction by introducing a one-cycle delay into the pipeline, sometimes called a bubble.



- 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

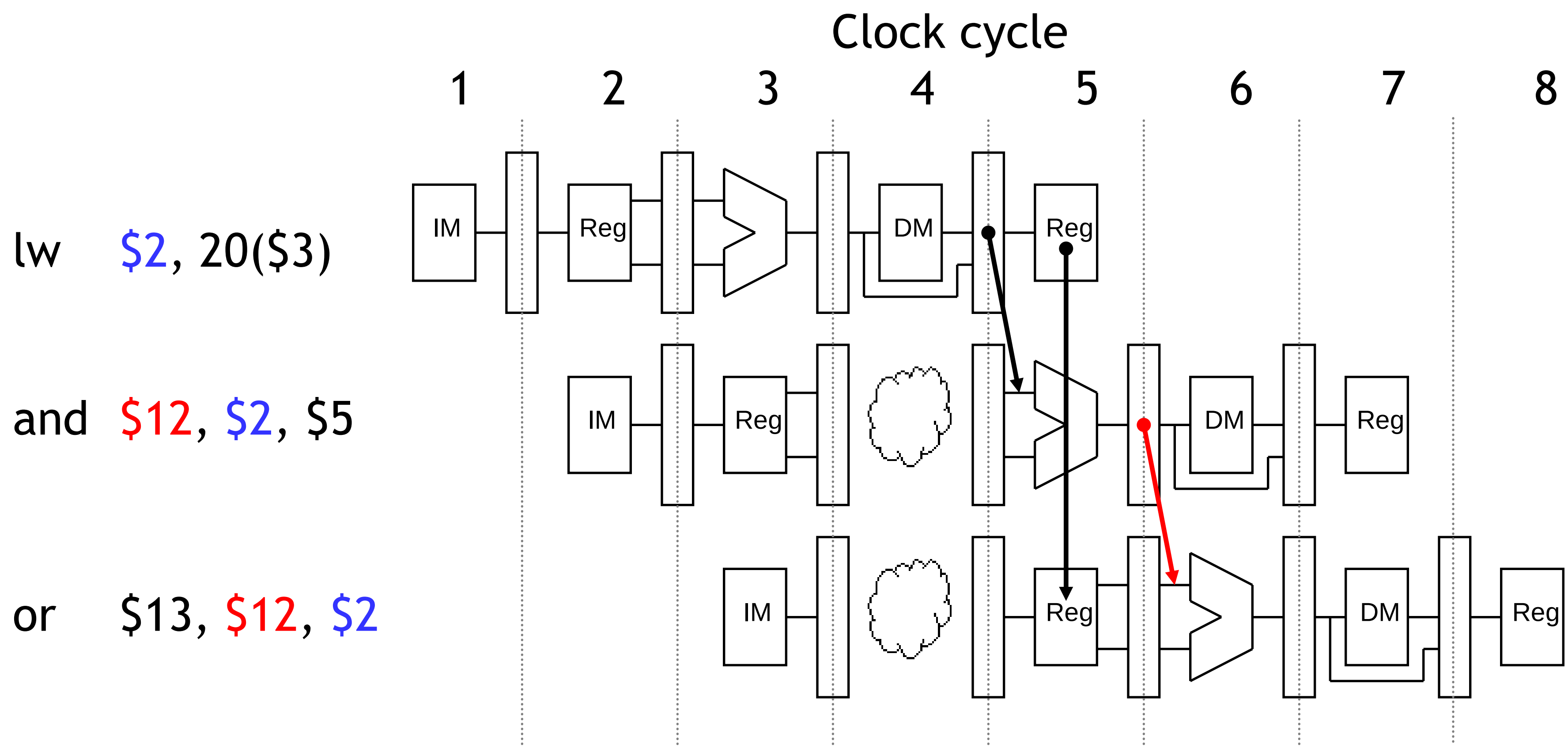
- Without forwarding, we'd have to stall for *two* cycles to wait for the LW instruction's writeback stage.



- 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.

