



Advanced Parallel Architecture

Lessons 5 and 6



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Pipelining

Hennessy, Patterson
Computer architecture A quantitative approach
Appendix C – Sections C.1, C.2

Pipelining

- ▶ *Pipelining* is an implementation technique whereby multiple instructions are overlapped in execution
- ▶ *Pipelining* takes advantage of parallelism that exists among the actions needed to execute an instruction
- ▶ In a computer pipeline:
 - ▶ **Each step** in the pipeline completes a part of an instruction
 - ▶ **Different steps** are completing different parts of different instructions in parallel.
 - ▶ Each of these steps is called a ***pipe stage*** or a ***pipe segment***
 - ▶ The stages are connected one to the next to form a pipe
→ instructions ***enter*** at one end, ***progress*** through the stages, and ***exit*** at the other end, as cars in an assembly line

Pipelining

- ▶ The **throughput** of an instruction pipeline is determined by how often an instruction exits the pipeline
- ▶ Because the *pipe stages are hooked together*, all the stages must be ready to proceed at the same time, just as we would require in an assembly line
- ▶ The time required between moving an instruction one step down the pipeline is a *processor cycle*
- ▶ The length of a processor cycle is determined by the time required for the *slowest pipe stage*
- ▶ In a computer, this *processor cycle* is usually 1 clock cycle

Pipelining

- ▶ The goal is to **balance** the **length of each pipeline stage**
- ▶ If the stages are perfectly balanced, *assuming ideal conditions*:
 - ▶ The time per instruction , on the pipelined processor is
$$\frac{\text{time per instruction on the unpipelined processor}}{\text{number of pipeline stages}}$$
- ▶ the *ideal speedup* due to pipelining is equal to the **number of pipeline stages**

Pipelining

- ▶ Usually, however, the *stages will not be perfectly balanced*
- ▶ Thus, the **time per instruction** on the pipelined processor will not have its minimum possible value (it can be close)
- ▶ Pipelining yields a *reduction in the average execution time per instruction*
- ▶ The reduction can be viewed as:
 - ▶ decreasing the number of clock ***cycles per instruction*** (CPI)
 - ▶ decreasing the clock cycle time
 - ▶ a combination

Pipelining

- ▶ Pipelining:

- ▶ is an implementation technique that exploits parallelism among the instructions in a sequential instruction stream
- ▶ is not visible to the programmer

- ▶ In the follow, we use a RISC architecture characterized by a few key properties, which simplify its implementation:

- ▶ All operations on data apply to data in registers
- ▶ The only operations that affect memory are **load** (move data from memory to a register) and **store** (to memory from a register) operations
- ▶ The instruction formats are few in number

Pipelining

- ▶ Most RISC architectures have three classes of instructions:
 - ▶ *ALU instructions*—These instructions take either two registers or a register and a sign-extended immediate, operate on them, and store the result into a third register
 - ▶ *Load and store instructions*—These instructions take a register source, called the *base register* and an *offset*, to compute *effective address*, as well as a second register operand
 - ▶ *Branches and jumps*—Branches are conditional transfers of control. Unconditional jumps are provided in many RISC architectures

Pipelining

- ▶ Every instruction in this RISC subset can be implemented in at most 5 clock cycles:
 - ▶ *Instruction fetch cycle* (IF)
 - ▶ *Instruction decode/register fetch cycle* (ID) - Decode the instruction and read the registers. Do the equality test on the registers as they are read, for a possible branch. Compute the possible branch target address by adding the sign-extended offset to the incremented PC

Pipelining

- ▶ Every instruction in this RISC subset can be implemented in at most 5 clock cycles:
 - ▶ *Execution/effective address cycle (EX)* - The ALU operates on the operands prepared in the prior cycle, performing one of three functions depending on the instruction type:
 - ▶ Memory reference—The ALU adds the base register and the offset to form the effective address
 - ▶ Register-Register ALU instruction—The ALU performs the operation (ALU opcode) on the values read from the register file
 - ▶ Register-Immediate ALU instruction—The ALU performs the operation (ALU opcode) on the first value read from the register file and the sign-extended immediate

Pipelining

- ▶ Every instruction in this RISC subset can be implemented in at most 5 clock cycles:
 - ▶ **Memory access** (MEM): If the instruction is a **load**, the memory does a read using the effective address. If it is a **store**, then the memory writes the data from the second register using the effective address
 - ▶ **Write-back cycle** (WB): Register-Register ALU instruction or load instruction: Write the result into the register file, whether it comes from the memory system (for a load) or from the ALU (for an ALU instruction)
- ▶ Branch instructions require 2 cycles, store instructions require 4 cycles, and all other instructions require 5 cycles

Pipelining

	Clock number								
	1	2	3	4	5	6	7	8	9
Instruction number									
Instruction i	IF	ID	EX	MEM	WB				
Instruction $i + 1$		IF	ID	EX	MEM	WB			
Instruction $i + 2$			IF	ID	EX	MEM	WB		
Instruction $i + 3$				IF	ID	EX	MEM	WB	
Instruction $i + 4$					IF	ID	EX	MEM	WB

- ▶ Each of the clock cycles from the previous section becomes a *pipe stage*—a cycle in the pipeline
- ▶ This results in the execution pattern above, which is the typical way a pipeline structure is drawn

Pipelining

	Clock number								
	1	2	3	4	5	6	7	8	9
Instruction number									
<i>Instruction i</i>	IF	ID	EX	MEM	WB				
<i>Instruction i + 1</i>		IF	ID	EX	MEM	WB			
<i>Instruction i + 2</i>			IF	ID	EX	MEM	WB		
<i>Instruction i + 3</i>				IF	ID	EX	MEM	WB	
<i>Instruction i + 4</i>					IF	ID	EX	MEM	WB

- ▶ Each instruction takes 5 clock cycles to complete
- ▶ During each clock cycle the hardware:
 - ▶ will initiate a new instruction
 - ▶ will be executing some part of the five different instructions

Pipelining

	Clock number								
	1	2	3	4	5	6	7	8	9
Instruction number									
Instruction i	IF	ID	EX	MEM	WB				
Instruction $i + 1$		IF	ID	EX	MEM	WB			
Instruction $i + 2$			IF	ID	EX	MEM	WB		
Instruction $i + 3$				IF	ID	EX	MEM	WB	
Instruction $i + 4$					IF	ID	EX	MEM	WB

- ▶ Pipelining seems simple, but it's not
 - ▶ two different operations **cannot** be performed with the same data path resource on the same clock cycle → for example, a single ALU cannot be asked to compute an effective address and perform a subtract operation at the same time

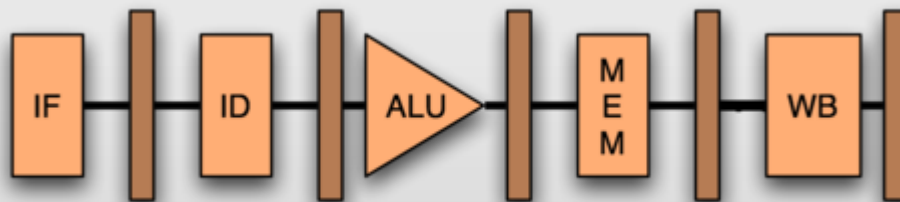
Pipelining

Observations

- ▶ The use of **separate caches** eliminates a **conflict** for a single memory that would arise between **instruction fetch** and **data memory access**
- ▶ The register file is used in the two stages: one for **reading in ID** and one for **writing in WB**. These uses are distinct
- ▶ To start a new instruction every clock, we must increment and store the PC every clock (IF stage). Furthermore, we must also have an adder to compute the potential branch target during ID. One further problem is that a **branch** does not change the PC until the ID stage. This causes a problem

Pipelining

- ▶ To ensure that instructions in different stages of the pipeline do not interfere with one another **pipeline registers** are introduced between successive stages of the pipeline:
 - ▶ at the end of a clock cycle all the results from a given stage are stored into a register that is used as the input to the next stage on the next clock cycle



Performance Issues in Pipelining

- ▶ Pipelining increases the CPU **instruction throughput** — *the number of instructions completed per unit of time* — but it does not reduce the execution time of a single instruction
- ▶ ***The increase in instruction throughput*** means that a ***program runs faster*** and has lower total execution time, even though ***no single instruction runs faster!***

Performance Issues in Pipelining

- ▶ In fact, the *execution time of each instruction is slightly increased* due to:
 - ▶ **imbalance** among the pipe stages
 - ▶ **overhead** in the control of the pipeline
- ▶ **Imbalance** among the pipe stages reduces performance since the clock can run no faster than the time needed for the slowest pipeline stage
- ▶ Pipeline **overhead** arises from the combination of pipeline register delay and clock skew

Example

- ▶ Assume that an **unpipelined** processor has a **1 ns clock cycle** and that it uses **4 cycles for ALU operations and branches** and **5 cycles for memory operations**
- ▶ Assume that the relative **frequencies** of these operations are 40%, 20%, and 40%, respectively
- ▶ Suppose that due to clock skew and setup, pipelining the processor adds 0.2 ns of overhead to the clock
- ▶ How much speedup in the instruction execution rate will we gain from a pipeline?

