

CS 61C
Great Ideas in Computer Architecture
(Machine Structures)

Lecture: Single-Cycle CPU
Datapath Design

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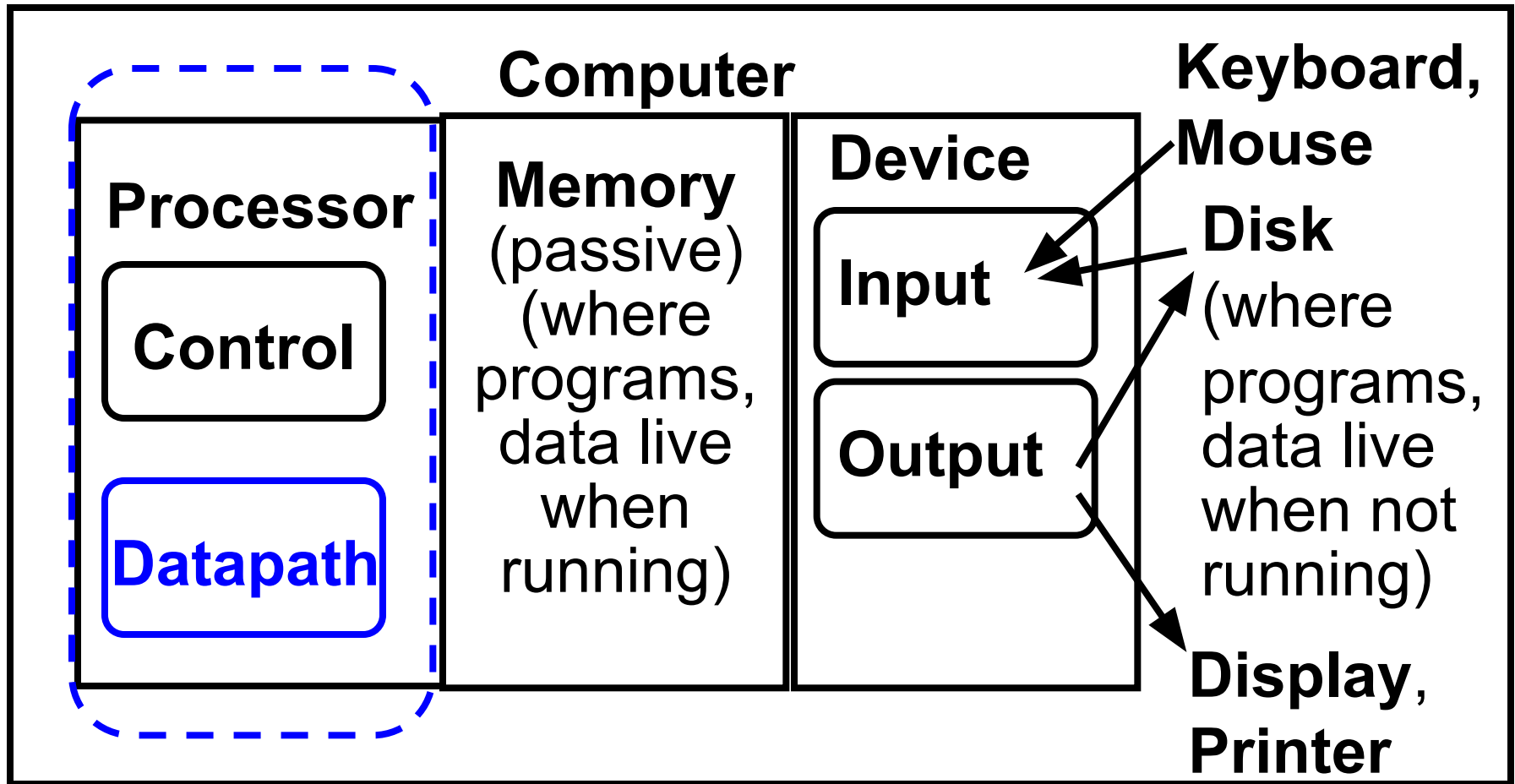
Review

- Use muxes to select among inputs
 - S control bits selects from 2^S inputs
 - Each input can be n-bits wide, indep of S
- Can implement muxes hierarchically
- ALU can be implemented using a mux
 - Coupled with basic block elements
- N-bit adder-subtractor done using N 1-bit adders with XOR gates on input
 - XOR serves as conditional inverter

Agenda

- Stages of the Datapath
- Datapath Instruction Walkthroughs
- Datapath Design

Five Components of a Computer



The CPU

- **Processor (CPU)**: the active part of the computer that does all the work (data manipulation and decision-making)
- **Datapath**: portion of the processor that contains hardware necessary to perform operations required by the processor (**the brawn**)
- **Control**: portion of the processor (also in hardware) that tells the datapath what needs to be done (**the brain**)

Stages of the Datapath : Overview

- Problem: a single, atomic block that “executes an instruction” (performs all necessary operations beginning with fetching the instruction) would be too bulky and inefficient
- Solution: break up the process of “executing an instruction” into **stages**, and then connect the stages to create the whole datapath
 - smaller stages are easier to design
 - easy to optimize (change) one stage without touching the others

Five Stages of the Datapath

- Stage 1: *Instruction Fetch*
- Stage 2: *Instruction Decode*
- Stage 3: *ALU* (Arithmetic-Logic Unit)
- Stage 4: *Memory Access*
- Stage 5: *Register Write*

Stages of the Datapath (1/5)

