Datapath & Control Design

- We will design a simplified MIPS processor
- The instructions supported are
  - memory-reference instructions: `lw, sw`
  - arithmetic-logical instructions: `add, sub, and, or, slt`
  - control flow instructions: `beq, j`
- Generic Implementation:
  - use the program counter (PC) to supply instruction address
  - get the instruction from memory
  - read registers
  - use the instruction to decide exactly what to do
- All instructions use the ALU after reading the registers

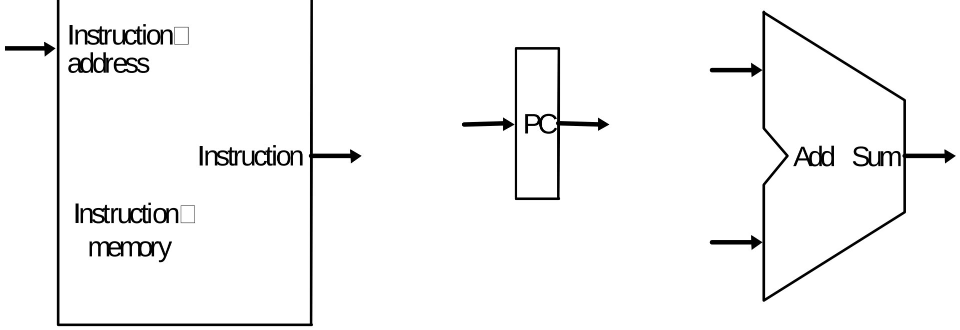
  Why? memory-reference? arithmetic? control flow?

What blocks we need

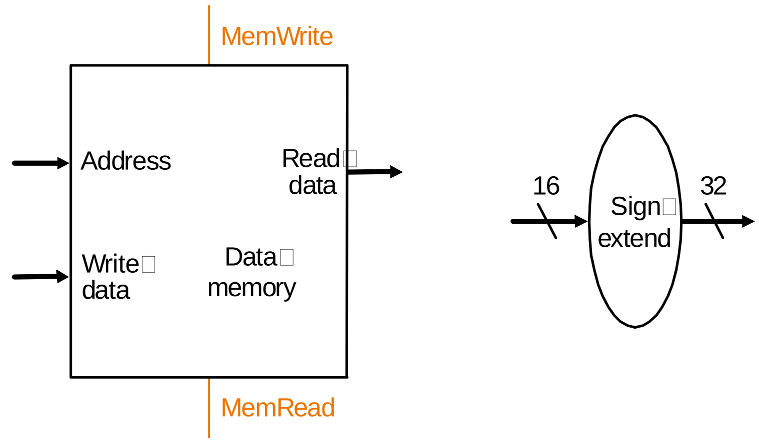
- We need an ALU
  - We have already designed that
- We need memory to store inst and data
  - Instruction memory takes address and supplies inst
  - Data memory takes address and supply data for lw
  - Data memory takes address and data and write into memory
- We need to manage a PC and its update mechanism
- We need a register file to include 32 registers
  - We read two operands and write a result back in register file
- Some times part of the operand comes from instruction
- We may add support of immediate class of instructions
- We may add support for J, JR, JAL

Simple Implementation

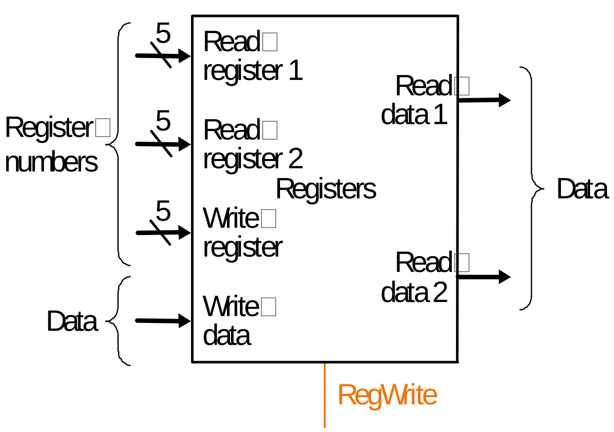
- Include the functional units we need for each instruction



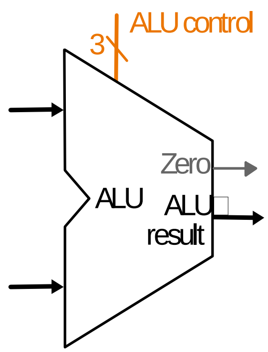
a. Instruction memory   b. Program counter   c. Adder



a. Data memory unit   b. Sign-extension unit



a. Registers

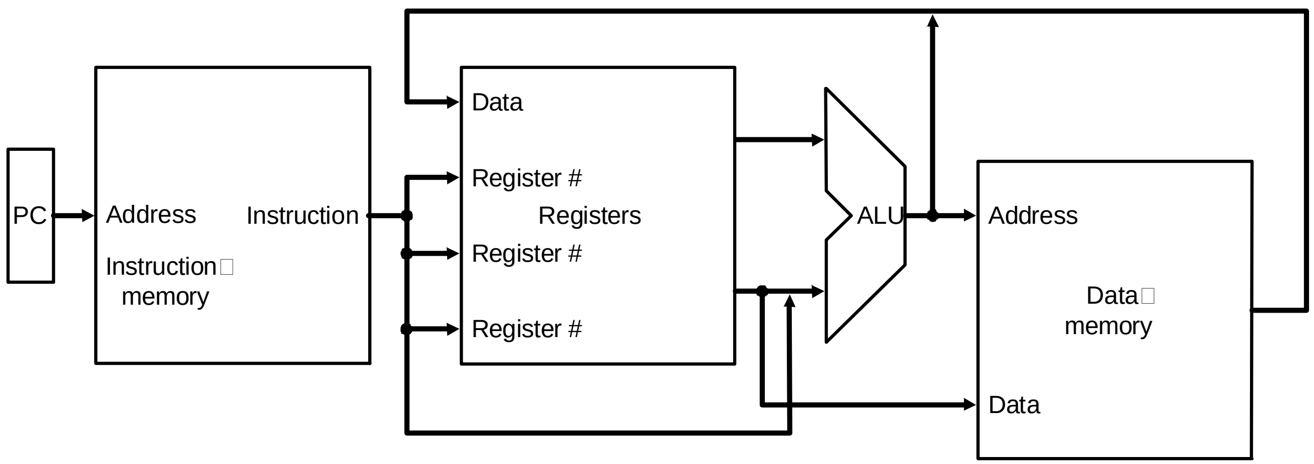


b. ALU

Why do we need this stuff?

More Implementation Details

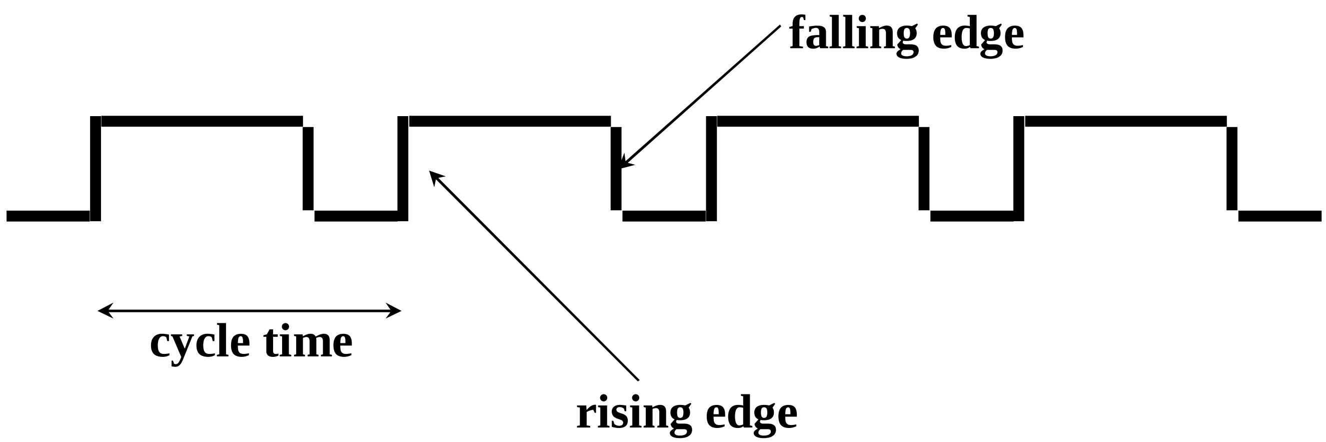
- **Abstract / Simplified View:**



- **Two types of functional units:**
  - **elements that operate on data values (combinational)**
    - **Example: ALU**
  - **elements that contain state (sequential)**
    - **Examples: Program and Data memory, Register File**

Managing State Elements

- Unclocked vs. Clocked
- Clocks used in synchronous logic
  - when should an element that contains state be updated?