Example

- ▶ The average instruction execution time on the **unpipelined** processor is:

$$\begin{aligned}\text{Average instruction execution time} &= \\ &= \text{Clock cycle} \times \text{Average CPI} = \\ &= 1 \text{ ns} \times [(40\% + 20\%) \times 4 + 40\% \times 5] = \\ &= 1 \text{ ns} \times 4.4 = 4.4 \text{ ns}\end{aligned}$$

Example

- ▶ In the **pipelined** implementation, the clock must run at the speed of the slowest stage plus overhead
- ▶ Average instruction execution time is $(1 + 0.2)\text{ns} = 1.2 \text{ ns}$
- ▶ Thus, the **speedup** from pipelining is

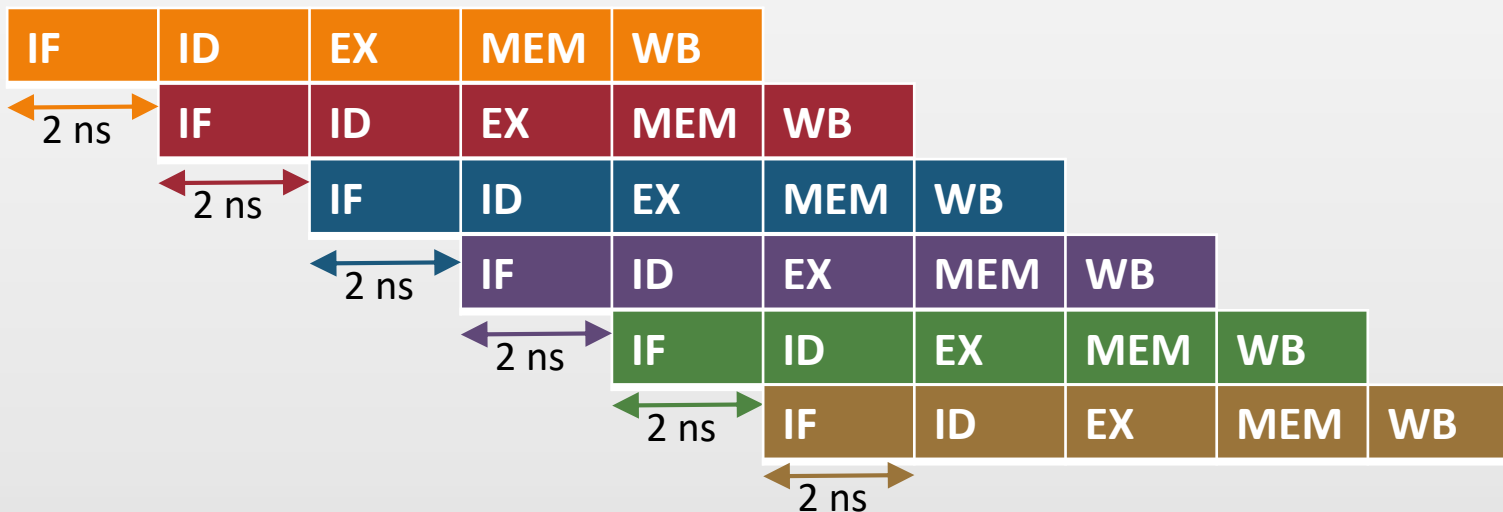
$$\begin{aligned} \text{Speedup from pipelining} &= \\ &= \frac{\text{Average instruction time unpipelined}}{\text{Average instruction time pipelined}} = \frac{4.4 \text{ ns}}{1.2 \text{ ns}} = 3.7 \text{ times} \end{aligned}$$

- ▶ The 0.2 ns overhead establishes a limit on the effectiveness of pipelining

Sequential vs Pipelining Execution



- ▶ Time 1 unpipelined instruction = 10 ns
- ▶ Time 6 unpipelined instruction = 60 ns
- ▶ Time N unpipelined instruction = $N \times 10$ ns



- ▶ Time pipe stage = 2 ns
- ▶ Time 6 pipelined instruction = Time 1 unpipelined instruction + 5 x Time pipe stage
= 10 ns + 10 ns = 20 ns
- ▶ Time N pipelined instruction = Time 1 unpip. instruction + $(N-1) \times$ Time pipe stage

Pipeline Hazards

- ▶ A **hazard** (*conflict*) is created whenever there is a dependence between instructions, and instructions are close enough that the overlap caused by pipelining would change the order of access to the operands involved in the dependence
- ▶ **Hazards:**
 - ▶ prevent the next instruction from executing during its clock cycle
 - ▶ reduce the performance from the ideal speedup

Pipeline Hazards

- ▶ There are three classes of hazards:
 - ▶ **Structural hazards** Attempt to use the same resource from different instructions simultaneously - arise when the hardware cannot support that instructions overlap their execution
 - ▶ Example: Single memory for instructions and data
 - ▶ **Data hazards** Attempt to use a result before it is ready - arise when an instruction depends on the results of a previous instruction still in the pipeline
 - ▶ **Control hazards** Attempt to make a decision on the next instruction to execute before the condition is evaluated
 - ▶ Example: conditional branch execution (change the PC)

Pipeline Hazards

- ▶ Hazards in pipelines can make it necessary **to stall the pipeline**
- ▶ Some instructions in the pipeline be allowed to proceed while others are delayed
- ▶ When an instruction is stalled:
 - ▶ all instructions issued *later* than the stalled instruction—and hence not as far along in the pipeline—are also stalled
 - ▶ Instructions issued *earlier* than the stalled instruction—and hence farther along in the pipeline—must continue
 - ▶ As a result, no new instructions are fetched during the stall

Performance of Pipelines with Stalls

- ▶ A stall causes the pipeline performance to degrade from the ideal performance
- ▶ Actual **speedup**, starting with the previous formula is:

$$\text{Speedup from pipelining} = \frac{\text{Average instruction time unpipelined}}{\text{Average instruction time pipelined}} =$$

$$= \frac{\text{CPI unpipelined} \times \text{Clock cycle unpipelined}}{\text{CPI pipelined} \times \text{Clock cycle pipelined}} =$$

$$= \frac{\text{CPI unpipelined}}{\text{CPI pipelined}} \times \frac{\text{Clock cycle unpipelined}}{\text{Clock cycle pipelined}}$$

Performance of Pipelines with Stalls

- ▶ The **ideal CPI** on a pipelined processor is almost always **1**
- ▶ Hence, we can compute the **pipelined CPI**:

$$\begin{aligned}\text{CPI pipelined} &= \text{Ideal CPI} + \text{Pipeline stall clock cycles per instruction} \\ &= 1 + \text{Pipeline stall clock cycles per instruction}\end{aligned}$$

- ▶ If we *ignore the cycle time overhead of pipelining* and assume that the *stages are perfectly balanced*, then the cycle time of the two processors can be equal, and

$$\text{Speedup} = \frac{\text{CPI unpipelined}}{1 + \text{Pipeline stall cycles per instruction}}$$

Performance of Pipelines with Stalls

- ▶ One important simple case is where all instructions take the same number of cycles, which must also equal the number of pipeline stages - ***depth of the pipeline***
- ▶ In this case, the unpipelined CPI is equal to the depth of the pipeline, leading to

$$\text{Speedup} = \frac{\text{pipeline depth}}{1 + \text{Pipeline stall cycles per instruction}}$$

- ▶ If there are no pipeline stalls, this leads to the intuitive result that ***pipelining can improve performance by the depth of the pipeline***

Performance of Pipelines with Stalls

- ▶ Alternatively, if we think of pipelining as improving the clock cycle time, then we can assume that the CPI of the unpipelined processor, as well as that of the pipelined processor, is 1
- ▶ This leads to

Speedup from pipelining=

$$= \frac{\text{CPI unpipelined}}{\text{CPI pipelined}} \times \frac{\text{Clock cycle unpipelined}}{\text{Clock cycle pipelined}} =$$

$$= \frac{1}{1 + \text{Pipeline stall cycles per instruction}} \times \frac{\text{Clock cycle unpipelined}}{\text{Clock cycle pipelined}}$$

Performance of Pipelines with Stalls

- ▶ In cases where the pipe stages are perfectly balanced and there is no overhead, the clock cycle on the pipelined processor is smaller than the clock cycle of the unpipelined processor by a factor equal to the pipelined depth:

$$\text{Clock cycle pipelined} = \frac{\text{Clock cycle unpipelined}}{\text{Pipeline depth}}$$

$$\text{Pipeline depth} = \frac{\text{Clock cycle unpipelined}}{\text{Clock cycle pipelined}}$$

Performance of Pipelines with Stalls

- ▶ This leads to

Speedup from pipelining=

$$= \frac{1}{1 + \text{Pipeline stall cycles per instruction}} \times \frac{\text{Clock cycle unpipelined}}{\text{Clock cycle pipelined}} =$$

$$= \frac{1}{1 + \text{Pipeline stall cycles per instruction}} \times \text{Pipeline depth}$$

Structural Hazards

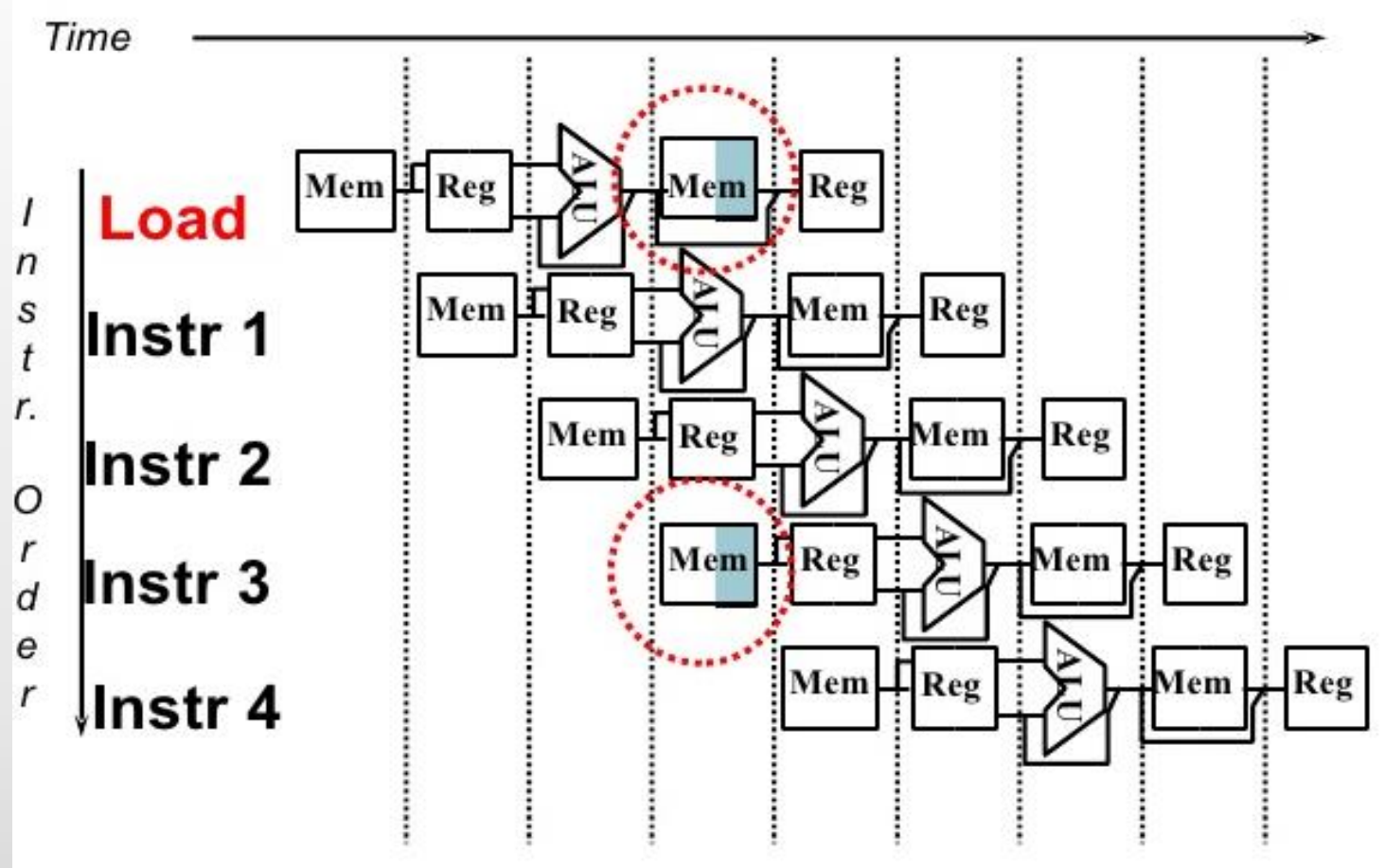
- ▶ When a processor is pipelined, the overlapped execution of instructions requires:
 - ▶ **pipelining of functional units**, and
 - ▶ **duplication of resources**to allow all possible combinations of instructions in the pipeline
- ▶ If some combination of instructions cannot be accommodated because of resource conflicts, the processor is said to have a ***structural hazard***

