

The Processor: Basic Pipeline



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CSE3666: Introduction to Computer Architecture

Outline

$$CPU_{time} = \underline{IC} \times \sqrt{CP2} \times CCT$$

- Concept of pipeline
- Implementation of a 5-stage pipeline
- Pipeline Hazards

Reading: Sections 4.6 and 4.7.

Skip discussions on hazards in Section 4.6, for now.

Review Clock Cycle Time of Single-Cycle Processor

- Assume time for stages is
 - 100ps for register read or write
 - Main control and register read can be done at the same time
 - 200ps for other stages

Instr	Instr fetch	Register read	ALU op	Memory access	Register write	Total time
lw	200ps	100ps	200ps	200ps	100ps	800ps
sw	200ps	100ps	200ps	200ps		700ps
R-format	200ps	100ps	200ps		100ps	600ps
beq	200ps	100ps	200ps			500ps

Performance Issues with Single-Cycle Implementation

- The cycle time is the same for all instructions
 - Not feasible to vary period for different instructions
- Longest delay determines clock period
 - **Critical path**: the load (LW) instruction

Instruction memory → Register file → ALU → Data memory → Register file

- Violates design principle
 - Making the common case fast
- How can we improve the performance ?

Five steps in RISC-V instruction execution

Observations in the single-cycle RISC-V execution.

The execution of an instruction has five important steps:

1. Fetch instruction from memory (IF)
2. Read register file and decode instructions (ID)
3. Use ALU to compare numbers or to compute results/addresses (EX)
4. Access data memory (MEM)
5. Write the result into register (WB)

Another Important Observation

- An instruction does not need to do all stages at the same time.
 - A hardware module is idle in most part of a cycle.

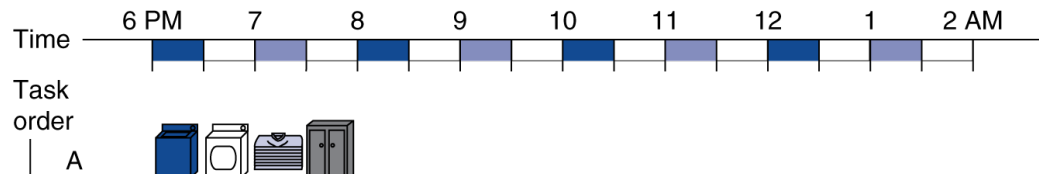
Instruction memory → Register file → ALU → Data memory → Register file

For example, an instruction only uses I-Mem at beginning of a cycle.
When it uses ALU, I_Mem is idle.

- We can try **pipelining!**

Pipelining Analogy

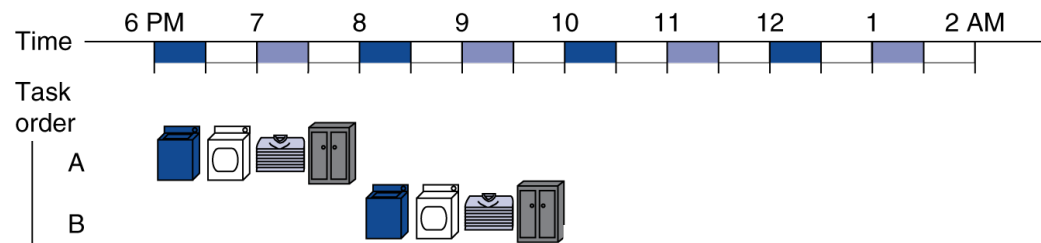
- 4-step laundry:
 - Place one dirty load of clothes in the **washer**.
 - When the washer is finished, place the wet load in the **dryer**.
 - When the dryer is finished, place the dry load on a table and **fold**.
 - When folding is finished, ask your roommate to **put** the clothes **away**.



1 task: 4 steps (2 hours)

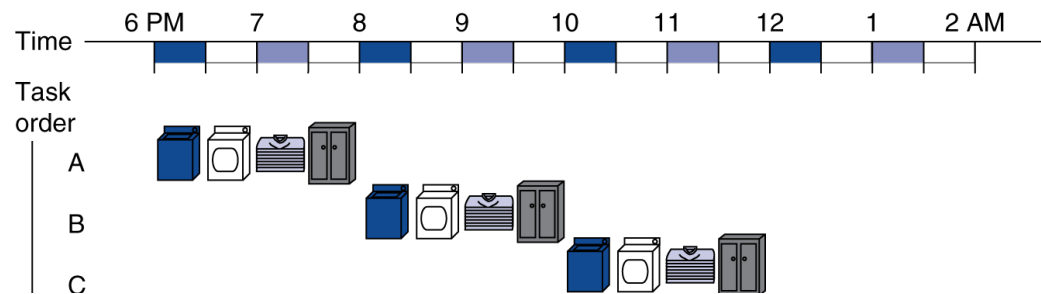
Pipelining Analogy

- Laundry: multiple tasks
 - washer
 - dryer
 - fold
 - put away



Pipelining Analogy

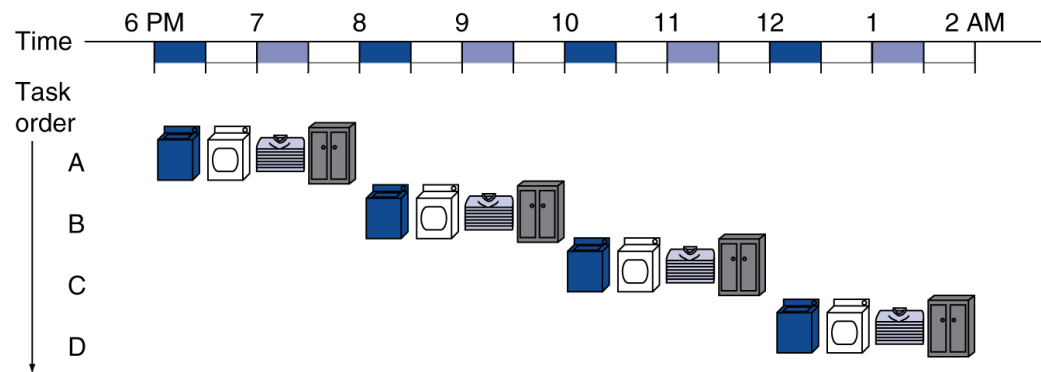
- Laundry: Multiple loads
 - washer
 - dryer
 - fold
 - put away



Pipelining Analogy

- Laundry: Multiple tasks

- washer
- dryer
- fold
- put away



4 tasks (6pm – 2am)

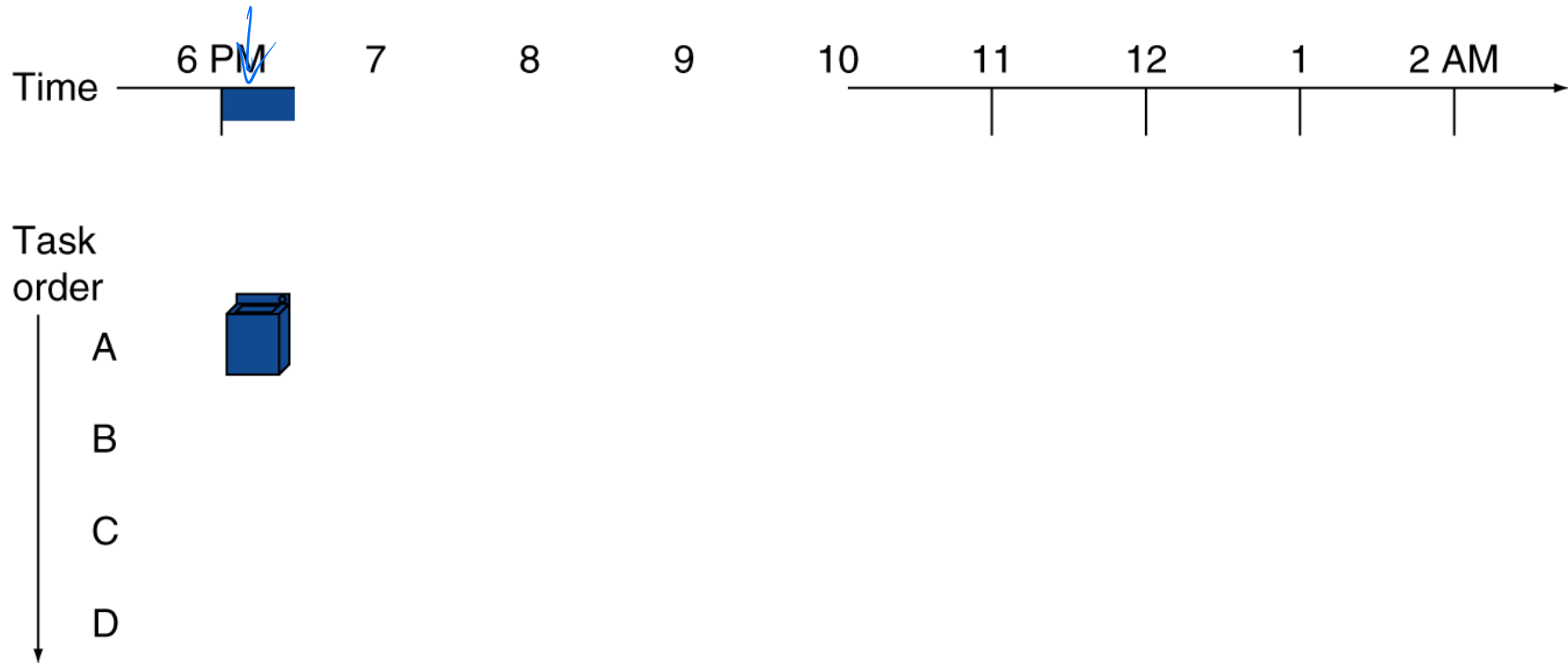
Execution time of Non-stop n tasks:
 $4n$

30 min

Question: how many “hardware” do we have?

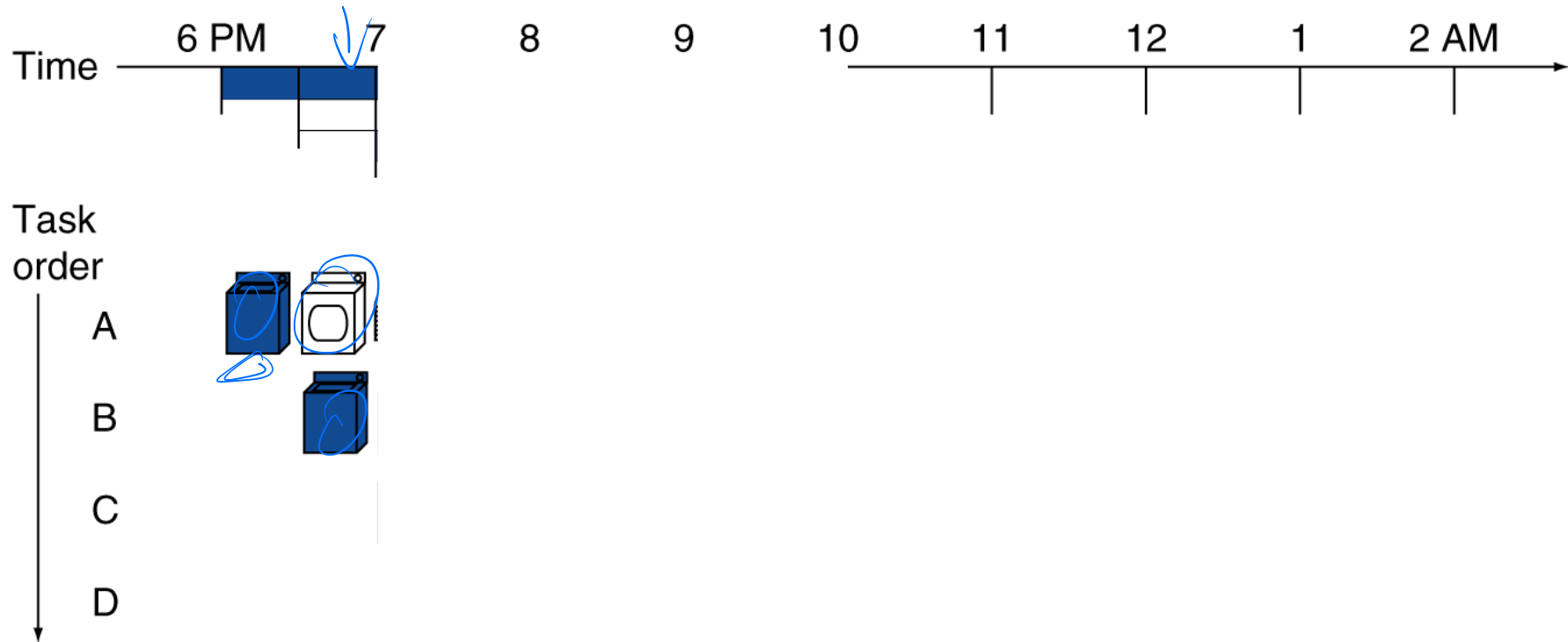
Pipelining Analogy

- Pipelined laundry: overlapping execution



Pipelining Analogy

- Pipelined laundry: overlapping execution

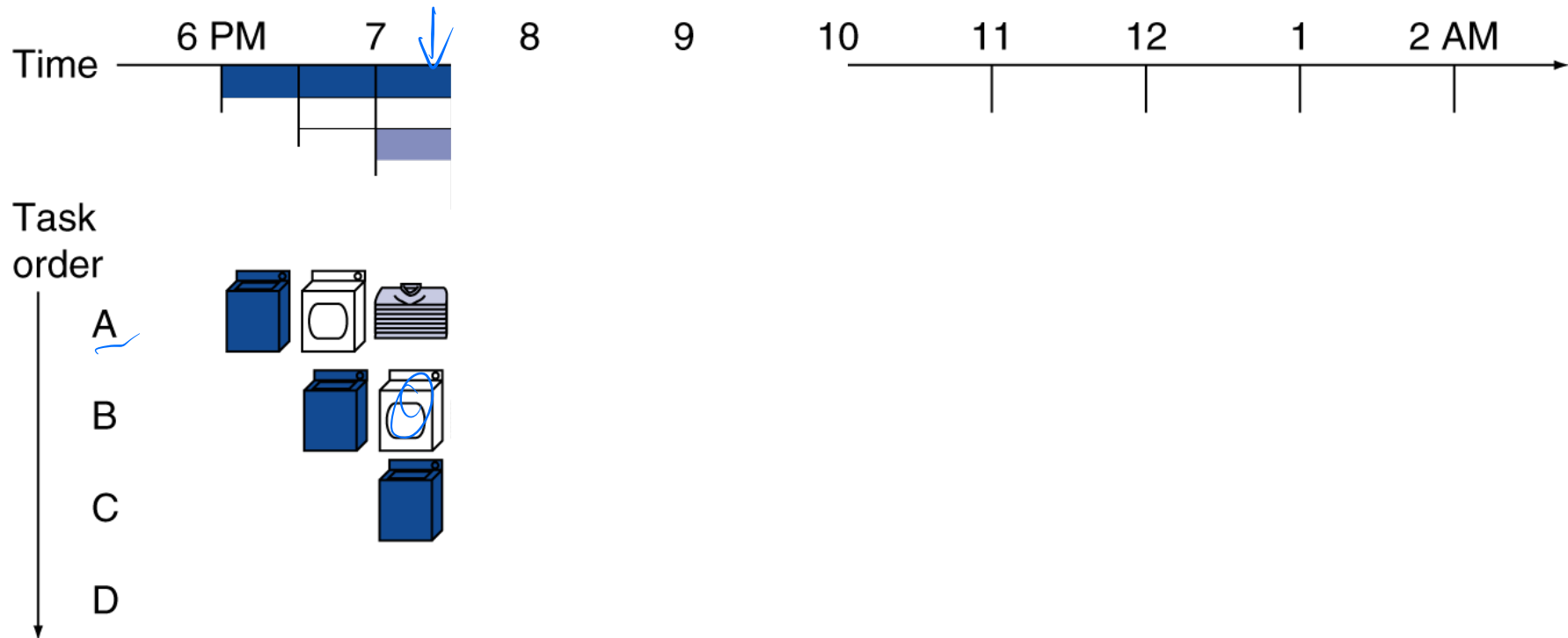


1 set

Question: how many “hardware” do we have?