MIPS Instruction Format

31 26	25 21	20 16	15 11	10 6	5 0
LW	REG 1	REG 2	LOAD ADDRESS		OFFSET

31 26	25 21	20 16	15 11	10 6	5 0
SW	REG 1	REG 2	STORE ADDRESS		OFFSET

31 26	25 21	20 16	15 11	10 6	5 0
BEQ/BNE/J	REG 1	REG 2	BRANCH ADDRESS		OFFSET

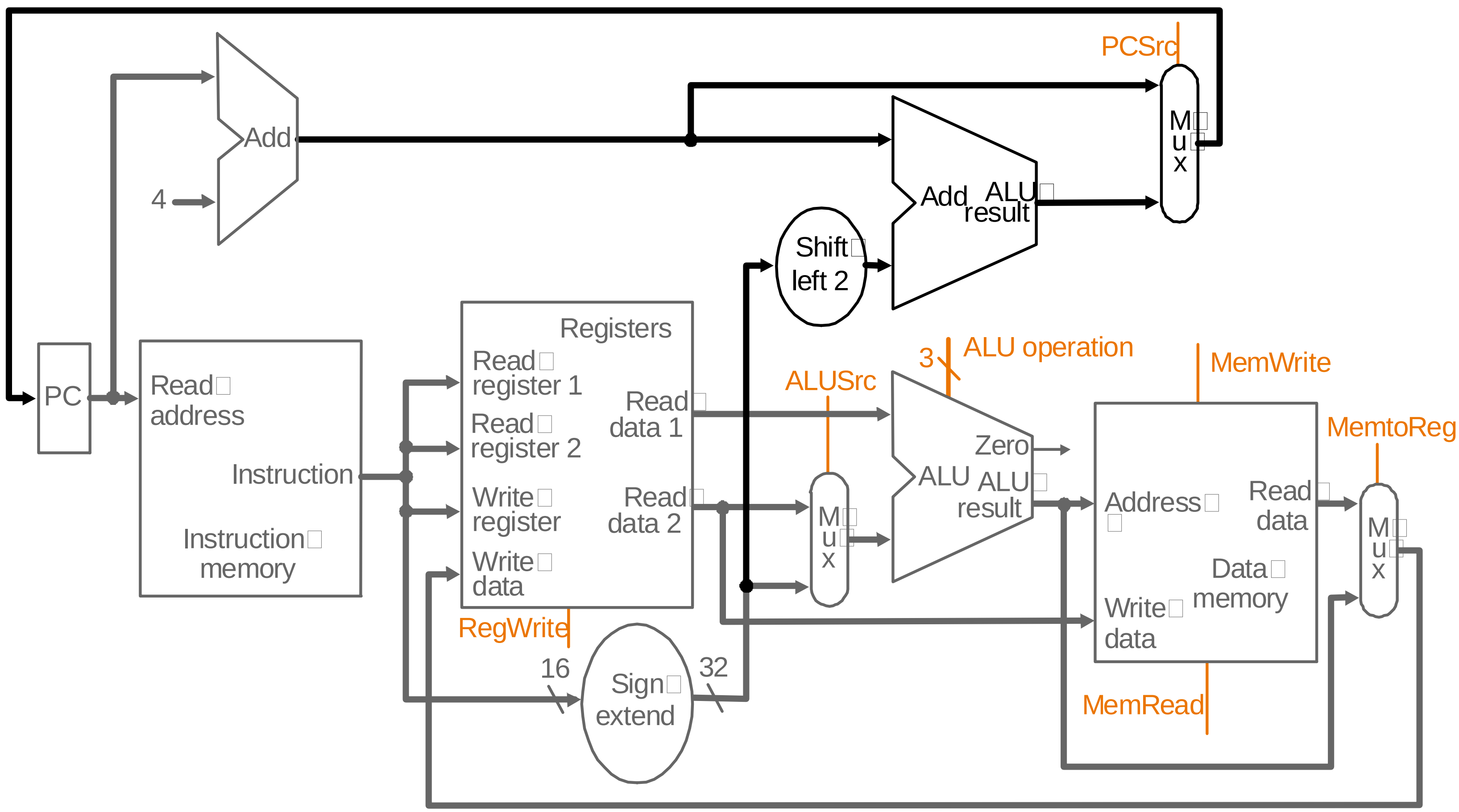
31 26	25 21	20 16	15 11	10 6	5 0
R-TYPE	REG 1	REG 2	DST	SHIFT AMOUNT	ADD/AND/OR/SLT

31 26	25 21	20 16	15 11	10 6	5 0
I-TYPE	REG 1	REG 2	IMMEDIATE DATA		

31 26	25 21	20 16	15 11	10 6	5 0
JUMP	JUMP			ADDRESS	

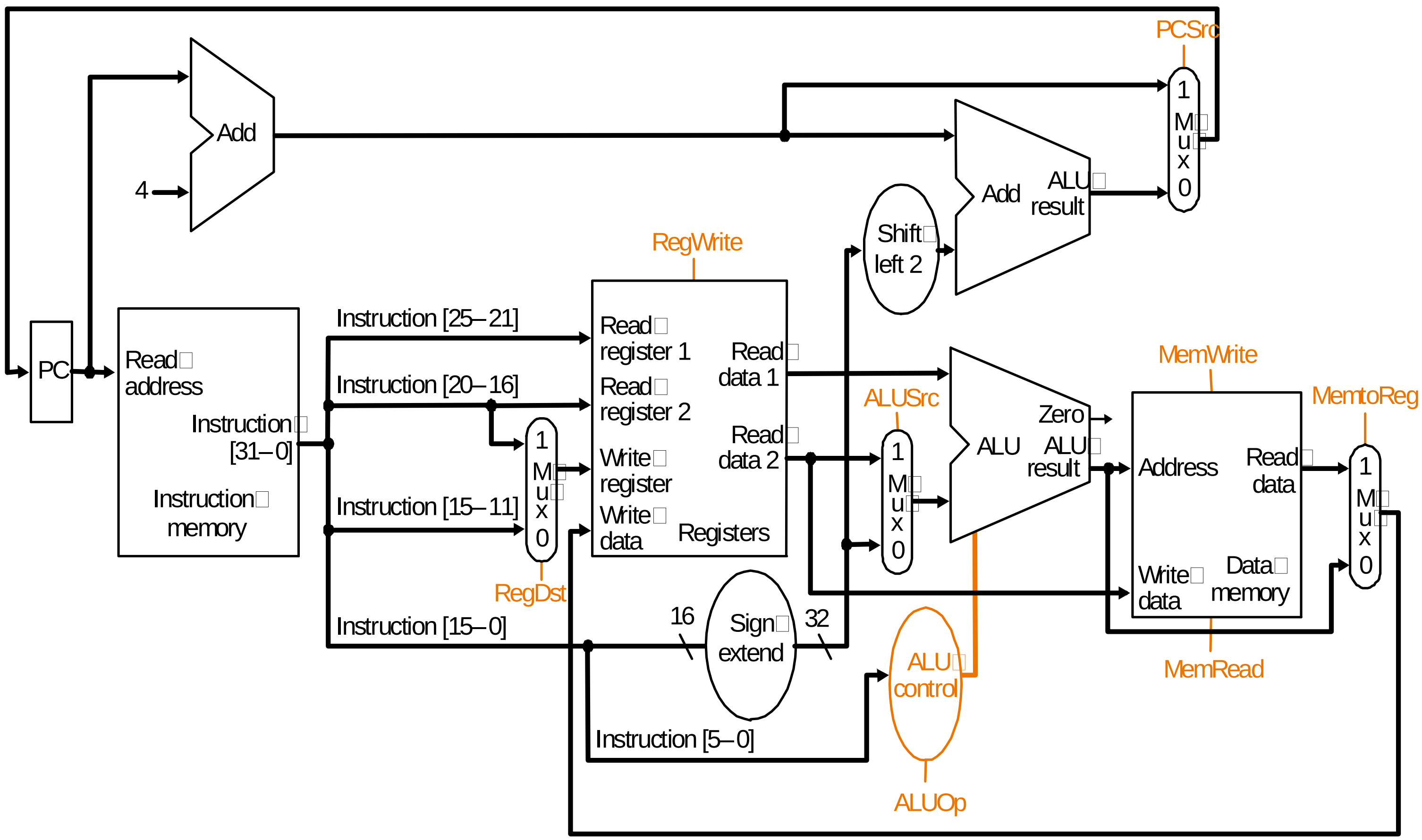
Building the Datapath

- **Use multiplexors to stitch them together**



A Complete Datapath for R-Type Instructions

- **Lw, Sw, Add, Sub, And, Or, Slt can be performed**
- **For j (jump) we need an additional multiplexor**