Structural Hazards

Examples:

- ▶ Some **functional unit** is **not fully pipelined** → a sequence of instructions using that unpipelined unit cannot proceed at the rate of one per clock cycle
- ▶ Some **resource** has **not** been **duplicated** enough to allow all combinations of instructions in the pipeline to execute → a processor may have only one register-file write port, but under certain circumstances, the pipeline might want to perform two writes in a clock cycle
- ▶ Some pipelined processors have shared a **single-memory pipeline for data and instructions** → when an instruction contains a data memory reference, it will conflict with the instruction reference for a later instruction

Structural Hazards - single-memory



To resolve this hazard, we **stall** the pipeline for **1 clock cycle** when the data memory access occurs

Structural Hazards

Example - Cost of the load structural hazard

- ▶ Suppose that:
 - ▶ data references constitute 40% of the mix
 - ▶ the ideal CPI of the pipelined processor is 1
- ▶ Assume that:
 - ▶ the processor with the structural hazard has a clock rate that is 1.05 times higher than the clock rate of the processor without the hazard
- ▶ Is the pipeline with or without the structural hazard faster, and by how much? (Disregarding any other performance losses)

Structural Hazards

Example - Cost of the load structural hazard

- ▶ A way to solve this problem is to compute the average instruction time on the two processors

$$\begin{aligned}\text{Average instruction time} &= \text{CPI} \times \text{Clock cycle time} = \\ &= (1 + 0.4 \times 1) \times \frac{\text{Clock cycle time}_{\text{ideal}}}{1.05} = \\ &= 1.3 \times \text{Clock cycle time}_{\text{ideal}}\end{aligned}$$

- ▶ The processor without the structural hazard is 1.3 times faster

Structural Hazards

- ▶ The designer could provide a separate memory access for instructions, either by **splitting the cache into separate instruction and data caches** or by using a set of buffers, usually called *instruction buffers*, to hold instructions
- ▶ A processor without structural hazards has always a lower CPI → why would a designer allow structural hazards?
- ▶ Pipelining all the functional units, or duplicating them, may be too costly
 - ▶ For example, processors that support both an instruction and a data cache access every require twice as much total memory bandwidth and often have higher bandwidth at the pins

Data Hazards

- ▶ Overlapping the execution of instructions introduces **data and control hazards**
- ▶ **Data hazards** occur when the pipeline changes the **order of read/write accesses to operands** so that the order differs from the order seen by sequentially executing instructions on an unpipelined processor

Data Hazards

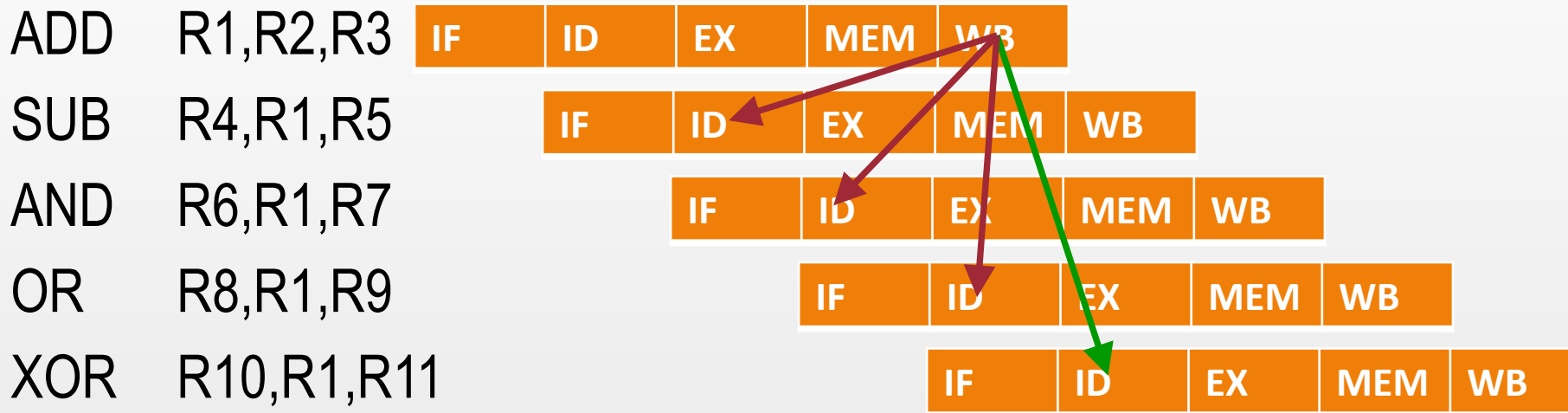
- | | | |
|-----|------------|--|
| ADD | R1,R2,R3 | ▶ All the instructions after the ADD use the result of the ADD instruction |
| SUB | R4,R1,R5 | |
| AND | R6,R1,R7 | ▶ The ADD instruction writes the value of R1 in the WB pipe stage |
| OR | R8,R1,R9 | |
| XOR | R10,R1,R11 | ▶ But the SUB instruction reads the value during its ID stage |
- ▶ This problem is called a ***data hazard***
 - ▶ Unless precautions are taken to prevent it, the **SUB instruction will read the wrong value** and try to use it

Data Hazards

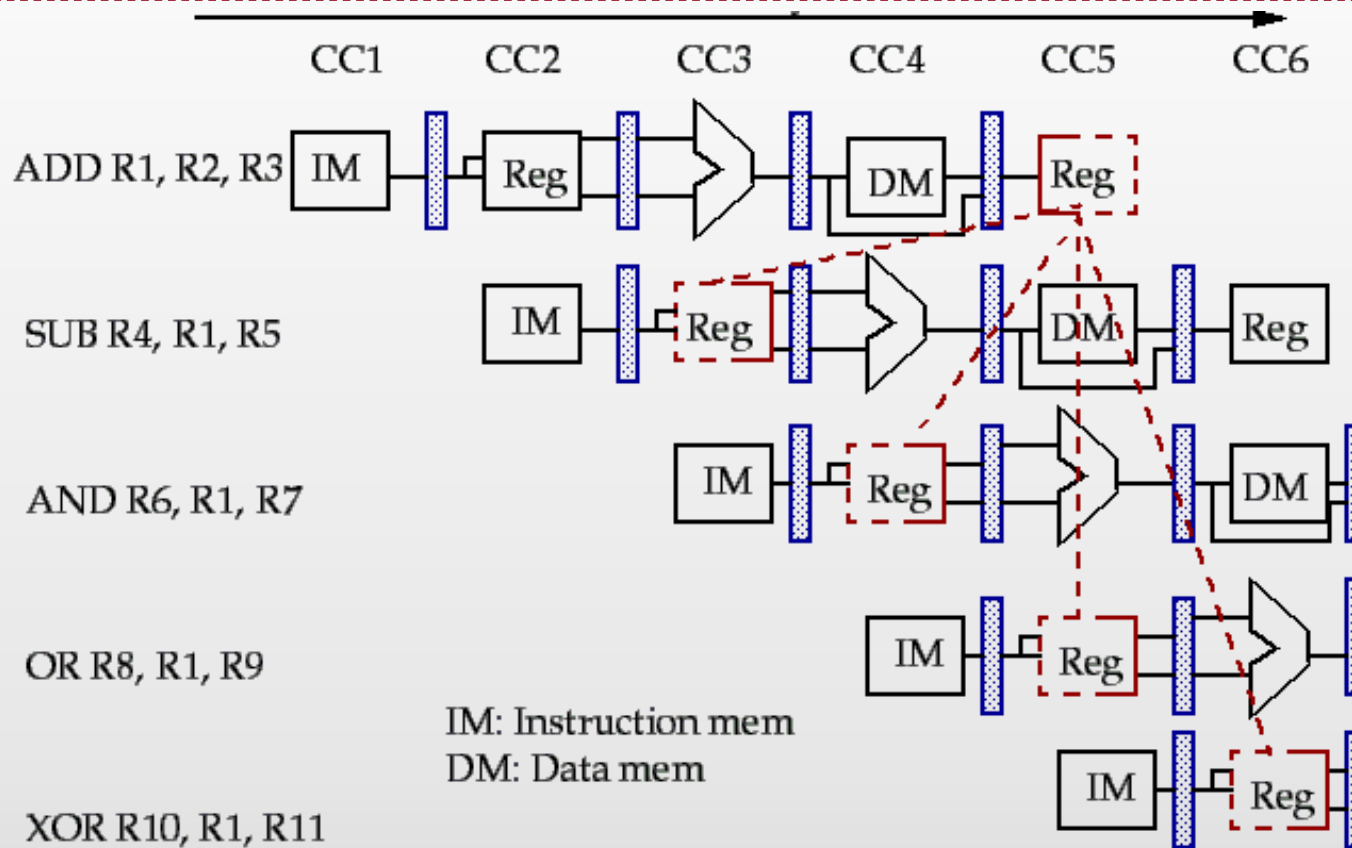
ADD R1,R2,R3
SUB R4,R1,R5
AND R6,R1,R7
OR R8,R1,R9
XOR R10,R1,R11