- There is a wide variety of MIPS instructions: so what general steps do they have in common?
- Stage 1: **Instruction Fetch**
 - no matter what the instruction, the 32-bit instruction word must first be fetched from memory (the cache-memory hierarchy)
 - also, this is where we **Increment PC** (that is, $PC = PC + 4$, to point to the next instruction: byte addressing so + 4)

Stages of the Datapath (2/5)

- Stage 2: **Instruction Decode**
 - upon fetching the instruction, we next gather data from the fields (decode all necessary instruction data)
 - first, read the `opcode` to determine instruction type and field lengths
 - second, read in data from all necessary registers
 - for `add`, read two registers
 - for `addi`, read one register
 - for `jal`, no reads necessary

Stages of the Datapath (3/5)

- Stage 3: **ALU** (Arithmetic-Logic Unit)
 - the real work of most instructions is done here: arithmetic (+, -, *, /), shifting, logic (&, |), comparisons (`slt`)
 - what about loads and stores?
 - `lw $t0, 40($t1)`
 - the address we are accessing in memory = the value in `$t1` PLUS the value 40
 - so we do this addition in this stage

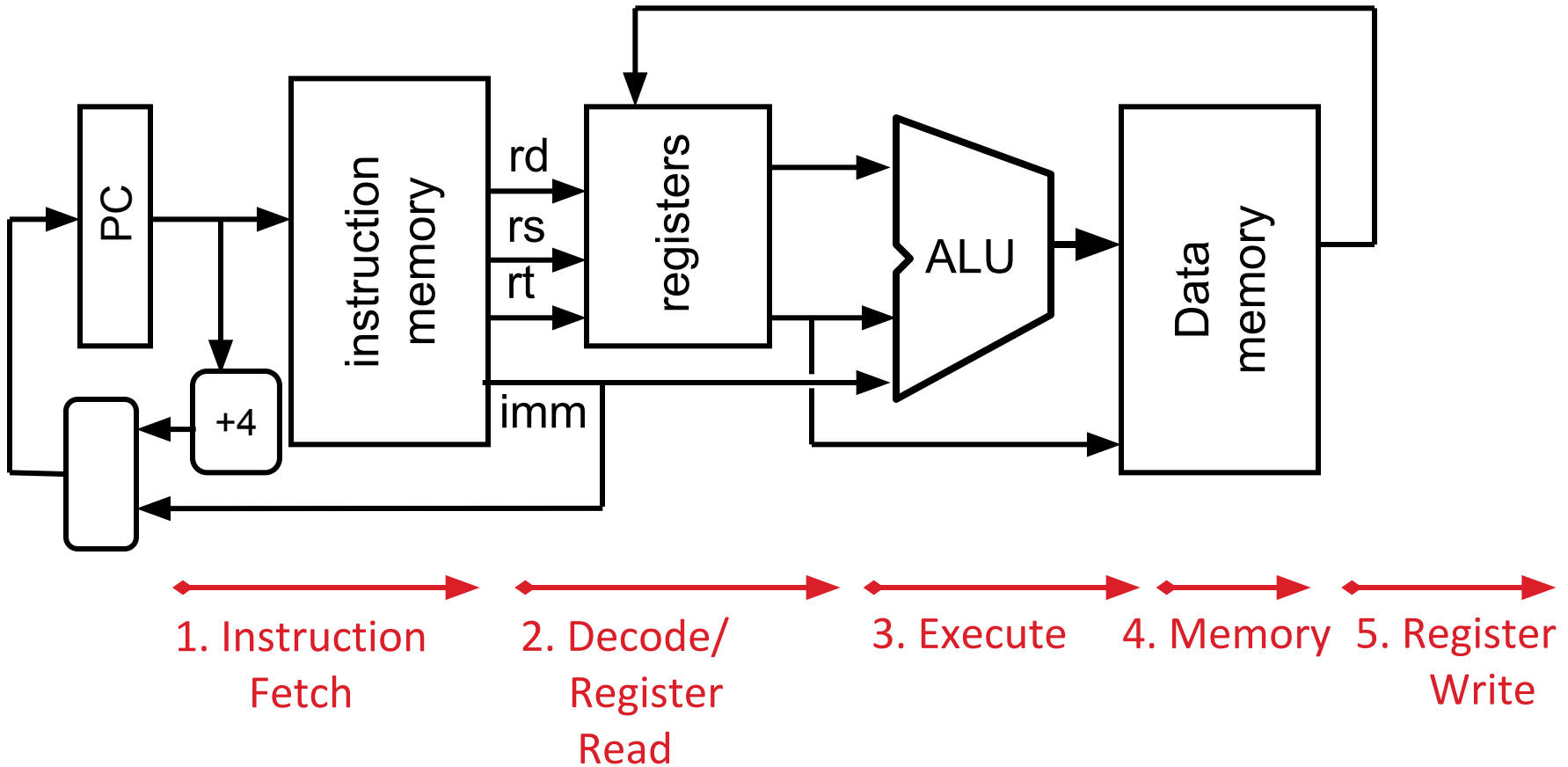
Stages of the Datapath (4/5)

- Stage 4: **Memory Access**
 - actually only the load and store instructions do anything during this stage; the others remain idle during this stage or skip it all together
 - since these instructions have a unique step, we need this extra stage to account for them
 - as a result of the cache system, this stage is expected to be fast

Stages of the Datapath (5/5)

- Stage 5: Register Write
 - most instructions write the result of some computation into a register
 - examples: arithmetic, logical, shifts, loads, slt
 - what about stores, branches, jumps?
 - don't write anything into a register at the end
 - these remain idle during this fifth stage or skip it all together