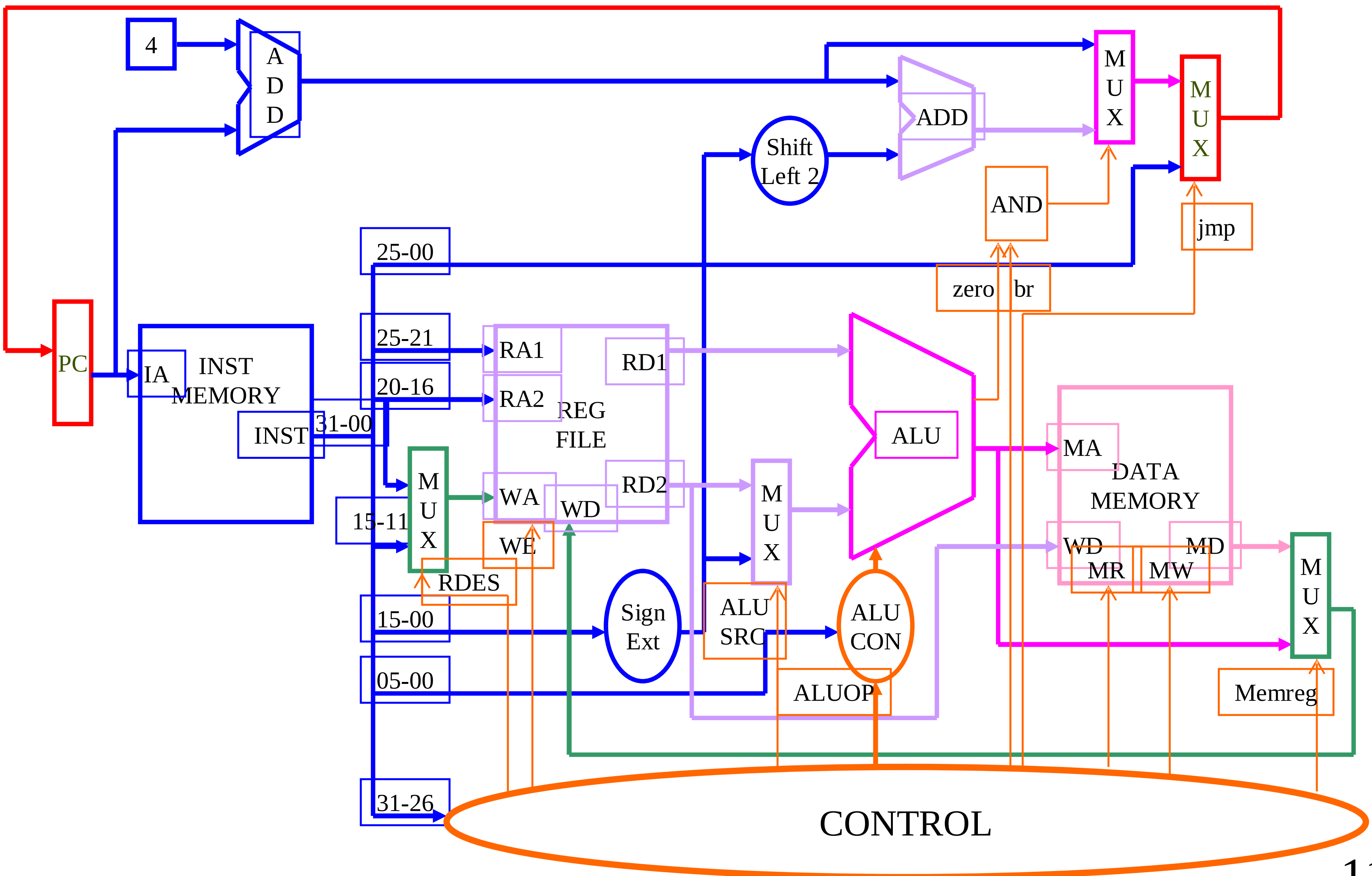
What Else is Needed in Data Path

- Support for j and jr
  - For both of them PC value need to come from somewhere else
  - For J, PC is created by 4 bits (31:28) from old PC, 26 bits from IR (27:2) and 2 bits are zero (1:0)
  - For JR, PC value comes from a register
- Support for JAL
  - Address is same as for J inst
  - OLD PC needs to be saved in register 31
- And what about immediate operand instructions
  - Second operand from instruction, but without shifting
- Support for other instructions like lw and immediate inst write

Operation for Each Instruction

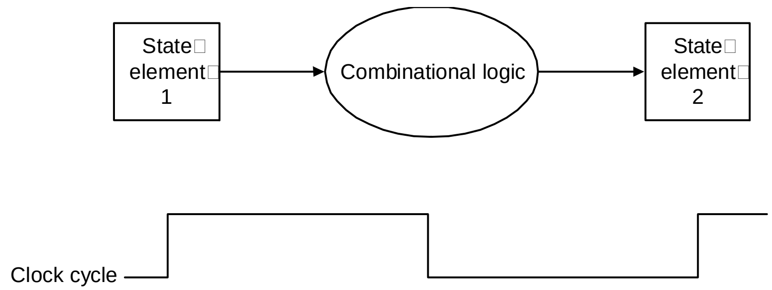
LW:	SW:	R/I/S-Type:	BR-Type:	JMP-Type:
1. READ INST	1. READ INST	1. READ INST	1. READ INST	1. READ INST
2. READ REG 1 *READ REG 2*	2. READ REG 1 READ REG 2	2. READ REG 1 READ REG 2	2. READ REG 1 READ REG 2	2.
3. ADD REG 1 + OFFSET	3. ADD REG 1 + OFFSET	3. OPERATE on REG 1 / REG 2	3. SUB REG 2 from REG 1	3.
4. READ MEM	4. WRITE MEM	4.	4.	4.
5. WRITE REG2	5.	5. WRITE DST	5.	5.

Data Path Operation



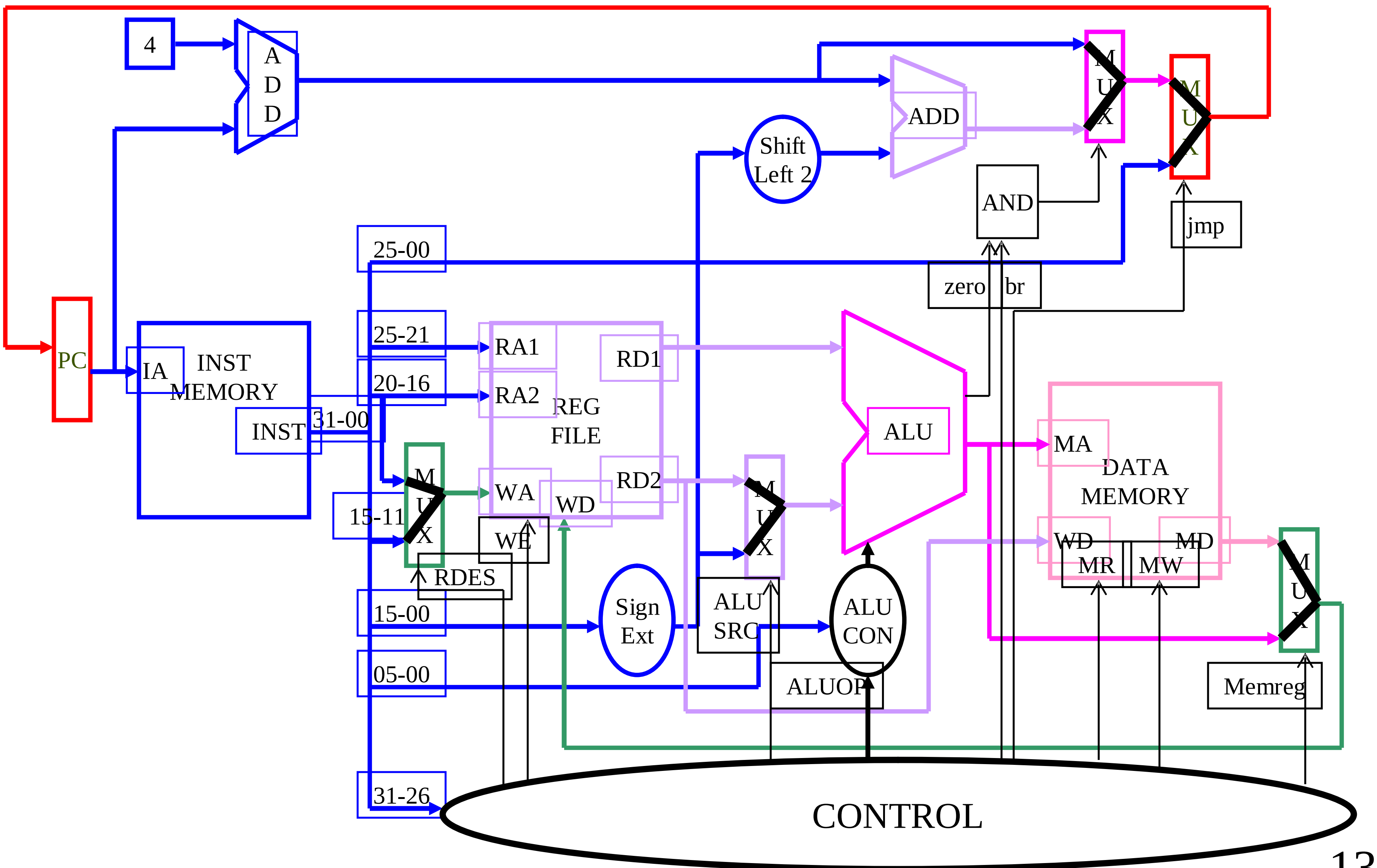
Our Simple Control Structure

- **All of the logic is combinational**
- **We wait for everything to settle down, and the right thing to be done**
  - **ALU might not produce "right answer" right away**
  - **we use write signals along with clock to determine when to write**
- **Cycle time determined by length of the longest path**