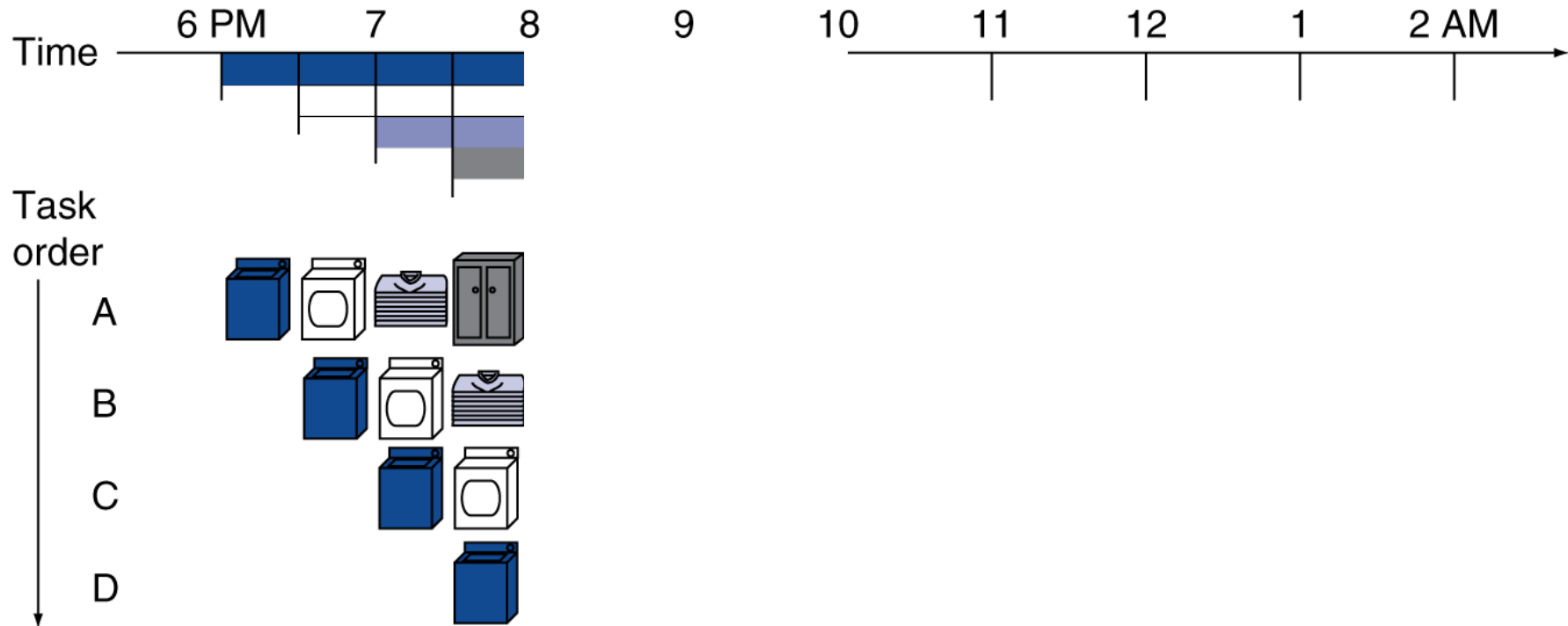
Pipelining Analogy

- Pipelined laundry: overlapping execution



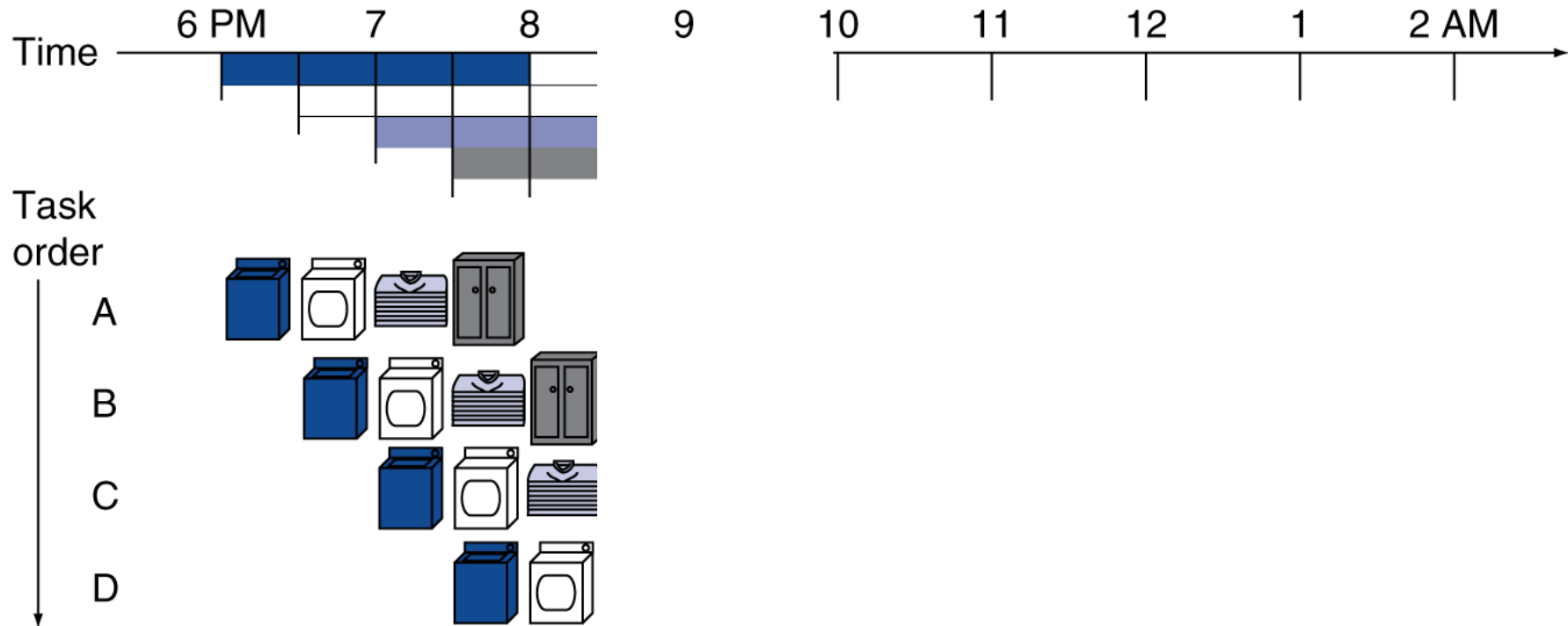
Pipelining Analogy

- Pipelined laundry: overlapping execution



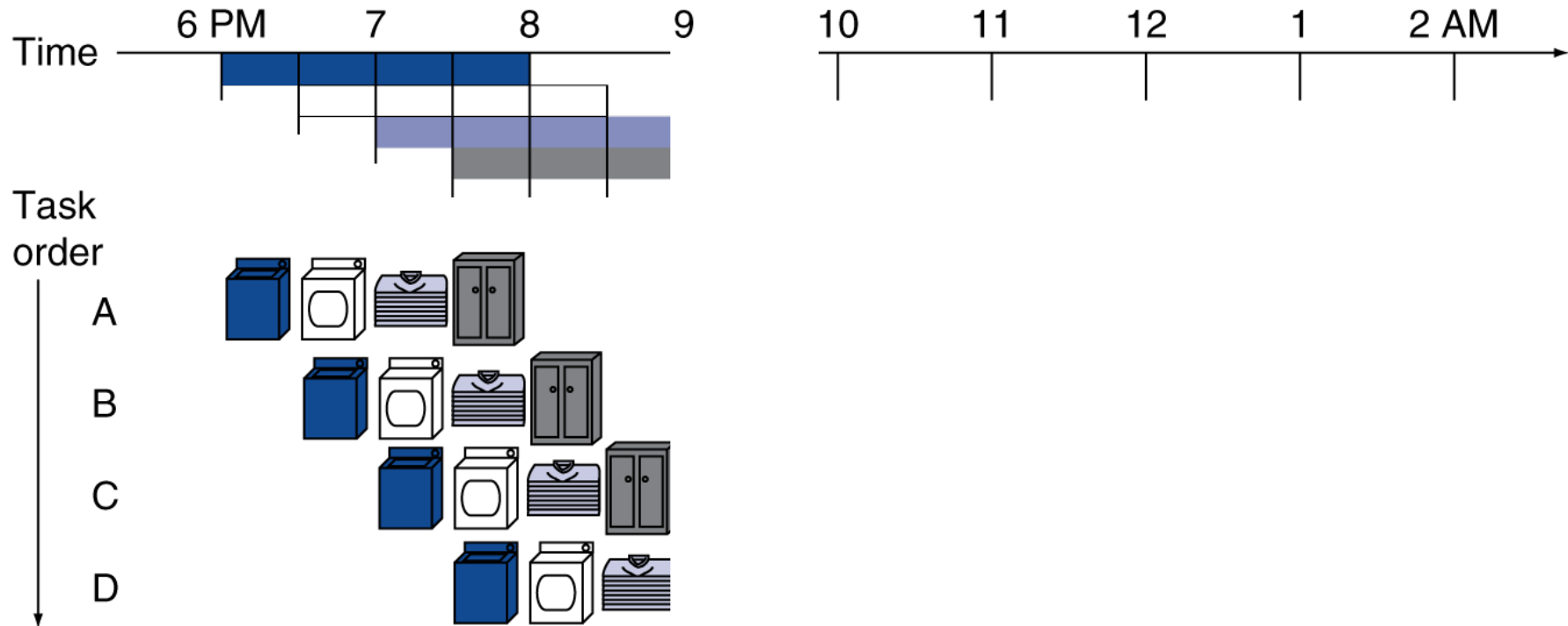
Pipelining Analogy

- Pipelined laundry: overlapping execution



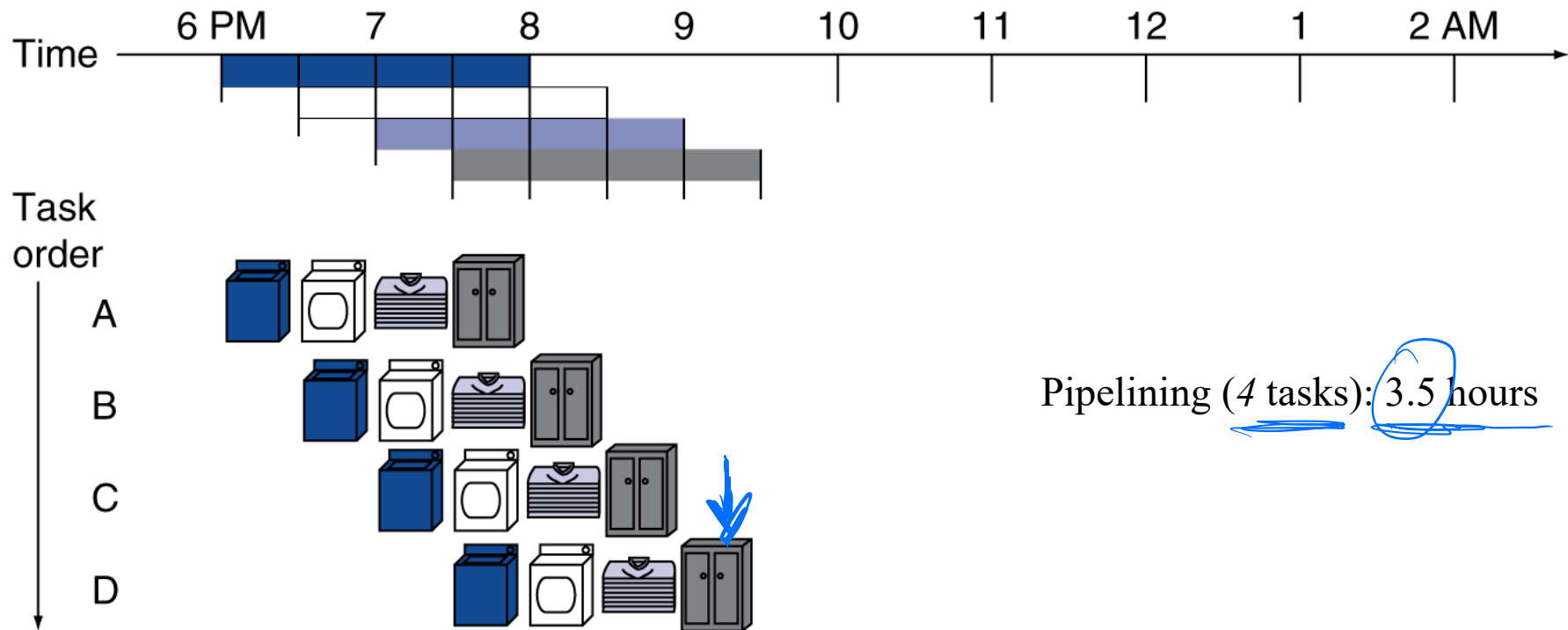
Pipelining Analogy

- Pipelined laundry: overlapping execution



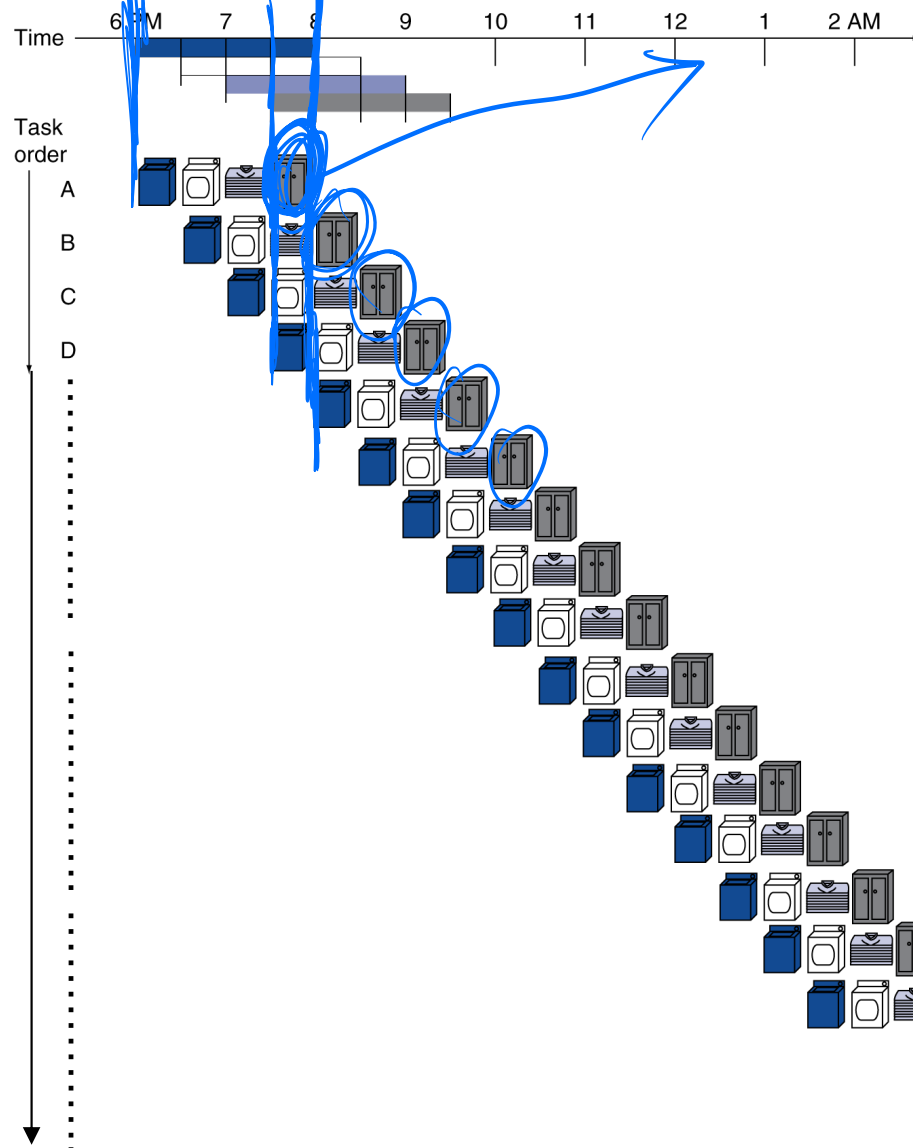
Pipelining Analogy

- Pipelined laundry: overlapping execution



Pipelining Analogy

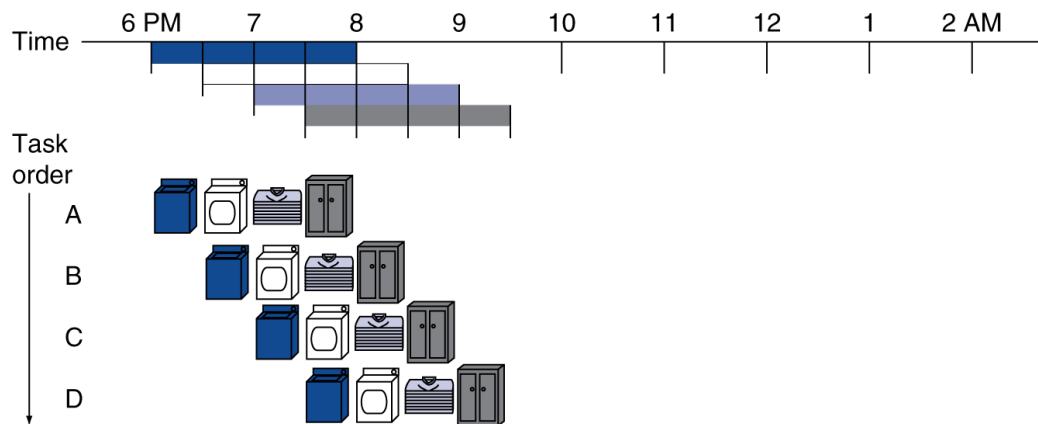
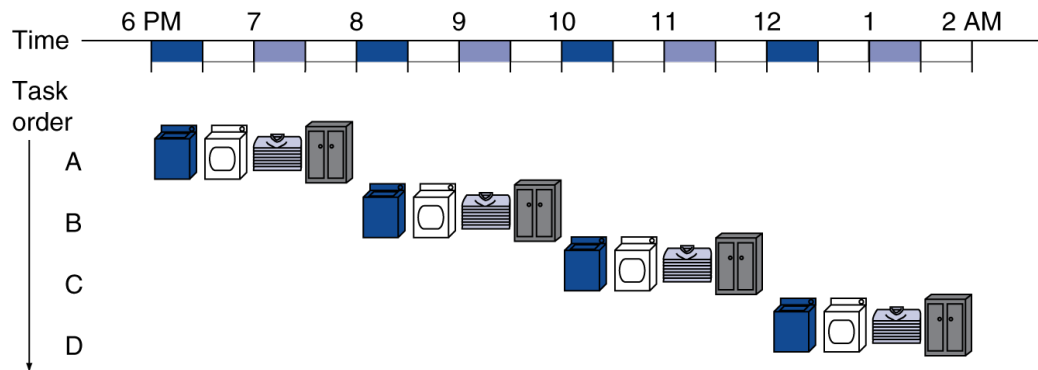
- Pipelined laundry: overlapping execution



Execution time of pipelining
 n tasks: $n+3$

Pipelining Analogy

- Pipelined laundry: overlapping execution
 - Parallelism improves performance
 - Do you see the parallelism in the figures?



Speedup

$$= \frac{2n}{0.5n + 1.5} \approx 4$$

= number of stages

billion

million

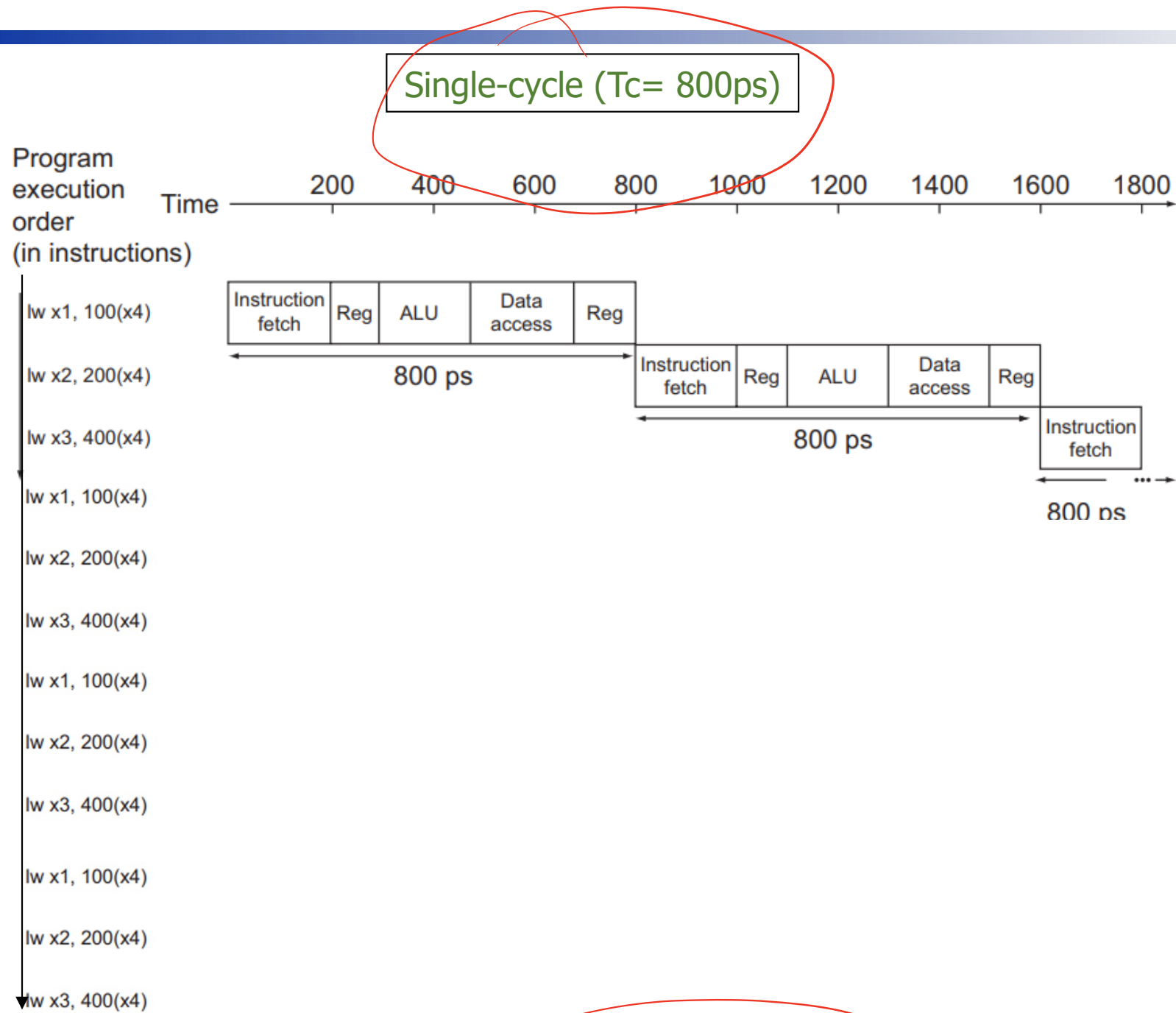
4n
n+3

RISC-V Pipeline

Create a pipeline of five stages, one step per stage.

1. IF: Instruction fetch from memory
2. ID: Instruction decode & register read
3. EX: Execute operation or calculate address
4. MEM: Access memory operand
5. WB: Write result back to register

Pipeline Performance



Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)

Program execution order (in instructions)

Time

200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000..

lw x1, 100(x4)

Instruction
fetch

200 ps

lw x2, 200(x4)

lw x3, 400(x4)

lw x1, 100(x4)

lw x2, 200(x4)

lw x3, 400(x4)

lw x1, 100(x4)

lw x2, 200(x4)

lw x3, 400(x4)

lw x1, 100(x4)

lw x2, 200(x4)

lw x3, 400(x4)

lw x1, 100(x4)

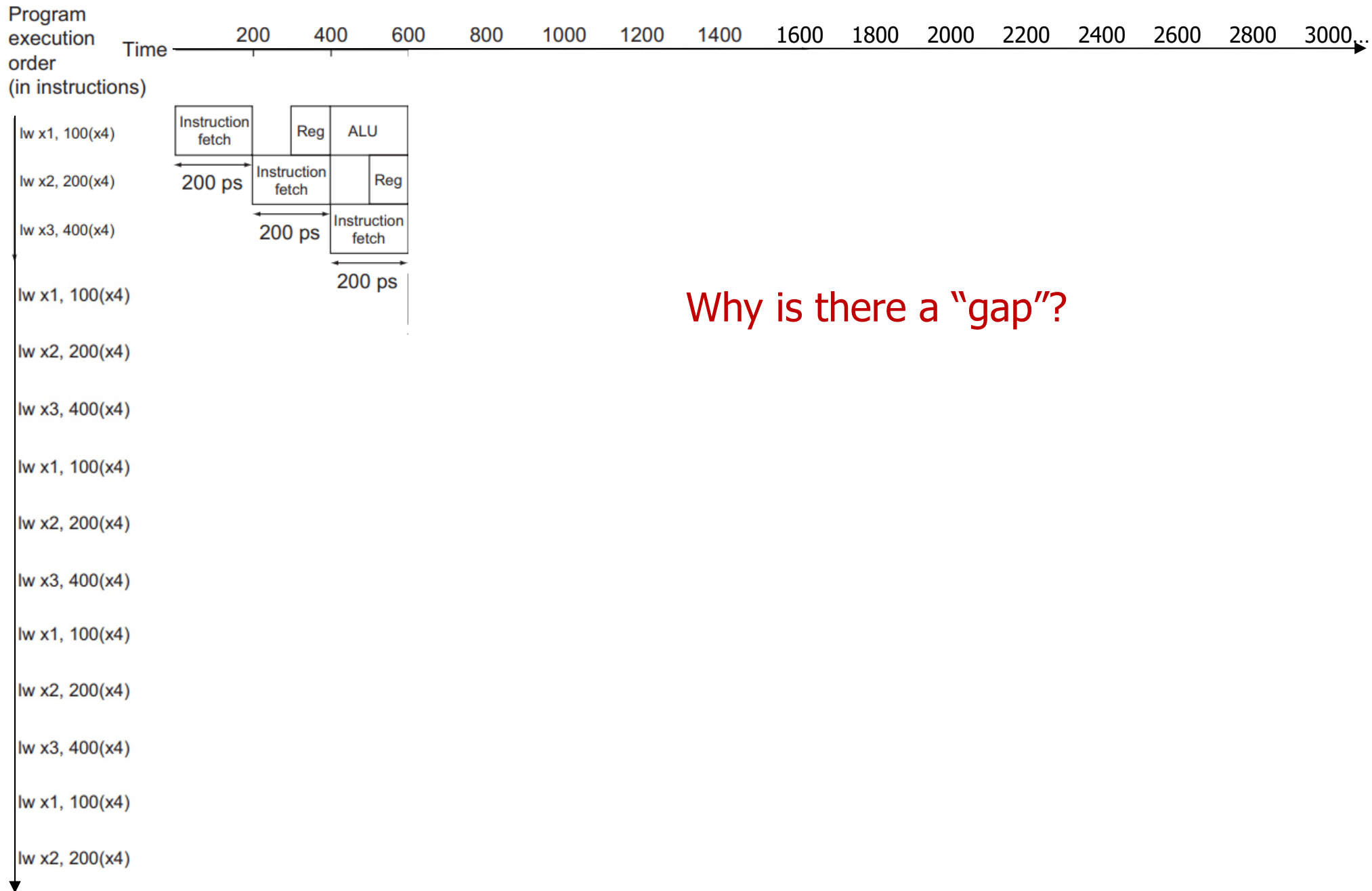
lw x2, 200(x4)

Pipelined ($T_c = 200\text{ps}$)



Pipeline Performance

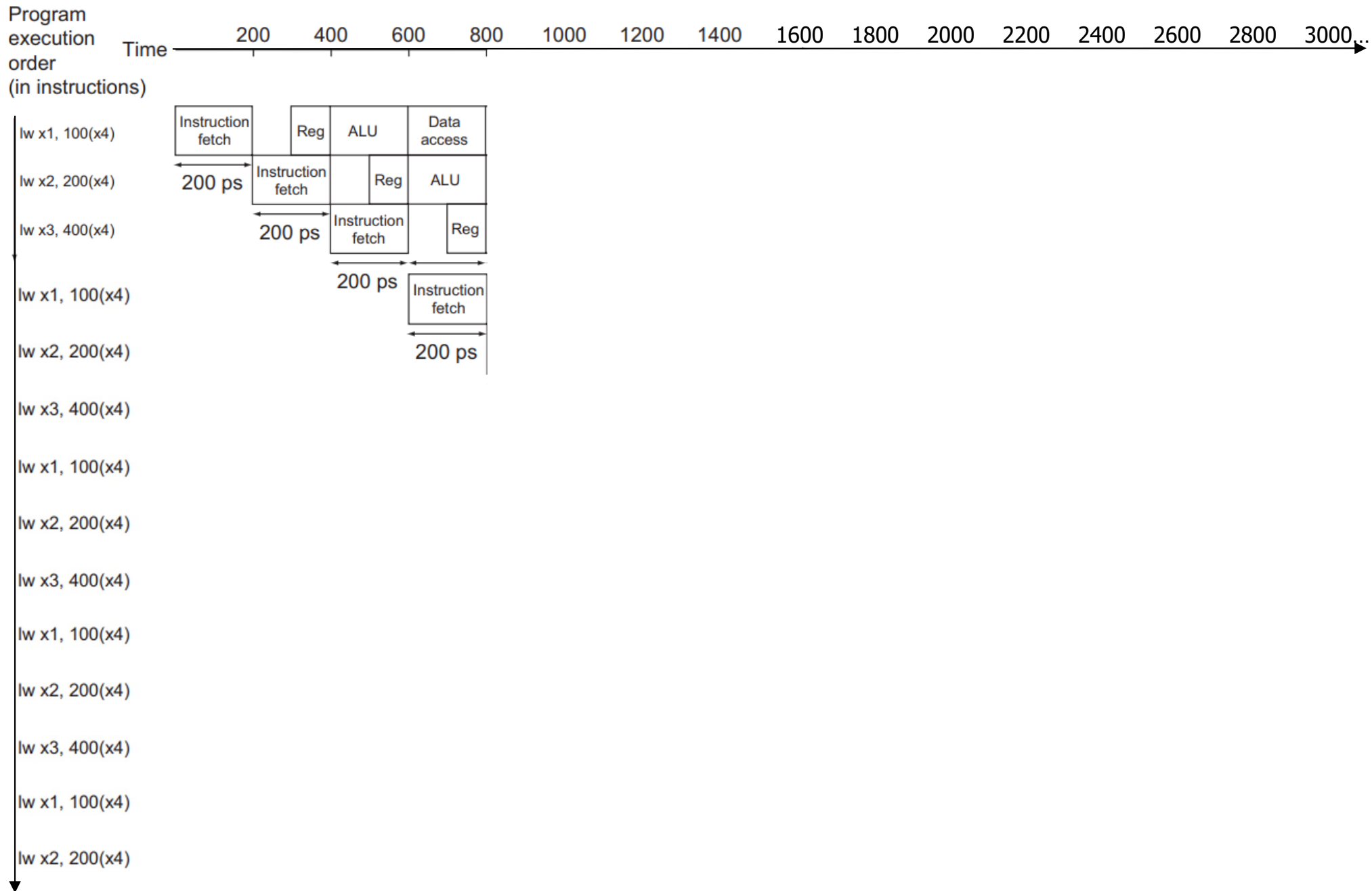
Pipelined ($T_c = 200\text{ps}$)



Why is there a "gap"?

Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)



Pipelined ($T_c = 200\text{ps}$)

Program execution order (in instructions)

Time

200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000...

