

# CENG 3420

# Computer Organization & Design



## Lecture 09: Pipeline – Basis

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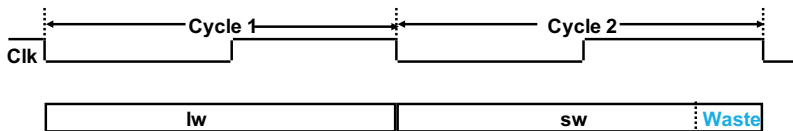
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(Textbook: Chapters 4.5 & 4.6)

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- **Single cycle**: the whole datapath is finished in one clock cycle
- It is simple and easy to understand
- Uses the clock cycle inefficiently – the clock cycle must be timed to accommodate the **slowest** instr
- Problematic for more complex instructions like floating point multiply
- May be wasteful of area since some functional units (e.g., adders) must be duplicated since they can not be shared during a clock cycle





- Though simple, the single cycle approach is not used because it is very slow
- Clock cycle must have the same length for every instruction
- What is the longest path (slowest instruction)? [Load instruction!](#)
- It is too long for the store instruction so the last part of the cycle here is wasted.



## EX: Instruction Critical Paths

Calculate cycle time assuming negligible delays (for muxes, control unit, sign extend, PC access, shift left 2, wires) except:

- Instruction fetch and update PC (**IF**), Read/write data from/to data memory (**MEM**) (4 ns)
- Execute R-type; calculate memory address (**EXE**) (2 ns)
- Register fetch and instruction decode (**ID**), Write the result data into the register file (**WB**) (1 ns)

Instr.	IF	ID	EXE	MEM	WB	Total
R/I-type						
lw						
sw						
beq						
J-type						
jal						
jalr						



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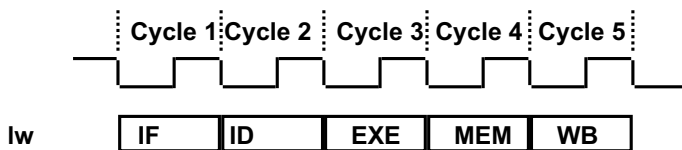
Instr.	IF	ID	EXE	MEM	WB	Total
R/I-type	4	1	2		1	8
lw	4	1	2	4	1	12
sw	4	1	2	4		11
beq	4	1	2			7
jal						
jalr						



$$\text{CPU time} = \text{CPI} \times \text{CC} \times \text{IC}$$

- Start fetching and executing the next instruction before the current one has completed
  - **Pipelining** – (all?) modern processors are pipelined for performance
  - Under ideal conditions and with a large number of instructions, the speedup from pipelining is approximately equal to the number of pipe stages
  - A five stage pipeline is nearly five times faster because the CC is “**nearly**” five times faster
- Fetch (and execute) **more than one** instruction at a time
  - **Superscalar** processing – stay tuned

# The Five Stages of Load Instruction

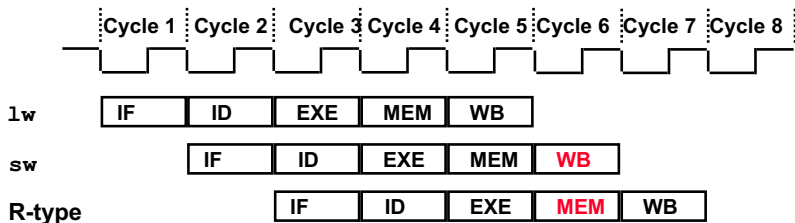


- **IF**: Instruction Fetch and Update PC
- **ID**: Registers Fetch and Instruction Decode
- **EXE**: Execute R-type; calculate memory address
- **MEM**: Read/write the data from/to the Data Memory
- **WB**: Write the result data into the register file



Start the next instruction before the current one has completed

- improves throughput - total amount of work done in a given time
- instruction **latency** (execution time, delay time, response time - time from the start of an instruction to its completion) is not reduced

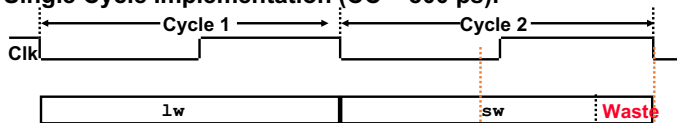


- 1 clock cycle (pipeline stage time) is limited by the slowest stage
- for some stages don't need the whole clock cycle (e.g., WB)
- for some instructions, some stages are wasted cycles (i.e., nothing is done during that cycle for that instruction)