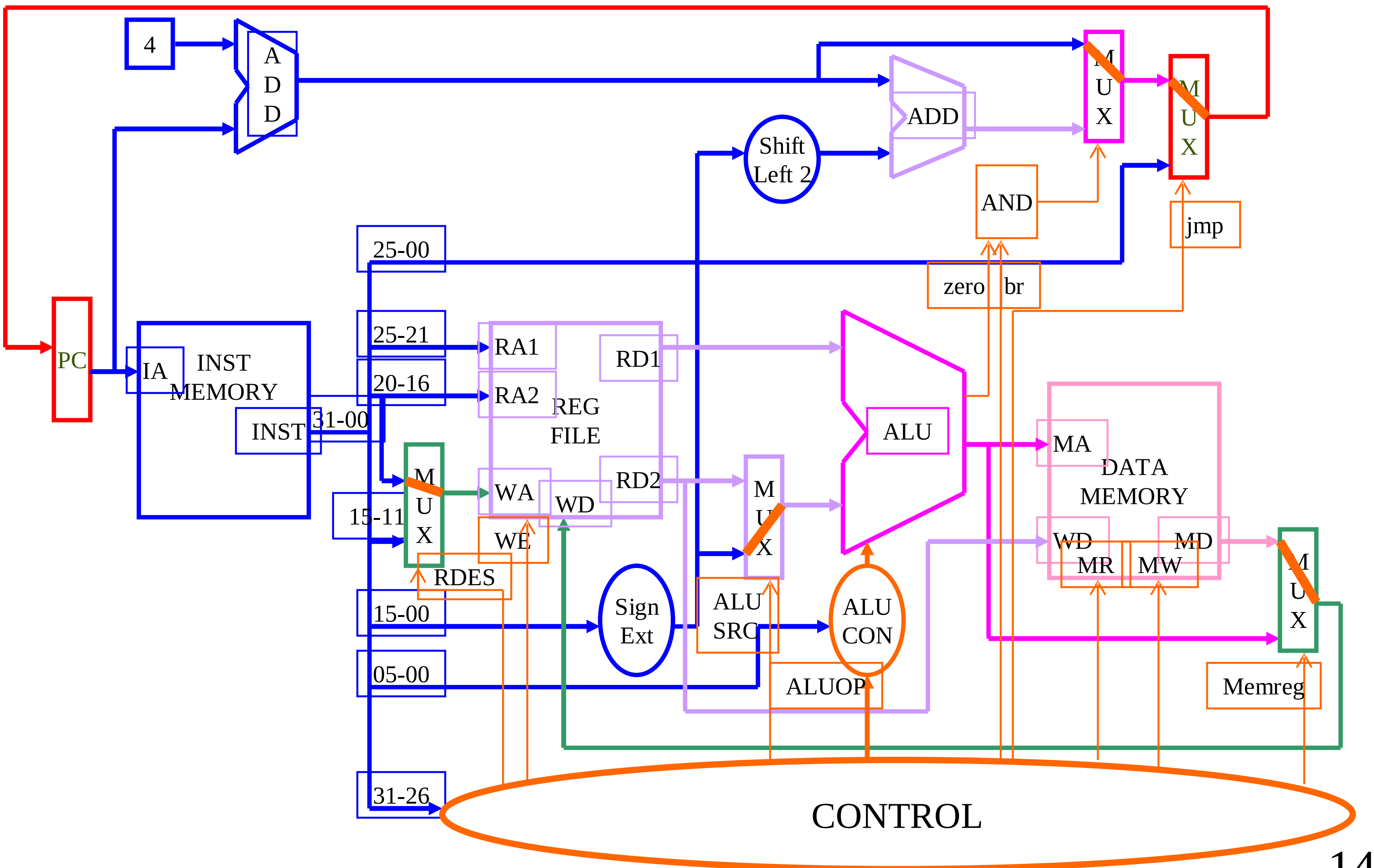


We are ignoring some details like setup and hold times

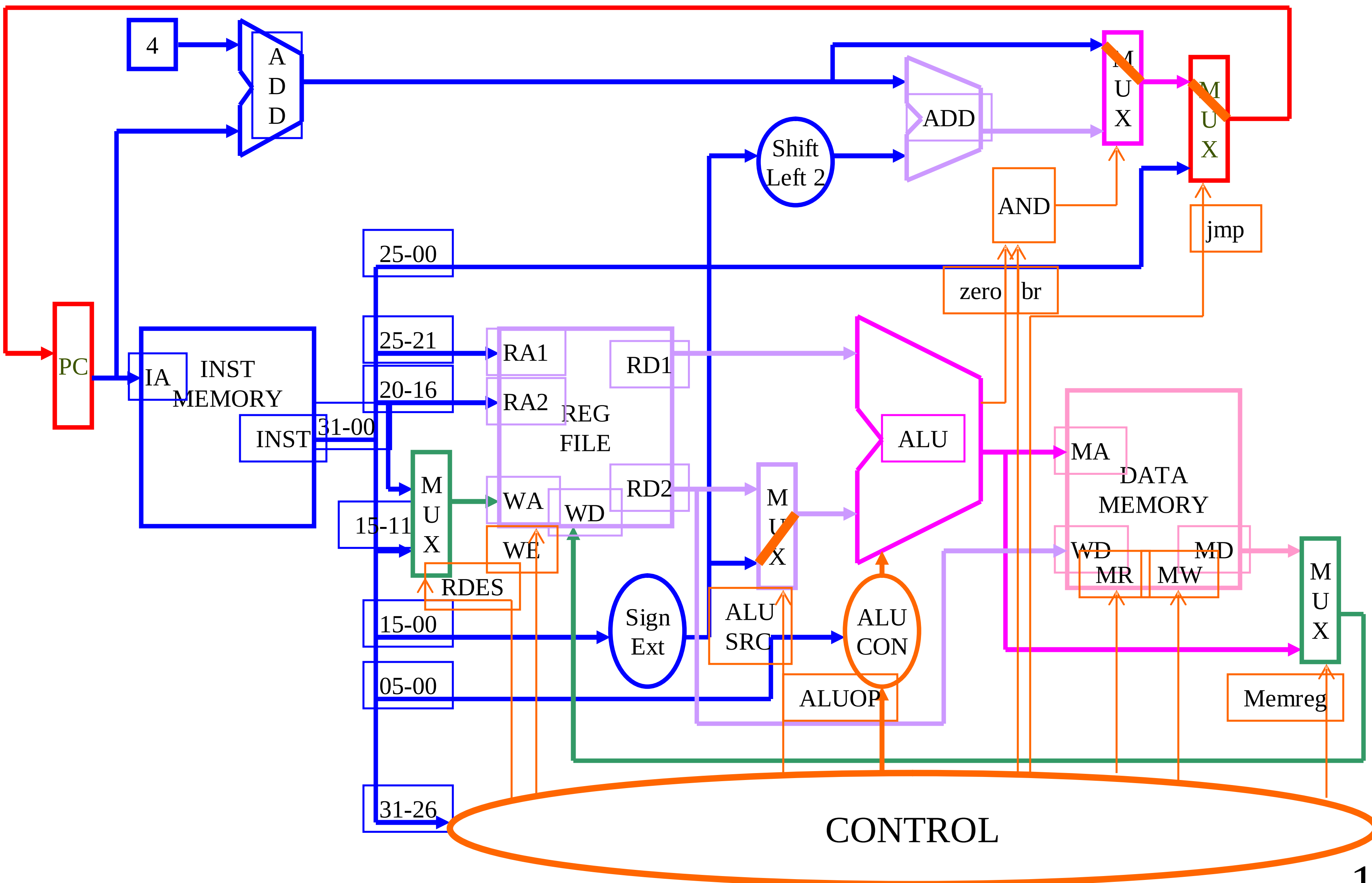
Control Points



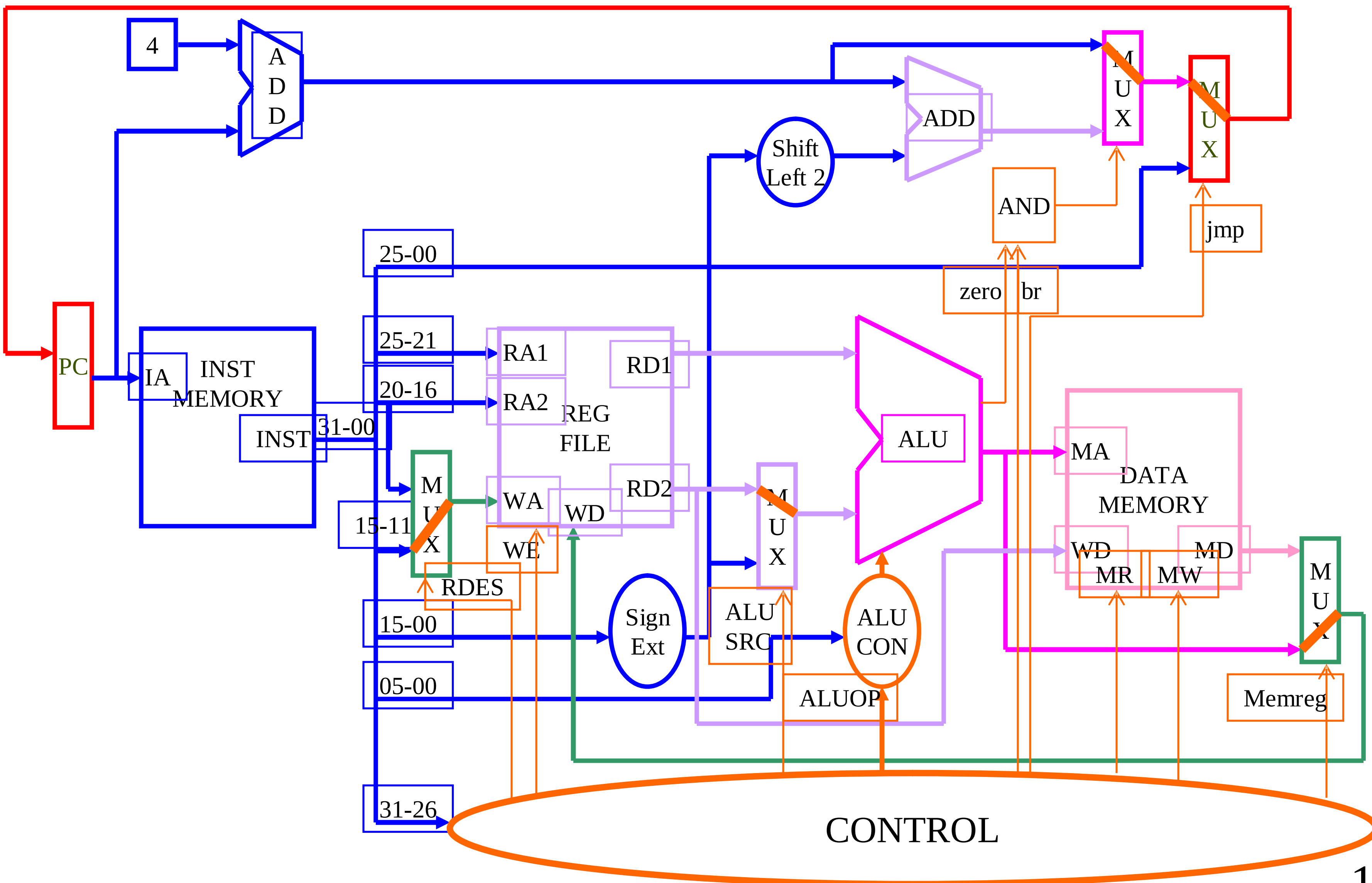
LW Instruction Operation



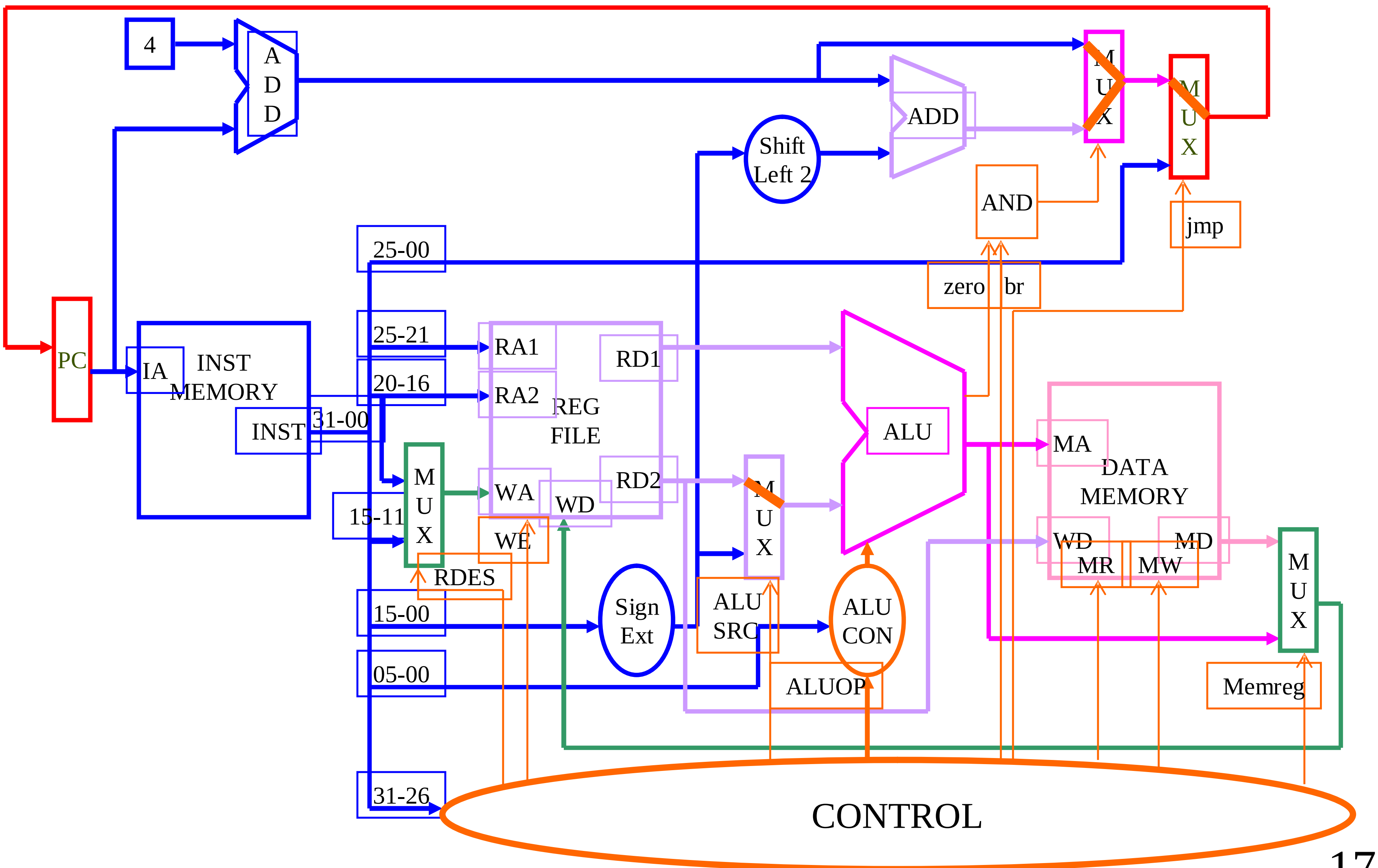
SW Instruction Operation



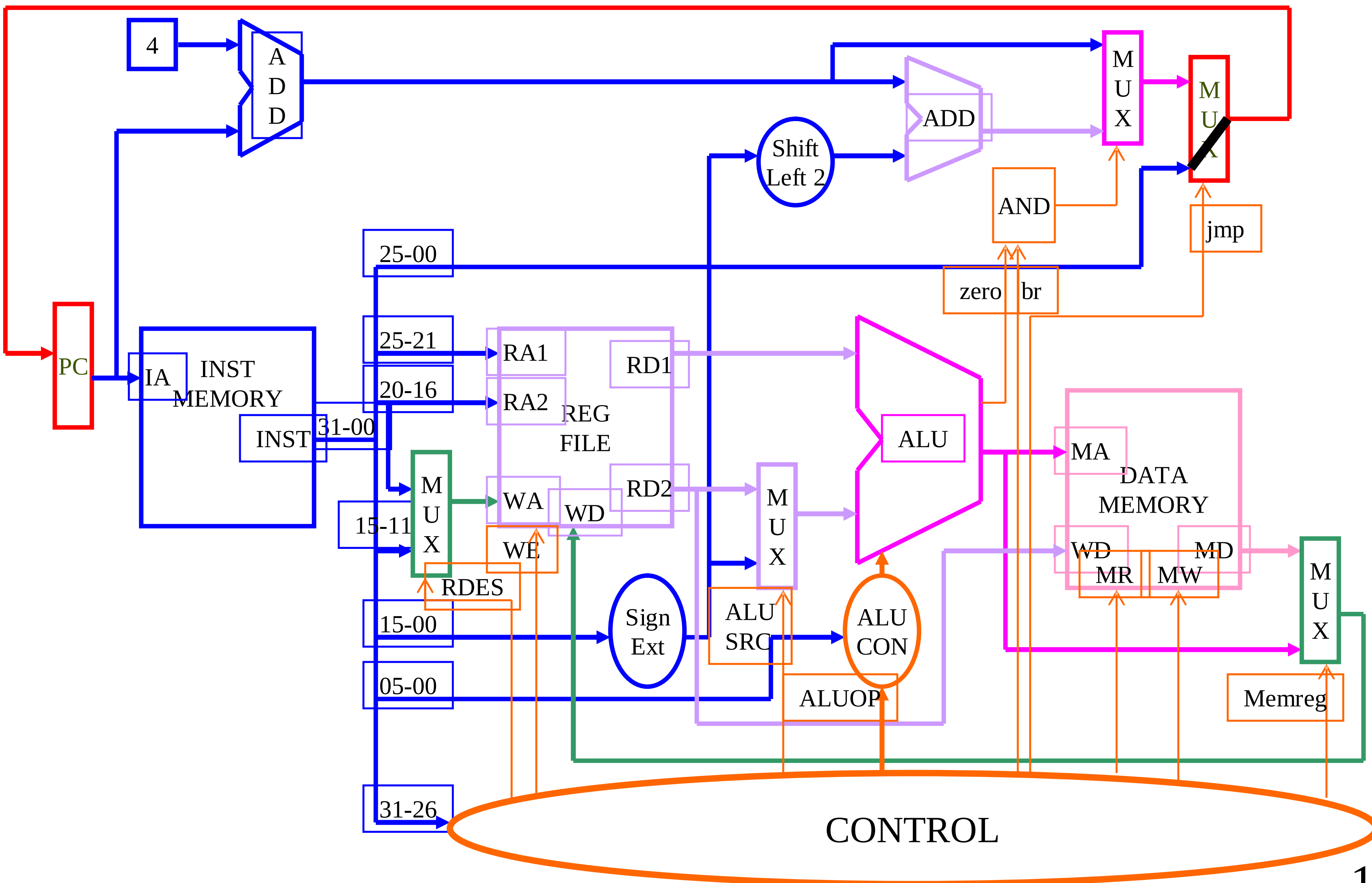
R-Type Instruction Operation



BR-Instruction Operation



Jump Instruction Operation



Control