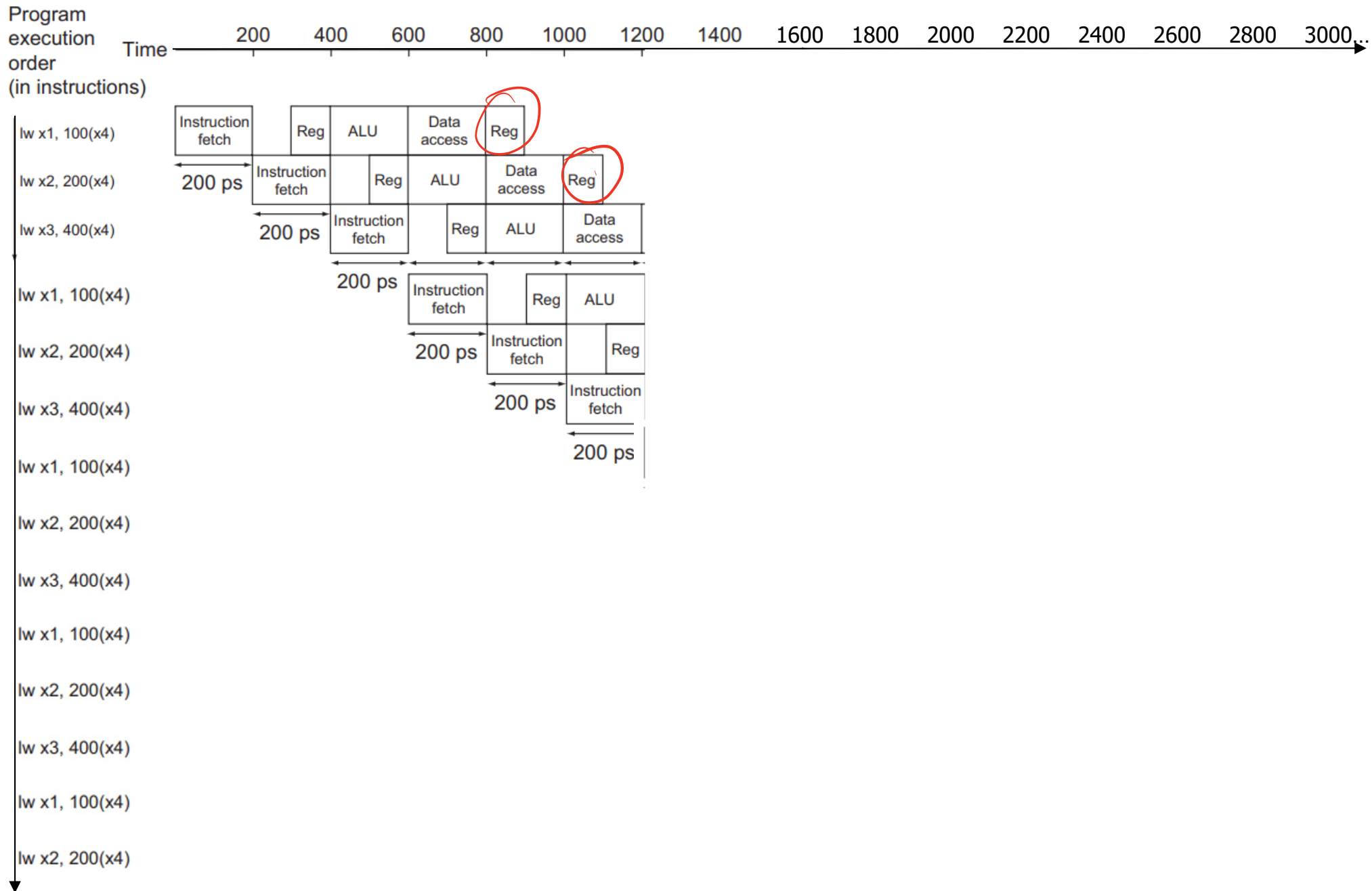
Write RF in 1st half



How many hardware components? e.g.,
Reg?

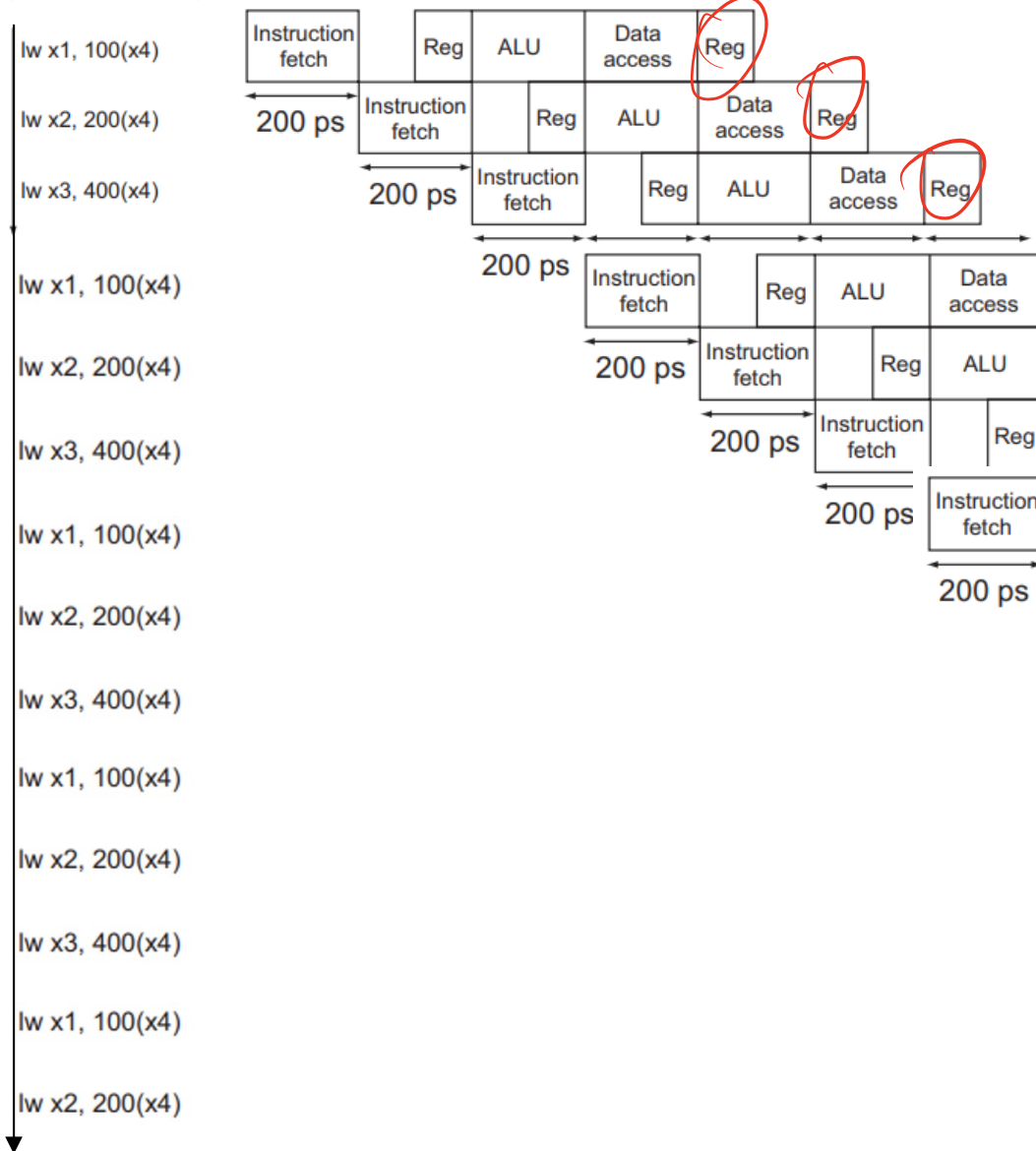
Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)



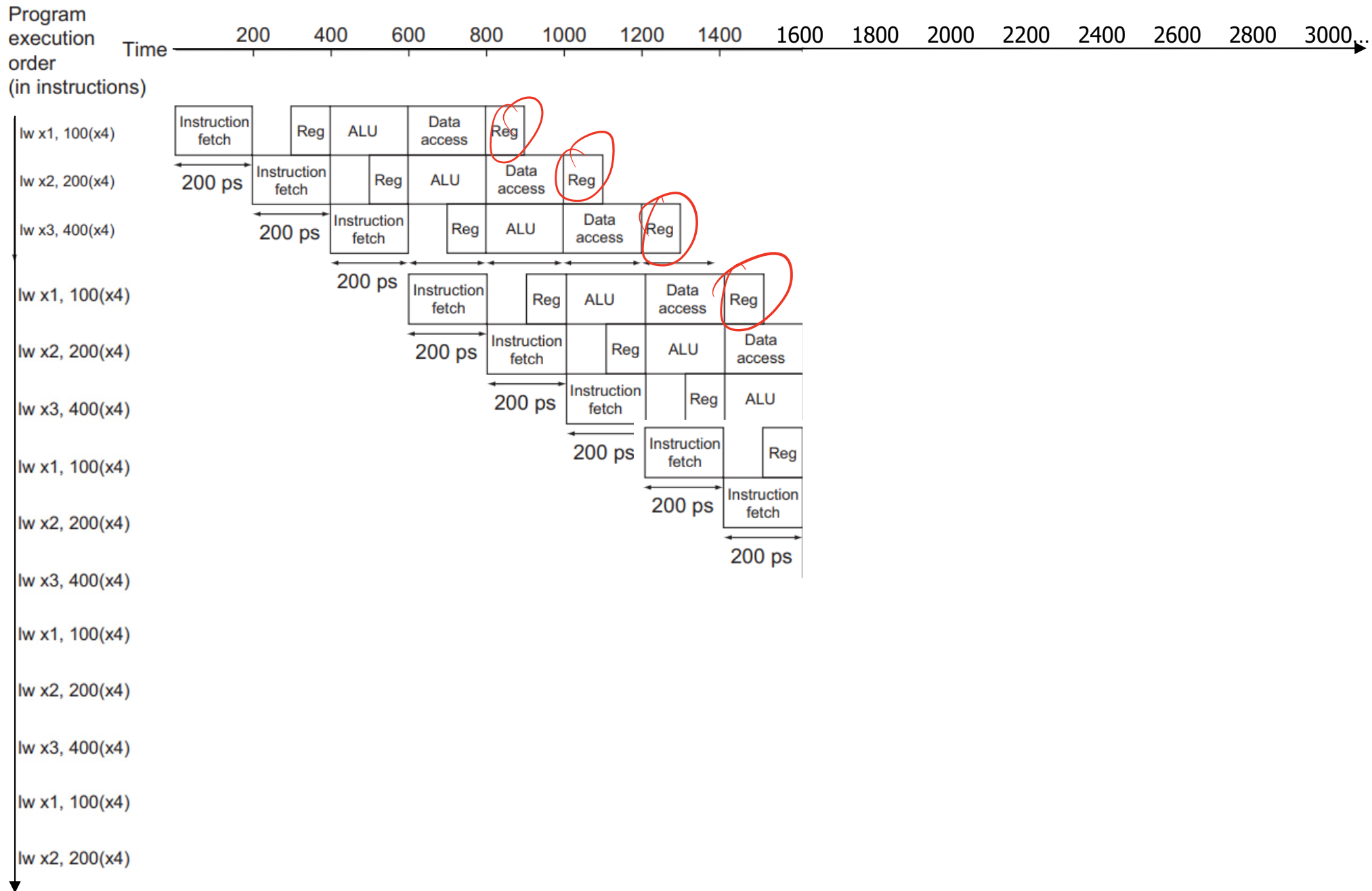
Pipelined ($T_c = 200\text{ps}$)

Time



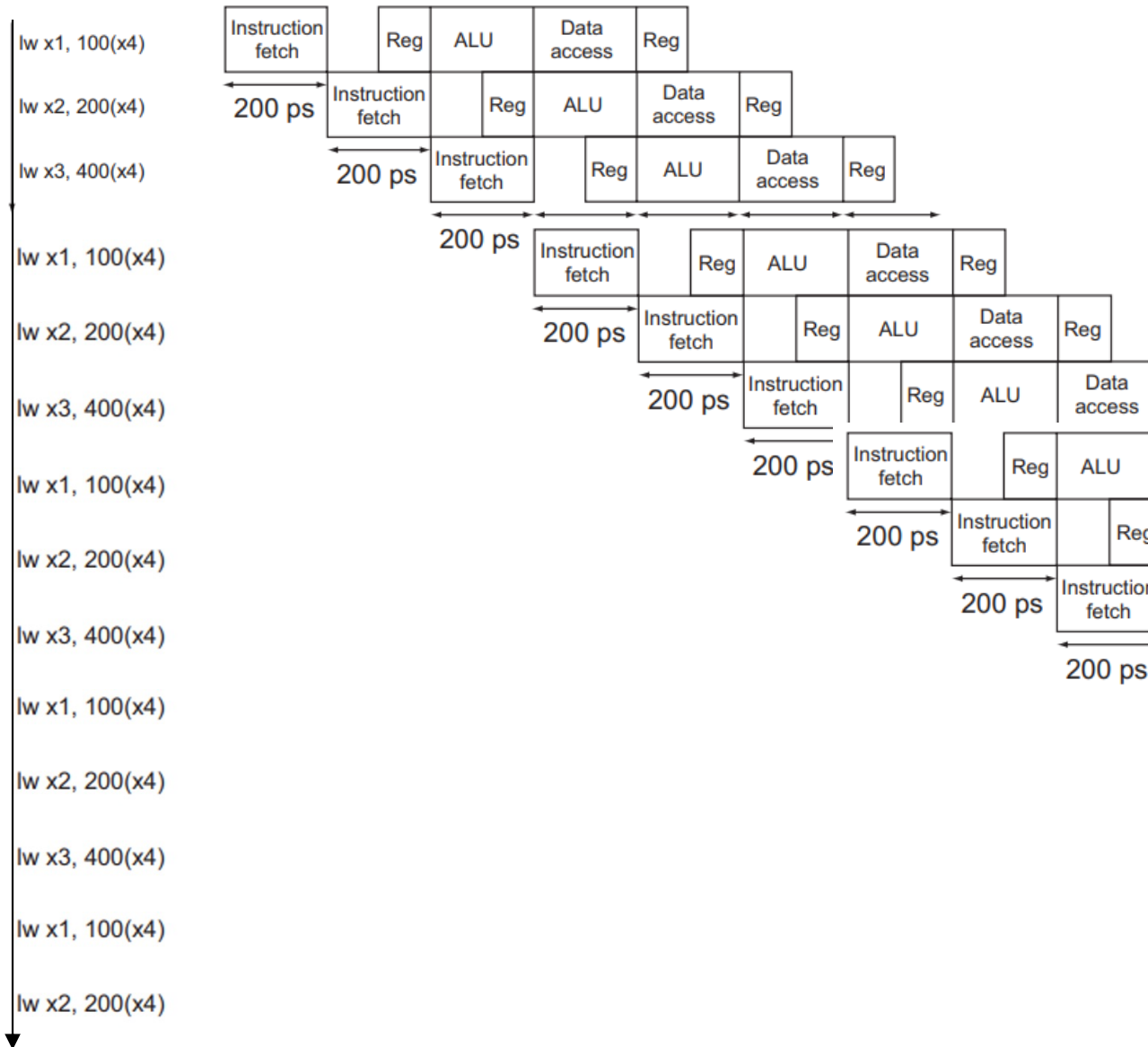
Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)



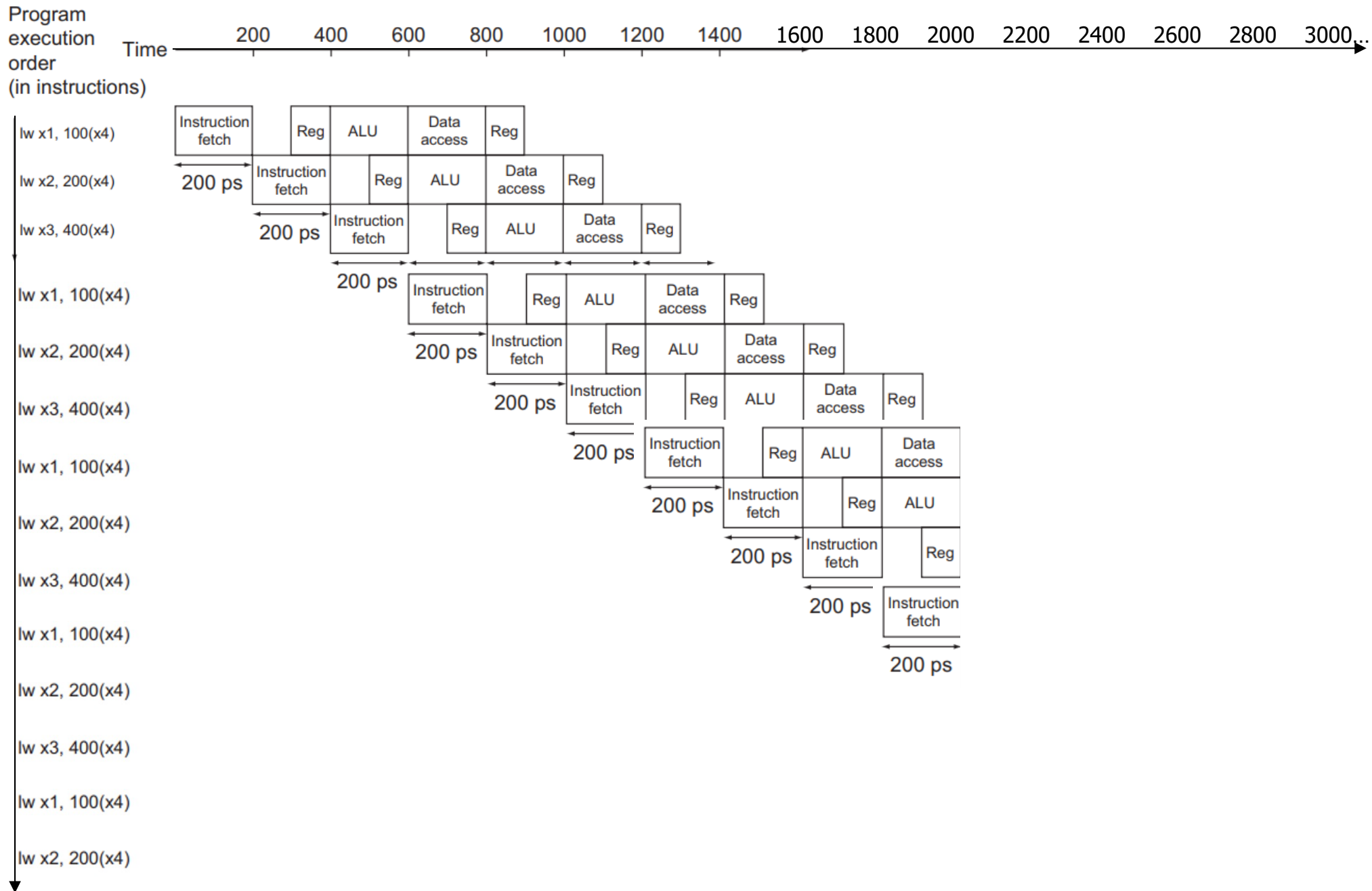
Pipelined ($T_c = 200\text{ps}$)

Time



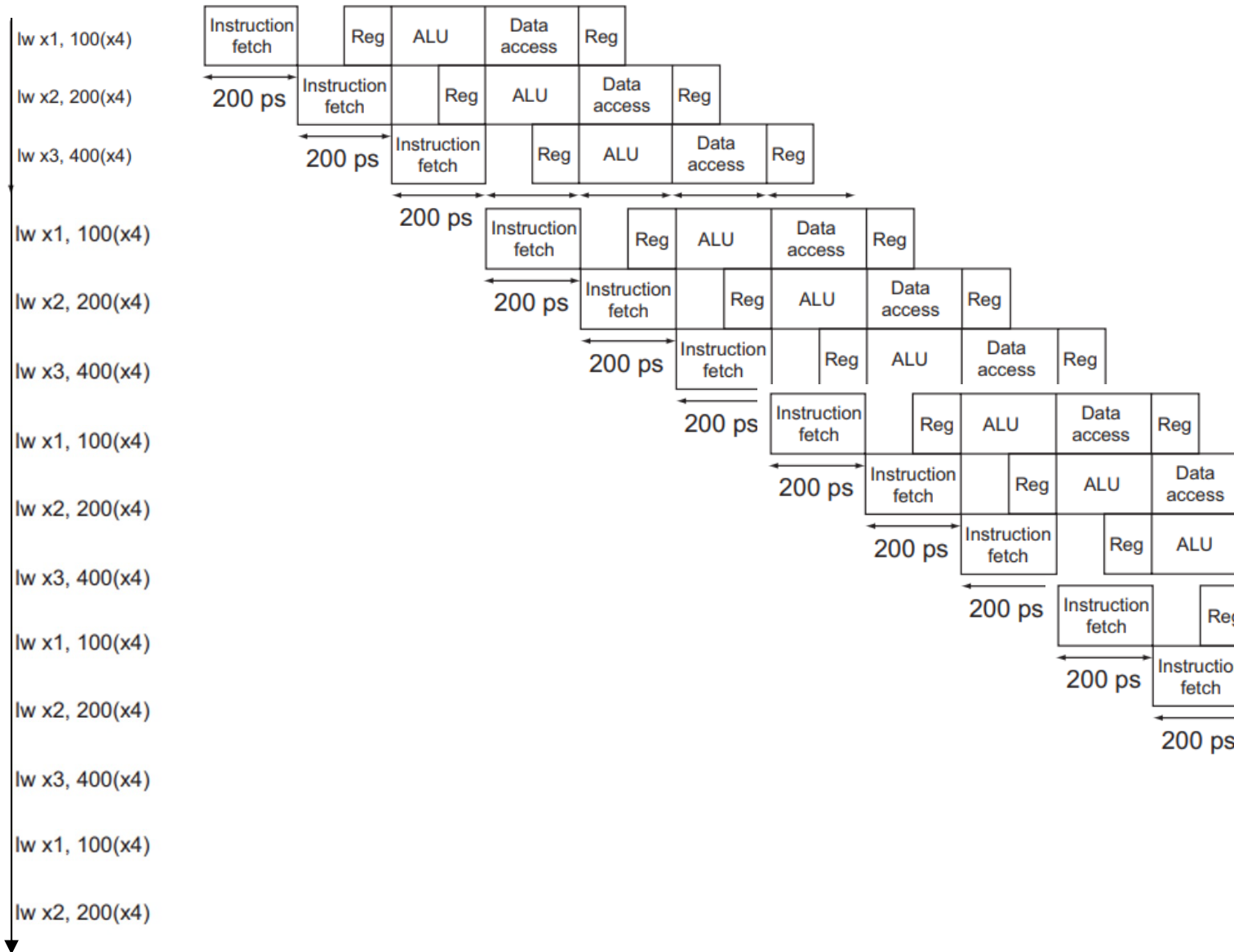
Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)



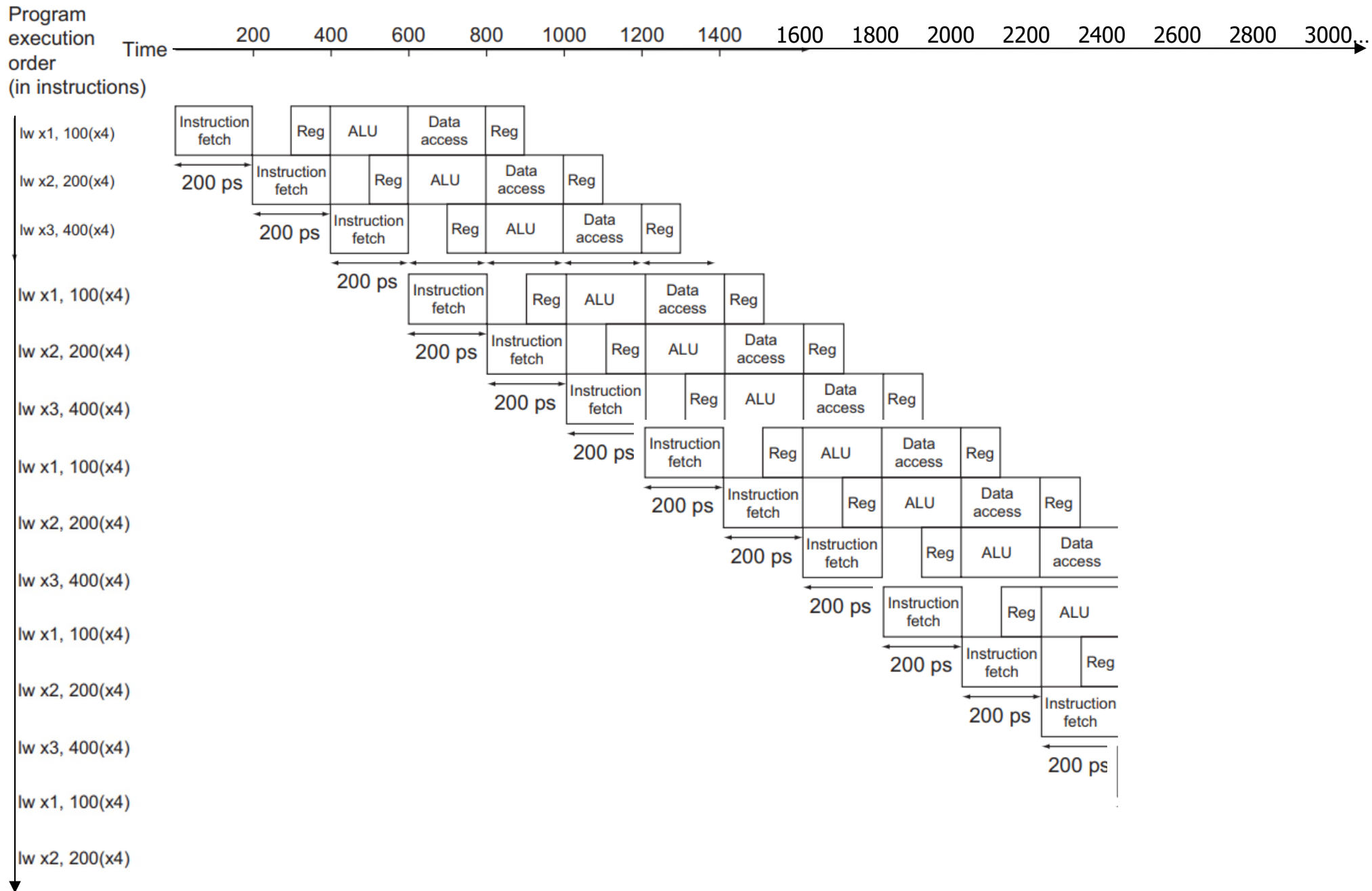
Pipelined ($T_c = 200\text{ps}$)

Time 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000...