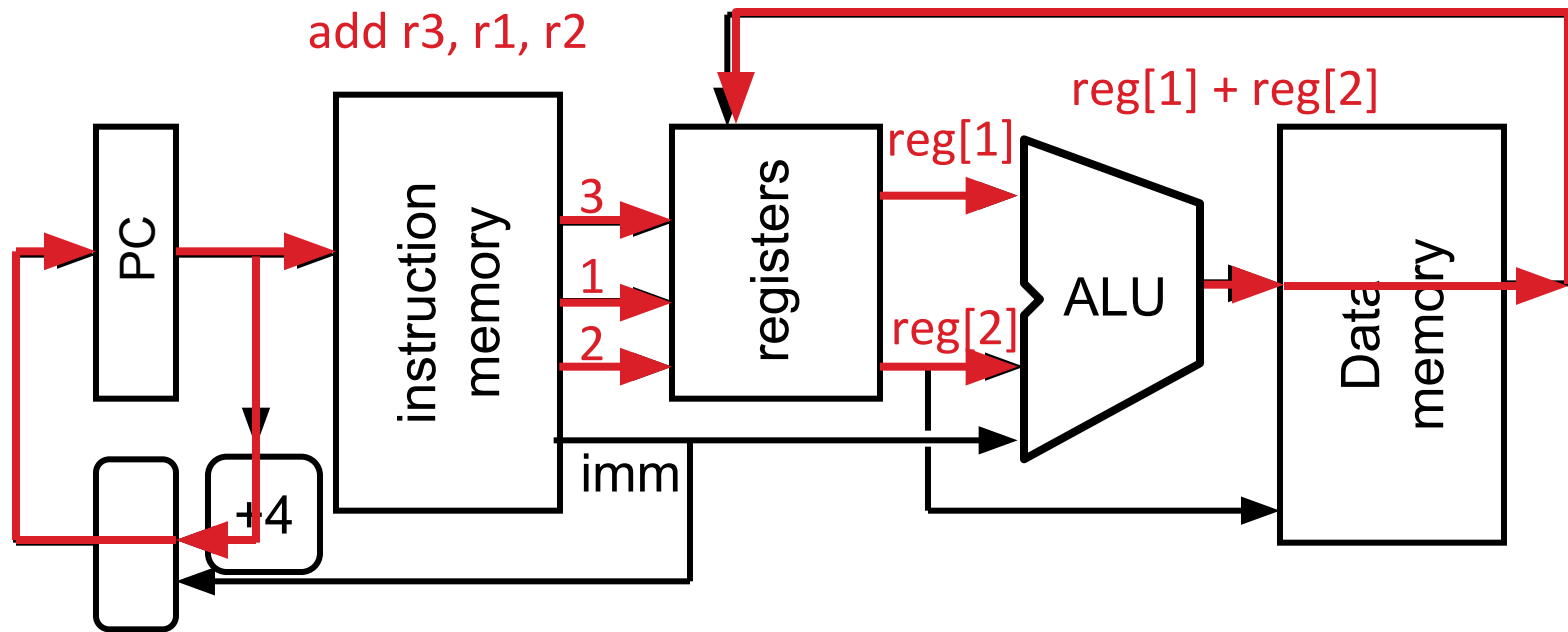
Generic Steps of Datapath



Datapath Walkthroughs (1/3)

- `add $r3, $r1, $r2 # r3 = r1+r2`
 - Stage 1: fetch this instruction, increment PC
 - Stage 2: decode to determine it is an `add`, then read registers `$r1` and `$r2`
 - Stage 3: add the two values retrieved in Stage 2
 - Stage 4: idle (nothing to write to memory)
 - Stage 5: write result of Stage 3 into register `$r3`