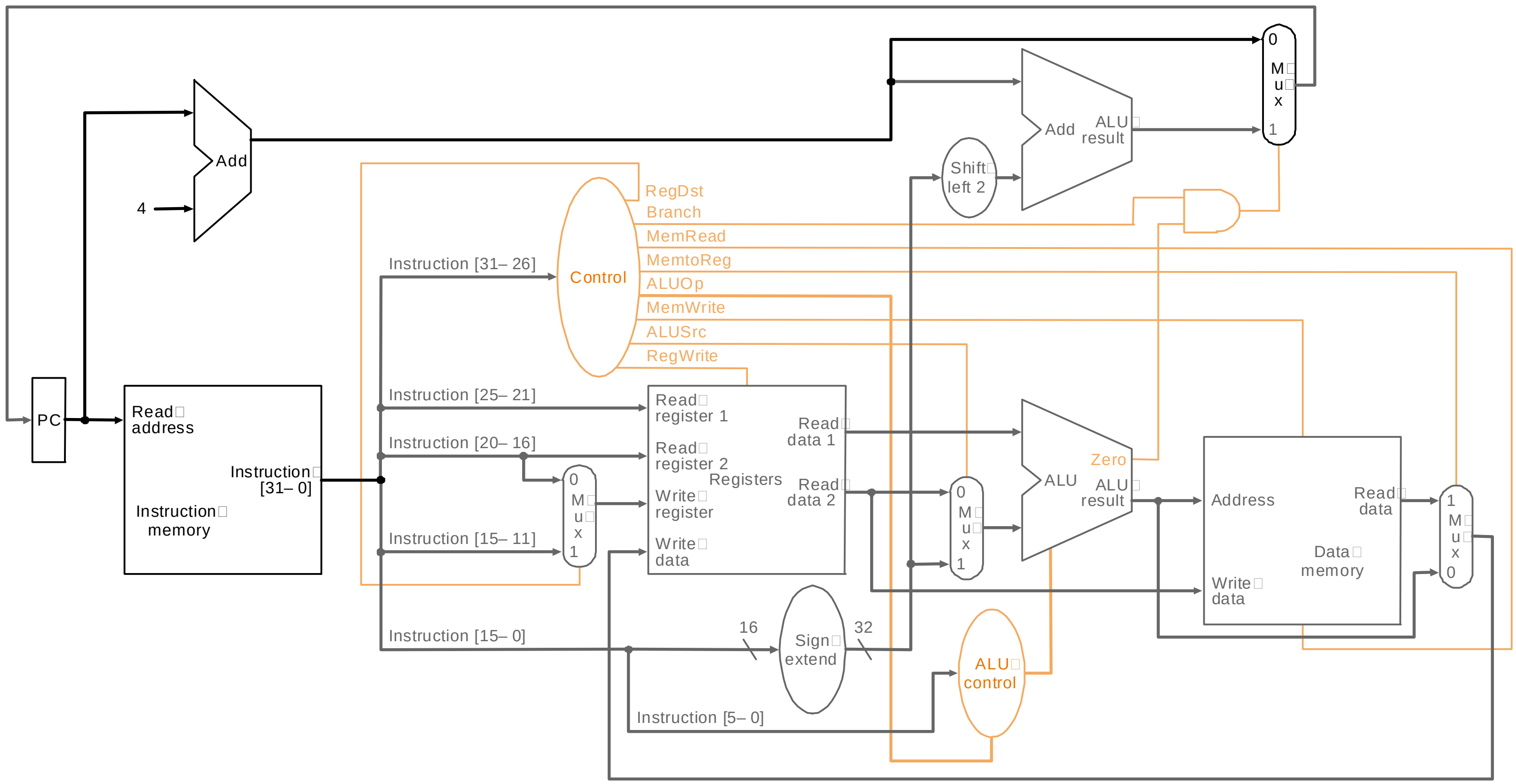
- For each instruction
  - Select the registers to be read (always read two)
  - Select the 2nd ALU input
  - Select the operation to be performed by ALU
  - Select if data memory is to be read or written
  - Select what is written and where in the register file
  - Select what goes in PC
- Information comes from the 32 bits of the instruction
- Example:

add $8, $17, $18   Instruction Format:

000000	10001	10010	01000	00000	100000

op	rs	rt	rd	shamt	funct

Adding Control to DataPath



Instruction	RegDst	ALUSrc	Memto-Reg	Reg Write	Mem Read	Mem Write	Branch	ALUOp1	ALUp0
R-format	1	0	0	1	0	0	0	1	0
`lw`	0	1	1	1	1	0	0	0	0
`sw`	X	1	X	0	0	1	0	0	0
`beq`	X	0	X	0	0	0	1	0	1

ALU Control

- ALU's operation based on instruction type and function code
  - e.g., what should the ALU do with any instruction
- Example: lw $1, 100($2)
-

35	2	1	100

op	rs	rt	16 bit offset

- ALU control input

```
000     AND
001     OR
010     add
110     subtract
111     set-on-less-than
```

- Why is the code for subtract 110 and not 011?

Other Control Information

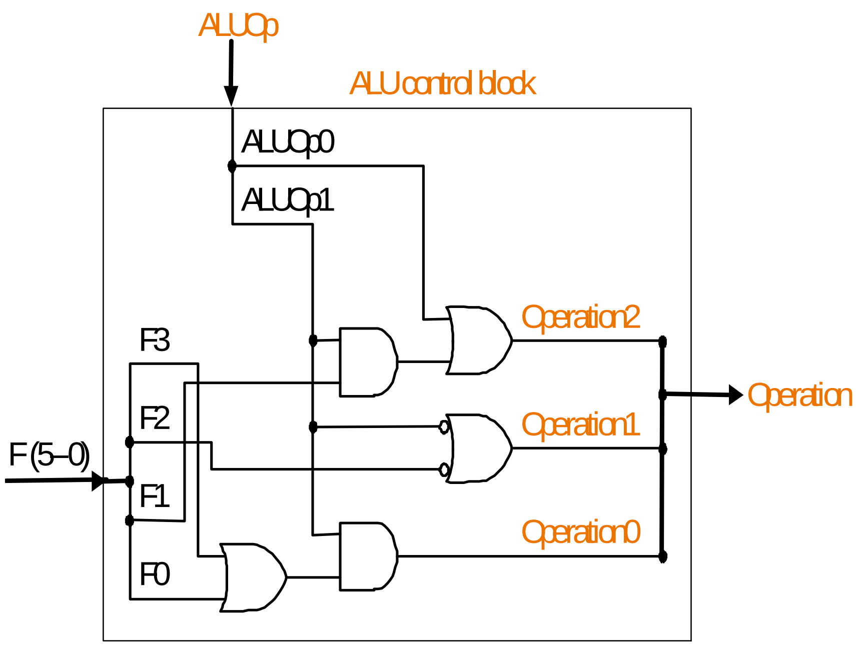
- Must describe hardware to compute 3-bit ALU conrol input
  - given instruction type
    - 00 = lw, sw
    - 01 = beq,
    - 10 = arithmetic
    - 11 = Jump

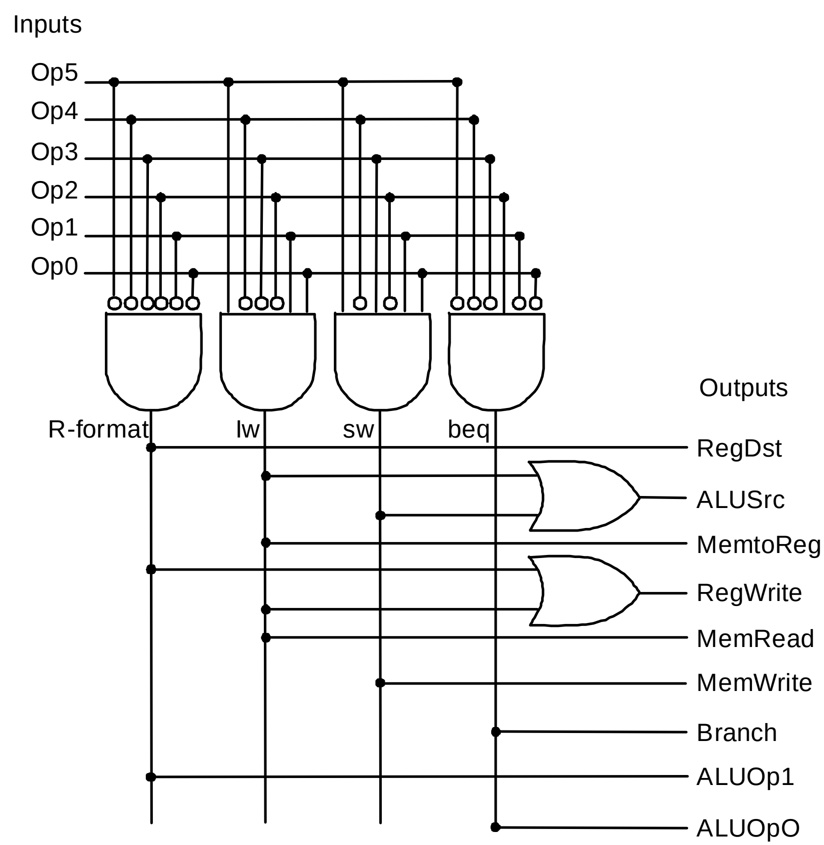
    ALUOp computed from instruction type
  - function code for arithmetic
- Control can be described using a truth table:

ALUOp		Funct field						Operation
ALUOp1	ALUOp0	F5	F4	F3	F2	F1	F0	
0	0	X	X	X	X	X	X	010
X	1	X	X	X	X	X	X	110
1	X	X	X	0	0	0	0	010
1	X	X	X	0	0	1	0	110
1	X	X	X	0	1	0	0	000
1	X	X	X	0	1	0	1	001
1	X	X	X	1	0	1	0	111