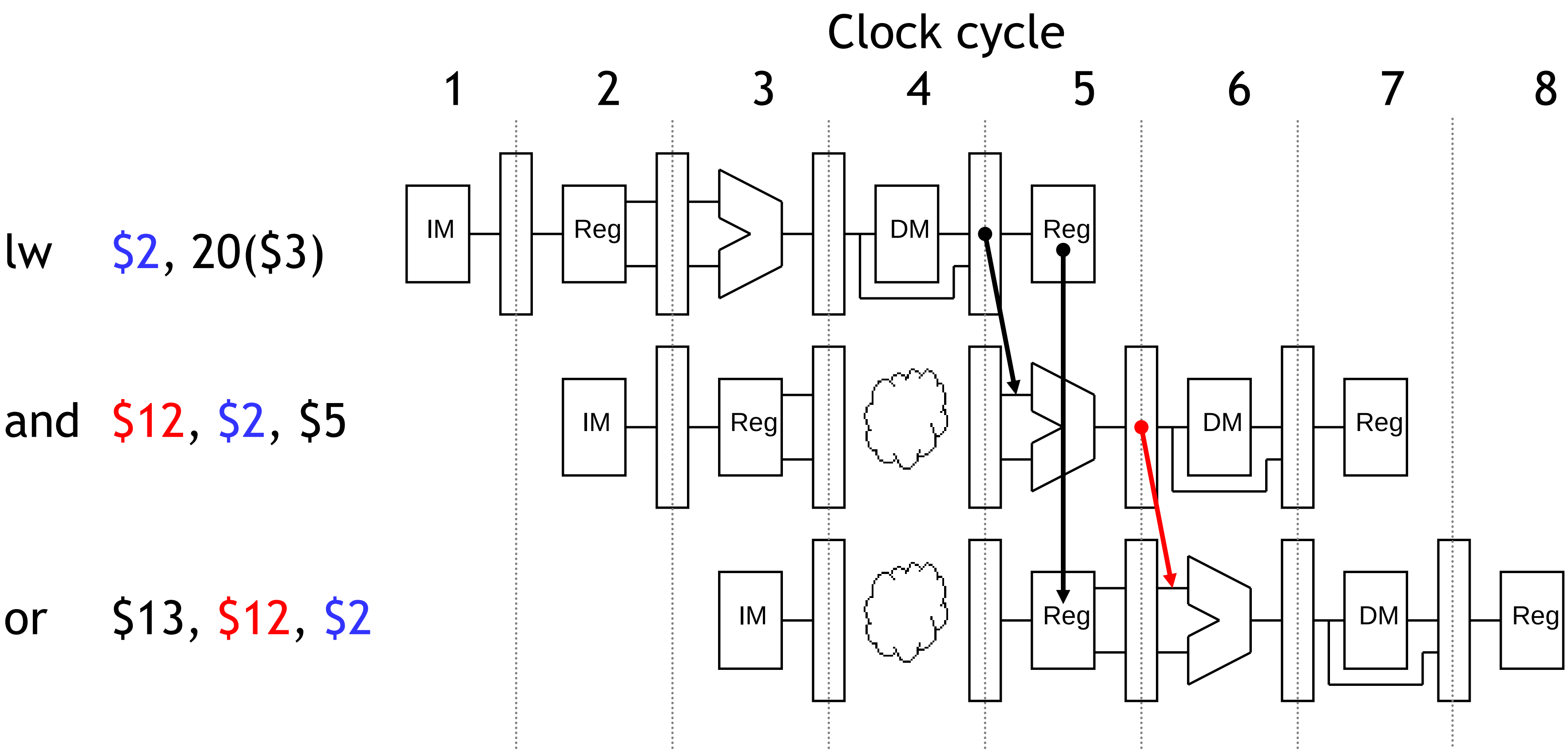
Stalling delays the entire pipeline

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



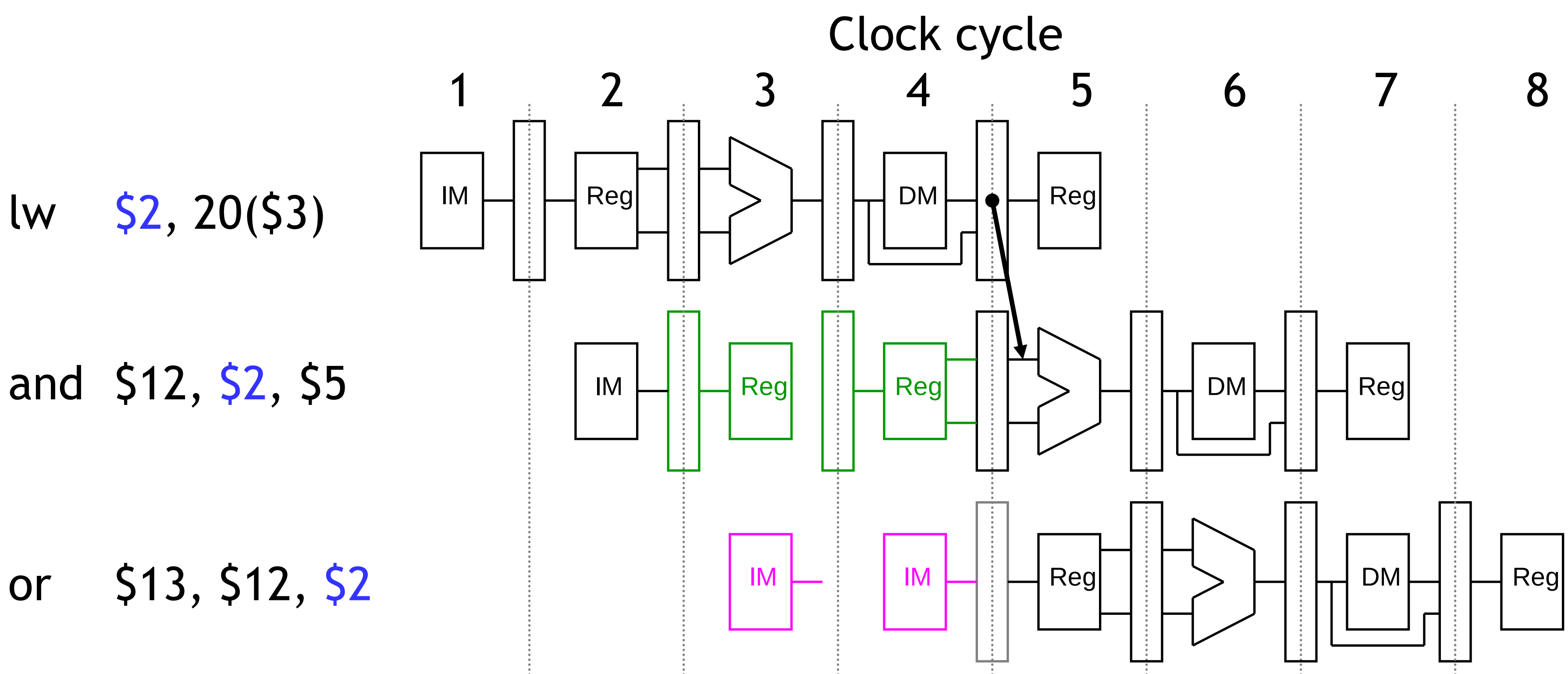
Stalling delays the entire pipeline

- 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.



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.