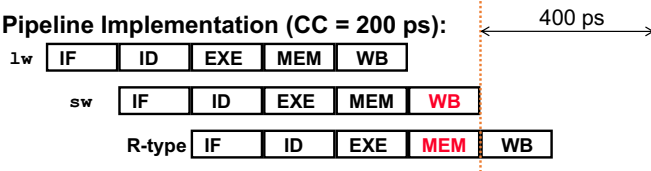




## Single Cycle Implementation (CC = 800 ps):



## Pipeline Implementation (CC = 200 ps):



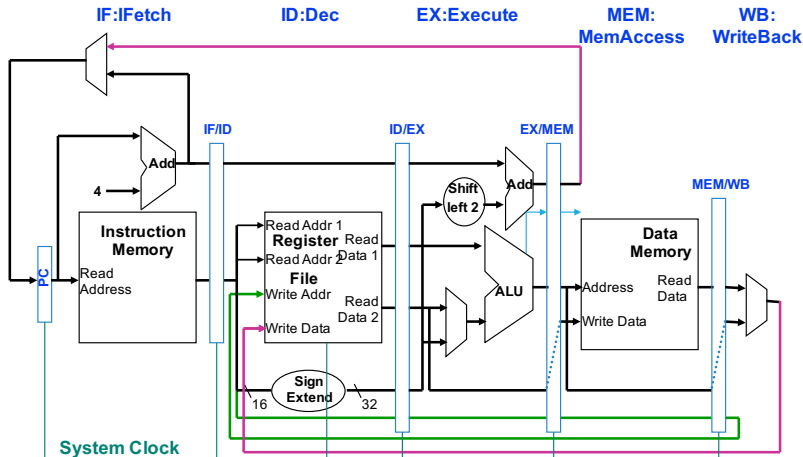
- To complete an entire instruction in the pipelined case takes 1000 ps (as compared to 800 ps for the single cycle case). Why ?
- How long does each take to complete 1,000,000 adds ?



## What makes it easy

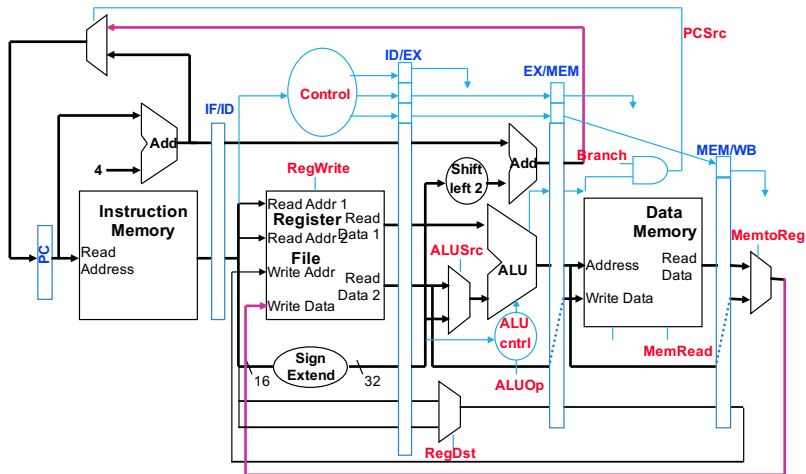
- all instructions are the same length (32 bits)
  - can fetch in the 1st stage and decode in the 2nd stage
- few instruction formats (three) with symmetry across formats
  - can begin reading register file in 2nd stage
- memory operations occur only in loads and stores
  - can use the execute stage to calculate memory addresses
- each instruction writes at most one result (i.e., changes the machine state) and does it in the last few pipeline stages (MEM or WB)
- operands must be aligned in memory so a single data transfer takes only one data memory access

State registers between each pipeline stage to isolate them



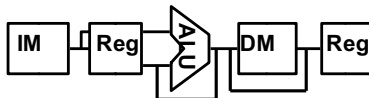
All control signals can be determined during Decode

- and held in the state registers between pipeline stages



- IF Stage: read Instr Memory (always asserted) and write PC (on System Clock)
- ID Stage: no optional control signals to set

	EX Stage				MEM Stage			WB Stage	
	Reg Dst	ALU Op1	ALU Op0	ALU Src	Brch	Mem Read	Mem Write	Reg Write	Mem toReg
R	1	1	0	0	0	0	0	1	0
lw	0	0	0	1	0	1	0	1	1
sw	X	0	0	1	0	0	1	0	X
beq	X	0	1	0	1	0	0	0	X

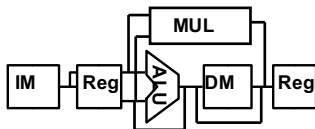


Can help with answering questions like:

- How many cycles does it take to execute this code?
- What is the ALU doing during cycle 4?
- Is there a hazard, why does it occur, and how can it be fixed?