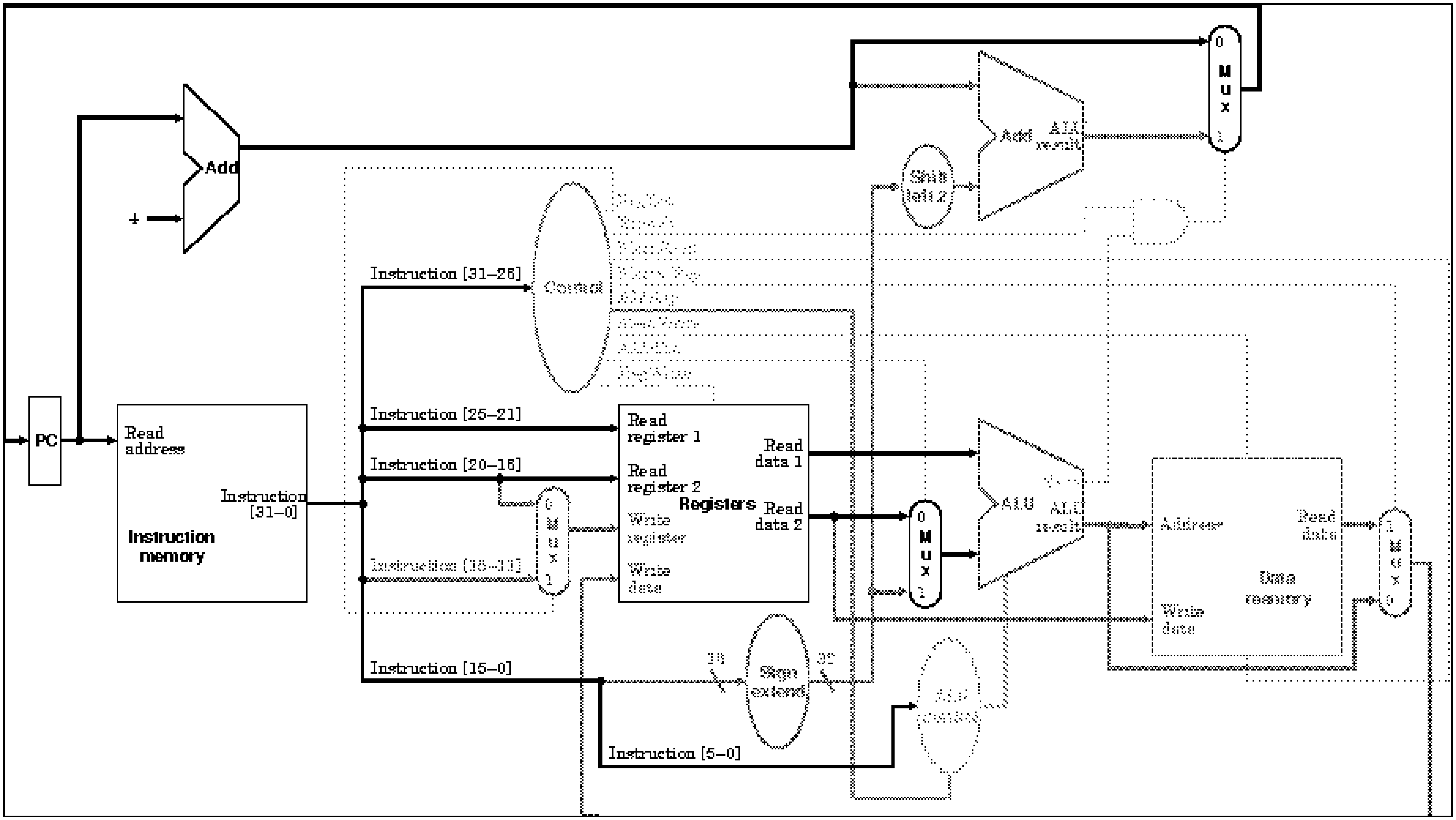
Implementation of Control

- **Simple combinational logic to realize the truth tables**

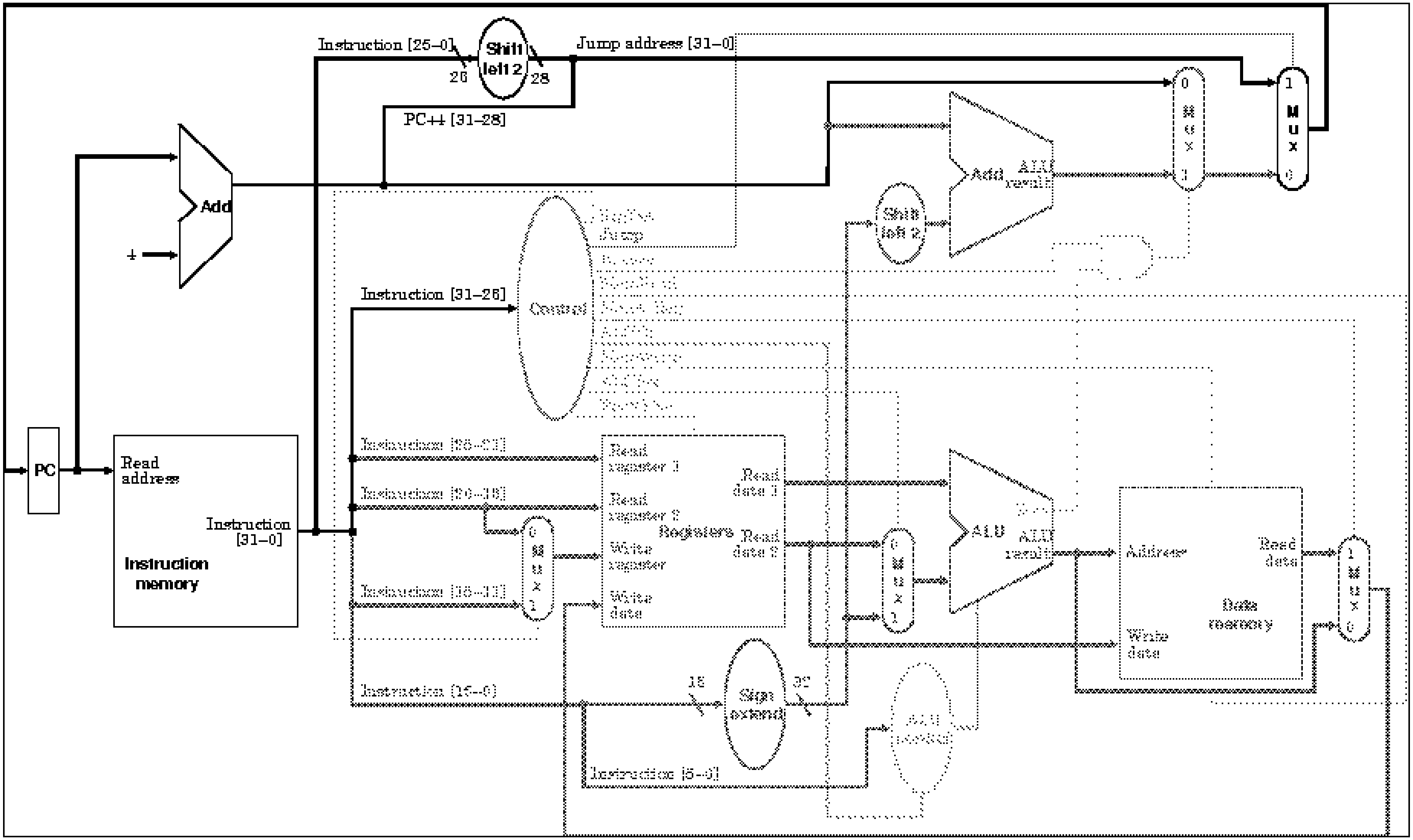




A Complete Datapath with Control

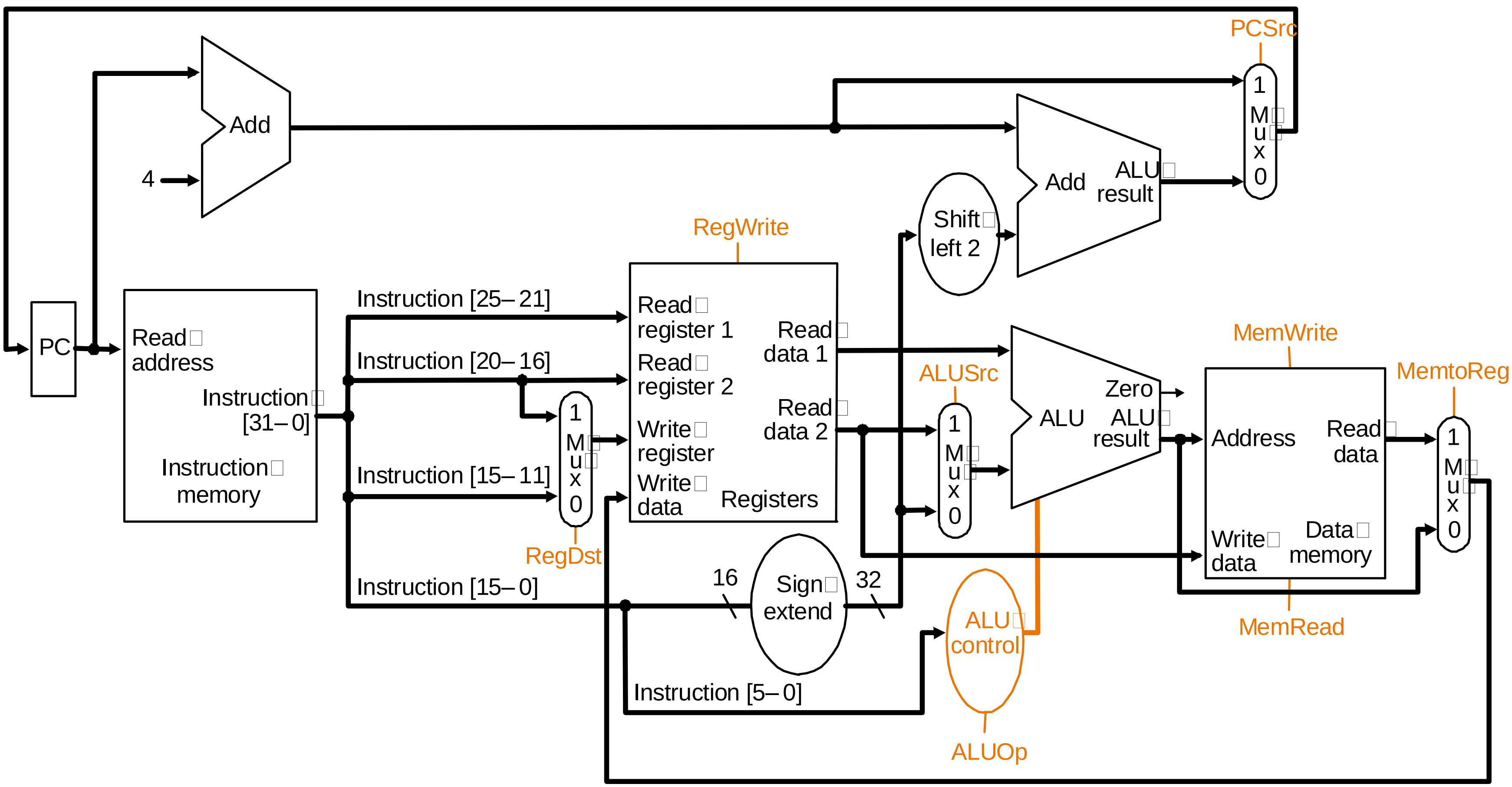


Datapath with Control and Jump Instruction



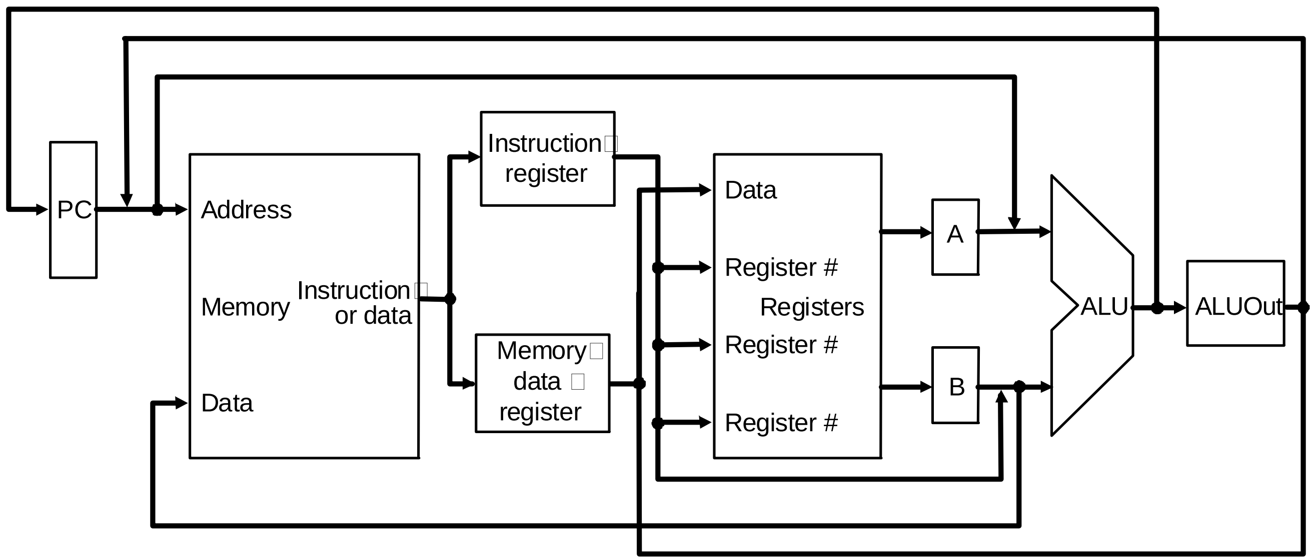
Timing: Single Cycle Implementation

- **Calculate cycle time assuming negligible delays except:**
  - **memory (2ns), ALU and adders (2ns), register file access (1ns)**