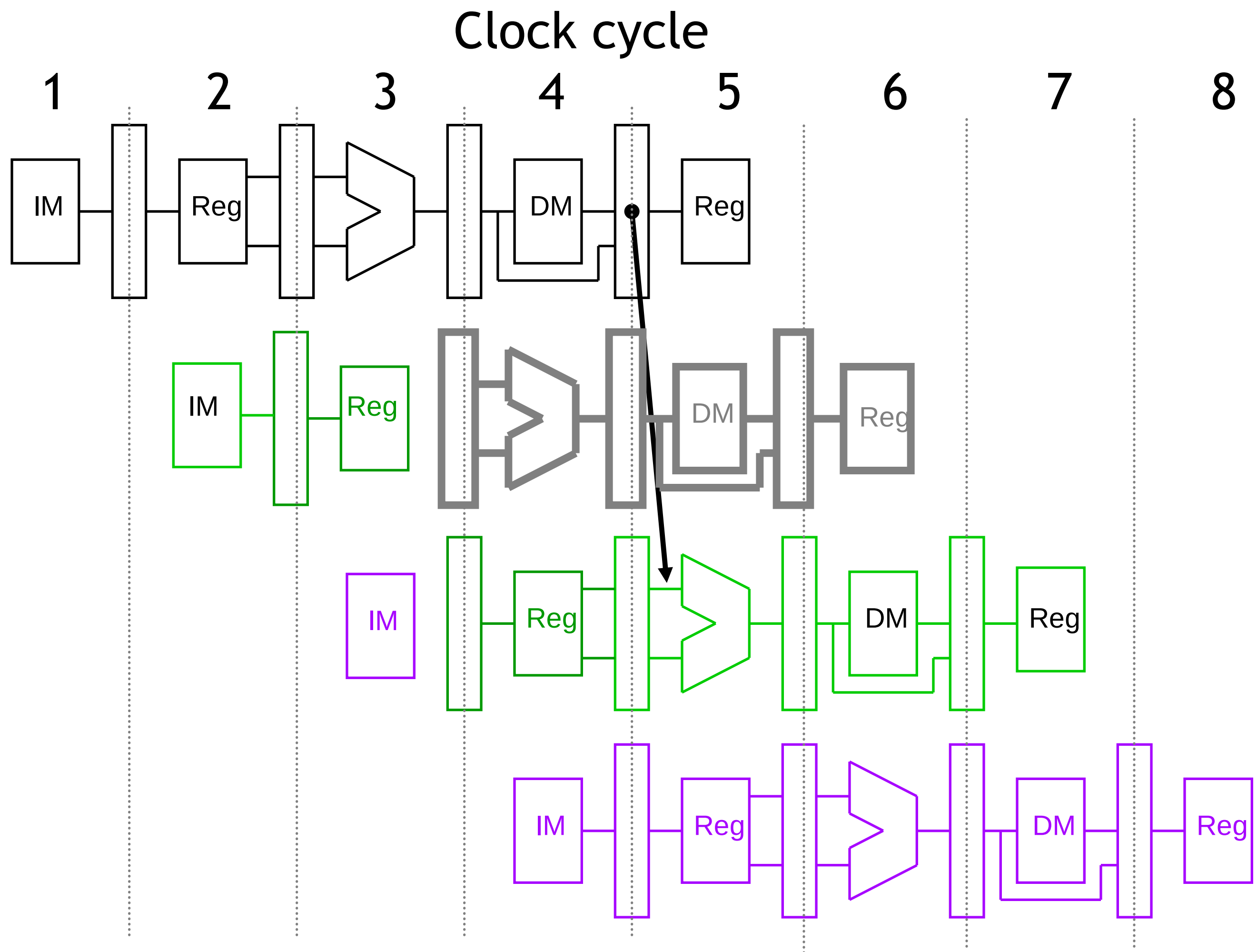
Stall = Nop conversion

lw $2, 20($3)

and -> nop

and $12, $2, $5

or $13, $12, $2



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

Detecting stalls

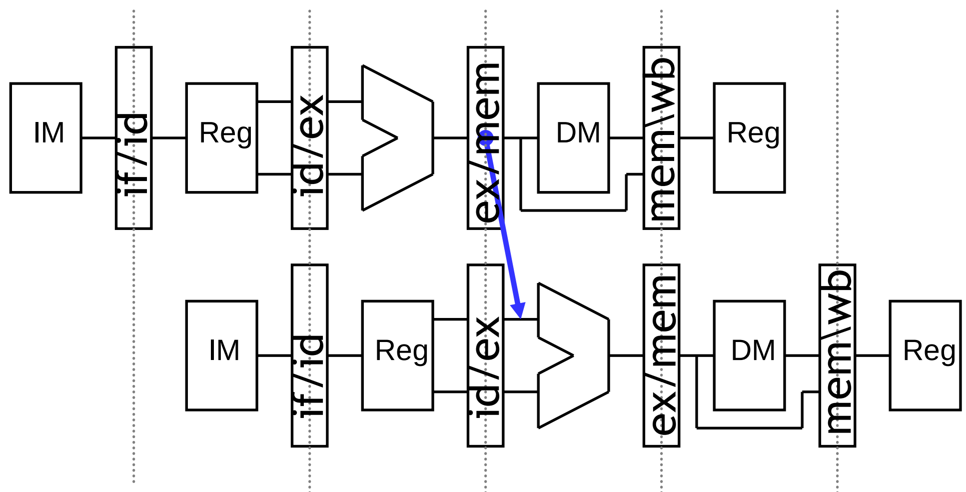
- Detecting stall is much like detecting data hazards.

- Recall the format of hazard detection equations:

if (EX/MEM.RegWrite = 1
    and EX/MEM.RegisterRd = ID/EX.RegisterRs)
then Bypass Rs from EX/MEM stage latch

sub $2, $1, $3

and $12, $2, $5

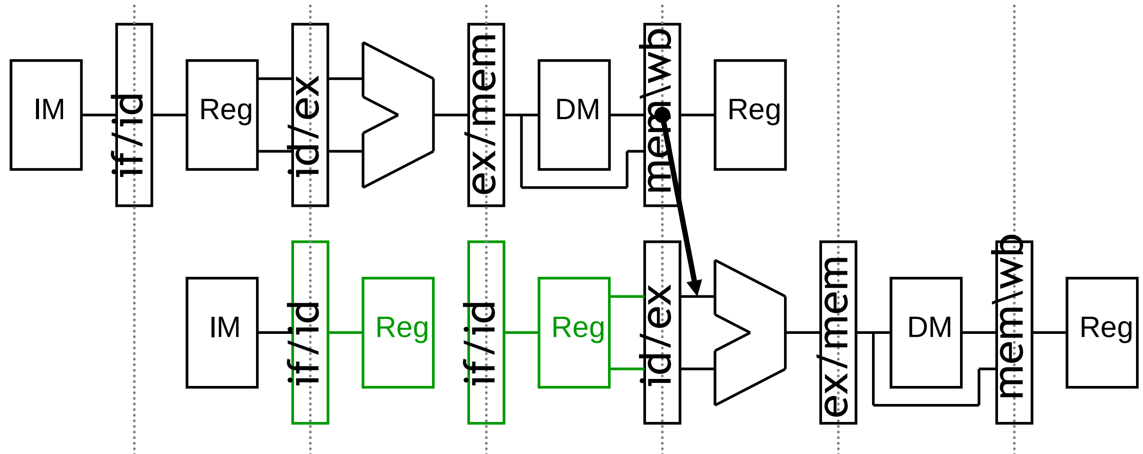


Detecting Stalls, cont.