- ▶ In fact, the value used by the SUB instruction is not even deterministic
- ▶ If an interrupt should occur between the ADD and SUB instructions, the WB stage of the ADD will complete, and the value of R1 at that point will be the result of the ADD
- ▶ **This unpredictable behavior is unacceptable**

Data Hazards

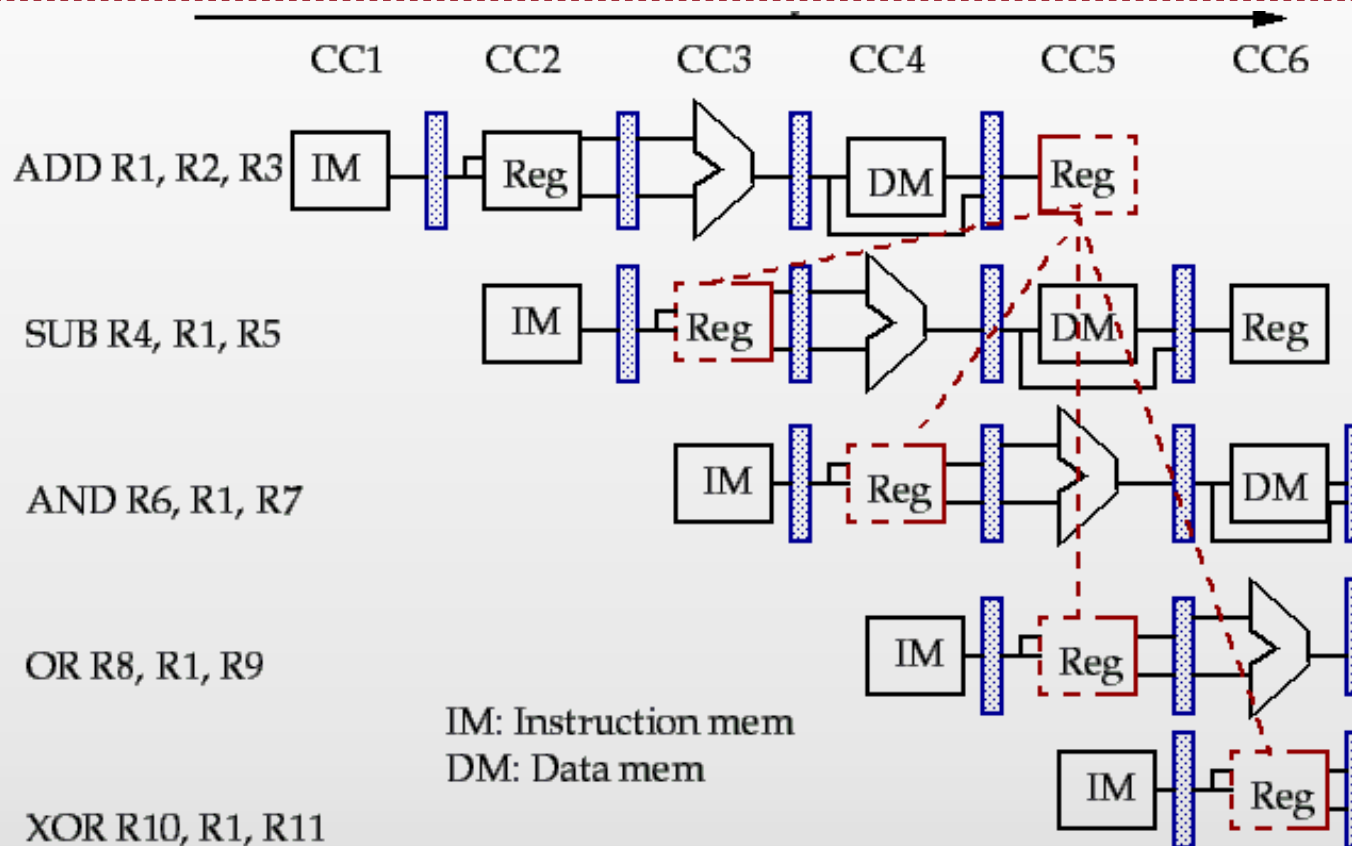


Data Hazards



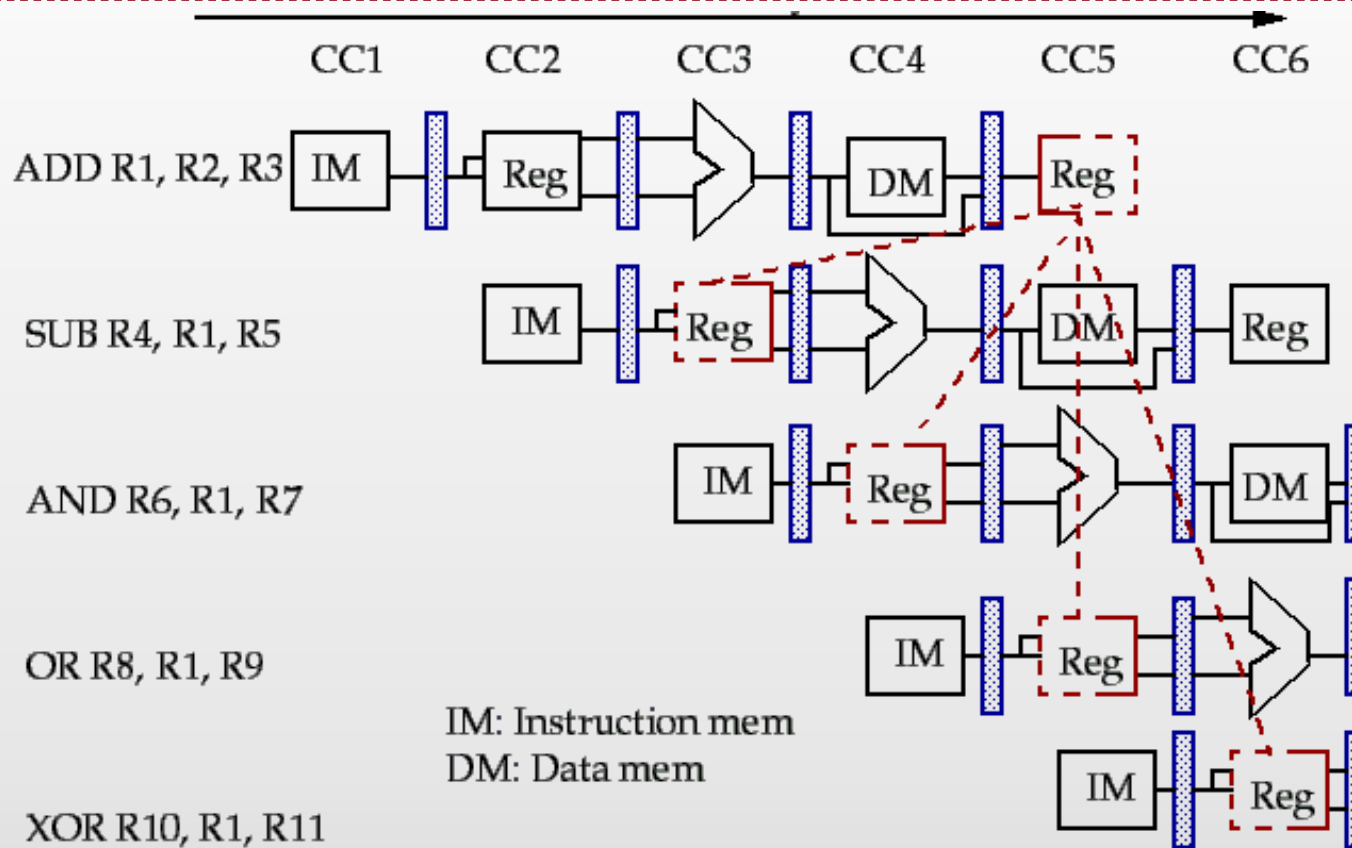
AND instruction is also affected by this hazard: the write of R1 does not complete until the end of clock cycle 5 → the AND instruction that reads the registers during clock cycle 4 will receive the wrong results

Data Hazards



The OR instruction also operates **without incurring a hazard** because we perform the register file reads in the second half of the cycle and the writes in the first half

Data Hazards



The XOR instruction operates properly because its register read occurs in clock cycle 6, after the register write