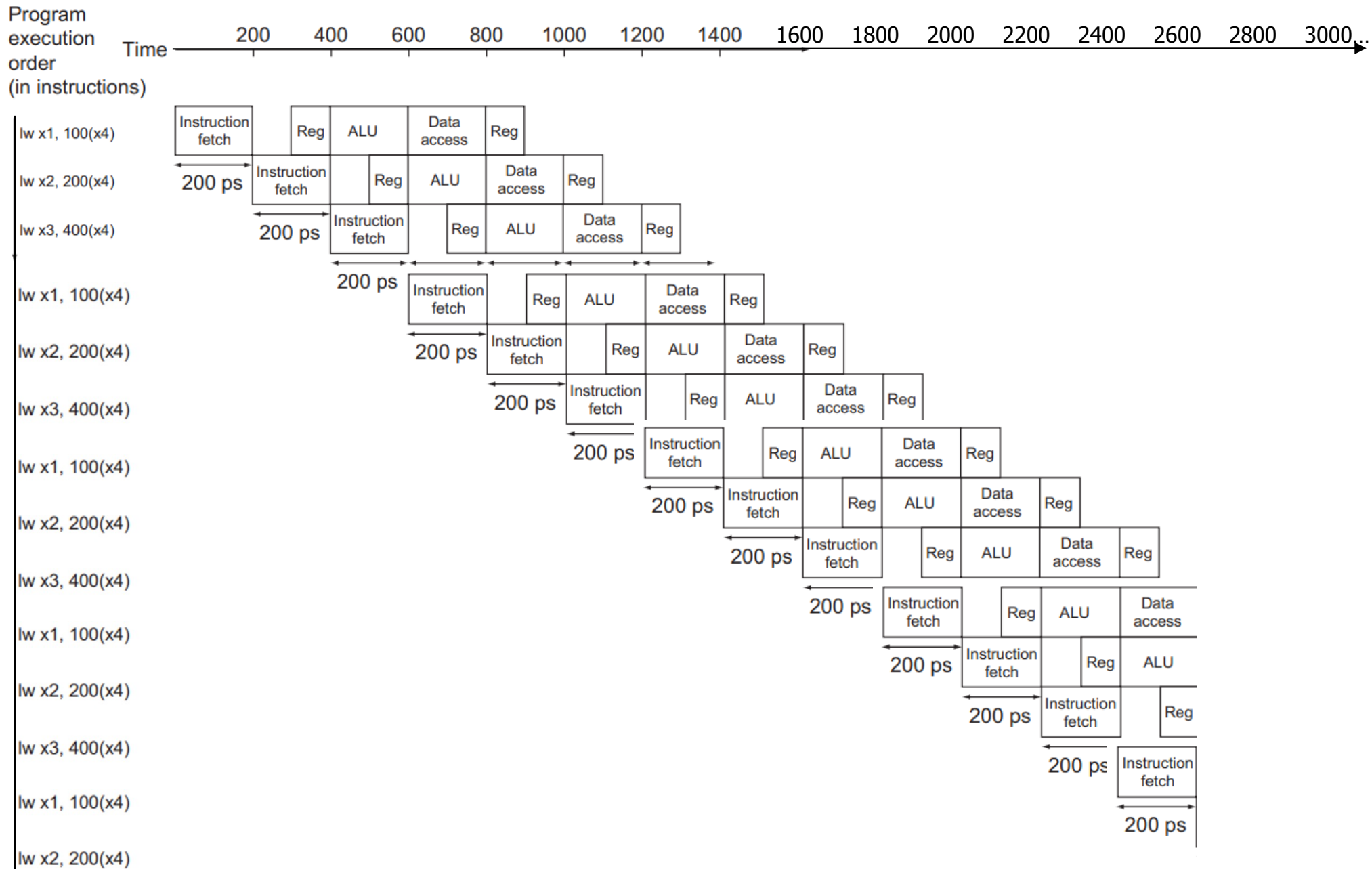
Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)



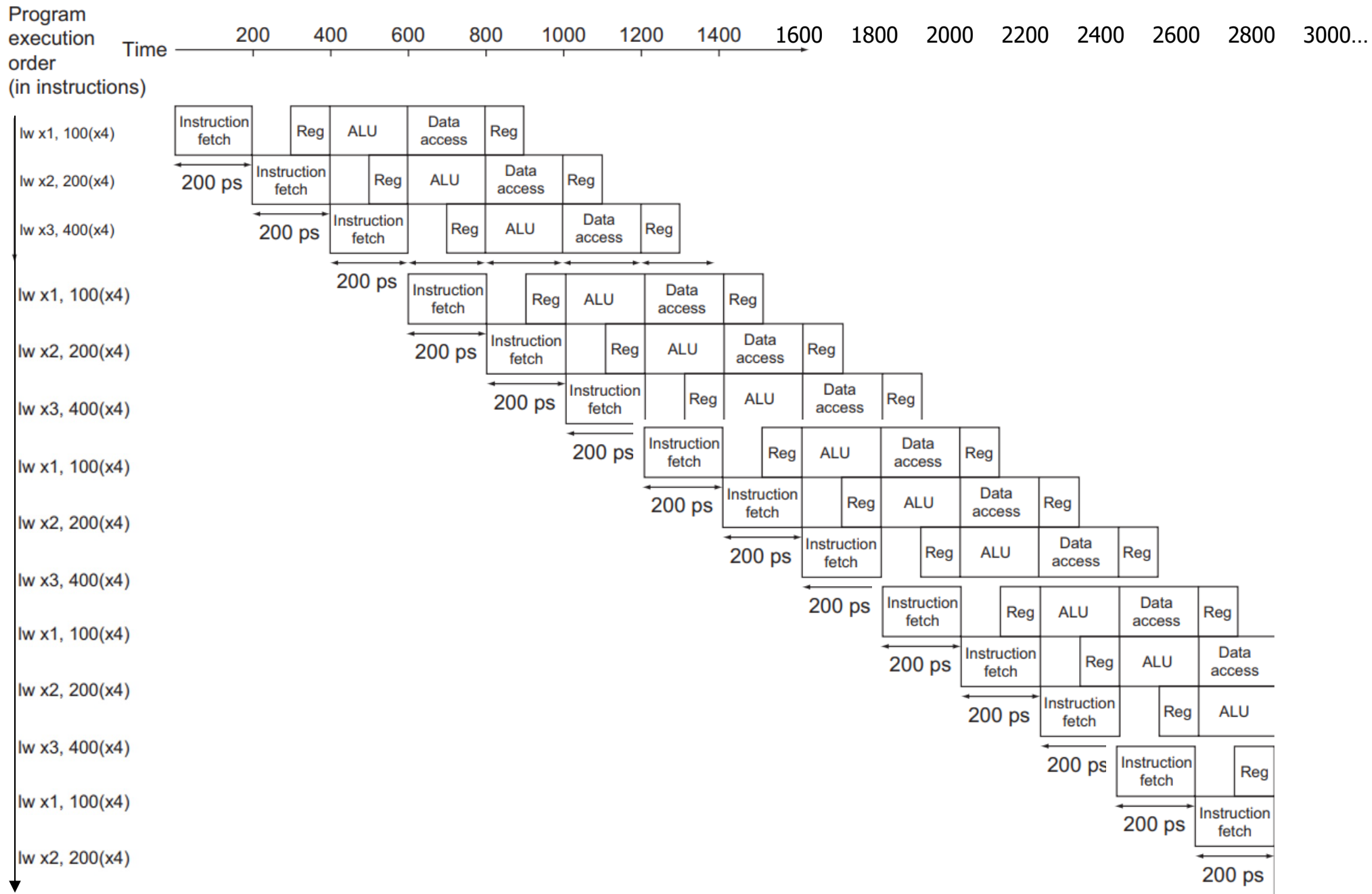
Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)

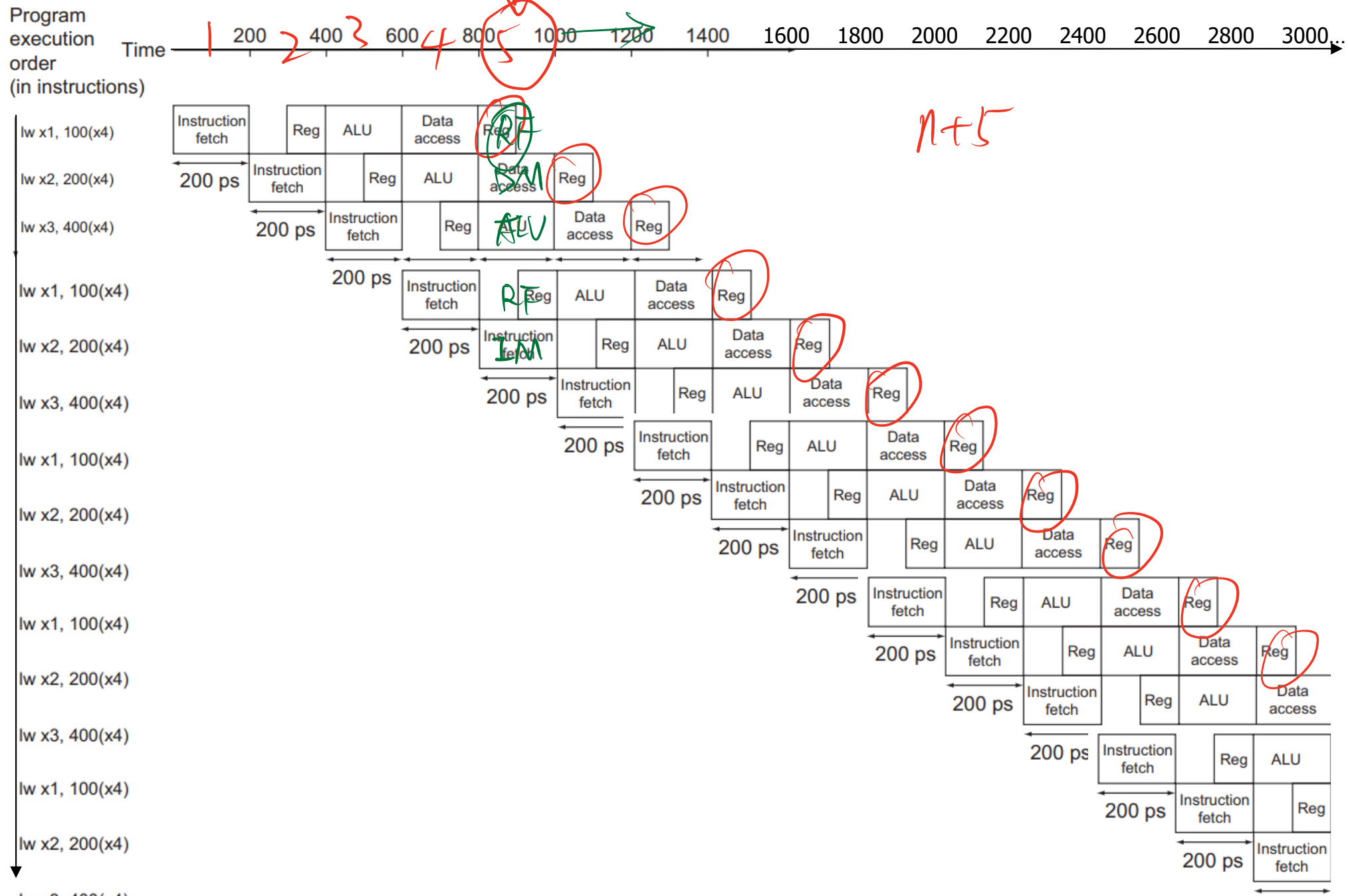


Pipeline Performance

Pipelined ($T_c = 200\text{ps}$)



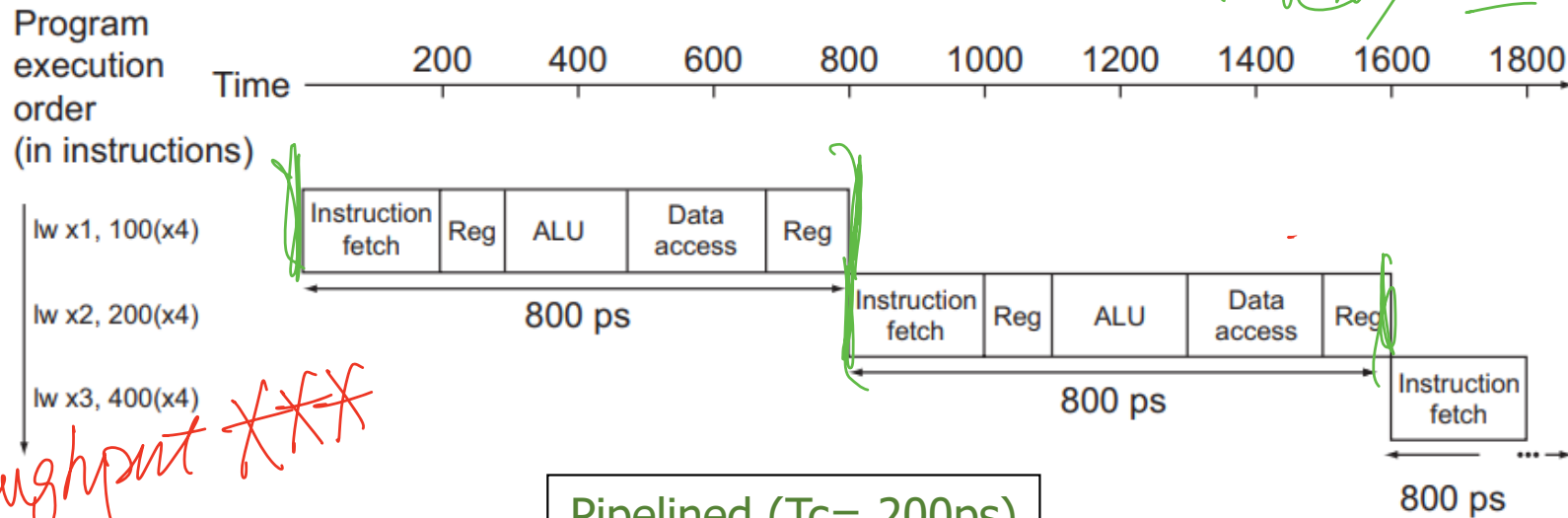
Pipelined ($T_c = 200\text{ps}$)



Pipeline Performance

Single-cycle ($T_c = 800\text{ps}$)

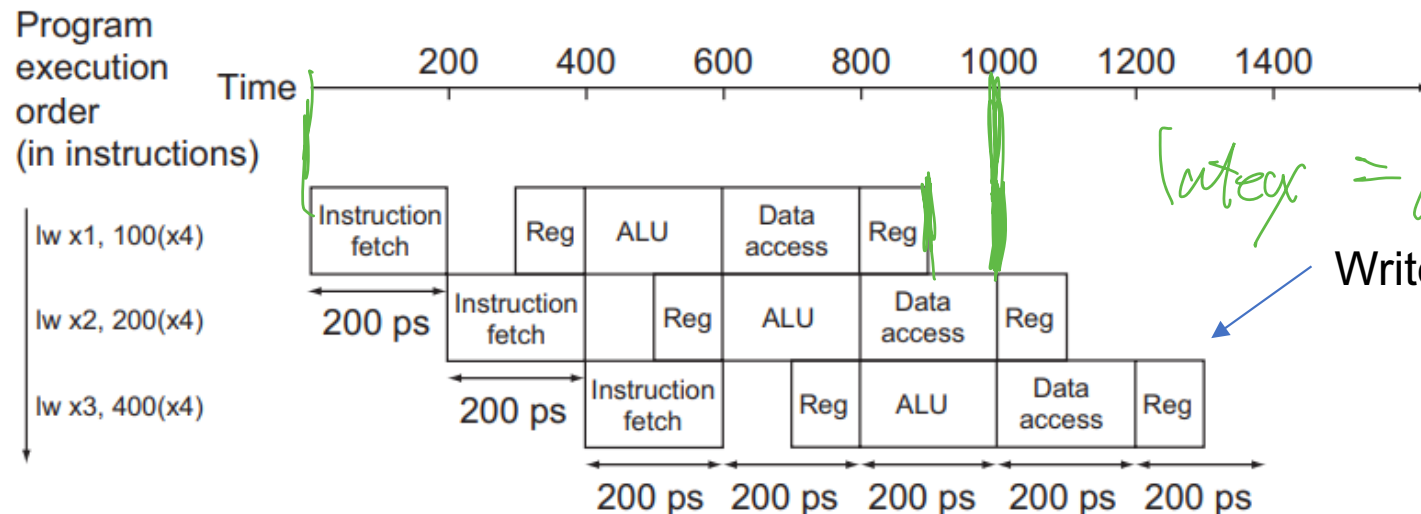
latency = 800 ps



*Throughput ****

Pipelined ($T_c = 200\text{ps}$)

latency = 1000 ps



Write RF in 1st half

What is the speedup for a long instruction sequence?

Ideal Pipeline Speedup

Ideally,

$$\text{Time Between Instr}_{\text{pipelined}} = \frac{\text{Time Between Instr}_{\text{nonpipelined}}}{\text{Number Of Stages}}$$

$$\text{Speedup} = \frac{\text{Time Between Instr}_{\text{nonpipelined}}}{\text{Time Between Instr}_{\text{pipelined}}} = \text{Number of Stages}$$

Actual speedup is less than the ideal speedup, why?

Pipeline Speedup

- Actual speedup is less than the ideal speedup
 - Pipeline stages are not balanced (bubble)
 - Overhead in pipeline X
 - Clock skew X
 - Hazard ?
- Speedup due to increased throughput
 - Latency (time for executing each instruction) does not decrease, but increases

RISC-V Datapath Divided in Five Stages

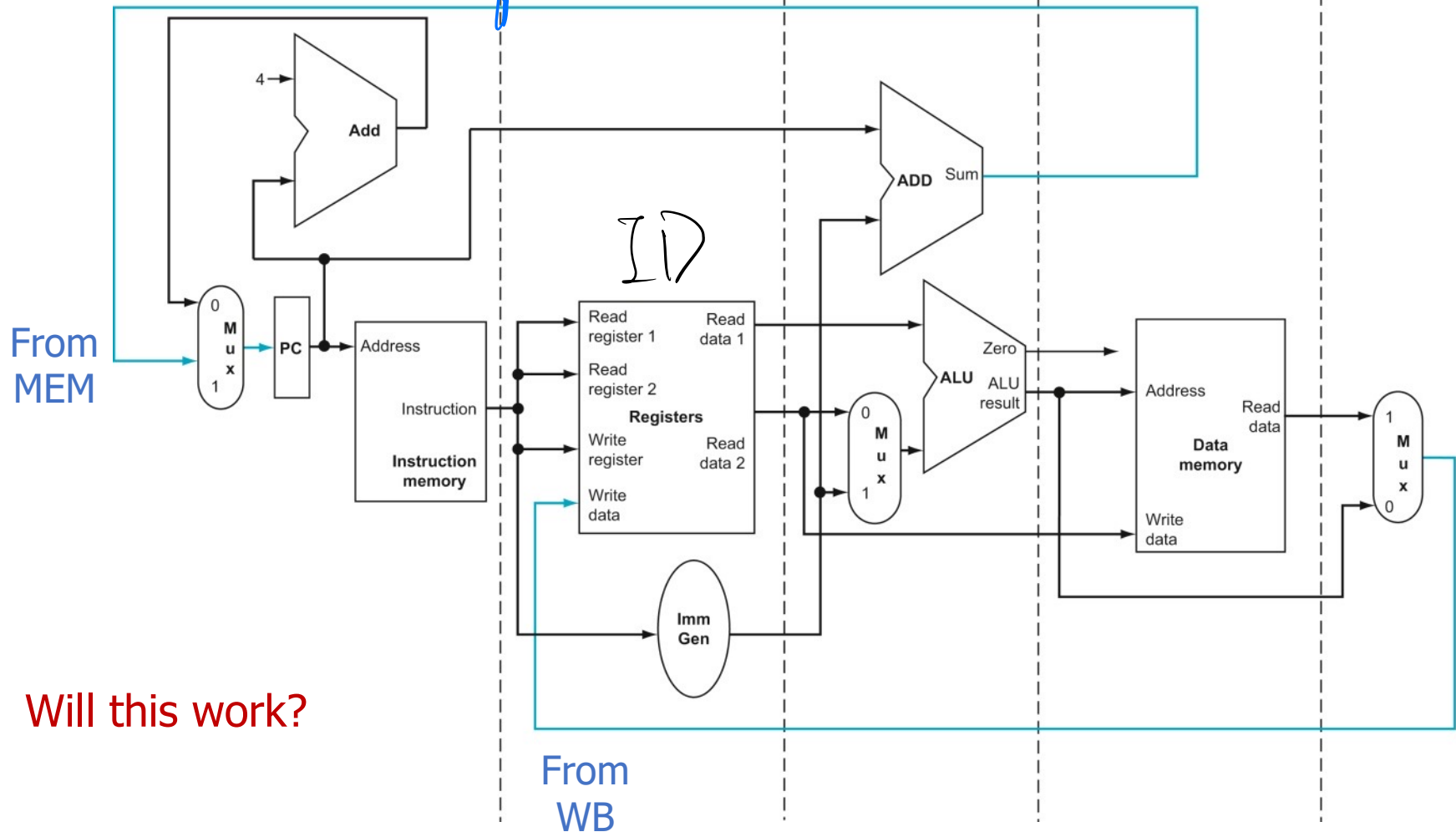
IF: Instruction fetch

ID: Instruction decode/
register file read

EX: Execute/
address calculation

MEM: Memory access

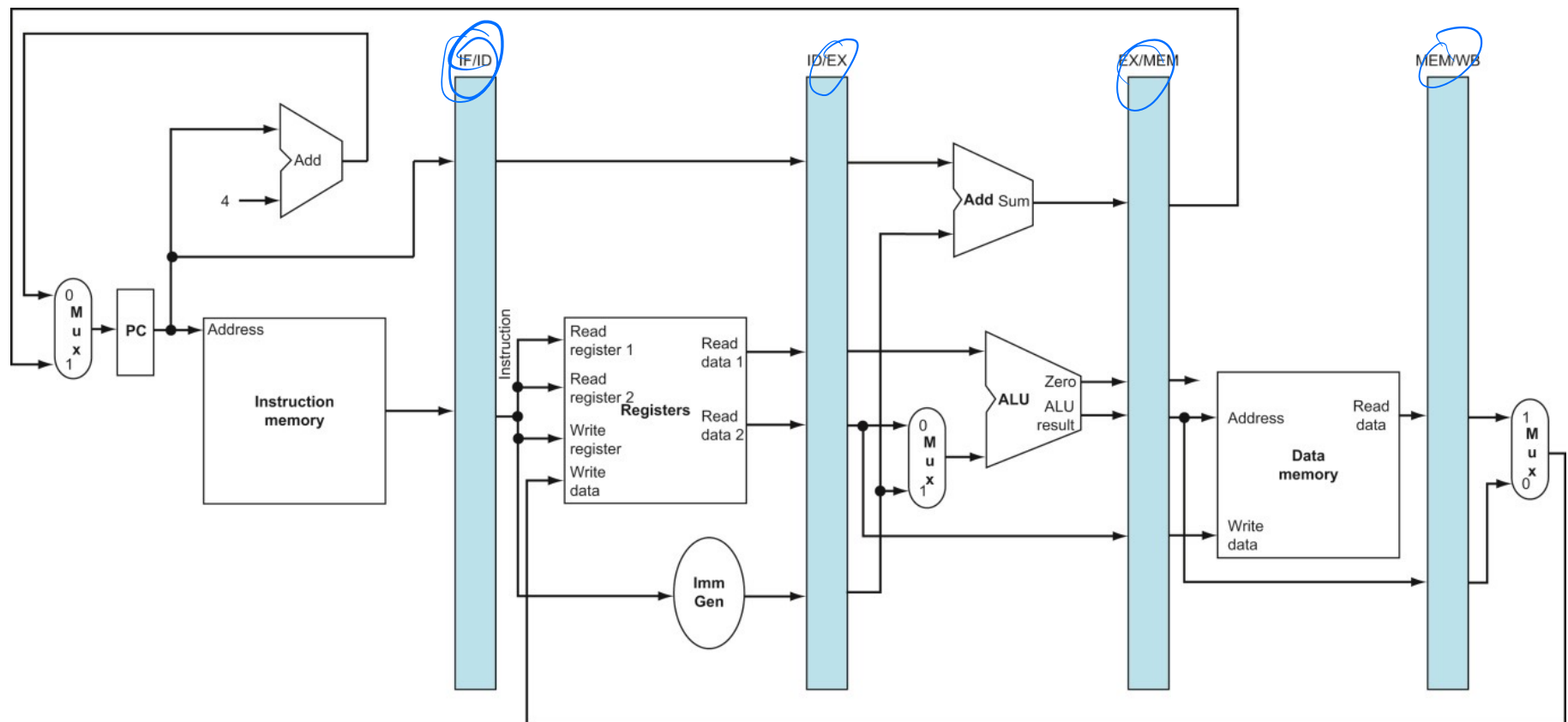
WB: Write back



Will this work?