- When should **stalls** be detected?

lw $2, 20($3)

and $12, $2, $5



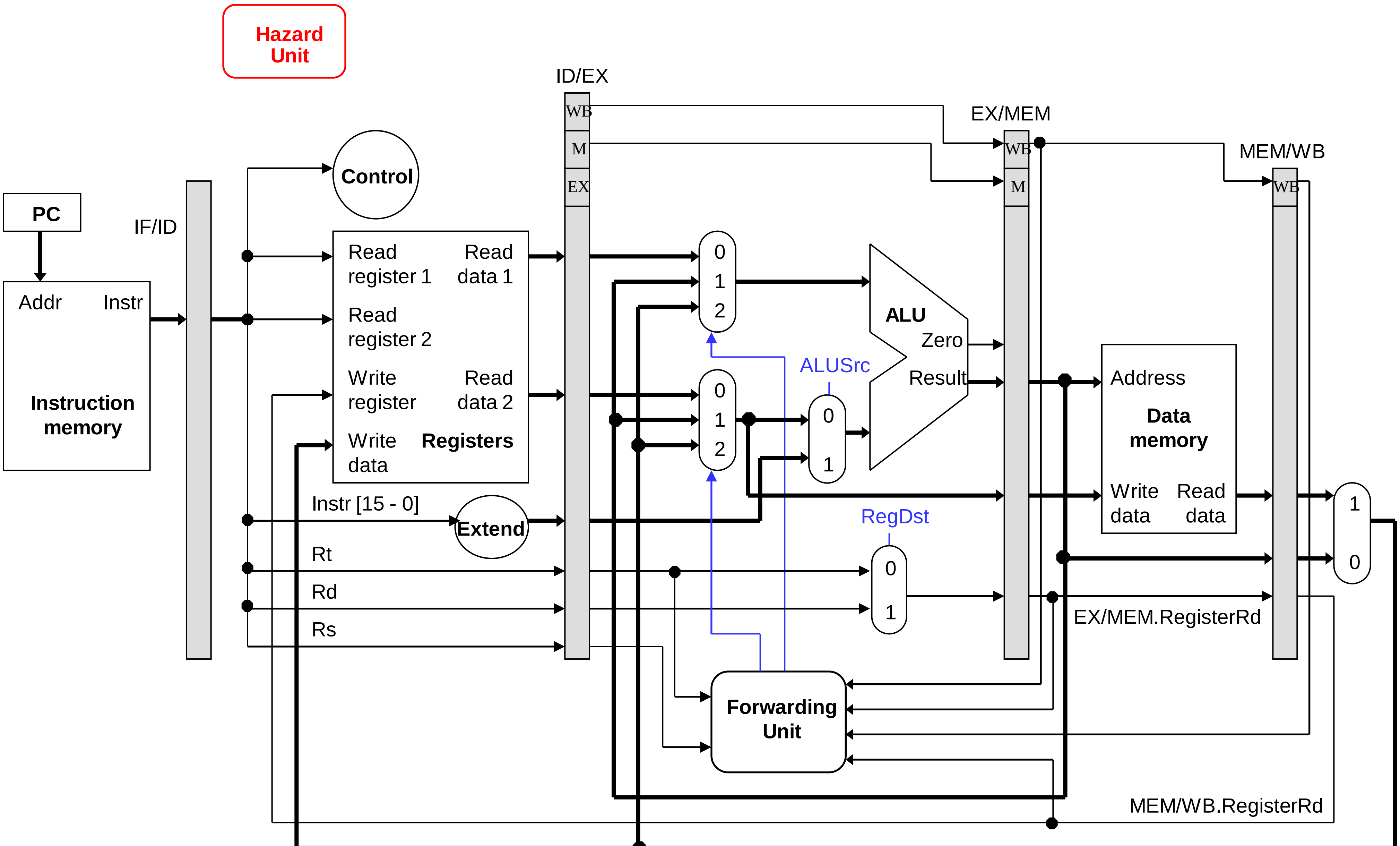
- What is the stall condition?

if (

)