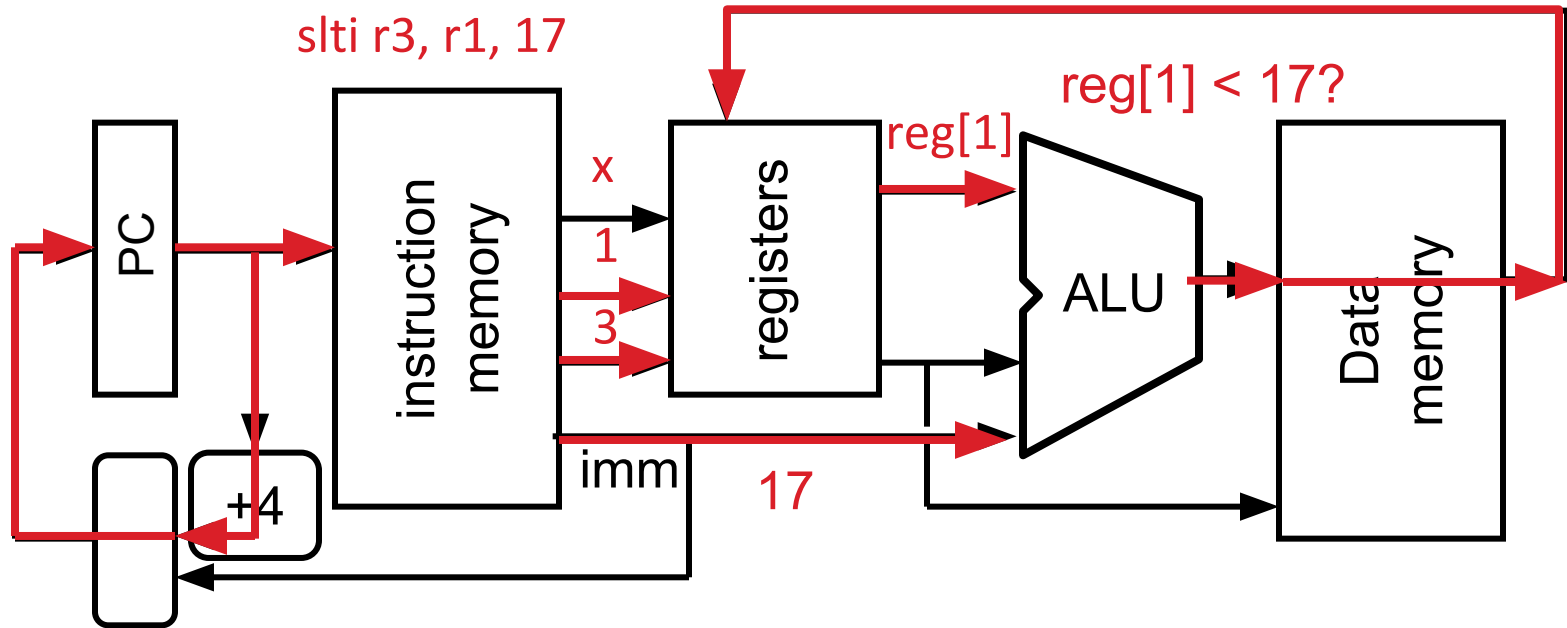
Example: add Instruction



Datapath Walkthroughs (2/3)

- `slti $r3,$r1,17`
`if (r1 < 17) r3 = 1 else r3 = 0`
 - Stage 1: fetch this instruction, increment PC
 - Stage 2: decode to determine it is an `slti`, then read register `$r1`
 - Stage 3: compare value retrieved in Stage 2 with the integer 17
 - Stage 4: idle
 - Stage 5: write the result of Stage 3 (1 if reg source was less than signed immediate, 0 otherwise) into register `$r3`

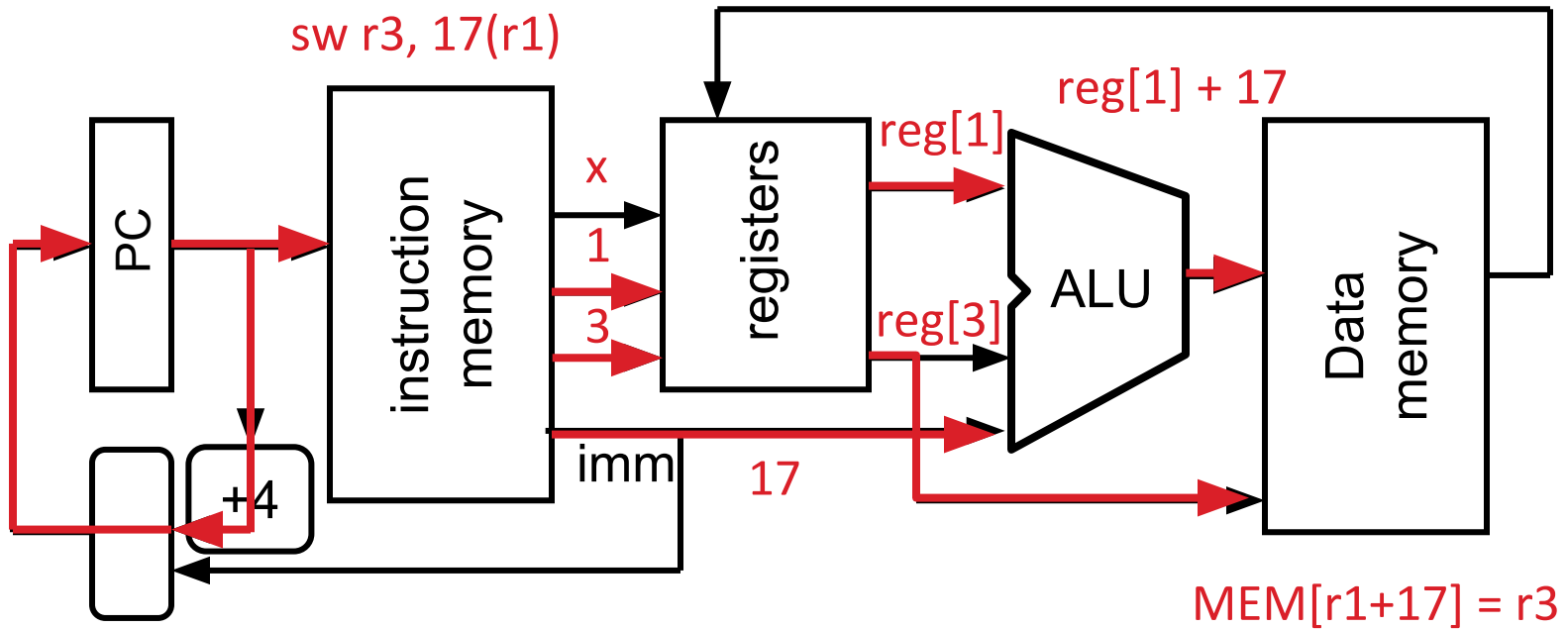
Example: `slti` Instruction



Datapath Walkthroughs (3/3)