Pipelined Datapath

- Add **pipeline registers** between pipeline stages to **isolate** them
 - Data stored in registers are stable for the cycle
 - Information needed in later stages are saved in pipeline registers



Two rules

- In general, we follow the following two rules
 - Do not use the signal generated in the same stage
 - To reduce the cycle time
 - Results are saved in pipeline registers and passed to later stage
 - Use a signal as early as possible
 - We do not need pass it to later stages

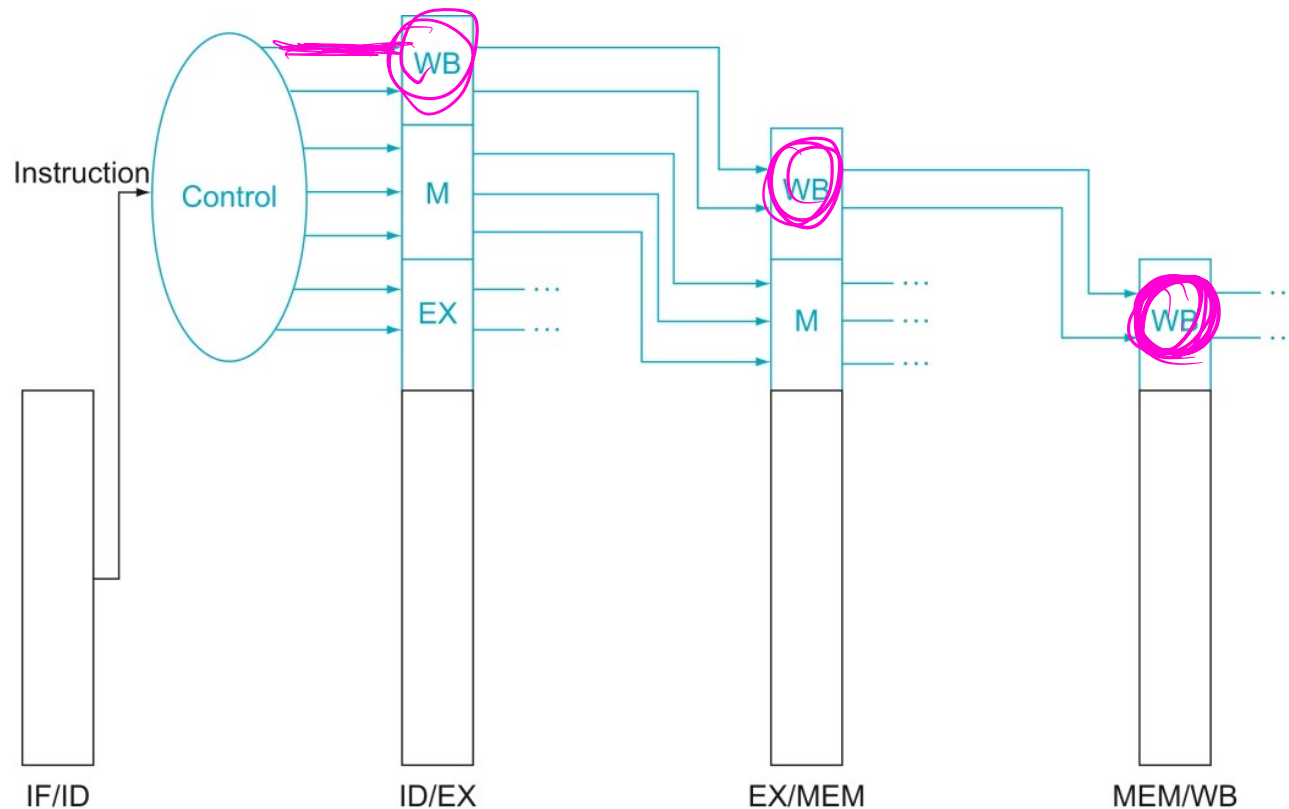
Control Signals in Pipeline

- Control signals derived from instruction, as in single-cycle implementation
- All control signals are generated in ID and passed to later stages through the **pipeline (also called state) registers**
 - 2 used in EX, 3 used in Mem, and 2 in WB

	EX Stage		MEM Stage			WB Stage	
	ALUOp	ALUSrc	Branch	Mem Read	Mem Write	Reg Write	Mem toReg
R	10	0	0	0	0	1	0
LW	00	1	0	1	0	1	1
SW	00	1	0	0	1	0	X
BEQ	01	0	1	0	0	0	X

Control Signals in Pipeline Registers

- Control signals are generated in ID and passed to later stages



RISC-V Pipeline

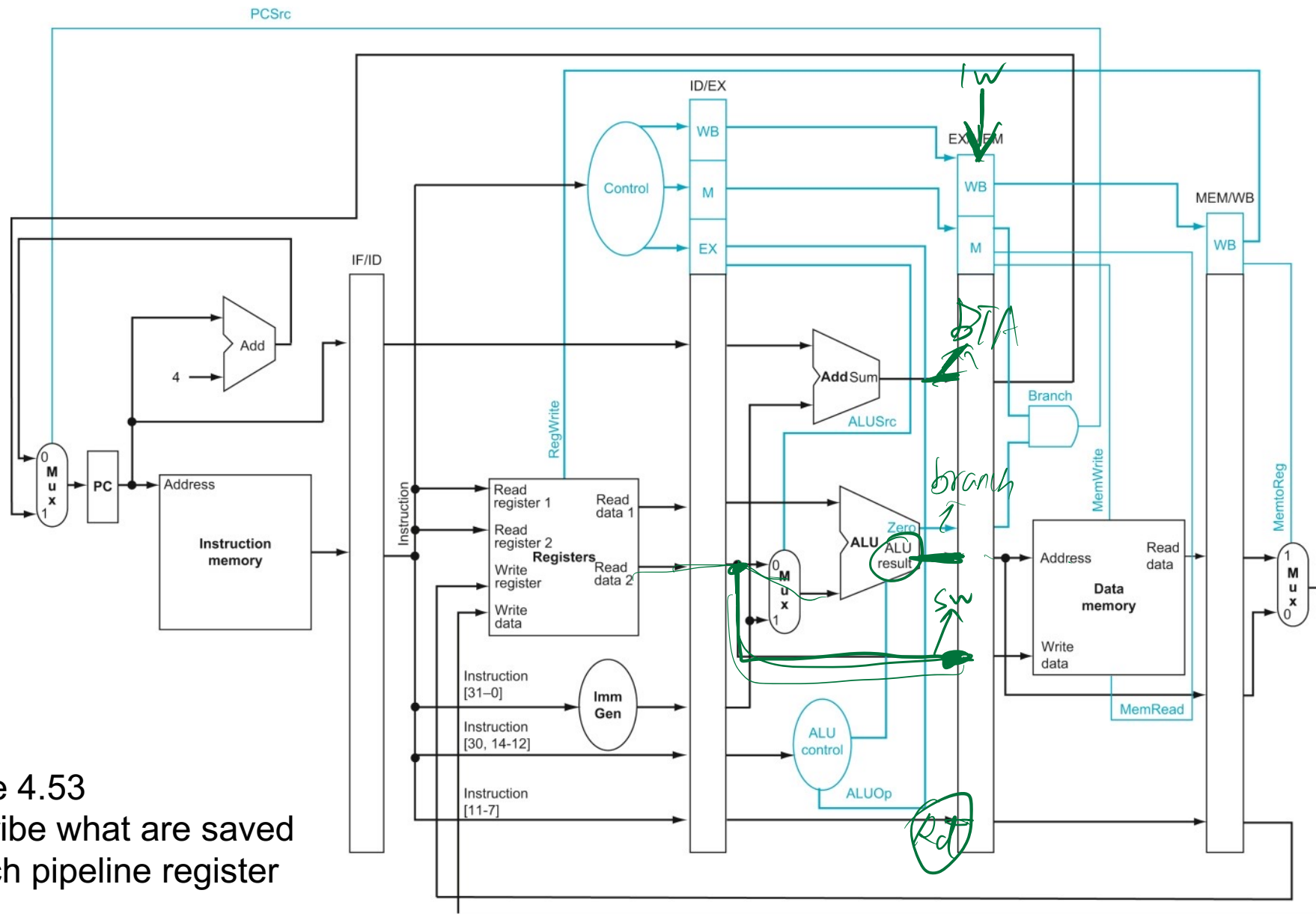


Figure 4.53
Describe what are saved
in each pipeline register

Explain why they need to be saved

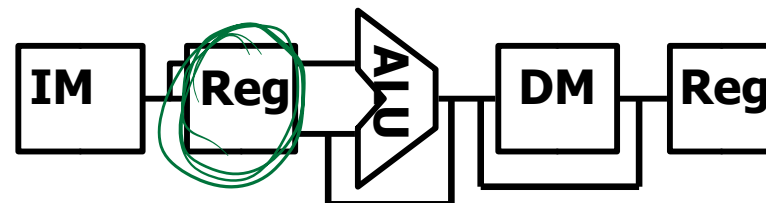
Information saved into pipeline registers

Any info needed in a later stage must be passed to that stage via pipeline registers
Study the diagram and check if any signal is missing

- IF/ID
 - PC, Instruction
 - ID/EX
 - PC
 - Read data 1, Read data 2, immd, funct3, and rd
 - Control signals
 - EX/MEM
 - Read data 2, rd, MemRead, MemWrite, Branch, RegWrite, and MemtoReg
 - ALU result and Zero, Branch target address, Write register
 - MEM/WB
 - ALU result, rd, RegWrite, and MemtoReg
 - Mem read data
-

Pipeline Diagrams

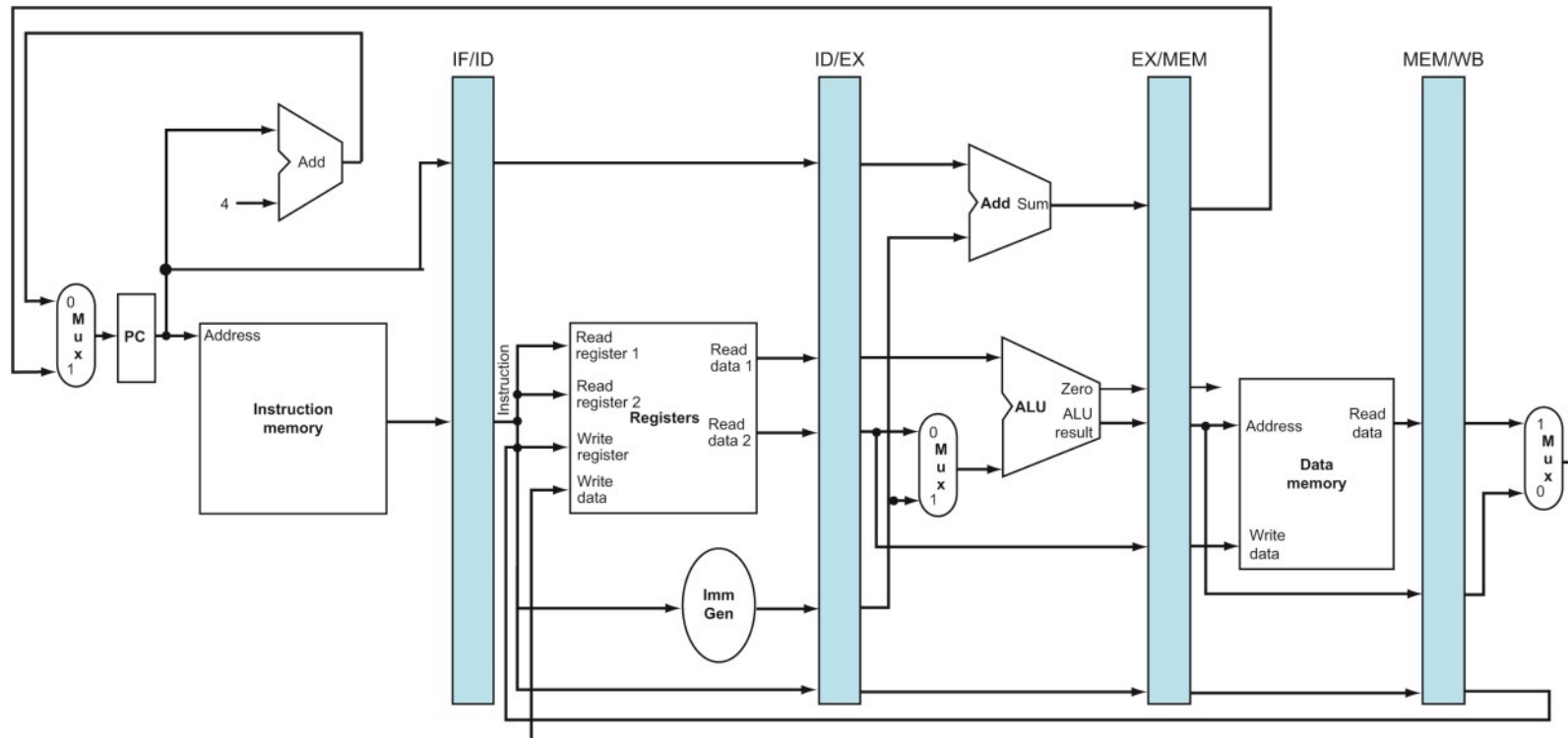
- Can help with answering questions like:
 - How many cycles does it take to execute this code?
 - What is the ALU doing during cycle 4?
 - Is there a hazard, why does it occur, and how can it be fixed?
- Two types of diagrams
 - “Single-clock-cycle” pipeline diagram
 - Shows pipeline usage in a single cycle
 - Highlight resources used
 - “Multi-clock-cycle” pipeline diagram
 - Showing how instructions are executed over time



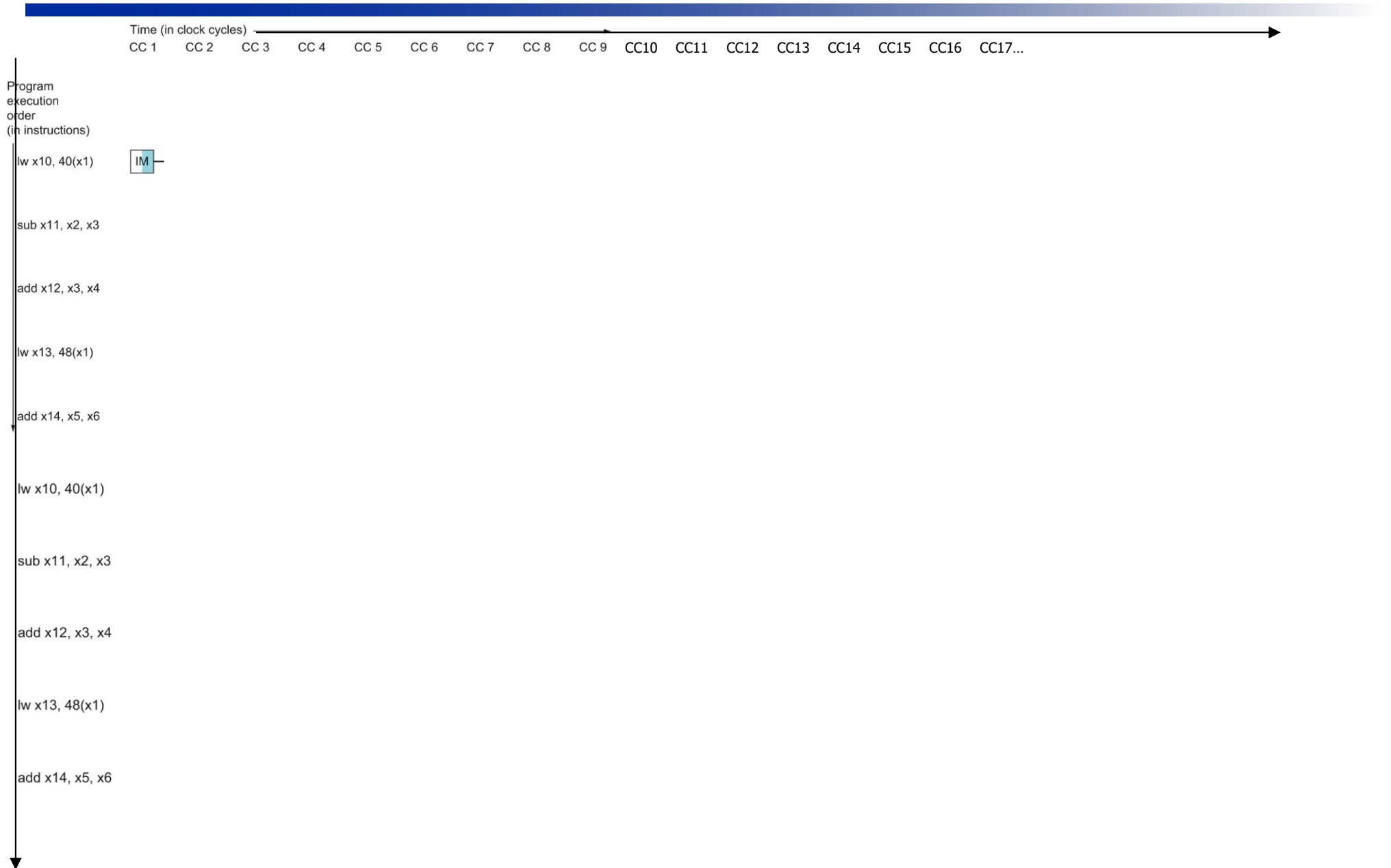
IF ID EX MEM WB

Single-Cycle Pipeline Diagram

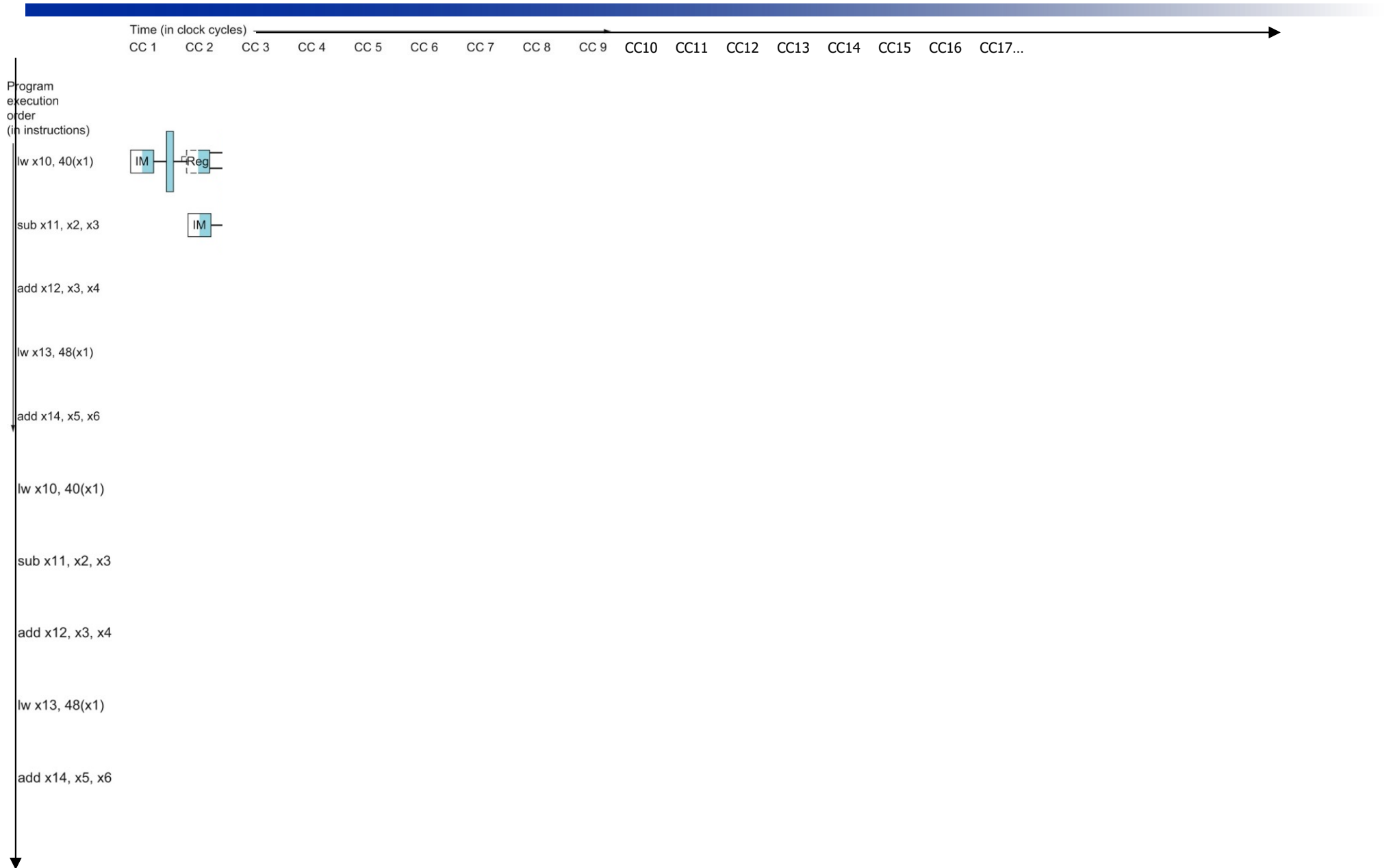
- State of pipeline in a given cycle
 - Instructions flow from left to right
 - Each pipeline stage has all the signals for the instruction in that stage