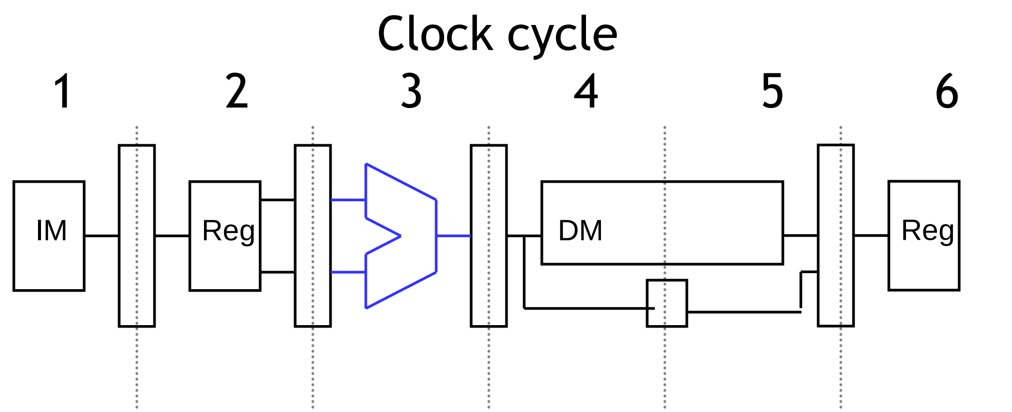
then stall

Adding hazard detection to the CPU



Generalizing Forwarding/Stalling

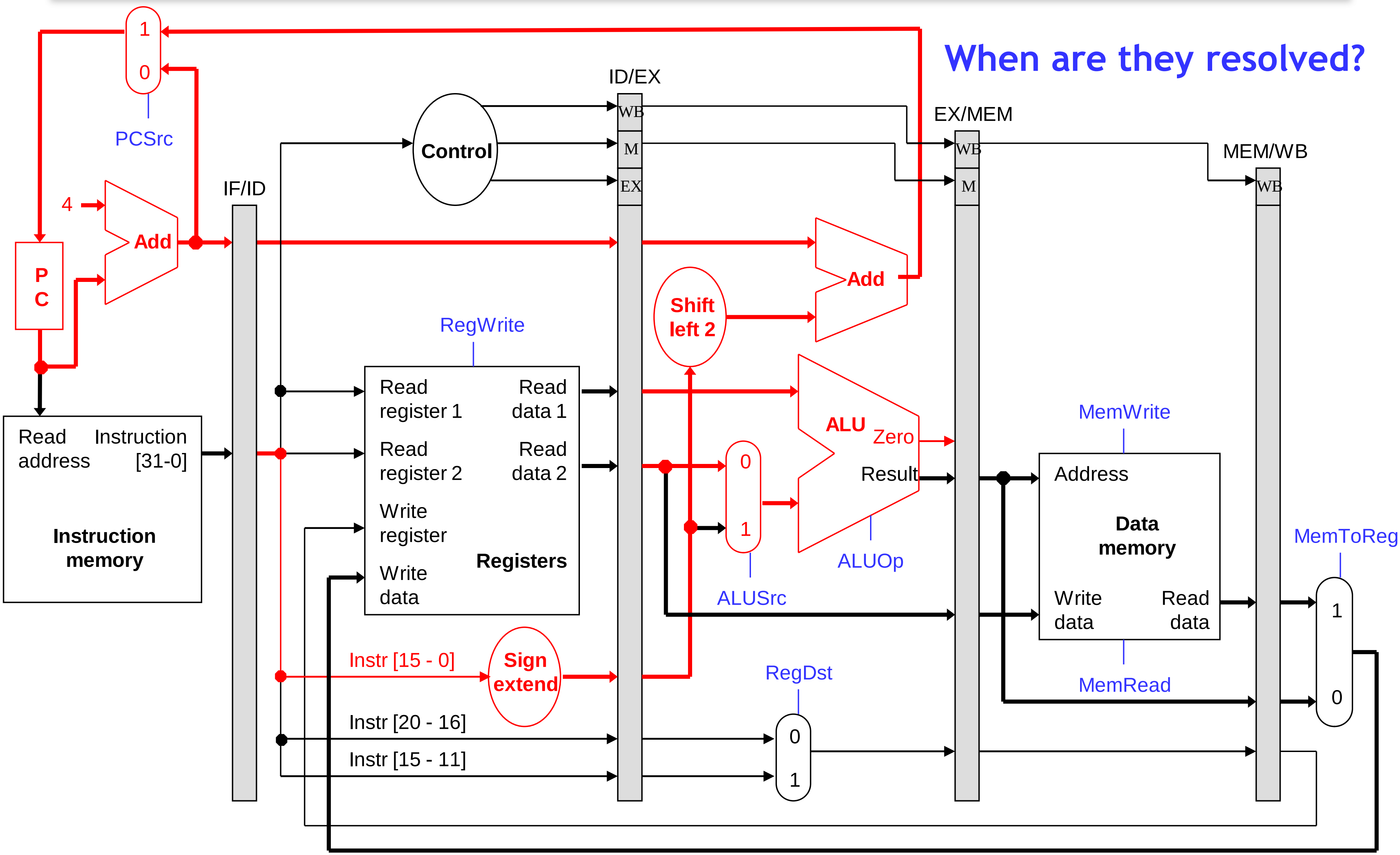
- What if data memory access was so slow, we wanted to pipeline it over 2 cycles?



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

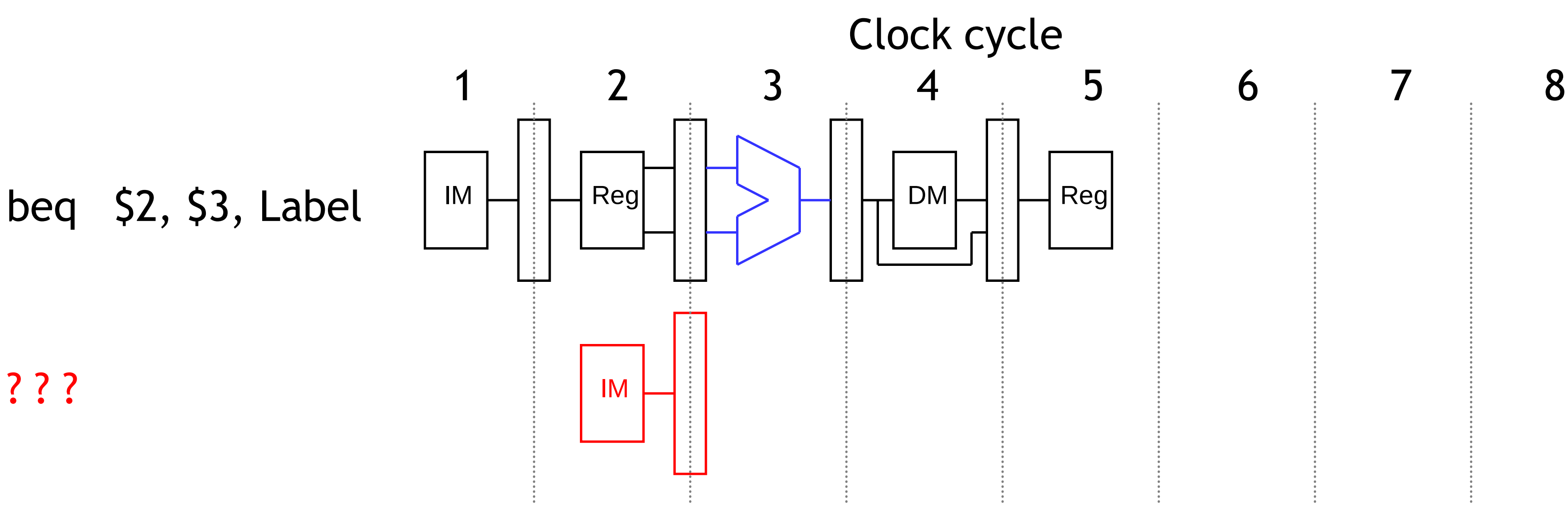
lw	r13, 0(r11)													
add	r7, r8, r9													
add	r15, r7, r13													