- `sw $r3, 17($r1) # Mem[r1+17]=r3`
 - Stage 1: fetch this instruction, increment PC
 - Stage 2: decode to determine it is a `sw`, then read registers `$r1` and `$r3`
 - Stage 3: add 17 to value in register `$r1` (retrieved in Stage 2) to compute address
 - Stage 4: write value in register `$r3` (retrieved in Stage 2) into memory address computed in Stage 3
 - Stage 5: idle (nothing to write into a register)

Example: *sw* Instruction



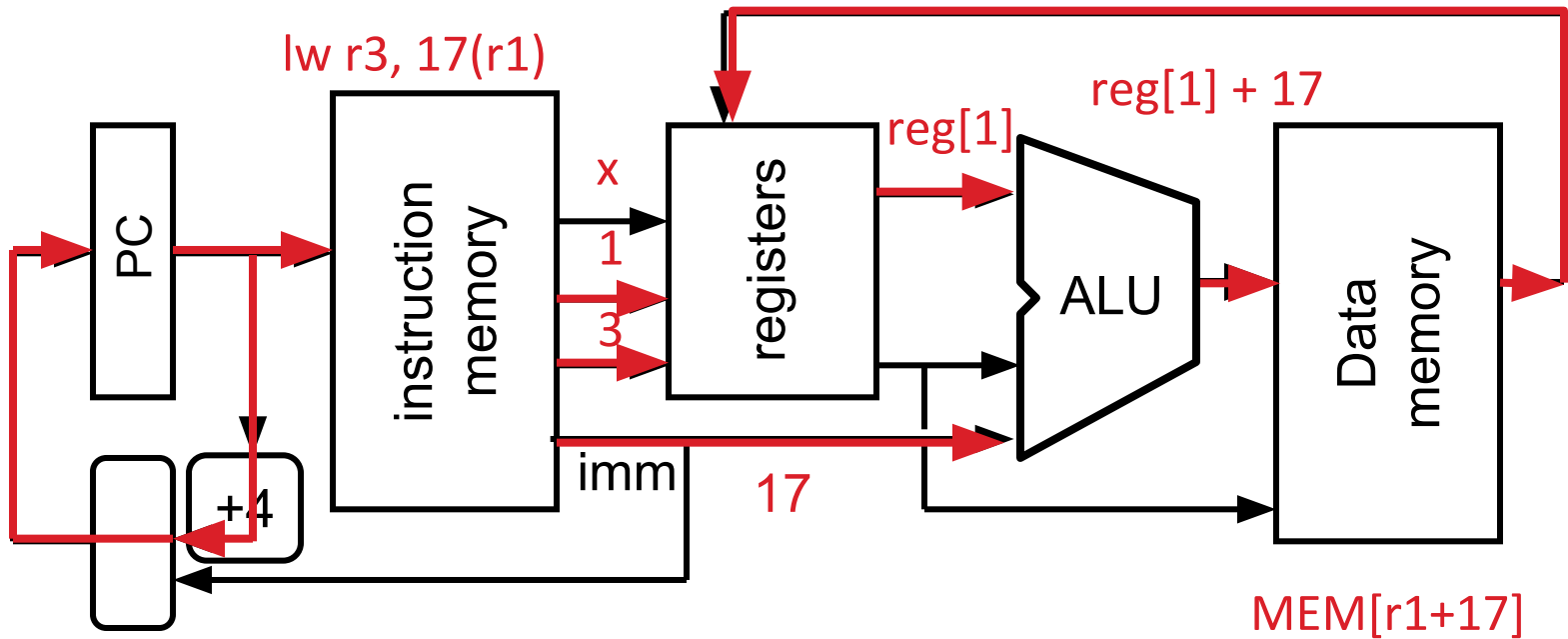
Why Five Stages? (1/2)

- Could we have a different number of stages?
 - Yes, and other architectures do
- So why does MIPS have five if instructions tend to idle for at least one stage?
 - Five stages are the union of all the operations needed by all the instructions.
 - One instruction uses all five stages: the **load**