Where we are headed

- Design a data path for our machine specified in the next 3 slides
- Single Cycle Problems:
  - what if we had a more complicated instruction like floating point?
  - wasteful of area
- One Solution:
  - use a “smaller” cycle time and use different numbers of cycles for each instruction using a “multicycle” datapath:



Machine Specification

- 16-bit data path (can be 4, 8, 12, 16, 24, 32)
- 16-bit instruction (can be any number of them)
- 16-bit PC (can be 16, 24, 32 bits)
- 16 registers (can be 1, 4, 8, 16, 32)
- With m register, log m bits for each register
- Offset depends on expected offset from registers
- Branch offset depends on expected jump address
- Many compromise are made based on number of bits in instruction

Instruction

- LW R2, #v(R1) ; Load memory from address (R1) + v
- SW R2, #v(R1) ; Store memory to address (R1) + v
- R-Type – OPER R3, R2, R1 ; Perform R3 ß R2 OP R1
  - Five operations ADD, AND, OR, SLT, SUB
- I-Type – OPER R2, R1, V ; Perform R2 ß R1 OP V
  - Four operation ADDI, ANDI, ORI, SLTI
- B-Type – BC R2, R1, V; Branch if condition met to address PC+V
  - Two operation BNE, BEQ
- Shift class – SHIFT TYPE R2, R1 ; Shift R1 of type and result to R2
  - One operation
- Jump Class -- JAL and JR (JAL can be used for Jump)
  - What are th implications of J vs JAL
  - Two instructions

Instruction bits needed

- LW/SW/BC – Requires opcode, R2, R1, and V values
- R-Type – Requires opcode, R3, R2, and R1 values
- I-Type – Requires opcode, R2, R1, and V values
- Shift class – Requires opcode, R2, R1, and shift type value
- JAL requires opcode and jump address
- JR requires opcode and register address
- Opcode – can be fixed number or variable number of bits
- Register address – 4 bits if 16 registers
- How many bits in V?
- How many bits in shift type?
  - 4 for 16 types, assume one bit shift at a time
- How many bits in jump address?

Performance

- **Measure, Report, and Summarize**
- **Make intelligent choices**
- **See through the marketing hype**
- **Key to understanding underlying organizational motivation**

Why is some hardware better than others for different programs?

What factors of system performance are hardware related?
(e.g., Do we need a new machine, or a new operating system?)

How does the machine's instruction set affect performance?

Which of these airplanes has the best performance?

Airplane	Passengers	Range (mi)	Speed (mph)
Boeing 737-100	101	630	598
Boeing 747	470	4150	610
BAC/Sud Concorde	132	4000	1350
Douglas DC-8-50	146	8720	544

- **How much faster is the Concorde compared to the 747?**
- **How much bigger is the 747 than the Douglas DC-8?**

Computer Performance: TIME, TIME, TIME

- **Response Time (latency)**
  - **— How long does it take for my job to run?**
  - **— How long does it take to execute a job?**
  - **— How long must I wait for the database query?**
- **Throughput**
  - **— How many jobs can the machine run at once?**
  - **— What is the average execution rate?**
  - **— How much work is getting done?**

- ***If we upgrade a machine with a new processor what do we increase?***

If we add a new machine to the lab what do we increase?

Execution Time

- **Elapsed Time**
  - **counts everything** ***(disk and memory accesses, I/O , etc.)***
  - **a useful number, but often not good for comparison purposes**
- **CPU time**
  - **doesn't count I/O or time spent running other programs**
  - **can be broken up into system time, and user time**

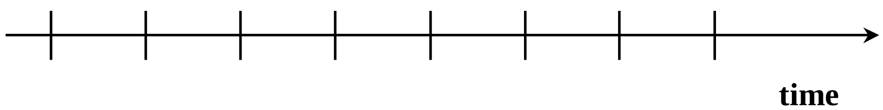
- **Our focus: user CPU time**
  - **time spent executing the lines of code that are "in" our program**

Clock Cycles

- **Instead of reporting execution time in seconds, we often use cycles**

$$\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}$$

- **Clock "ticks" indicate when to start activities (one abstraction):**



- **cycle time = time between ticks = seconds per cycle**
- **clock rate (frequency) = cycles per second (1 Hz. = 1 cycle/sec)**

A 200 Mhz. clock has a $\frac{1}{200 \times 10^6} \times 10^9 = 5 \text{ nanoseconds}$ **cycle time**

How to Improve Performance

$$\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}$$

So, to improve performance (everything else being equal) you can either

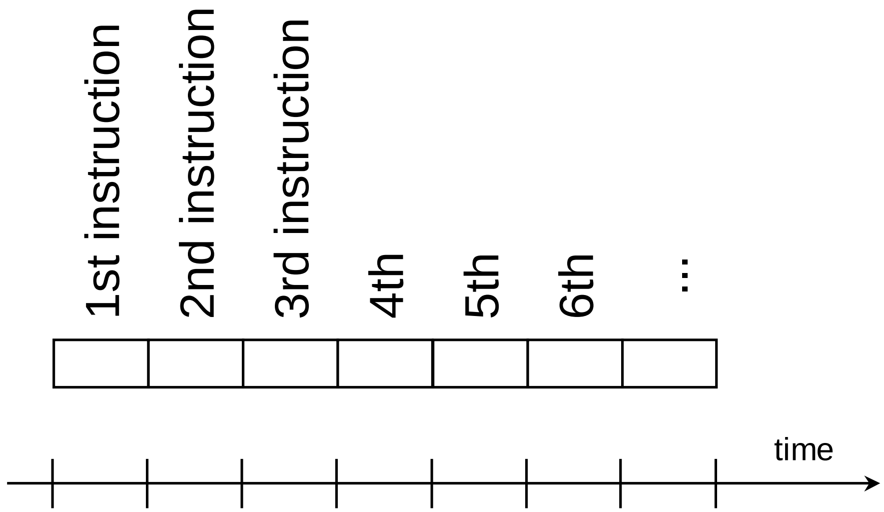
________ the # of required cycles for a program, or

________ the clock cycle time or, said another way,

________ the clock rate.

How many cycles are required for a program?

- **Could assume that # of cycles = # of instructions**

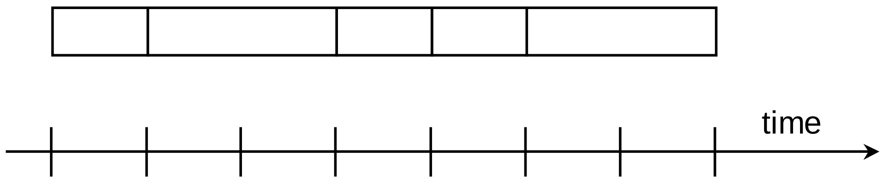


This assumption is incorrect,

different instructions take different amounts of time on different machines.

Why? hint: remember that these are machine instructions, not lines of C code

Different numbers of cycles for different instructions



- **Multiplication takes more time than addition**
- **Floating point operations take longer than integer ones**
- **Accessing memory takes more time than accessing registers**

- ***Important point: changing the cycle time often changes the number of cycles required for various instructions (more later)***

Now that we understand cycles

- **A given program will require**
  - **some number of instructions (machine instructions)**
  - **some number of cycles**
  - **some number of seconds**
- **We have a vocabulary that relates these quantities:**
  - **cycle time (seconds per cycle)**
  - **clock rate (cycles per second)**
  - **CPI (cycles per instruction)**

    a floating point intensive application might have a higher CPI
  - **MIPS (millions of instructions per second)**

    this would be higher for a program using simple instructions

Performance

- **Performance is determined by execution time**
- **Do any of the other variables equal performance?**
  - **# of cycles to execute program?**
  - **# of instructions in program?**
  - **# of cycles per second?**
  - **average # of cycles per instruction?**
  - **average # of instructions per second?**

- **Common pitfall: thinking one of the variables is indicative of performance when it really isn't.**

of Instructions Example

- A compiler designer is trying to decide between two code sequences for a particular machine. Based on the hardware implementation, there are three different classes of instructions: Class A, Class B, and Class C, and they require one, two, and three cycles (respectively).

  The first code sequence has 5 instructions: 2 of A, 1 of B, and 2 of C
  The second sequence has 6 instructions: 4 of A, 1 of B, and 1 of C.

  Which sequence will be faster? How much?
  What is the CPI for each sequence?

MIPS example

- Two different compilers are being tested for a 100 MHz. machine with three different classes of instructions: Class A, Class B, and Class C, which require one, two, and three cycles (respectively). Both compilers are used to produce code for a large piece of software.

  The first compiler's code uses 5 million Class A instructions, 1 million Class B instructions, and 1 million Class C instructions.

  The second compiler's code uses 10 million Class A instructions, 1 million Class B instructions, and 1 million Class C instructions.

- Which sequence will be faster according to MIPS?
- Which sequence will be faster according to execution time?