Branches in the original pipelined datapath



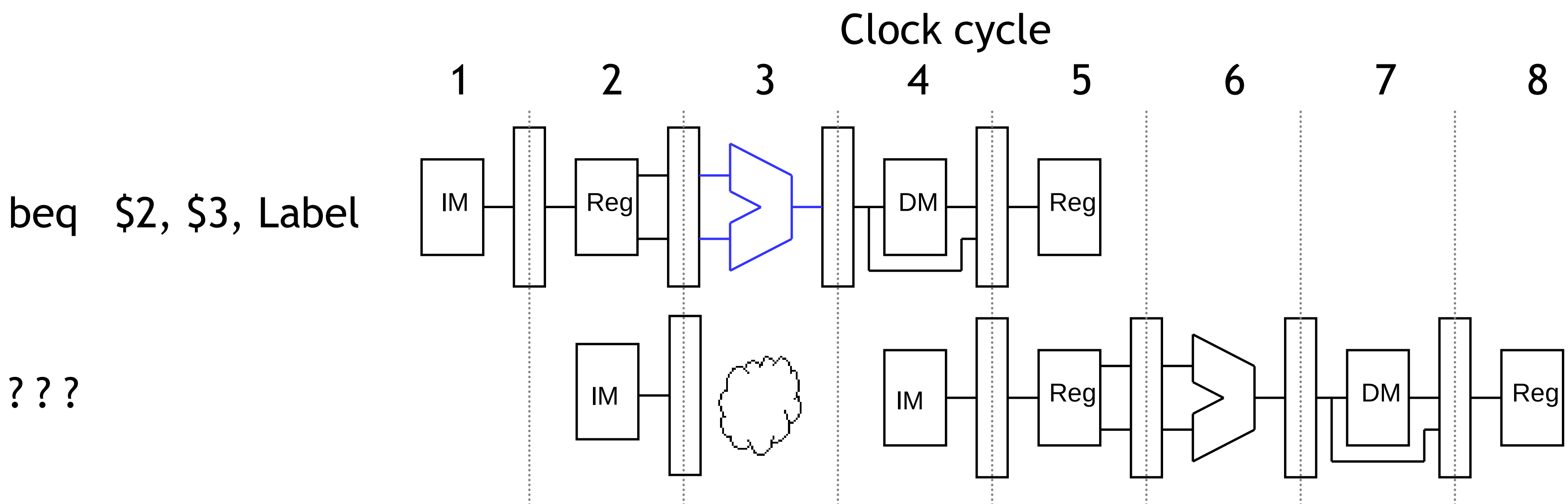
Branches

- 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

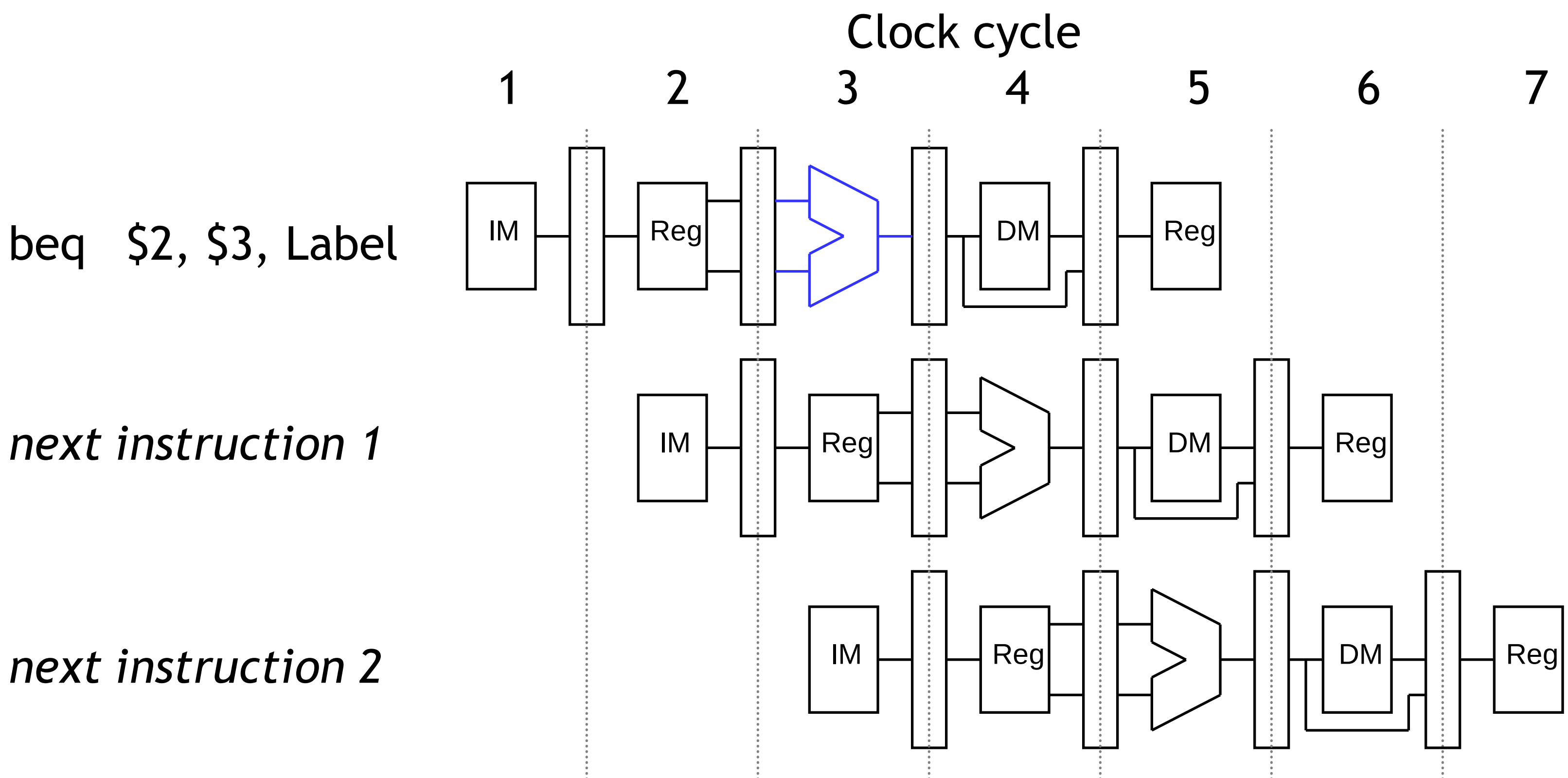
- Again, stalling is always one possible solution.