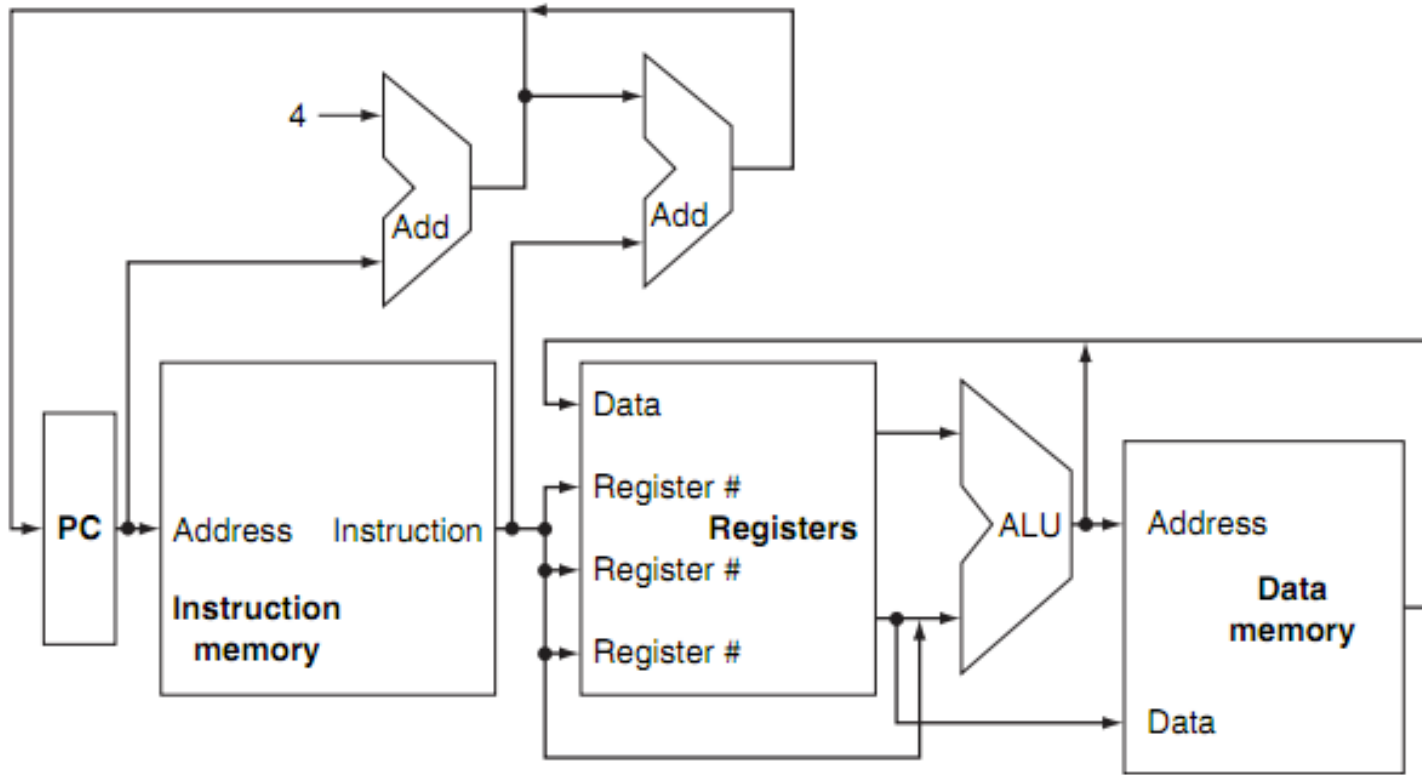
Why Five Stages? (2/2)

- `lw $r3, 17($r1) # r3=Mem[r1+17]`
 - Stage 1: fetch this instruction, increment PC
 - Stage 2: decode to determine it is a `lw`, then read register `$r1`
 - Stage 3: add 17 to value in register `$r1` (retrieved in Stage 2)
 - Stage 4: read value from memory address computed in Stage 3
 - Stage 5: write value read in Stage 4 into register `$r3`

Example: `lw` Instruction



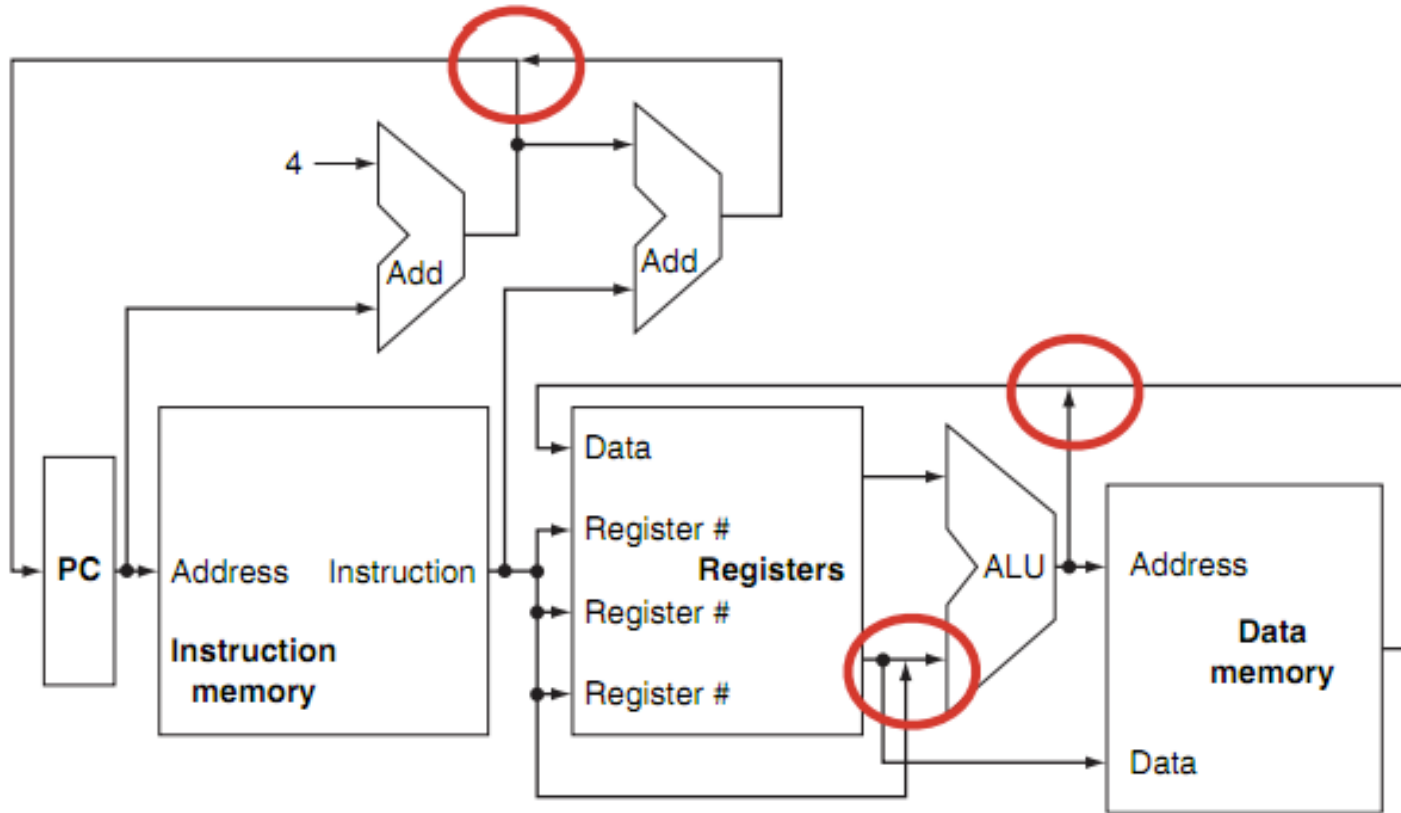
Peer Instruction



How many places in this diagram will need a multiplexer to select one from multiple inputs?