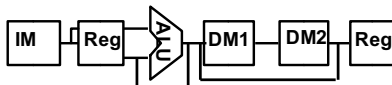
What about the (slow) multiply operation?

- Make the clock twice as slow or ...
- let it take two cycles (since it doesn't use the MEM stage)

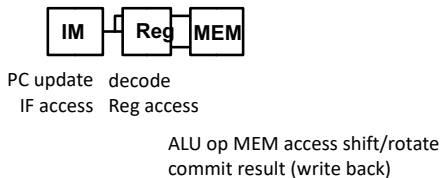


What if the data memory access is twice as slow as the instruction memory?

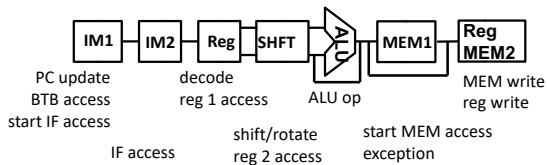
- make the clock twice as slow or ...
- let data memory access take two cycles (and keep the same clock rate)



- ARM7:

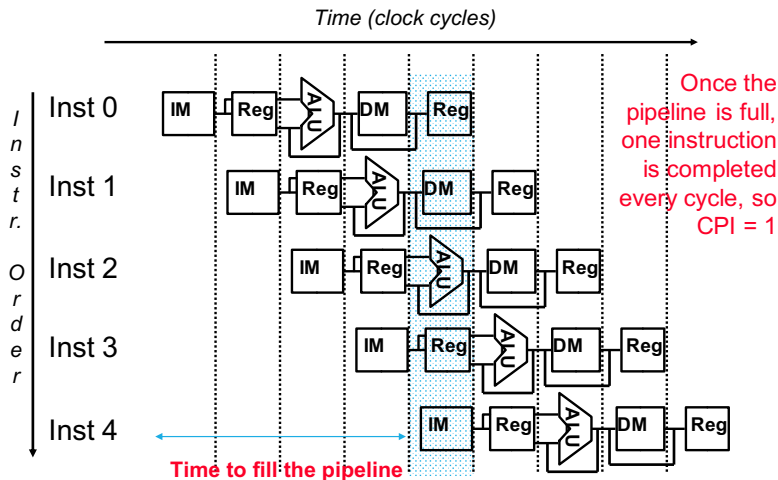


- XScale:





# Why Pipeline? For Performance!



## Yes! Pipeline Hazards

- **structural** hazards: a required resource is busy
- **data** hazards: attempt to use data before it is ready
- **control** hazards: deciding on control action depends on previous instruction

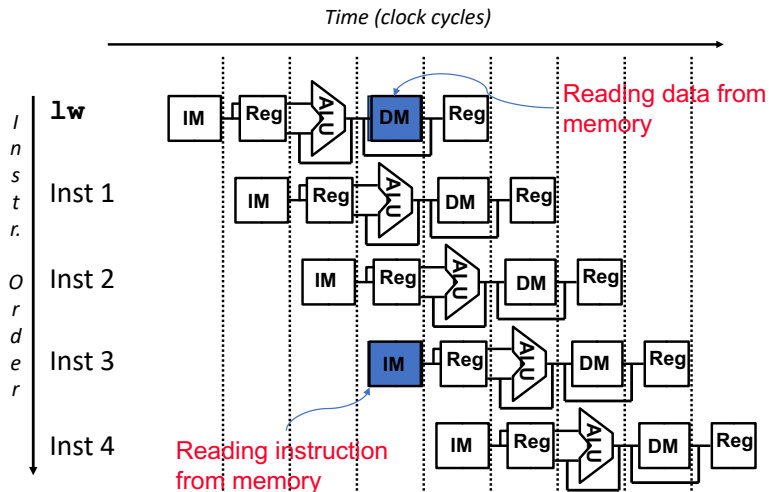
Can usually resolve hazards by **waiting**

- pipeline control must **detect** the hazard
- and take action to **resolve** hazards



- Conflict for use of a resource
- In RISC-V pipeline with a single memory
  - Load/store requires data access
  - Instruction fetch requires instruction access
- Hence, pipeline datapaths require separate instruction/data memories
  - Or separate instruction/data caches
- Since Register File

# Resolve Structural Hazard 1



□ Fix with separate instr and data memories (I\$ and D\$)

Fix with separate instr and data memories (I\$ and D\$)

# Resolve Structural Hazard 2