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

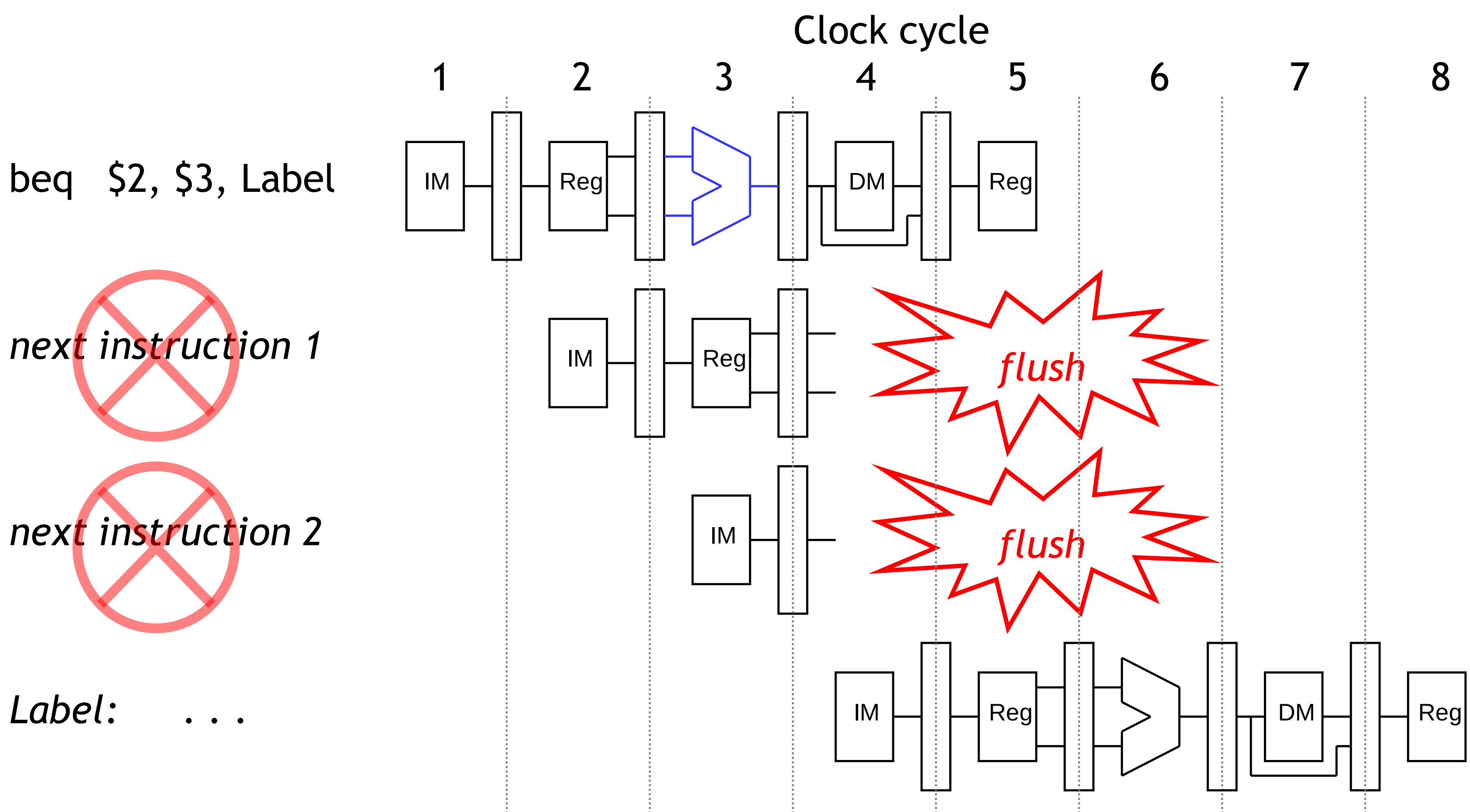
Branch prediction

- 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.



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.