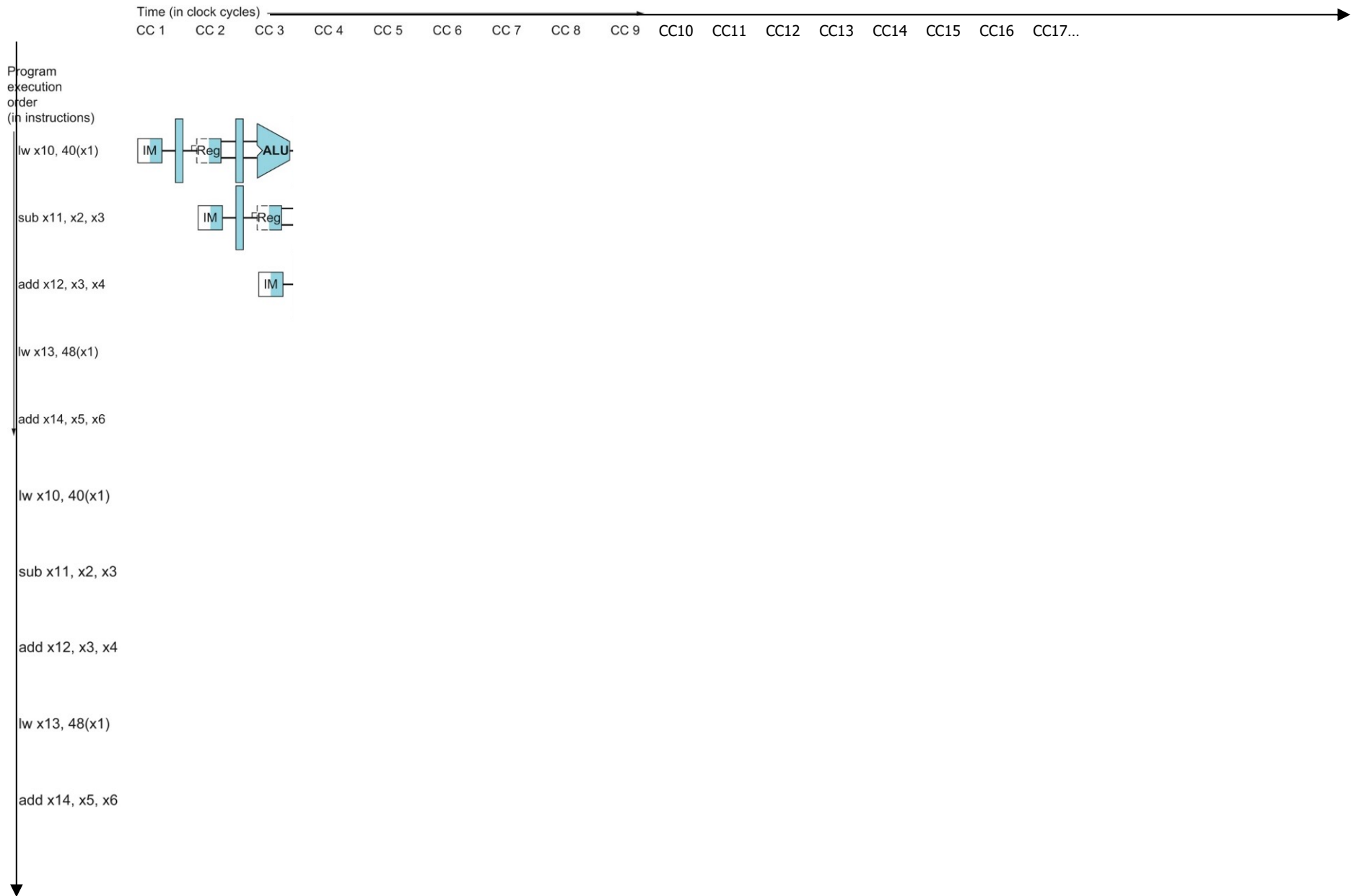
Multi-Cycle Pipeline Diagram



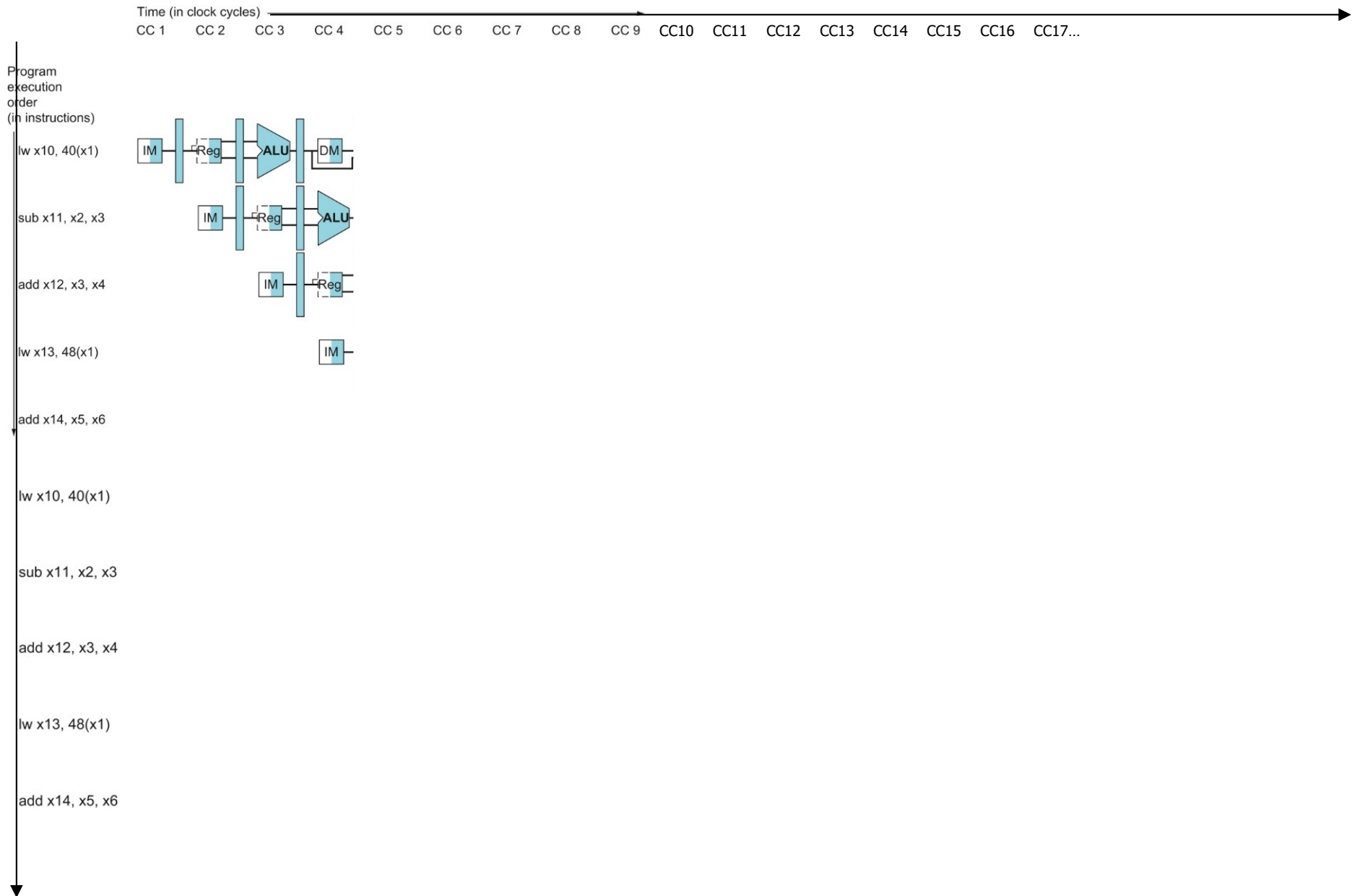
Multi-Cycle Pipeline Diagram



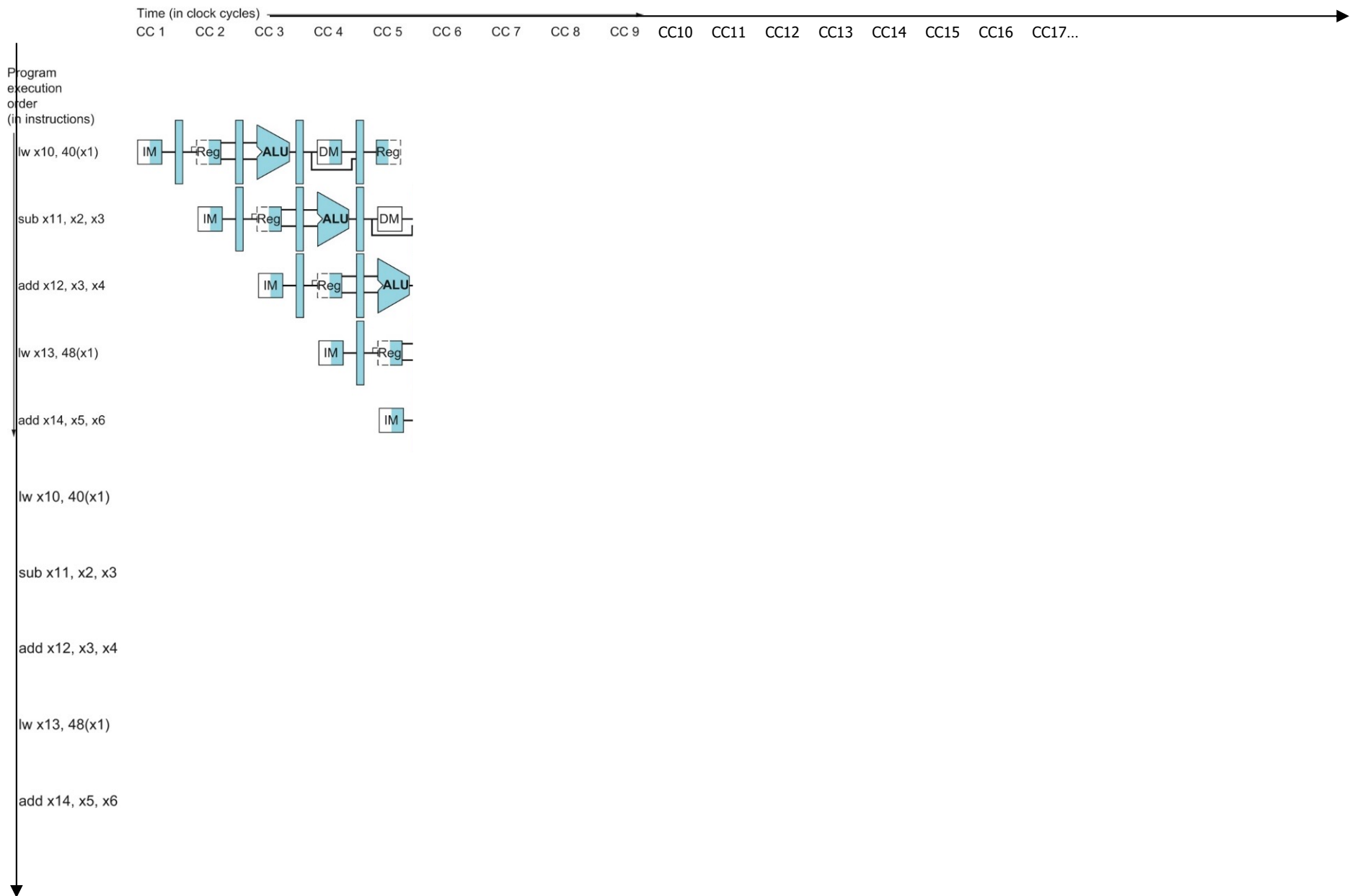
Multi-Cycle Pipeline Diagram



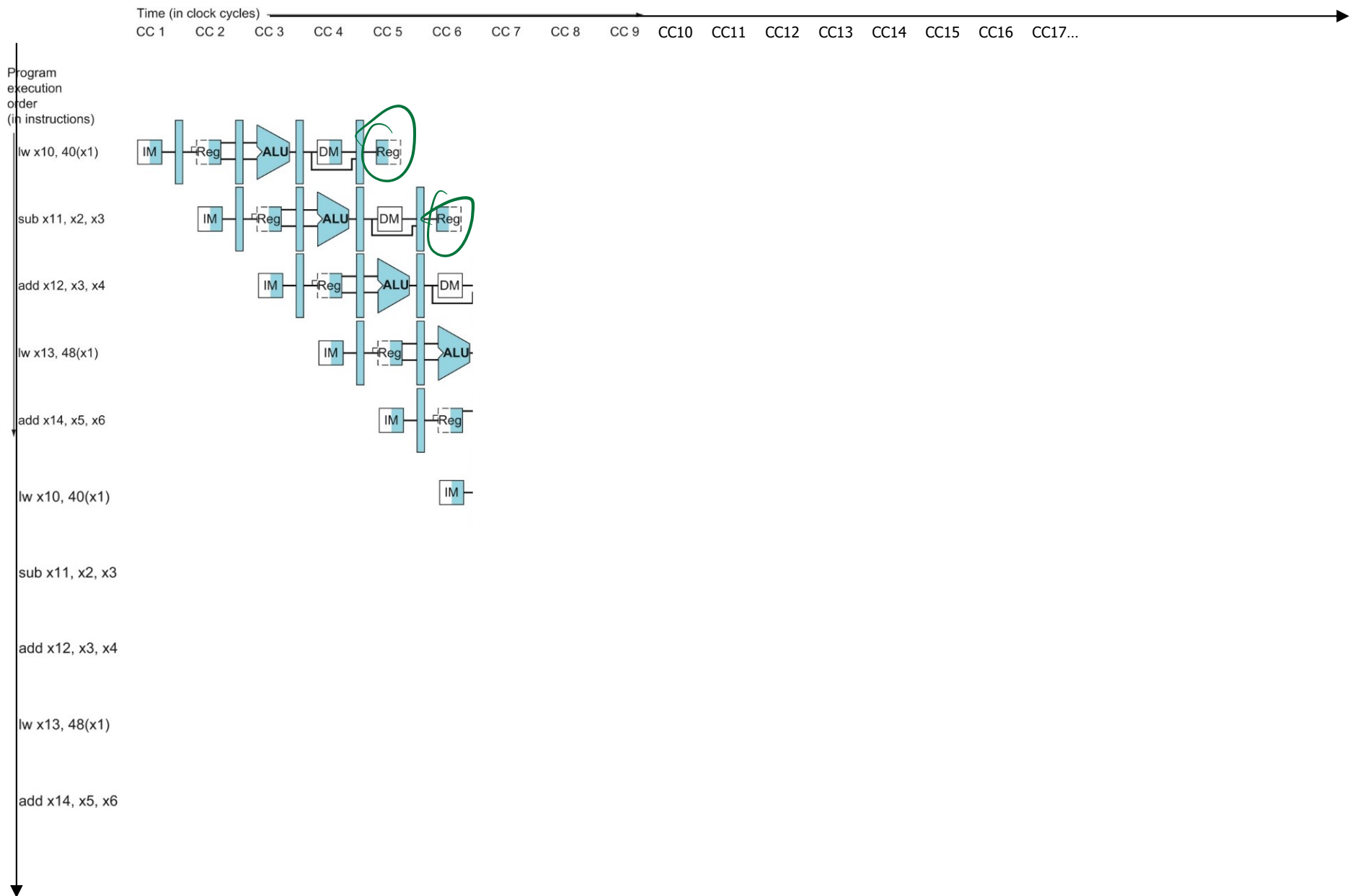
Multi-Cycle Pipeline Diagram



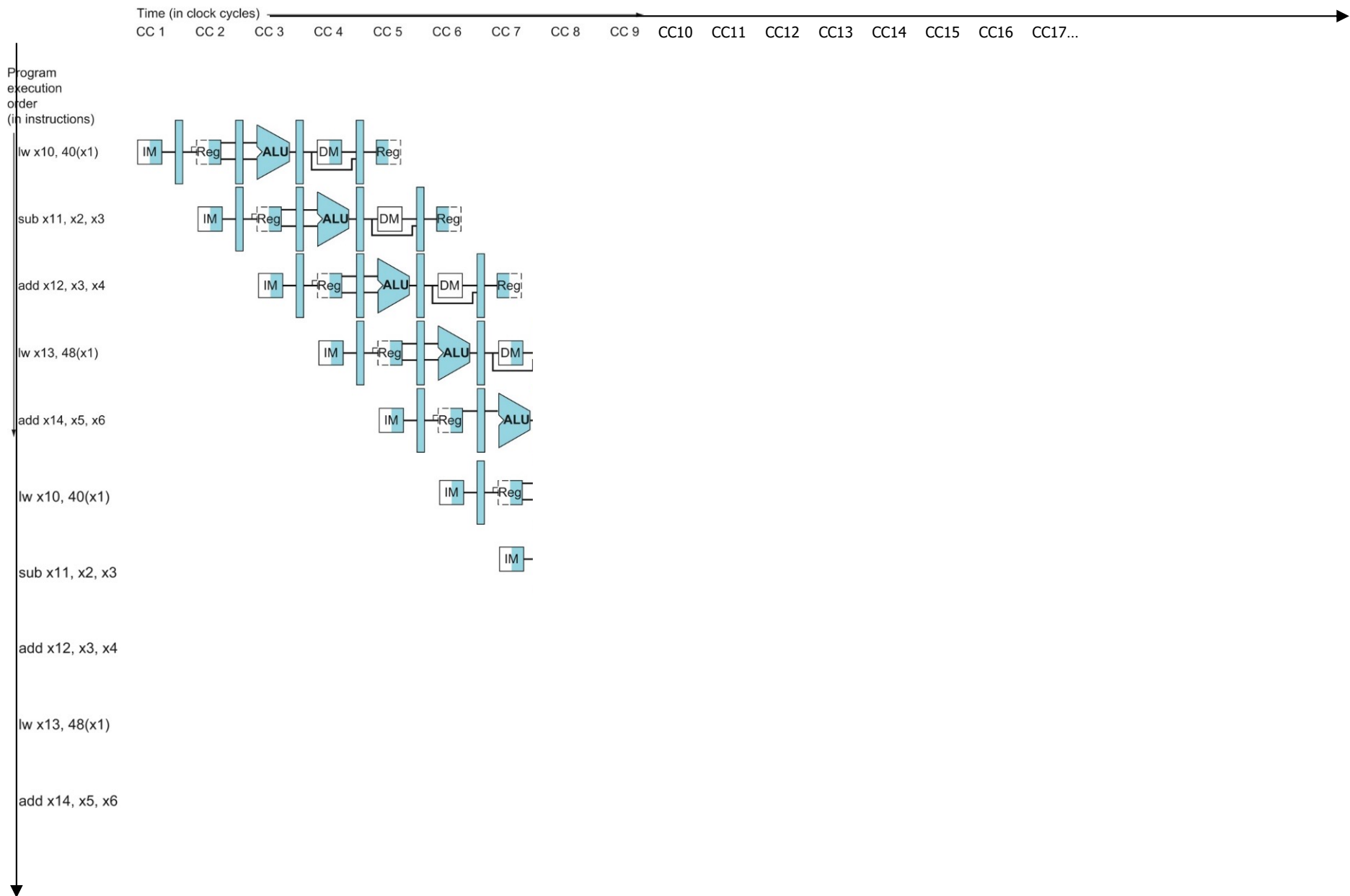
Multi-Cycle Pipeline Diagram



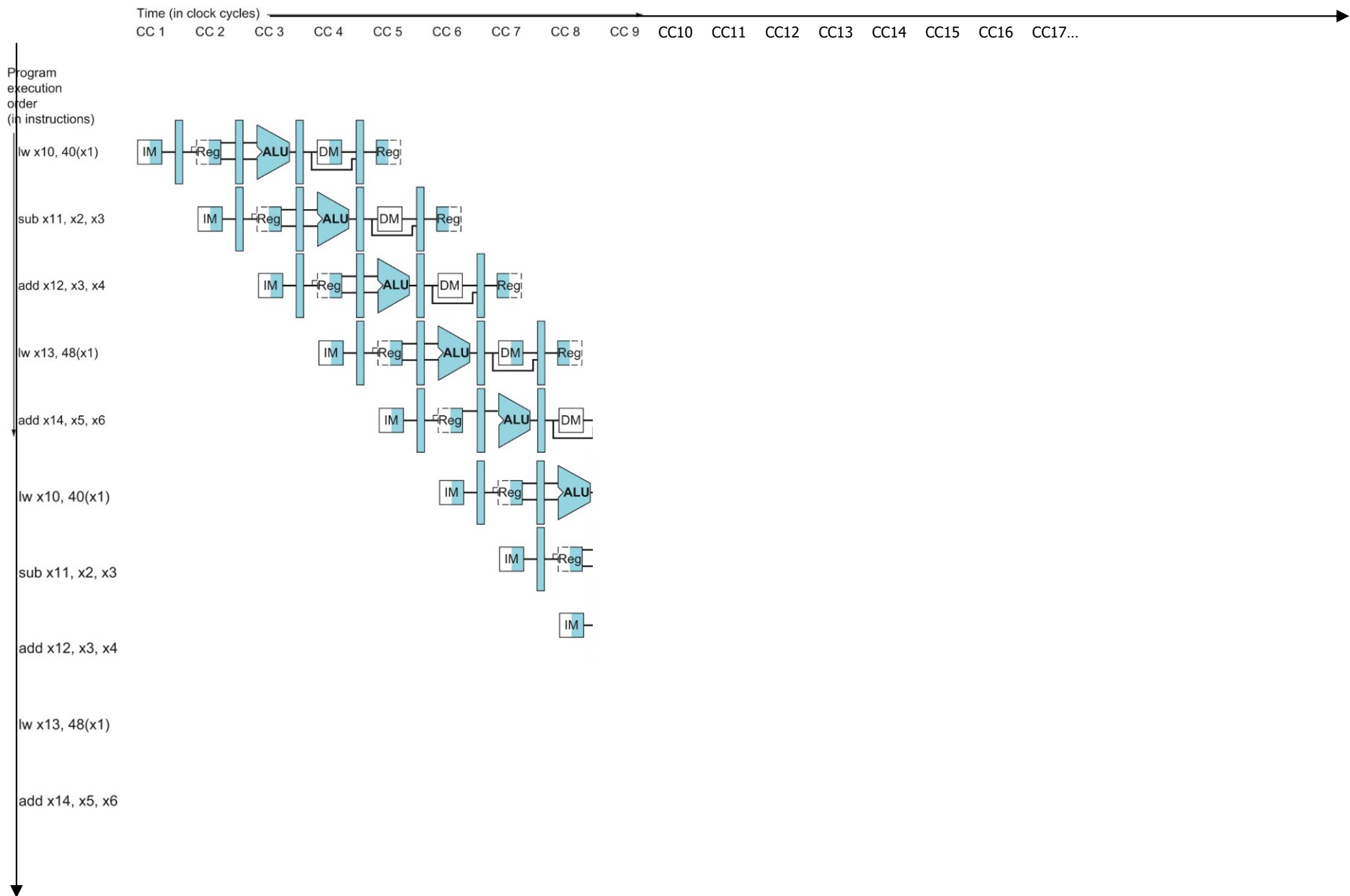
Multi-Cycle Pipeline Diagram



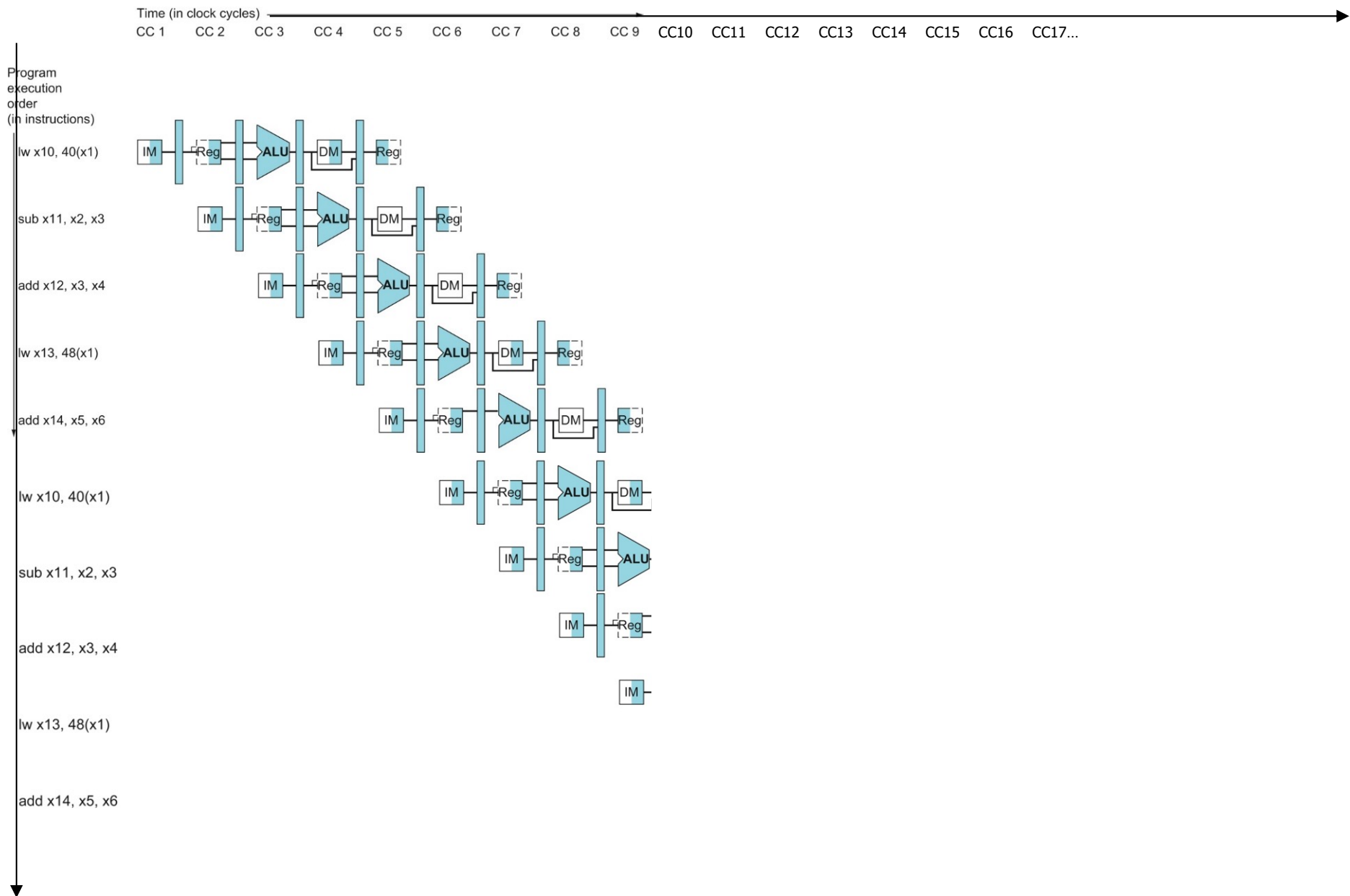
Multi-Cycle Pipeline Diagram



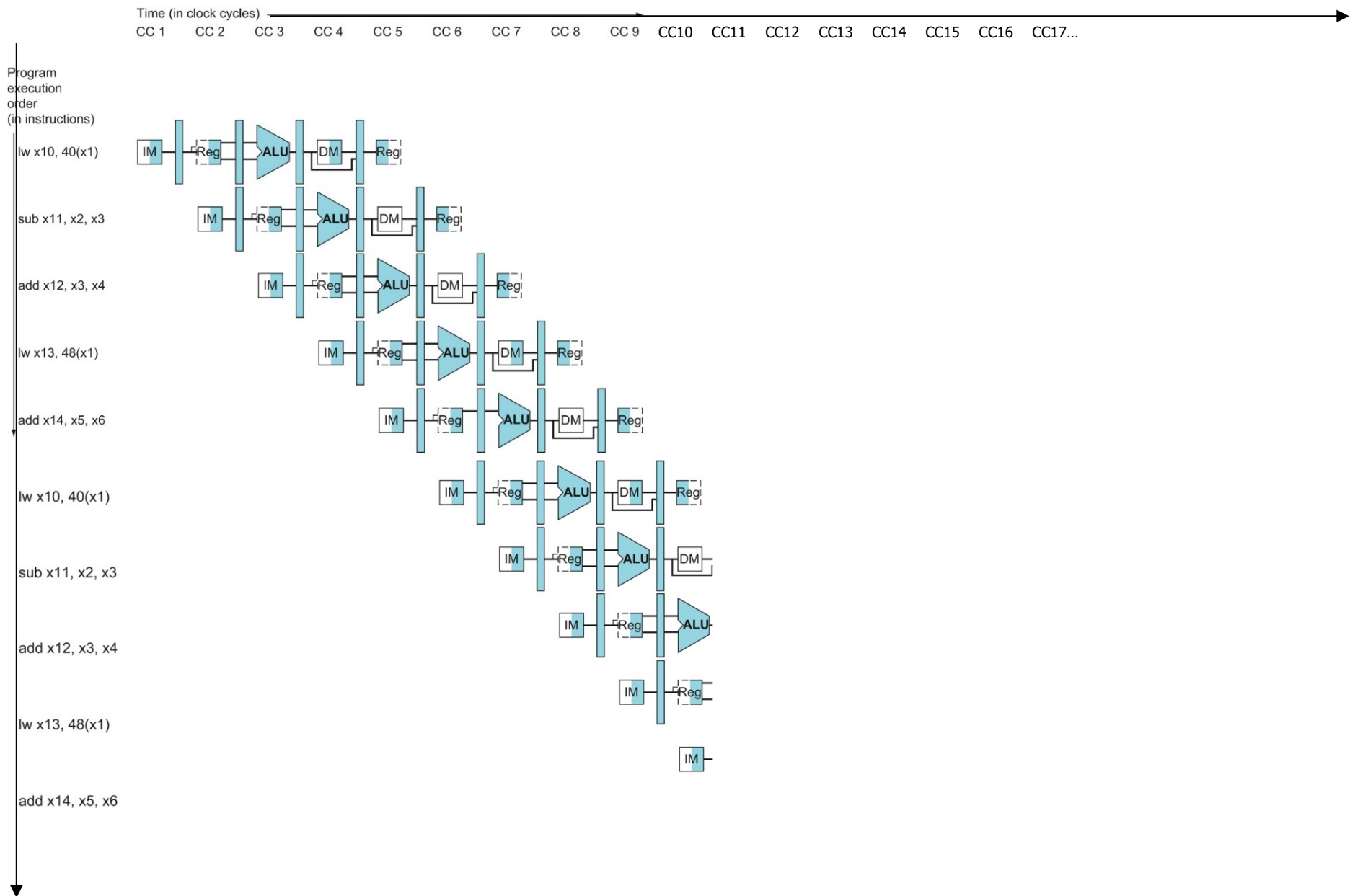
Multi-Cycle Pipeline Diagram



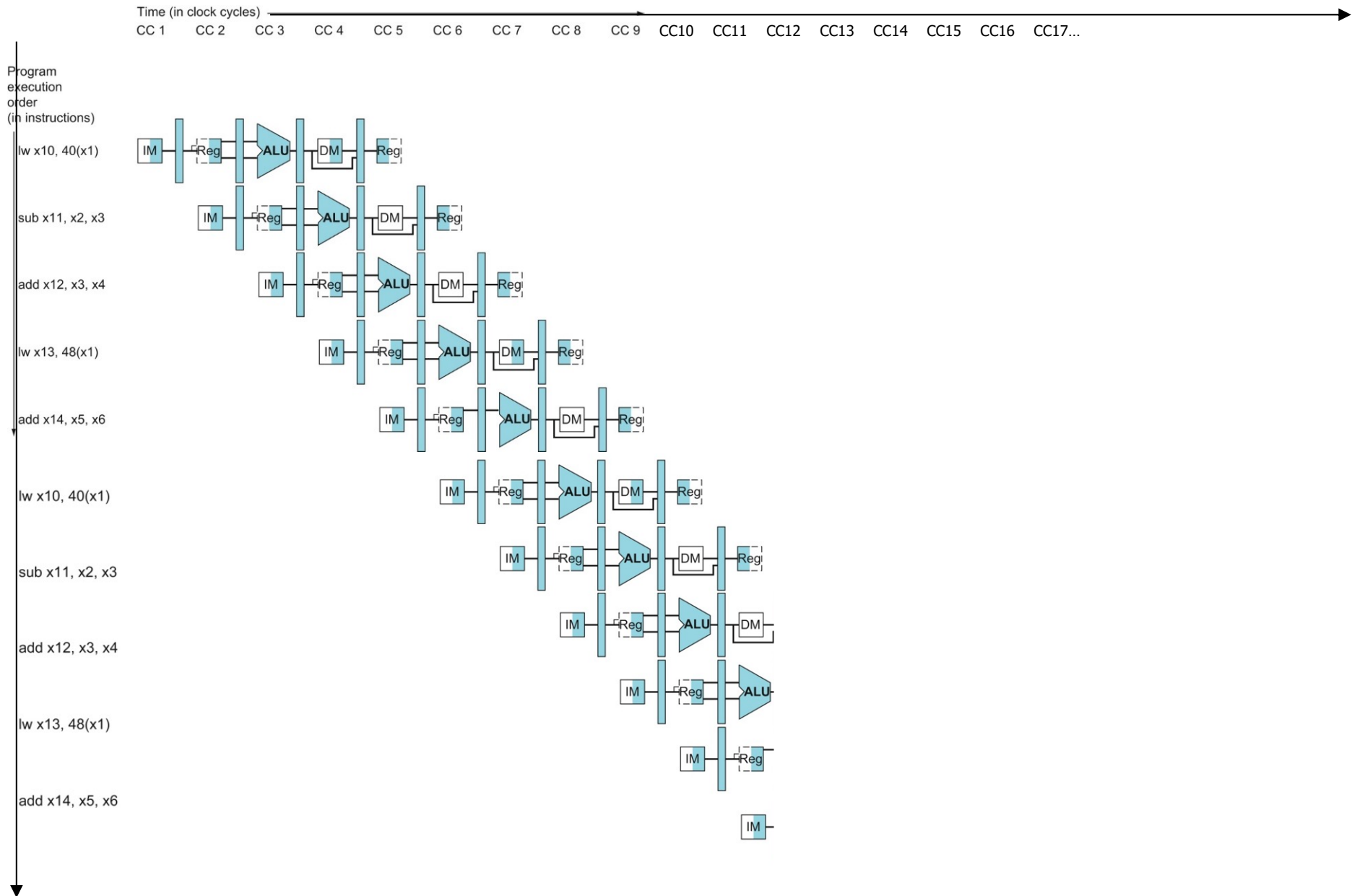
Multi-Cycle Pipeline Diagram



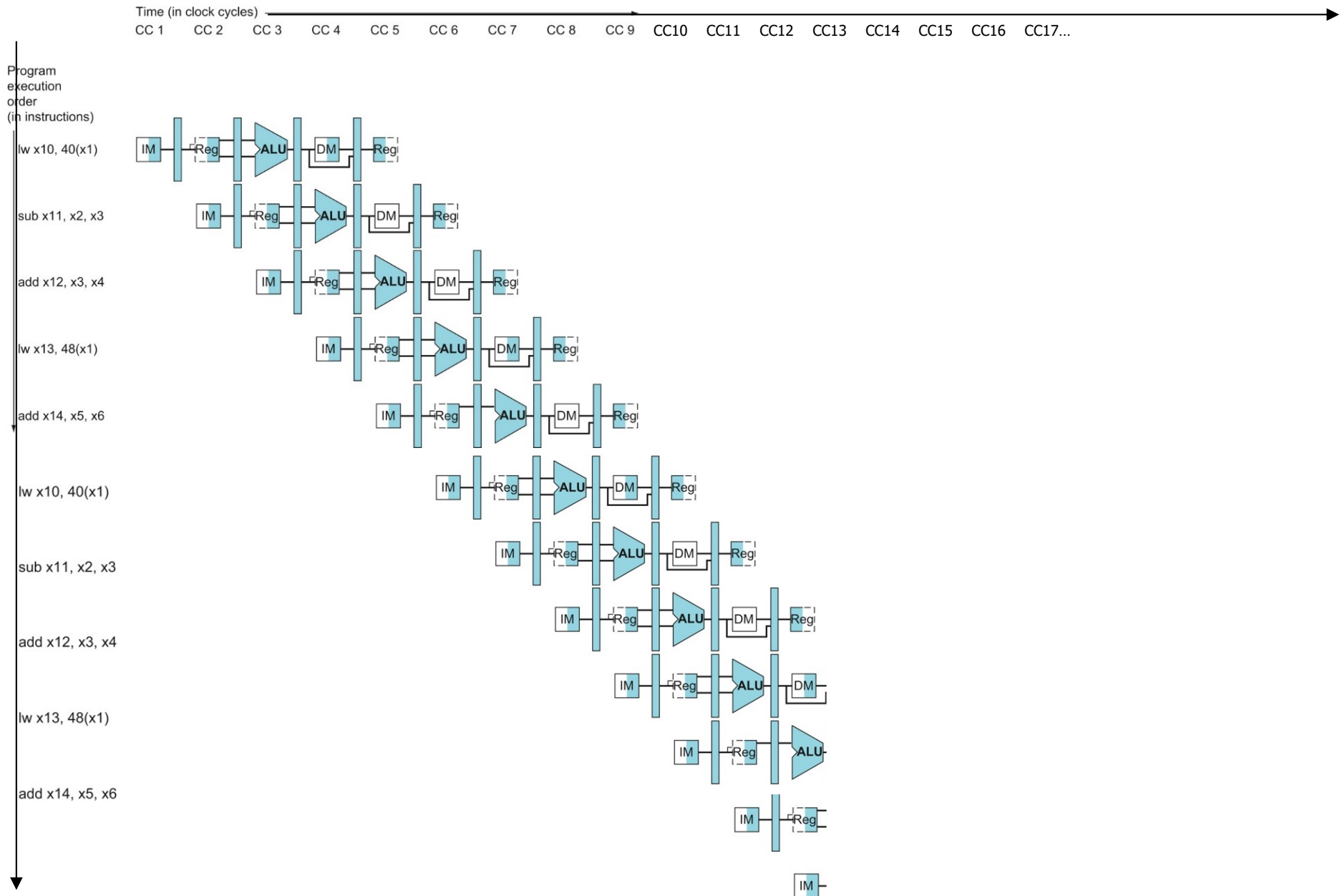
Multi-Cycle Pipeline Diagram



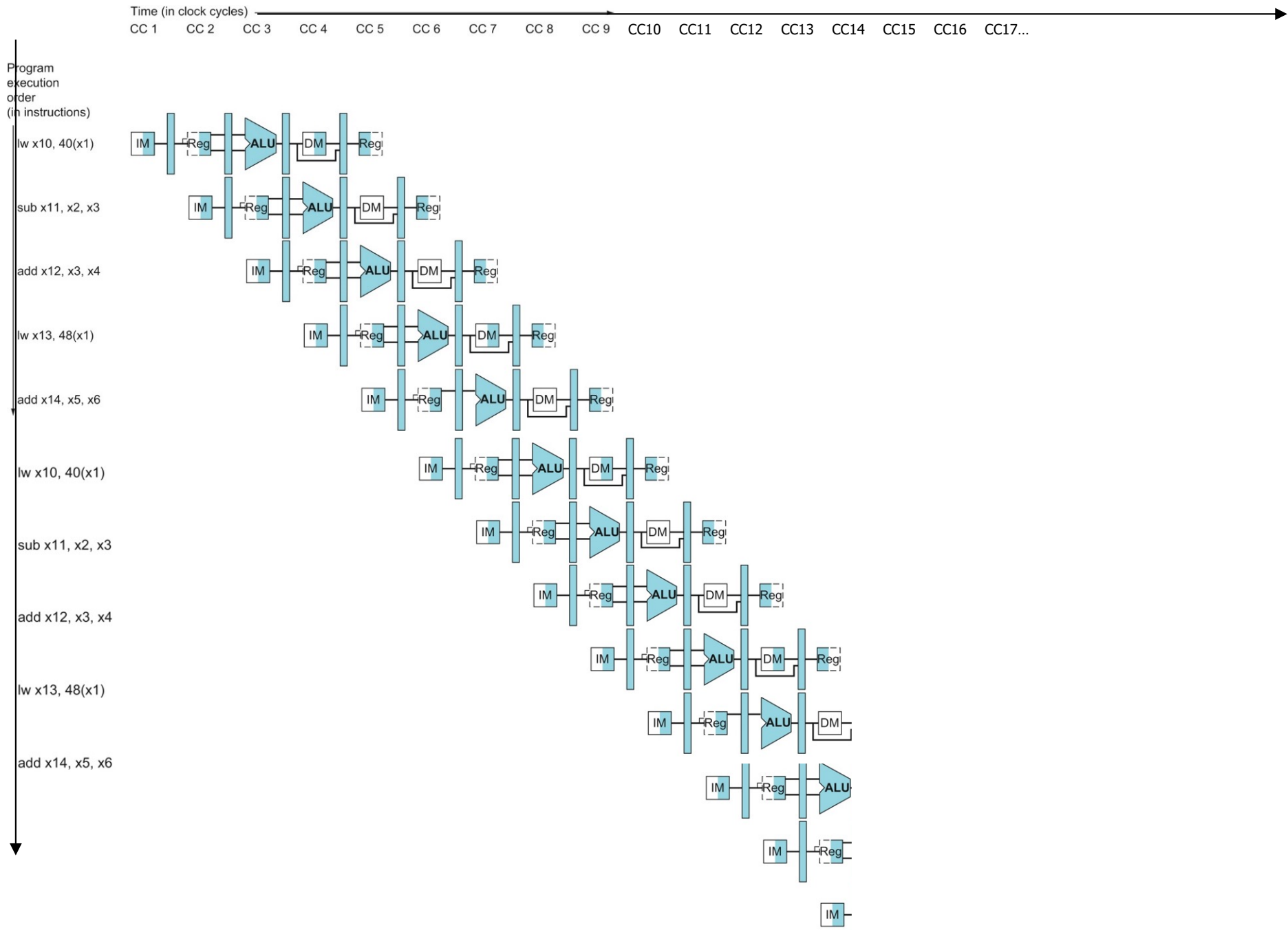
Multi-Cycle Pipeline Diagram



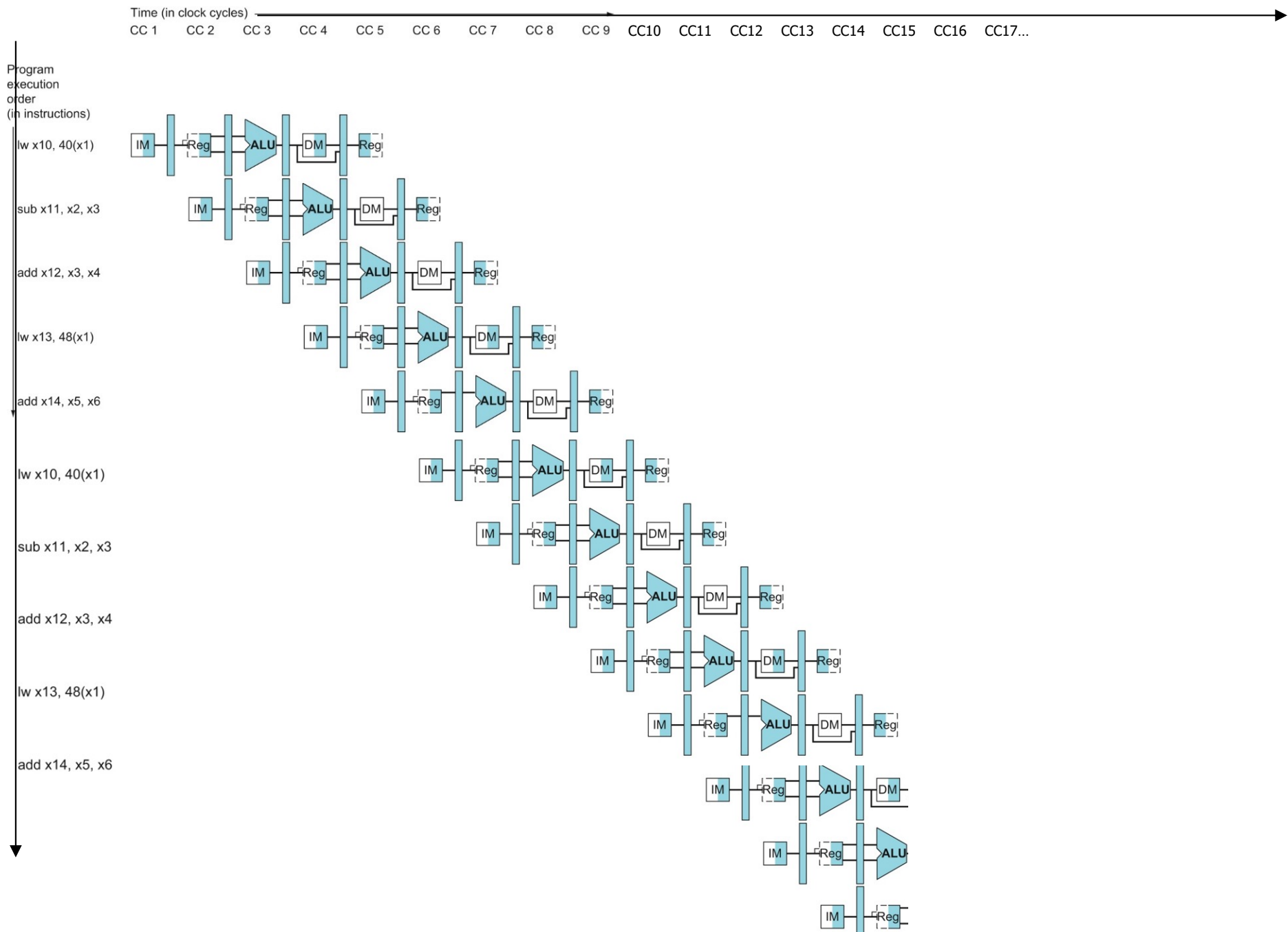
Multi-Cycle Pipeline Diagram



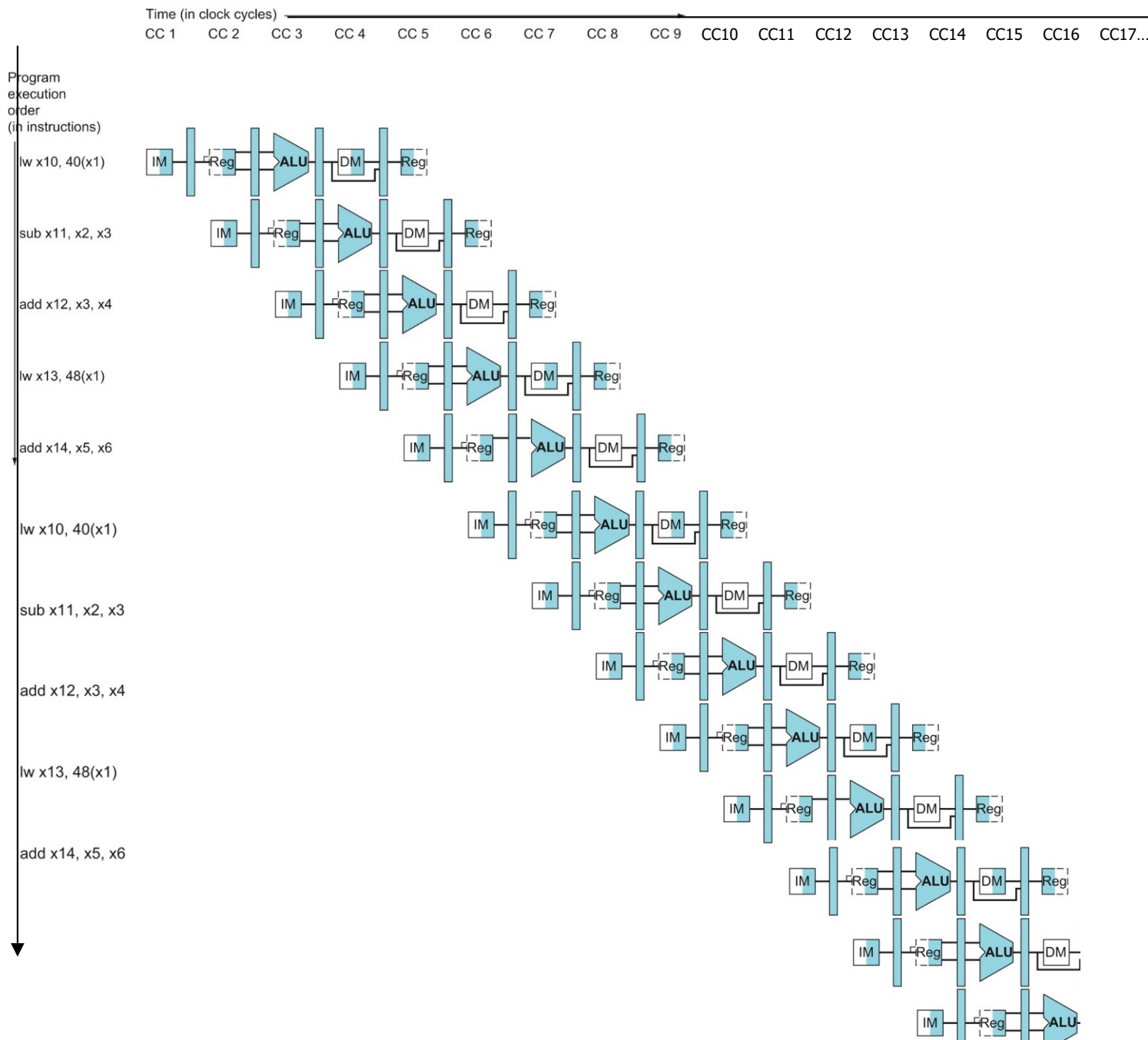
Multi-Cycle Pipeline Diagram



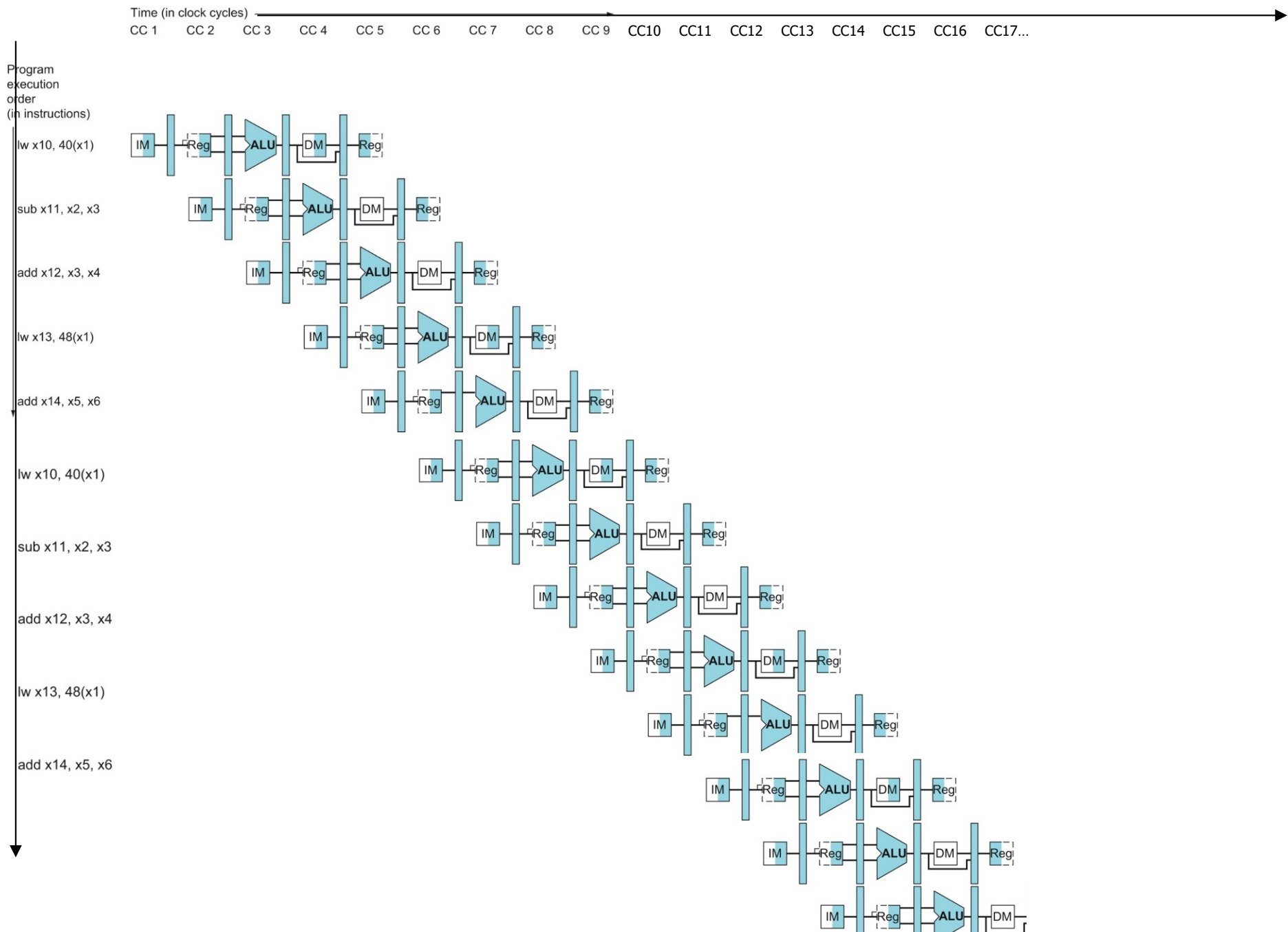
Multi-Cycle Pipeline Diagram



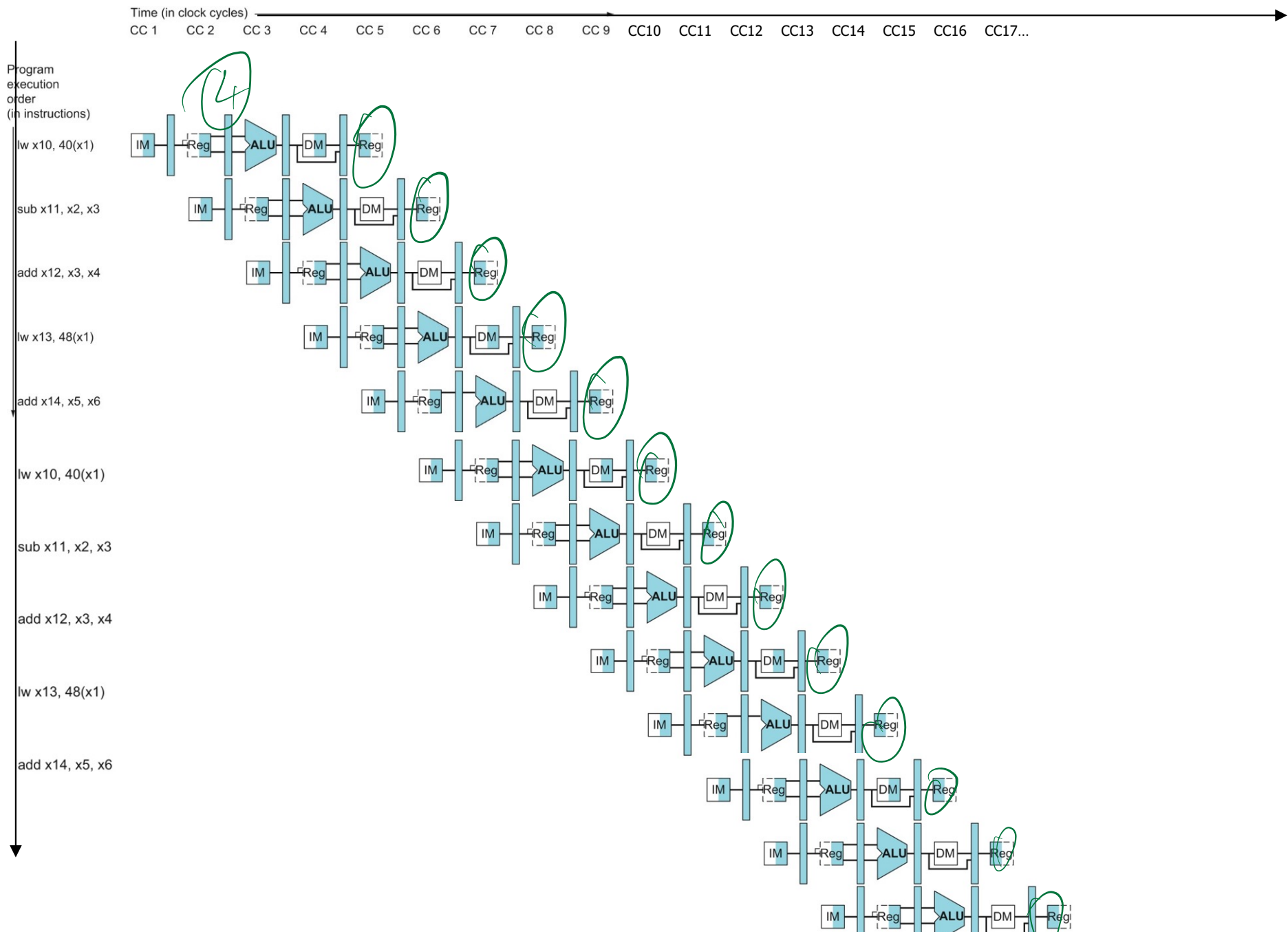
Multi-Cycle Pipeline Diagram



Multi-Cycle Pipeline Diagram

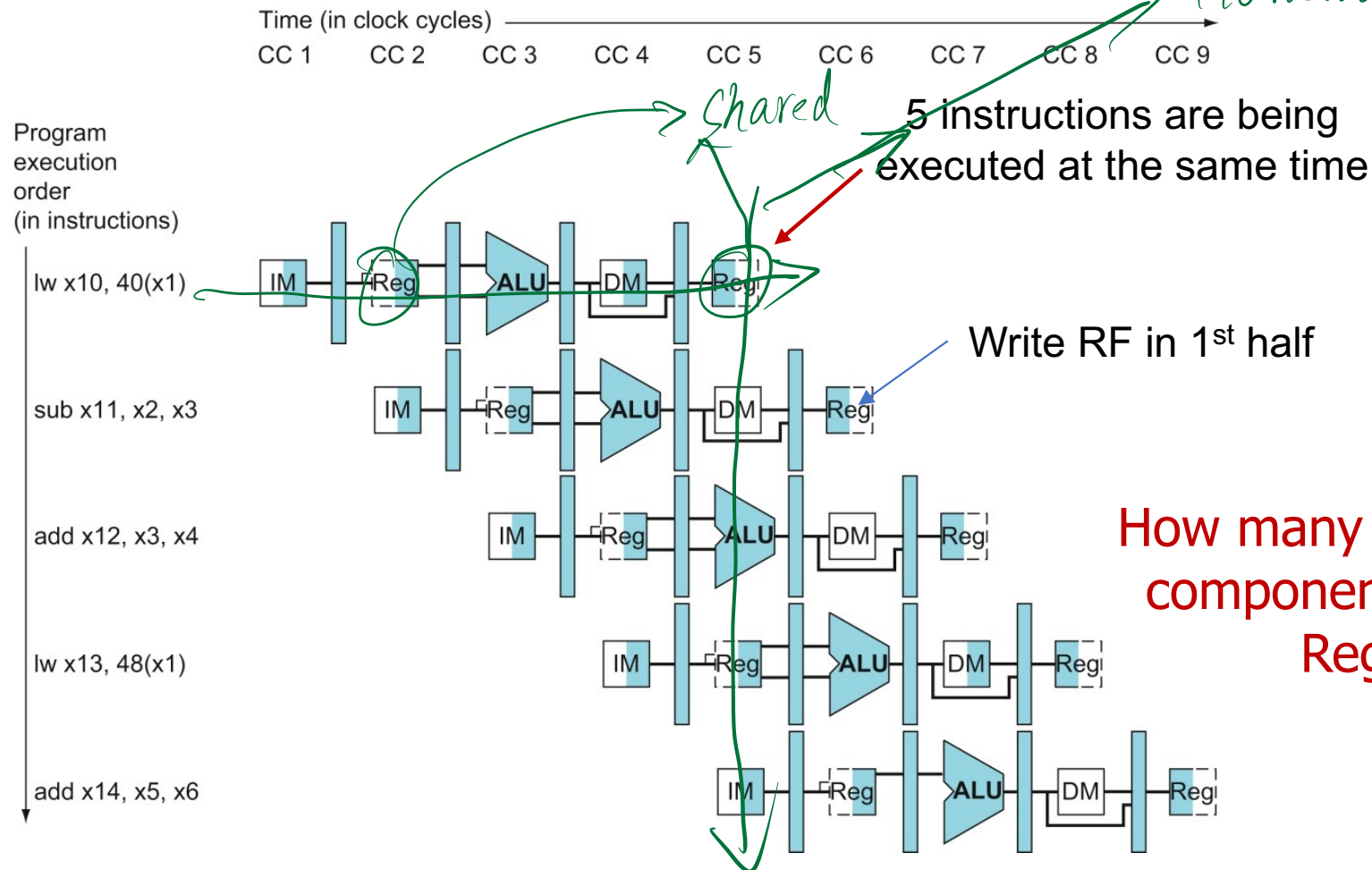


Multi-Cycle Pipeline Diagram



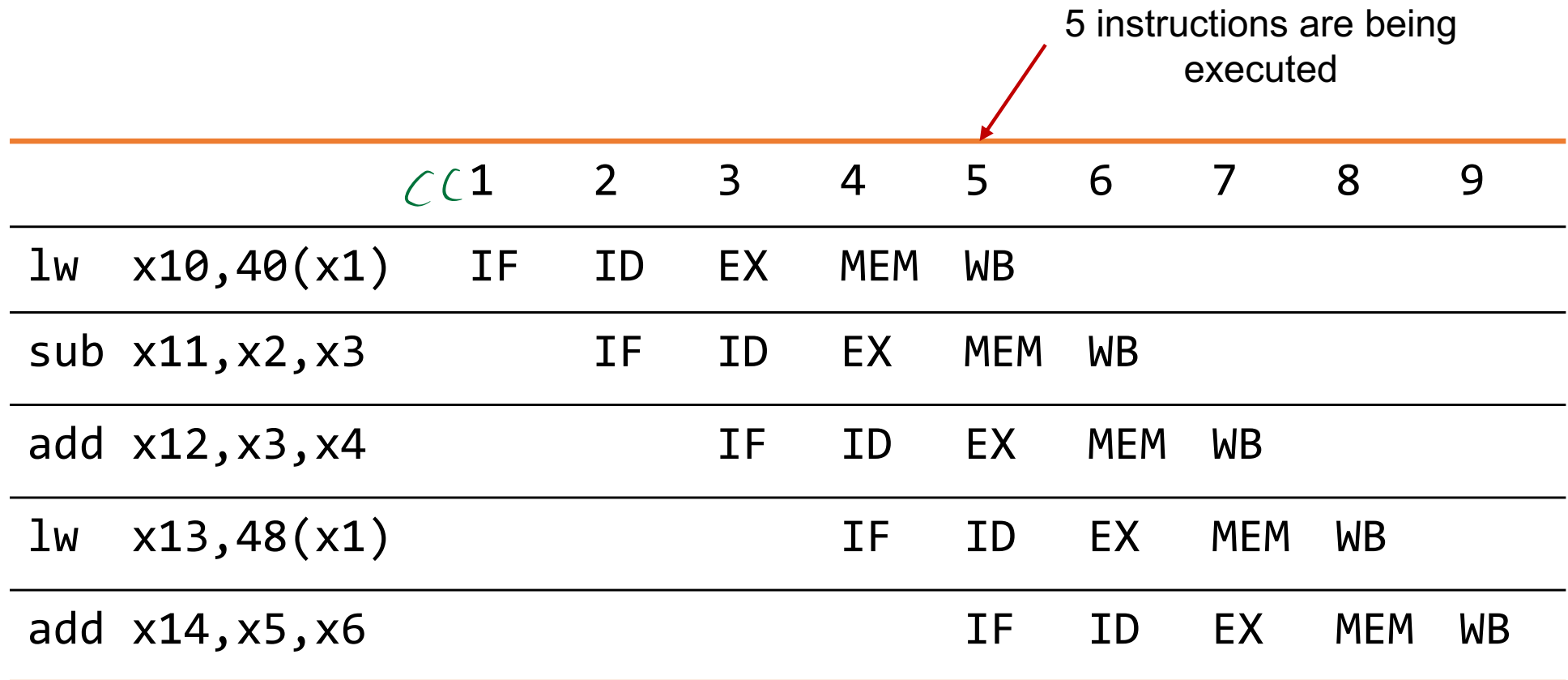