- a) 0 b) 1 c) 2 d) 3 e) 4 or more

Peer Instruction

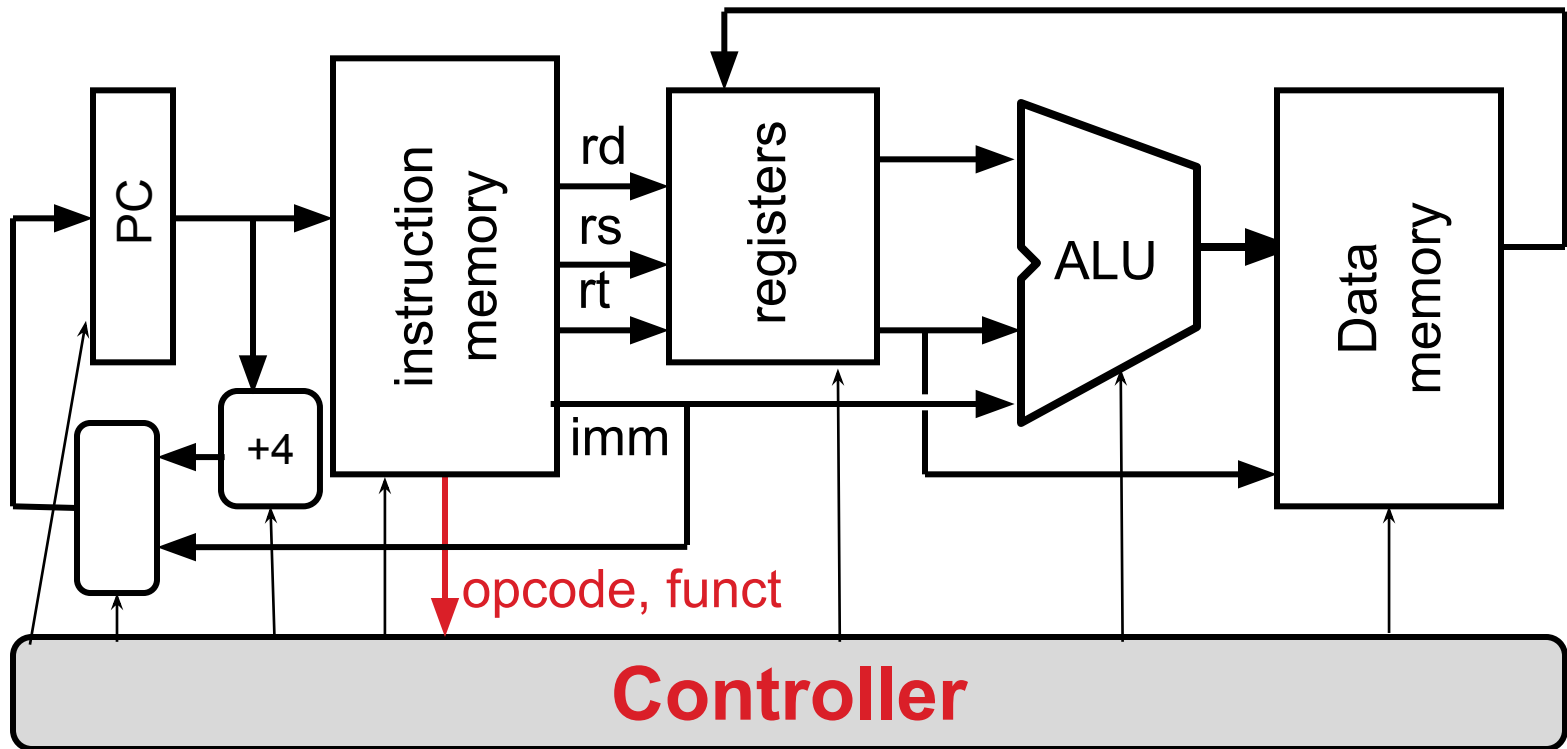


How many places in this diagram will need a multiplexer to select one from multiple inputs?