Data Hazards: Possible Solutions

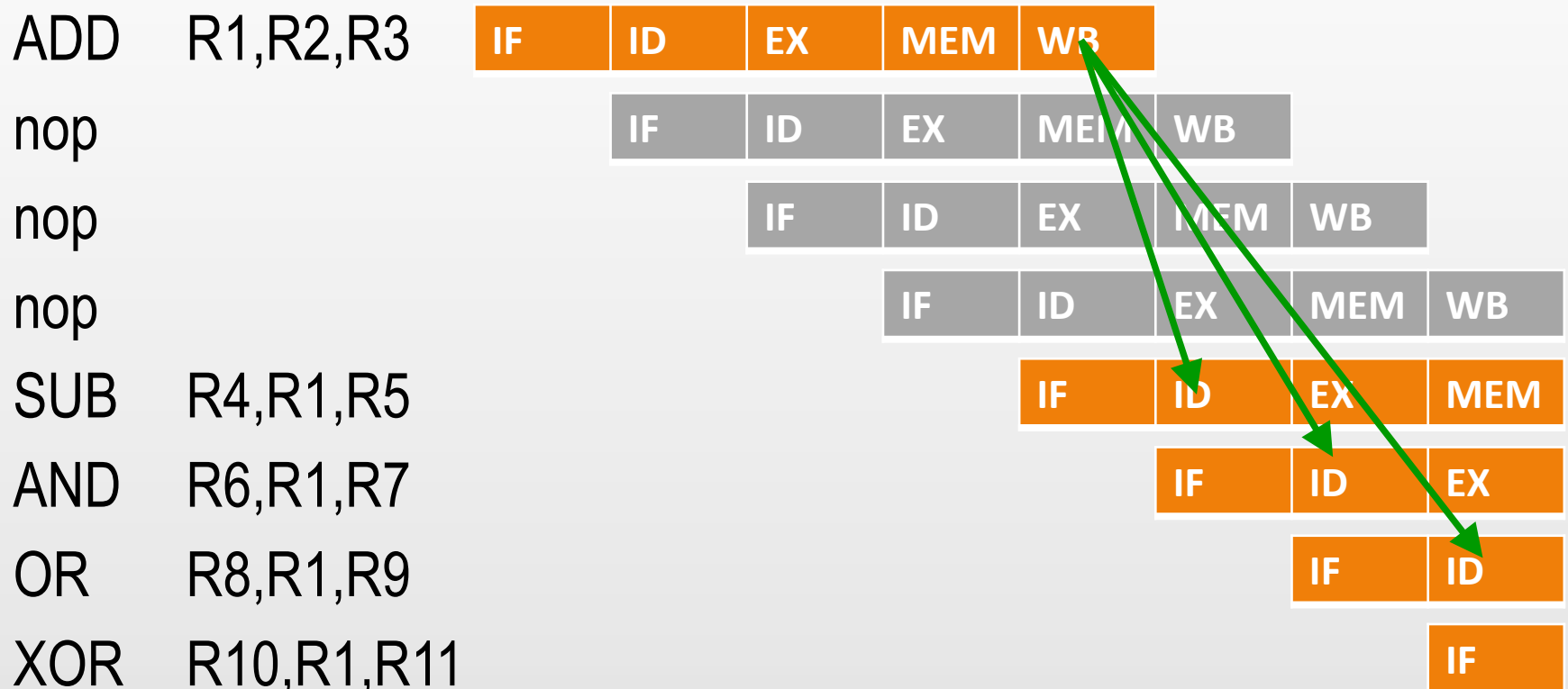
▶ Compilation Techniques:

- ▶ Insertion of **nop** (no operation) instructions
- ▶ Instructions **scheduling** to avoid that correlating instructions are too close
 - ▶ The compiler tries to insert independent instructions among correlating instructions
 - ▶ When the compiler does not find independent instructions, it insert nops

▶ Hardware Techniques:

- ▶ Insertion of **stalls** or “**bubbles**” in the pipeline
- ▶ Data **forwarding** or bypassing

Insertion of nop



Scheduling

Example

sub **\$2**, \$1, \$3
and \$12, **\$2**, \$5
or \$13, \$6, **\$2**
add \$14, **\$2**, **\$2**
sw \$15,100(**\$2**)

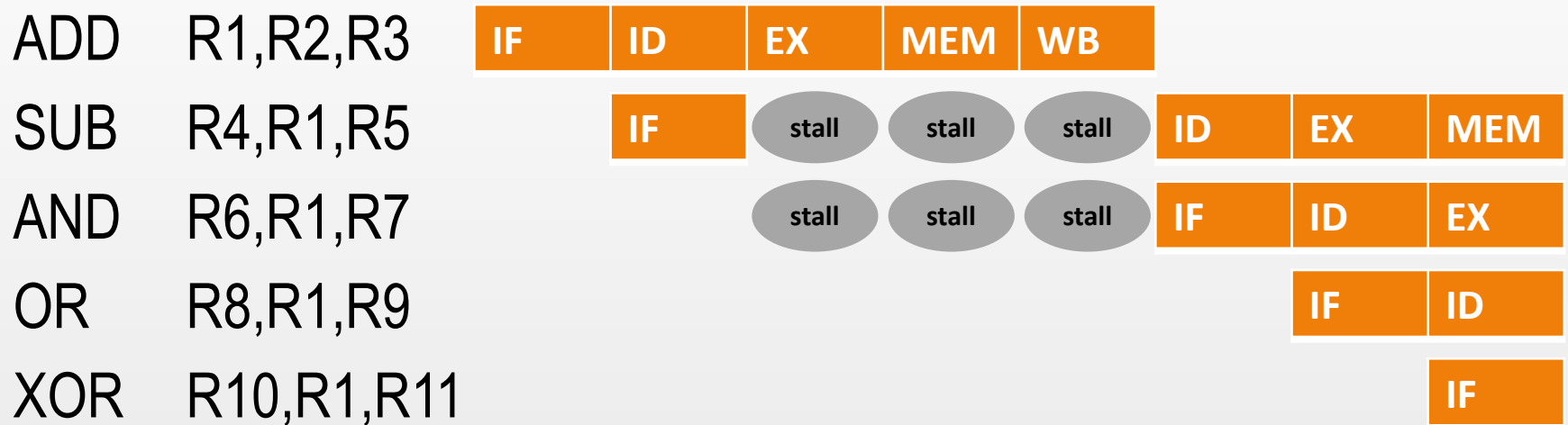
add \$4, \$10, \$11
and \$7, \$8, \$9
lw \$16, 100(\$18)

sub **\$2**, \$1, \$3
add \$4, \$10, \$11
and \$7, \$8, \$9
lw \$16, 100(\$18)
and \$12, **\$2**, \$5
or \$13, \$6, **\$2**
add \$14, **\$2**, **\$2**
sw \$15,100(**\$2**)

Data Hazards Requiring Stalls

- ▶ **Hardware**, called *pipeline interlock*, is added to:
 - ▶ preserve the correct execution pattern
 - ▶ detect a hazard
 - ▶ stall the pipeline until the hazard is cleared
- ▶ The interlock stalls the pipeline:
 - ▶ beginning with the instruction that wants to use the data until the source instruction produces it
 - ▶ introducing a stall or bubble, as for the structural hazard
- ▶ The CPI for the stalled instruction increases by the length of the stall

Insertion of stalls



Data Hazards Requiring Stalls

- ▶ Consider the following sequence of instructions:

LD **R1**,0(R2)

SUB R4,**R1**,R5

AND R6,**R1**,R7

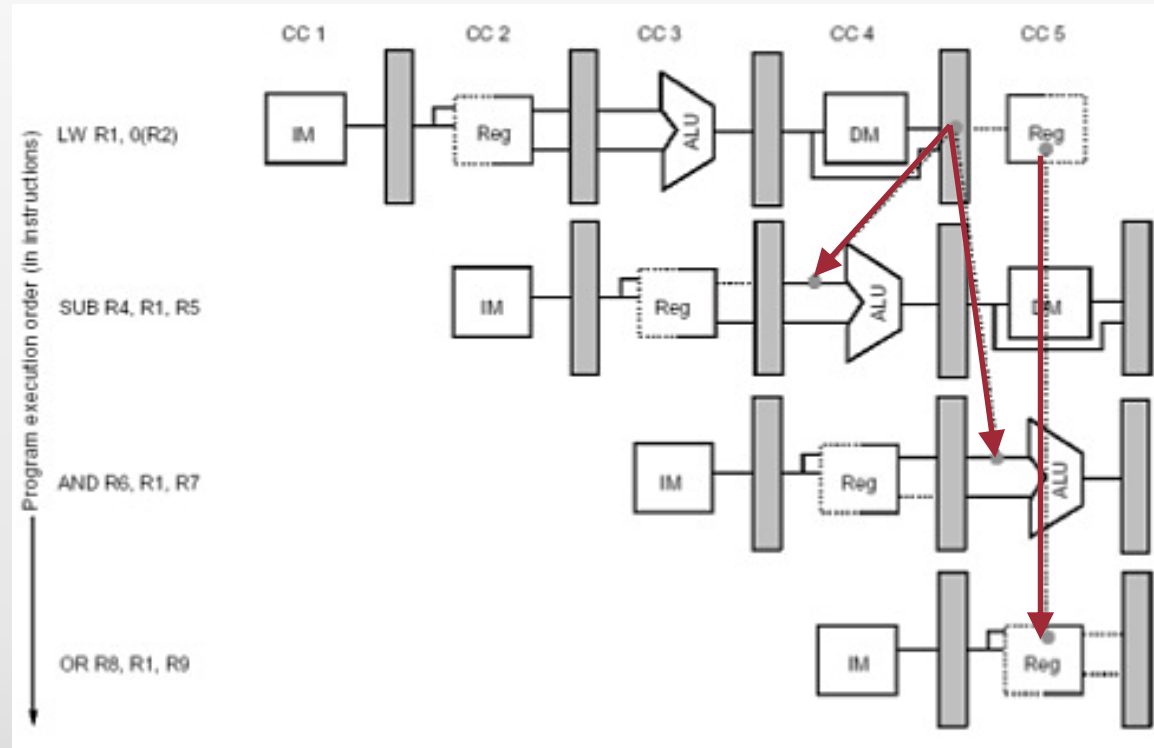
OR R8,**R1**,R9

- ▶ LD instruction does not have the data until the end of clock cycle 4 (its MEM cycle)
- ▶ SUB instruction needs to have the data by the beginning of that clock cycle
- ▶ the data hazard from using the result of a load instruction cannot be completely eliminated with simple hardware

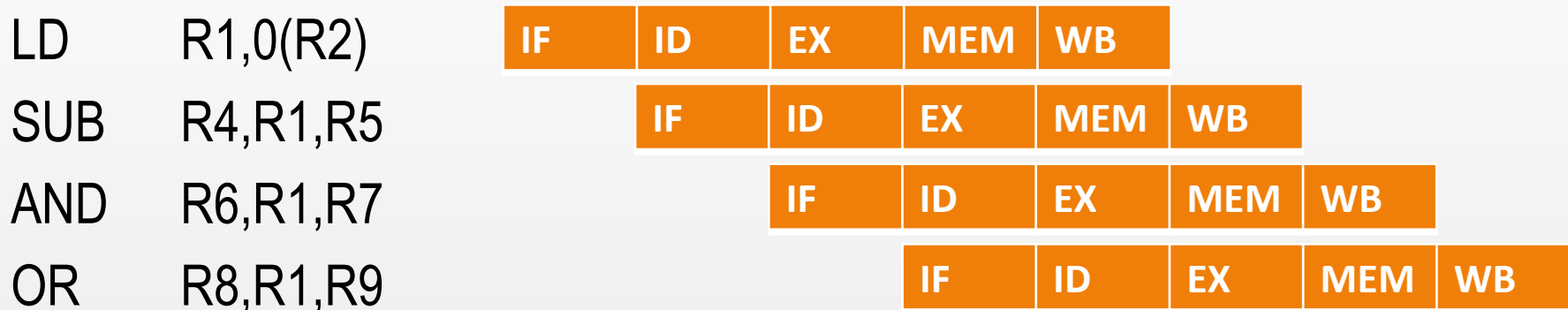
Data Hazards Requiring Stalls

- Consider the following sequence of instructions:

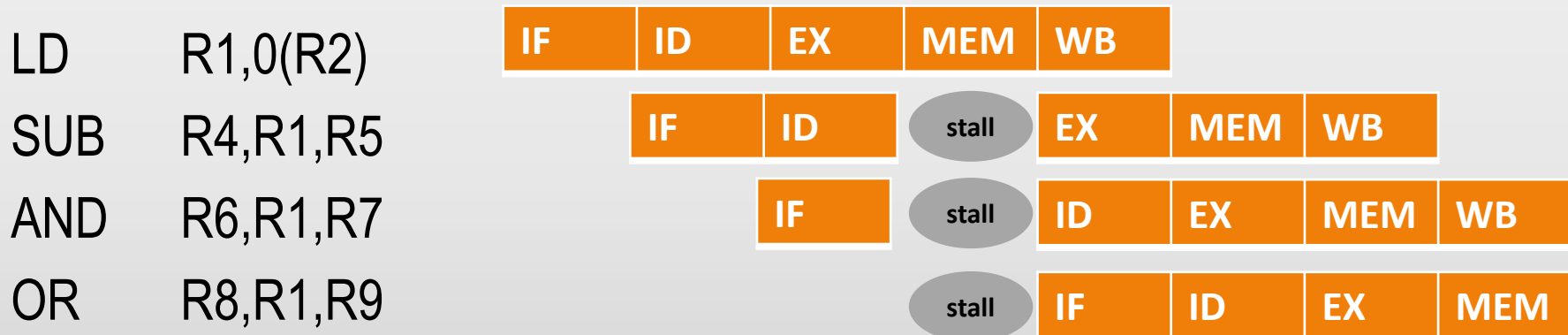
```
LD    R1,0(R2)
SUB   R4,R1,R5
AND   R6,R1,R7
OR    R8,R1,R9
```



Data Hazards Requiring Stalls



► Before stall insertion



► After stall insertion

Forwarding

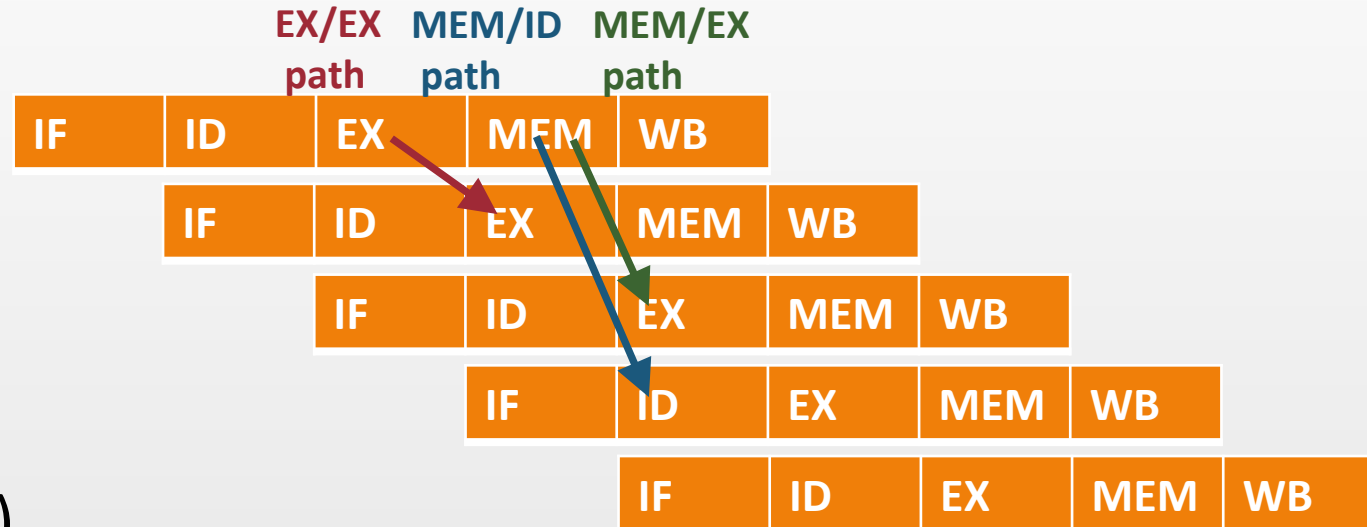
- ▶ **Data *forwarding*** (also *bypassing* or *short-circuiting*):
 - ▶ Temporary results stored in the **pipeline registers** instead of waiting for the write back of results in the RF (register file)
 - ▶ **A result** is forwarded **from the pipeline register** (**output** of one unit) **to the input** of **another unit**

Forwarding

- ▶ Forwarding works as follows:
 - ▶ The **ALU result from** both the EX/MEM and MEM/WB pipeline registers is always **fed back to the ALU inputs**
 - ▶ If the **forwarding hardware detects** that the previous ALU operation has written the **register** of a source for the current ALU operation, **control logic selects the forwarded result as the ALU input**

Forwarding

SUB \$2, \$1, \$3
AND \$12, \$2, \$5
OR \$13, \$6, \$2
ADD \$14, \$2, \$2
SW \$15, 100(\$2)



Minimizing Data Hazard Stalls by Forwarding

Program
execution
order
(in instructions)

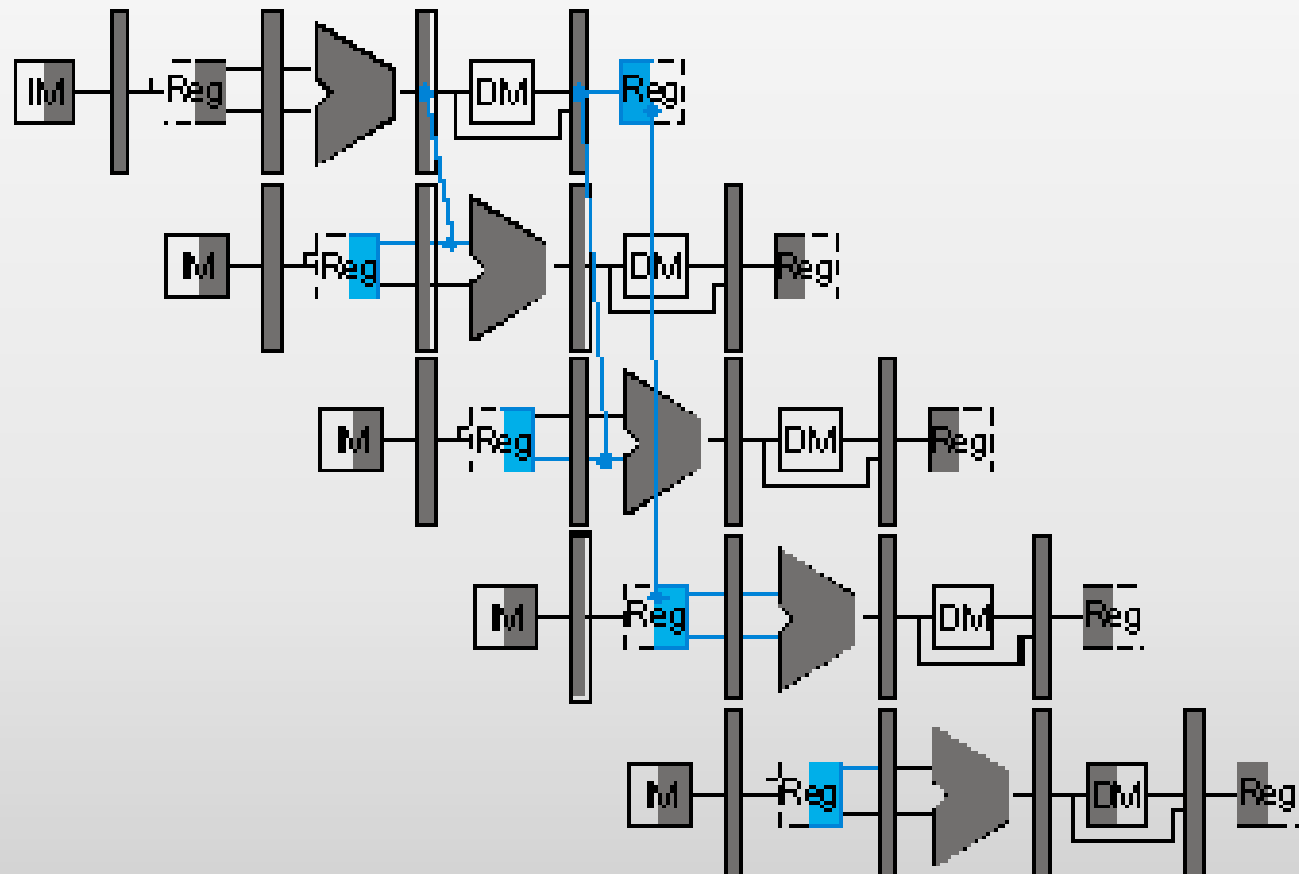
sub \$2, \$1, \$3

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

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

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

sw \$15, 100(\$2)



Type of Data Hazards

- ▶ **RAW (READ AFTER WRITE) hazard**

- ▶ instruction $n+1$ tries to read a source register before the previous instruction n has written it in the RF

- ▶ **Example:**

ADD \$R1, \$R2, \$R3

SUB \$R4, \$R1, \$R5

- ▶ By using forwarding, it is always possible to solve this conflict without introducing stalls, except for the load/use hazards where it is necessary to add one stall