Multi-Cycle Pipeline Diagram

- Showing resource usage in multiple cycles
 - For each instruction, knows when a block is used
 - For each cycle, knows which block is doing what



Examples of Pipeline Diagram

- Use IF, ID, EX, MEM, WB to indicate pipe stages
 - Sometimes use EXE for EX and ME for MEM



One of the online chapters shows more detailed pipeline diagrams.

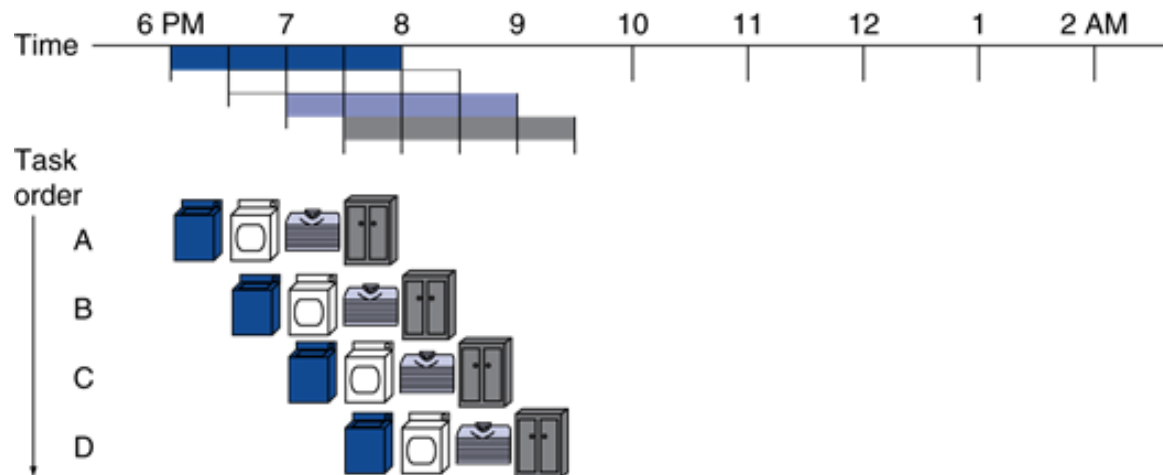
[Ch04_e2.pdf \(elsevier.com\)](#)

Troubles from Pipelining

- Pipeline Hazards
 - **Structural hazards**: attempt to use the same resource by two different instructions at the same time
 - **Data hazards**: attempt to use data before it is ready
 - An instruction's source operand(s) are produced by a prior instruction still in the pipeline
 - **Control hazards**: attempt to make a decision about program control flow before the condition has been evaluated and the new PC target address calculated
 - branch and jump instructions, exceptions
- Pipeline control must detect and take action to resolve hazards

Potential hazards in pipelined laundry example

- What if you have a washer and dryer combo?
- What if you are the only person doing the laundry?

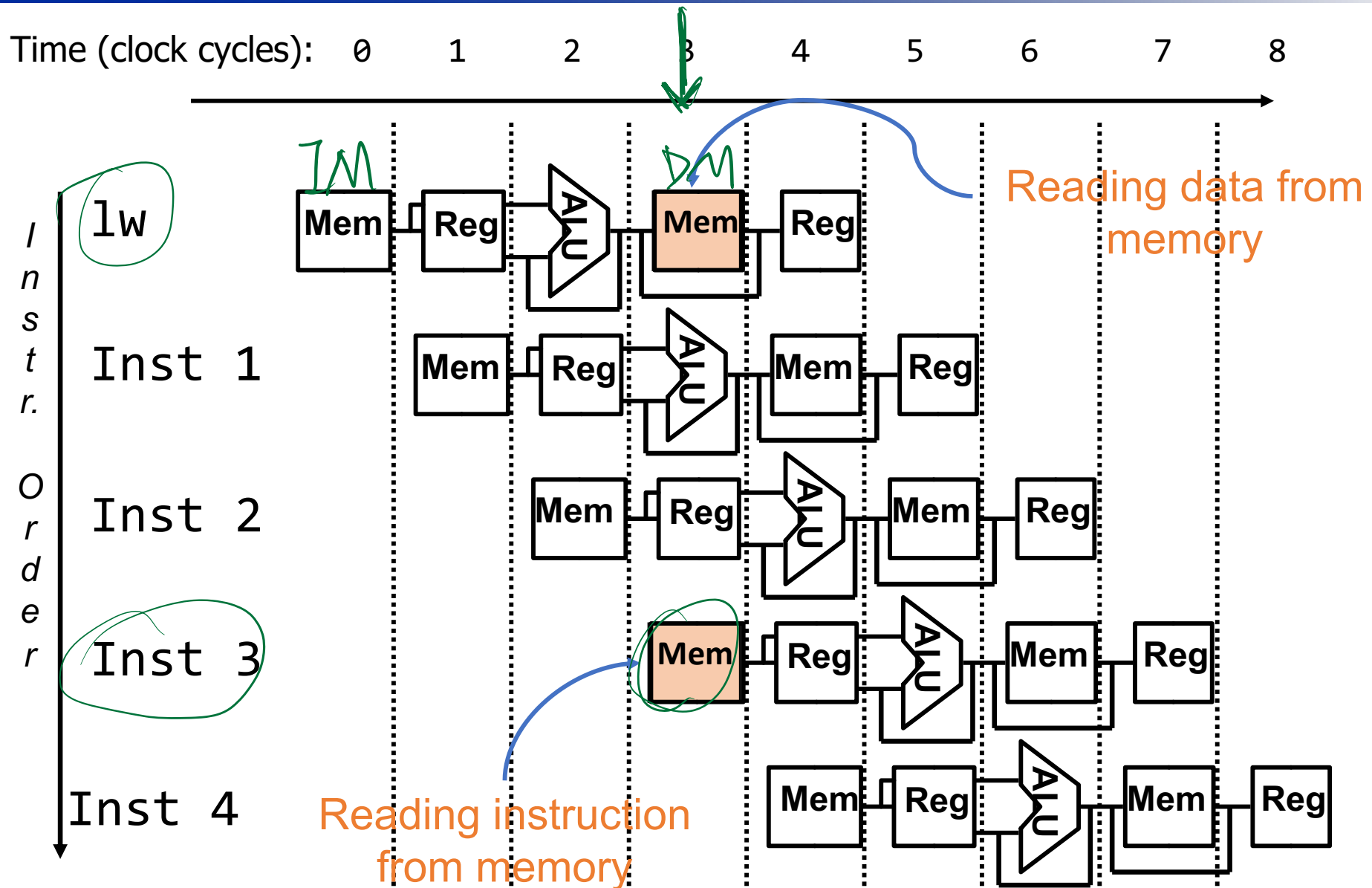


Dealing with Hazards