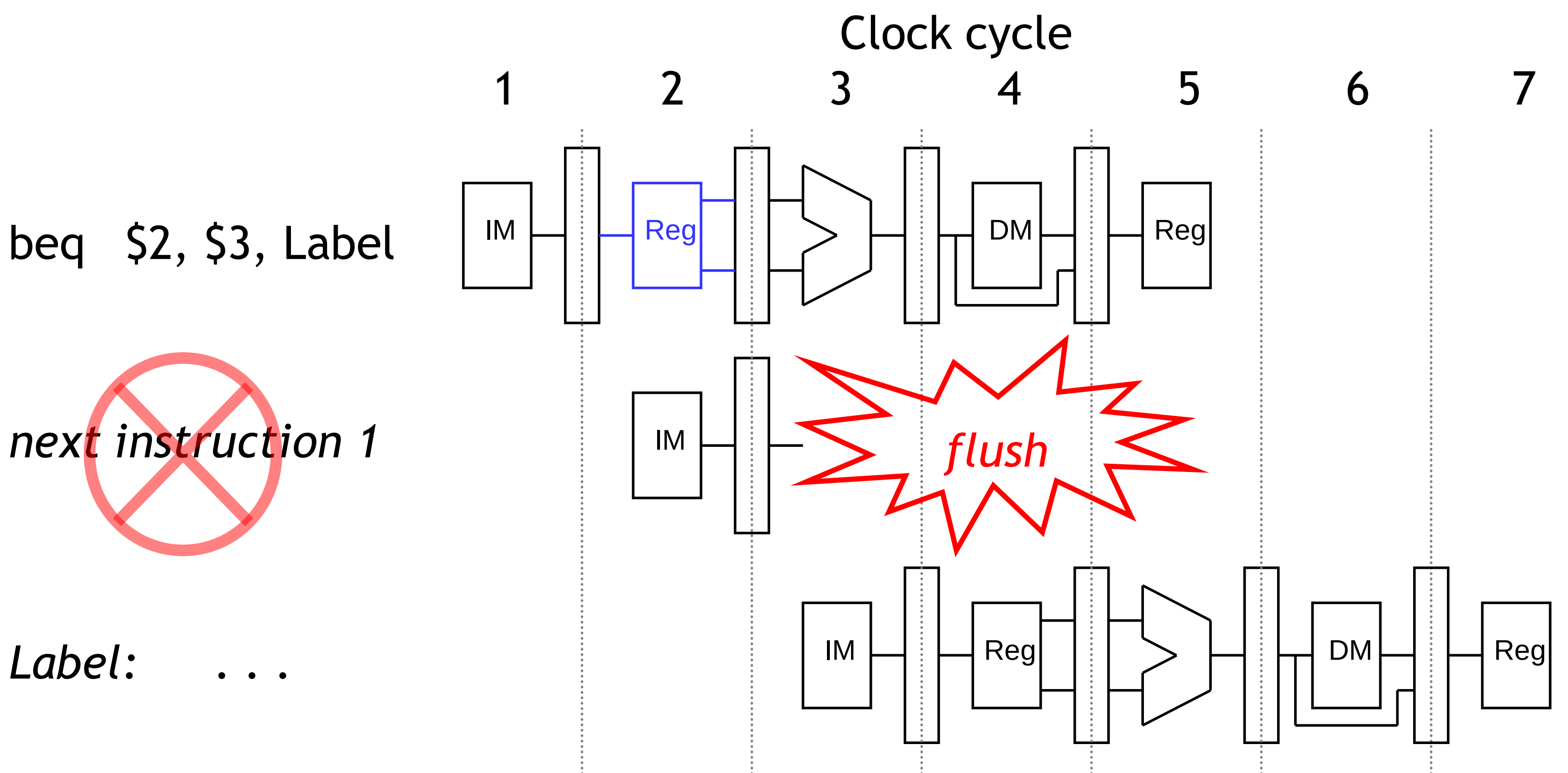


Performance gains and losses

- 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

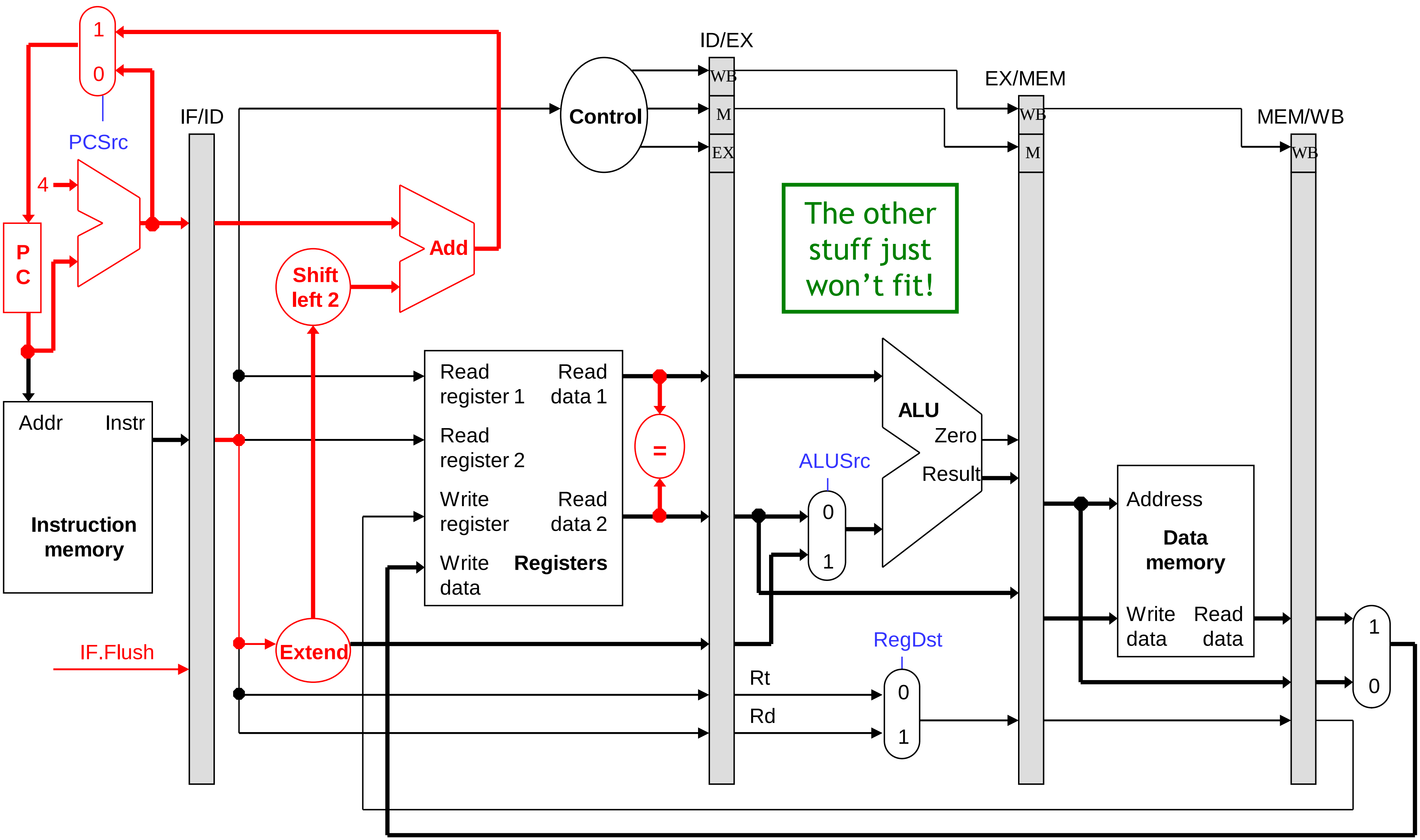
- We can actually decide the branch a little earlier, in ID instead of EX.
  - Our sample instruction set has only a BEQ.
  - We can add a small comparison circuit to the ID stage, after the source registers are read.
- Then we would only need to flush one instruction on a misprediction.



Implementing flushes

- We must flush one instruction (in its IF stage) if the previous instruction is BEQ and its two source registers are equal.
- 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

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.