Type of Data Hazards

- ▶ **WAW (WRITE AFTER WRITE) hazard**

- ▶ Instruction n+1 tries to write a destination operand before it has been written by the previous instruction n → write operations executed in the wrong order (out-of-order)

- ▶ **Example:**

LW \$R1, 0(\$R2)

ADD \$R1,\$R2,\$R3

Type of Data Hazards

▶ **WAR (WRITE AFTER READ) hazard**

- ▶ Instruction $n+1$ tries to write a destination operand before it has been read from the previous instruction $n \rightarrow$ instruction n reads the wrong value

▶ **Example**

- ▶ `SW $Y, 0($X)` # sw has to read \$x
- ▶ `ADDI $X, $X, 4` # addi writes Sx

- ▶ As before, if we assume the register write in the ALU instructions occurs in the fourth stage and that we need two stages to access the data memory, some instructions could read operands too late in the pipeline

Control hazards

- ▶ **Control hazards** can cause a **greater performance loss** for our MIPS pipeline than do data hazards
- ▶ When a **branch** is executed, it may change the PC to something other than next address (PC plus 4):
 - ▶ the branch decision (to change or not change the PC) is taken during the MEM stage
 - ▶ if a branch changes the PC to its target address, it is a **taken** branch
 - ▶ if it falls through, it is **not taken, or untaken**

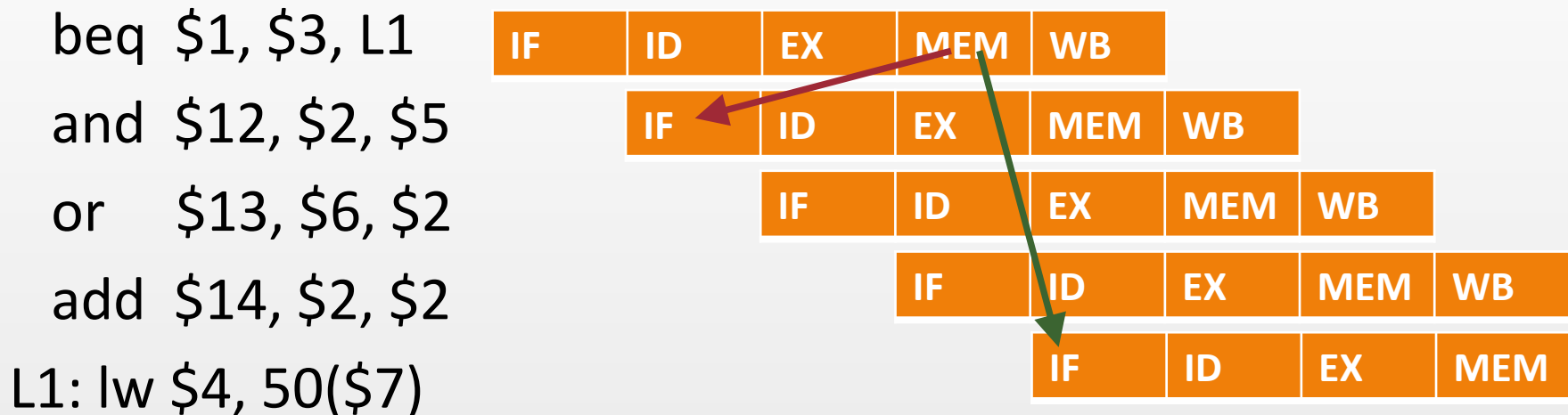
Control hazards

- ▶ Examples of branches (for MIPS processor):
 - ▶ beq (branch on equal) and bne (branch on not equal)
 - ▶ beq \$s1, \$s2, L1 # go to L1 if ($\$s1 == \$s2$)
 - ▶ bne \$s1, \$s2, L1 # go to L1 if ($\$s1 \neq \$s2$)
- ▶ **Branch Outcome** and **Branch Target Address** are ready at the end of the **EX stage** (3th stage)
- ▶ **Conditional branches** are solved when PC is updated at the end of the **MEM stage** (4th stage)

Control hazards

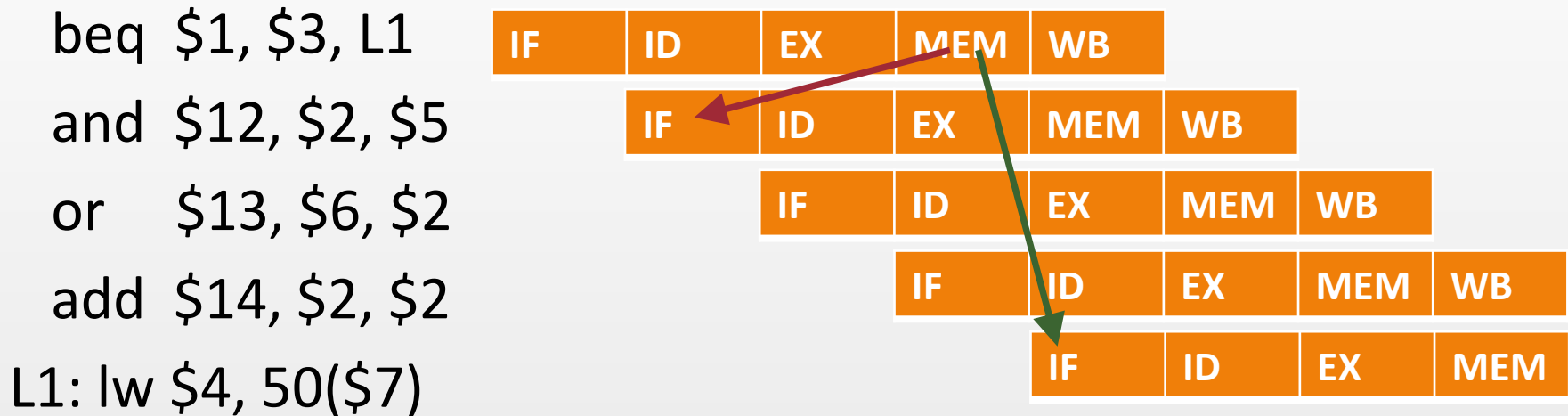
- ▶ **Control hazards**: Attempt to make a decision on the next instruction to fetch before the branch condition is evaluated
- ▶ **Control hazards** arise from the pipelining of conditional branches and other instructions changing the PC
- ▶ **Control hazards** reduce the performance from the ideal speedup gained by the pipelining since they can make it necessary to stall the pipeline

Example



- ▶ The branch instruction may or may not change the PC (MEM stage)
- ▶ The next 3 instructions are fetched and their execution is started

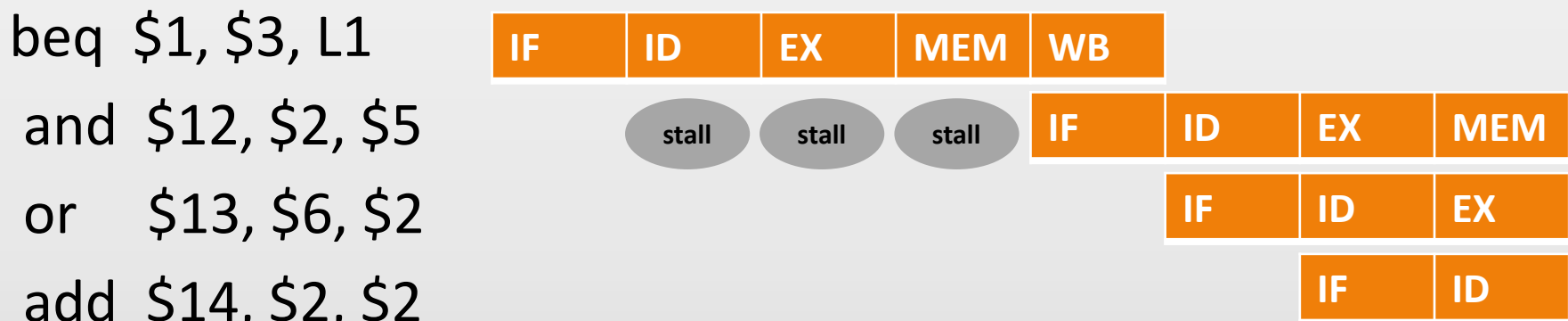
Example



- ▶ If the **branch is not taken**, the pipeline execution is **OK**
- ▶ If the **branch is taken**, it is necessary to **flush** the next 3 instructions in the pipeline and **fetch** the lw instruction at the **branch target address** (L1)

Solutions

- ▶ **Stalling until resolution:** To stall the pipeline until the branch decision is taken and then fetch the correct instruction flow
 - ▶ Without forwarding: for three clock cycles (*end MEM stage*)



- ▶ Each branch costs **three stalls** to fetch the correct instruction flow: (PC+4) or Branch Target Address

Solutions

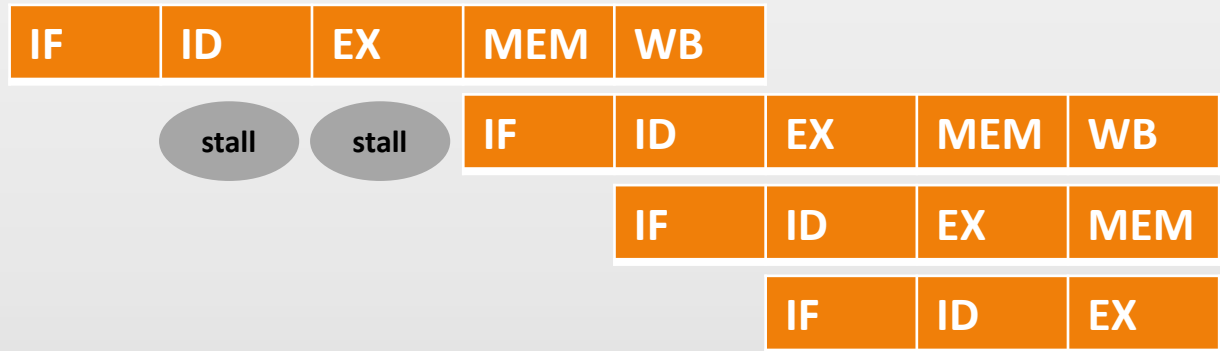
- ▶ **Stalling until resolution:** To stall the pipeline until the branch decision is taken and then fetch the correct instruction flow
 - ▶ With forwarding: for two clock cycles (*end EX stage*)

```
beq $1, $3, L1
```