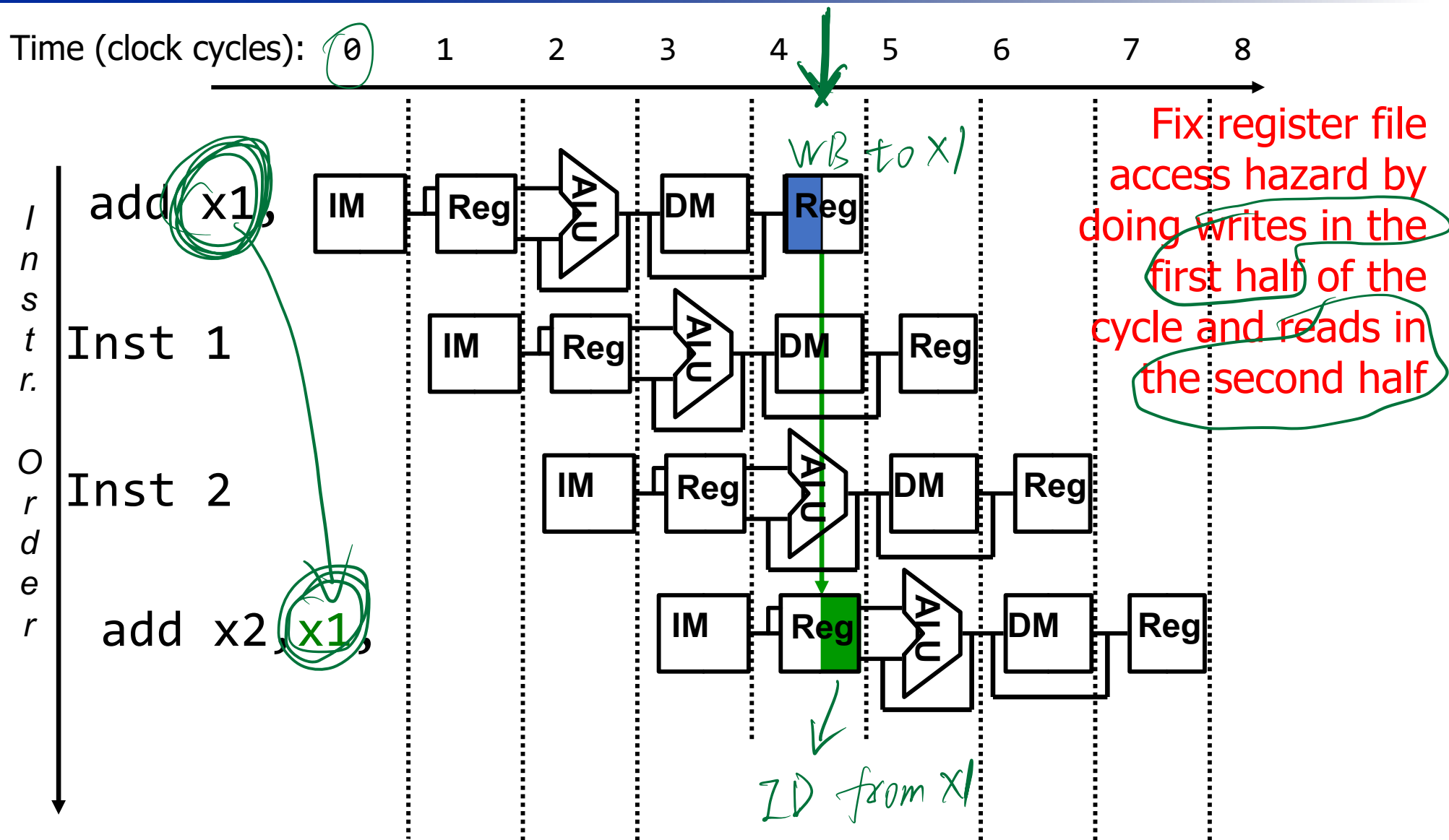
- We can usually resolve hazards by **waiting**
- We will find better ways to deal with hazards
- Dealing with structural hazards
 - Add more resources
 - Or share resources

A Single Memory Would Be a Structural Hazard



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

How About Register File Access?



Structural hazards in 5-stage pipeline

- Dealing with structural hazards
 - Add more resources
 - Or Share resources
- Memory
 - Add more resources: instruction memory and data memory
- Register
 - Share resources: write in the first half of a cycle and read in the second

Pipelining and ISA Design

- RISC-V ISA designed for pipelining
 - All instructions are 32-bits
 - Easier to fetch and decode in one cycle
 - c.f. x86: 1- to 17+ bytes instructions
 - Few and regular instruction formats
 - Can decode and read registers at the same time
 - Load/store addressing
 - Can calculate address in 3rd stage, access memory in 4th stage

Question

- In which stage are the control signals generated?

A. IF

B. ID

C. EX

D. MEM

E. It depends on instruction types

Question

- In which stage is RegWrite used?

A. IF

B. ID

C. EX

D. MEM

E. WB



Timing of writing to register file