- a) 0 b) 1 c) 2 **d) 3** e) 4 or more

Datapath and Control

- Datapath based on data transfers required to perform instructions
- Controller causes the right transfers to happen



What Hardware Is Needed? (1/2)

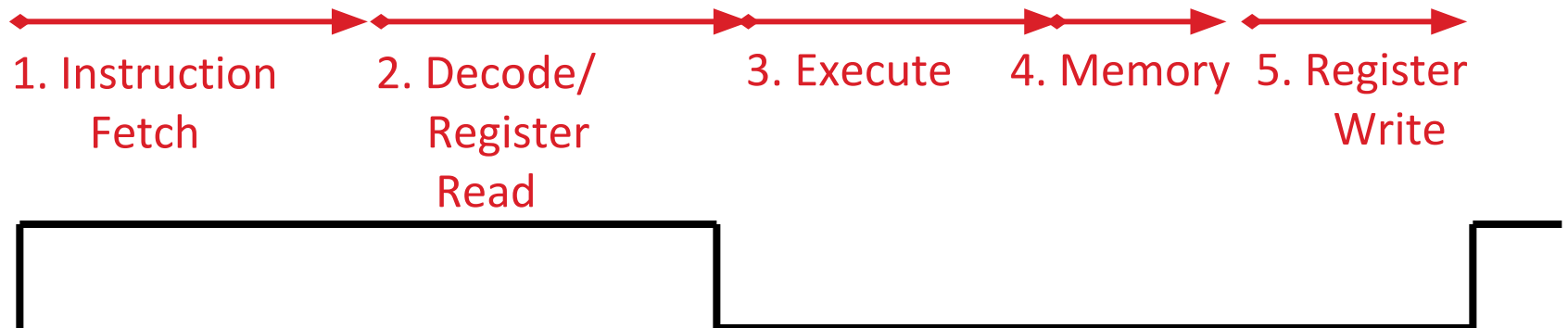
- PC: a register that keeps track of address of the *next* instruction to be fetched
- General Purpose Registers
 - Used in Stages 2 (Read) and 5 (Write)
 - MIPS has 32 of these
- Memory
 - Used in Stages 1 (Fetch) and 4 (R/W)
 - Caches makes these stages as fast as the others (on average, otherwise multicycle stall)

What Hardware Is Needed? (2/2)

- ALU
 - Used in Stage 3
 - Performs all necessary functions: arithmetic, logicals, etc.
- Miscellaneous Registers
 - One stage per clock cycle: Registers inserted between stages to hold intermediate data and control signals as they travel from stage to stage
 - Note: Register is a general purpose term meaning something that stores bits. Realize that not all registers are in the “register file”

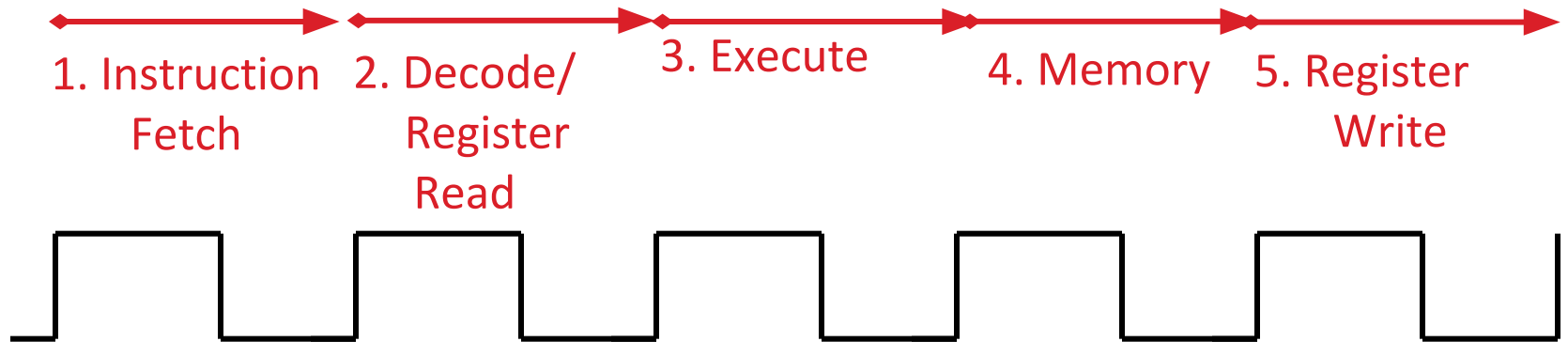
CPU Clocking (1/2)

- For each instruction, how do we control the flow of information through the datapath?
- Single Cycle CPU: All stages of an instruction completed within one long clock cycle
 - Clock cycle sufficiently long to allow each instruction to complete all stages without interruption within one cycle



CPU Clocking (2/2)

- Alternative multiple-cycle CPU: only one stage of instruction per clock cycle
 - Clock is made as long as the slowest stage



- Several significant advantages over single cycle execution:
 - Unused stages in a particular instruction can be skipped
 - OR instructions can be pipelined (overlapped)

Processor Design

- Analyze instruction set architecture (ISA) to determine datapath requirements
 - Meaning of each instruction is given by register transfers
 - Datapath must include storage element for ISA registers
 - Datapath must support each register transfer
- Select set of datapath components and establish clocking methodology
- Assemble datapath components to meet requirements
- Analyze each instruction to determine sequence of control point settings to implement the register transfer
- Assemble the control logic to perform this sequencing

Summary

- CPU design involves Datapath, Control
 - 5 Stages for MIPS Instructions
 1. Instruction Fetch
 2. Instruction Decode & Register Read
 3. ALU (Execute)
 4. Memory
 5. Register Write
- Datapath timing: single long clock cycle or one short clock cycle per stage

Instruction Level Parallelism

	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T 8	T 9	T 10	T 11	T 12
Instr 1	IF	ID	ALU	MEM	WR							
Instr 2		IF	ID	ALU	MEM	WR						
Instr 3			IF	ID	ALU	MEM	WR					
Instr 4				IF	ID	ALU	MEM	WR				
Instr 5					IF	ID	ALU	MEM	WR			
Instr 6						IF	ID	ALU	MEM	WR		
Instr 7							IF	ID	ALU	MEM	WR	
Instr 8								IF	ID	ALU	MEM	WR