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

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

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



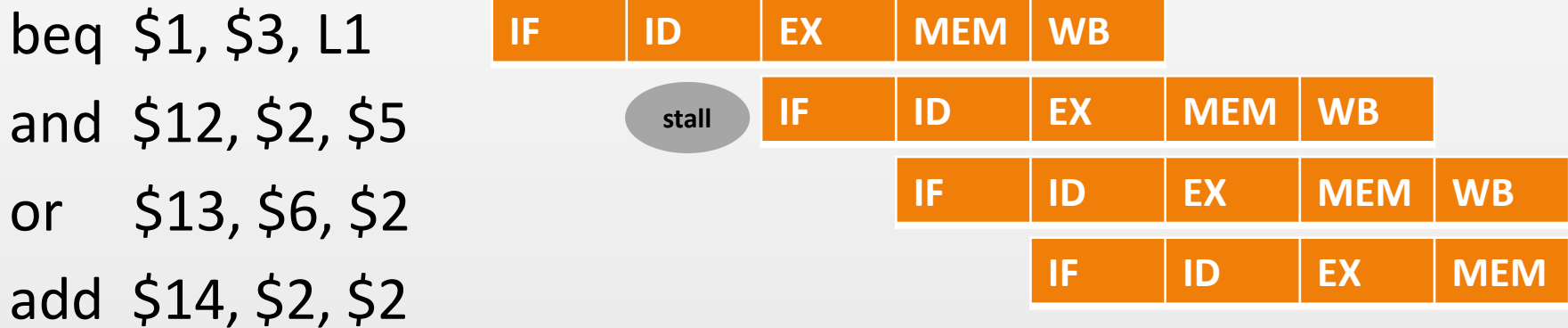
- ▶ Each branch costs **two stalls** to fetch the correct instruction flow: (PC+4) or Branch Target Address

Solutions

- ▶ **Early Evaluation of the PC:** To improve performance in case of branch hazards, additional hardware resources are needed to to:
 - ▶ Compare registers to derive the Branch Outcome
 - ▶ Compute the Branch Target Address
 - ▶ Update the PC register as soon as possible in the
- ▶ MIPS processor compares registers, computes branch target address and updates PC during ID stage

Solutions

- ▶ **Stalling until resolution** at the end of the ID stage

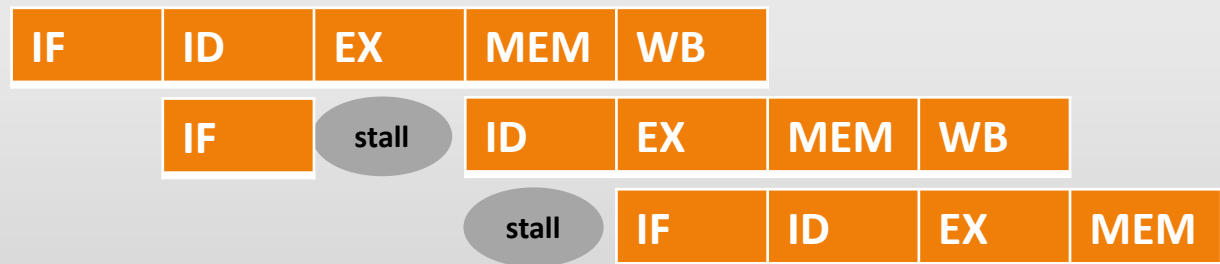


- ▶ Each branch costs **one stalls** to fetch the correct instruction flow: (PC+4) or Branch Target Address

Solutions

- ▶ Consequence of early evaluation of the branch decision in ID stage:
 - ▶ In case of **add** instruction **followed by a branch** testing the result → we need to introduce **one stall** before ID stage of branch to enable the forwarding (EX-ID) of the result from EX stage of previous instruction
 - ▶ We also need one stall **after** the branch for branch resolution

addi \$1, \$1, 4
beq \$1, \$6, L1
and \$12, \$2, \$5



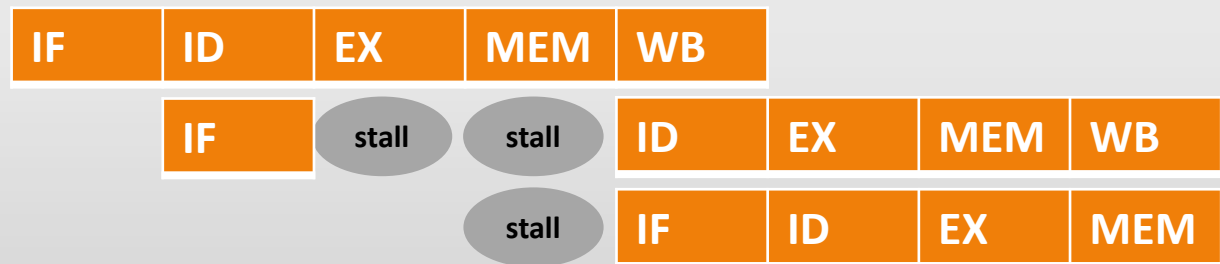
Solutions

- ▶ Consequence of early evaluation of the branch decision in ID stage:
 - ▶ In case of **load** instruction **followed by a branch** testing the result → we need to introduce **two stalls** before ID stage of branch to enable the forwarding (ME-ID) of the result from EX stage of previous instruction
 - ▶ We also need one stall **after** the branch for branch resolution

lw \$1, BASE(\$2)

beq \$1, \$6, L1

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



Solutions

- ▶ With the branch decision made during ID stage, there is a reduction of the cost associated with each branch (branch penalty):
 - ▶ We need only one-clock-cycle stall after each branch
 - ▶ Or a flush of only one instruction following the branch
- ▶ There are techniques to reduce the performance loss

Solutions

- ▶ **Branch prediction techniques** try to predict ASAP the outcome of a branch instruction
- ▶ **Static Branch Prediction Techniques:** The actions for a branch are fixed for each branch during the entire execution. The actions are fixed at compile time
 - ▶ Branch Always Not Taken (Predicted-Not-Taken)
 - ▶ Branch Always Taken (Predicted-Taken)
 - ▶ Backward Taken Forward Not Taken (BTFNT)
 - ▶ Profile-Driven Prediction
 - ▶ Delayed Branch

Solutions

- ▶ **Branch prediction techniques** try to predict ASAP the outcome of a branch instruction
- ▶ **Dynamic Branch Prediction Techniques:** The decision causing the branch prediction can dynamically change during the program execution
 - ▶ Basic Idea: To use the past branch behavior to predict
 - ▶ We use hardware to dynamically predict the outcome of a branch: the prediction will depend on the behavior of the branch at run time and will change if the branch changes its behavior during execution

Exercise - Midterm 2014/2015

- ▶ Consider the following loop in a high level language:

```
for (i =0; i < N; i ++)  
{  
  vectA[i] = vectB[i]  
  vectB[i] = vectB[i] + 4;  
}
```

- ▶ The program in MIPS assembly code is:

```
FOR: beq $t6,$t7,END  
      lw $t2,VECTB($t6)  
      sw $t2,VECTA($t6)  
      addi $t2,$t2,4  
      sw $t2,VECTB($t6)  
      addi $t6,$t6,4  
      blt $t6,$t7, FOR
```

- ▶ Registers \$t6 and \$t7 are initialized with 0 and 4N
- ▶ VECTB is a 16-bit constant

Exercise

- ▶ Let us consider the loop executed by 5-stage pipelined MIPS processor WITHOUT any optimisation in the pipeline:
 - ▶ Identify the **Hazard Type** (Data Hazard or Control Hazard)
 - ▶ Identify the **number of stalls** to be inserted before each instruction (or between stages IF and ID of each instruction) to solve the hazards
 - ▶ For each hazard, add an **ARROW** to indicate the pipeline stages involved in the hazard

Num. Stalls	INSTRUCTION	C1	C2	C3	C4	C5	C7	C6	C8	C9	C10	C11	Hazard Type
	FOR: beq \$t6,\$t7,END	IF	ID	EX	ME	WB							
	lw \$t2,VECTB(\$t6)		IF	ID	EX	ME	WB						
	sw \$t2,VECTA(\$t6)			IF	ID	EX	ME	WB					
	addi \$t2,\$t2,4				IF	ID	EX	ME	WB				
	sw \$t2,VECTB(\$t6)					IF	ID	EX	ME	WB			
	addi \$t6,\$t6,4						IF	ID	EX	ME	WB		
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	sw \$t2,VECTA(\$t6)			IF	ID	EX	ME	WB					
	addi \$t2,\$t2,4				IF	ID	EX	ME	WB				
	sw \$t2,VECTB(\$t6)					IF	ID	EX	ME	WB			
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3	sw \$t2,VECTA(\$t6)			IF	ID	EX	ME	WB					DATA
2	addi \$t2,\$t2,4				IF	ID	EX	ME	WB				DATA
	sw \$t2,VECTB(\$t6)					IF	ID	EX	ME	WB			
	addi \$t6,\$t6,4						IF	ID	EX	ME	WB		
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3	sw \$t2,VECTB(\$t6)					IF	ID	EX	ME	WB			DATA
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3	sw \$t2,VECTB(\$t6)					IF	ID	EX	ME	WB			DATA
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	addi \$t6,\$t6,4						IF	ID	EX	ME	WB		
3	blt \$t6,\$t7, FOR							IF	ID	EX	ME	WB	DATA

Exercise

- ▶ For each instruction
 - ▶ Write the phases and insert the stalls to solve the hazards identified → take into account that solving some hazards can help to solve those that follow
 - ▶ Specify the number of stalls actually inserted

Num. Stalls	INSTRUCTION	C1	C2	C3	C4	C5	C7	C6	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
	FOR: beq \$t6,\$t7,END																								
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2	addi \$t2,\$t2,4				IF	ID	EX	ME	WB				DATA
3	sw \$t2,VECTB(\$t6)					IF	ID	EX	ME	WB			DATA
	addi \$t6,\$t6,4						IF	ID	EX	ME	WB		
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