

CENG 3420

Computer Organization & Design



Lecture 08: Datapath

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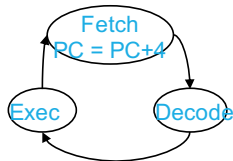
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(Textbook: Chapters 4.1 – 4.4)

2024 Spring



- We're ready to look at an implementation of RISC-V
- Simplified to contain only:
 - Memory-reference instructions: `lw`, `sw`
 - Arithmetic-logical instructions: `add`, `addu`, `sub`, `subu`, `and`, `or`, `xor`, `nor`, `slt`, `sltu`
 - Arithmetic-logical immediate instructions: `addi`, `addiu`, `andi`, `ori`, `xori`, `slti`, `sltiu`
 - Control flow instructions: `beq`, `j`
- Generic implementation:
 - Use the program counter (**PC**)
 - To supply the instruction address and fetch the instruction from memory (and update the PC)
 - Decode the instruction (and read registers)
 - Execute the instruction

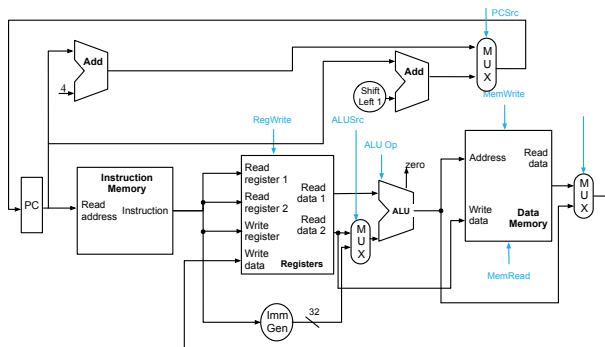




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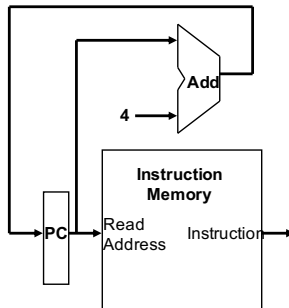
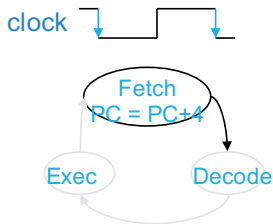
- **memory reference**: uses ALU to compute addresses
- **arithmetic**: uses the ALU to do the require arithmetic
- **control**: uses the ALU to compute branch conditions.

- Two types of functional units:
 - elements that operate on data values (**combinational**)
 - elements that contain state (**sequential**)

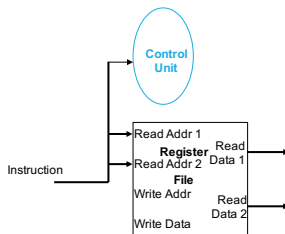
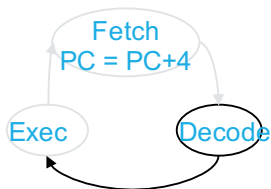


- Single cycle operation
- Split memory (Harvard) model - one memory for instructions and one for data

- 1 Reading the instruction from the Instruction Memory
- 2 Updating the PC value to be the address of the next (sequential) instruction
- 3 PC is updated every clock cycle, so it does not need an explicit write control signal
- 4 Instruction Memory is read every clock cycle, so it doesn't need an explicit read control signal



- 1 Sending the fetched instruction's opcode and function field bits to the control unit
- 2 Reading two values from the Register File
- 3 (Register File addresses are contained in the instruction)





- Both RegFile read ports are active for all instructions during the Decode cycle
- Using the `rs1` and `rs2` instruction field addresses
- Since haven't decoded the instruction yet, don't know what the instruction is
- Just in case the instruction uses values from the RegFile do “work ahead” by reading the two source operands



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Question

Which instructions do make use of the RegFile values?



EX-1

All instructions (except `j`) use the ALU after reading the registers. Please analyze memory-reference, arithmetic, and control flow instructions.



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- Memory reference use ALU to compute addresses:

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lw s1, 20 (s2)
```



EX-1

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- Memory reference use ALU to compute addresses:
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- Arithmetic use the ALU to do the require arithmetic:
`add s1, s2, s3 # (s1 = s2 + s3)`



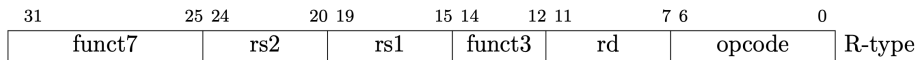
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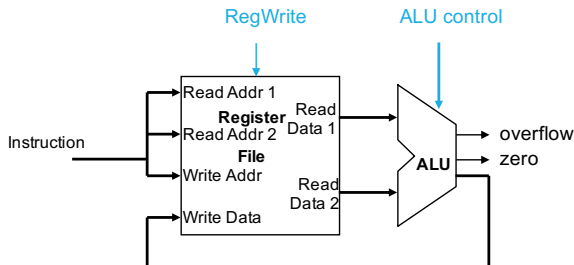
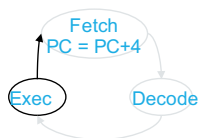
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`lw s1, 20 (s2)`
- Arithmetic use the ALU to do the require arithmetic:
`add s1, s2, s3 # (s1 = s2 + s3)`
- Control use the ALU to compute branch conditions:
`beq s1, s2, 25`



R format operations: `add`, `sub`, `sll`, `slt`, `xor`, `srl`, `sra`, `or`, and



- Perform operation (op, funct3 or funct7) on values in rs1 and rs2
- Store the result back into the Register File (into location rd)
- Note that Register File is not written every cycle (e.g. `sw`), so we need an explicit write control signal for the Register File



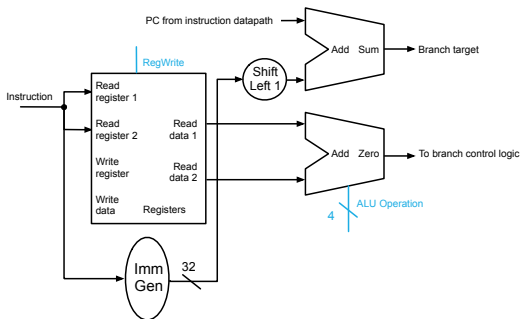
Consider the `slt` Instruction



- Remember the R format instruction `slt`

```
slt t0, s0, s1  # if    s0 < s1  
                  # then  t0 = 1  
                  # else  t0 = 0
```

- Where does the 1 (or 0) come from to store into `t0` in the Register File at the end of the execute cycle?





imm[11:0]	rs1	funct3	rd	opcode	I-type
-----------	-----	--------	----	--------	--------

imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode	S-type
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Load and store operations have to

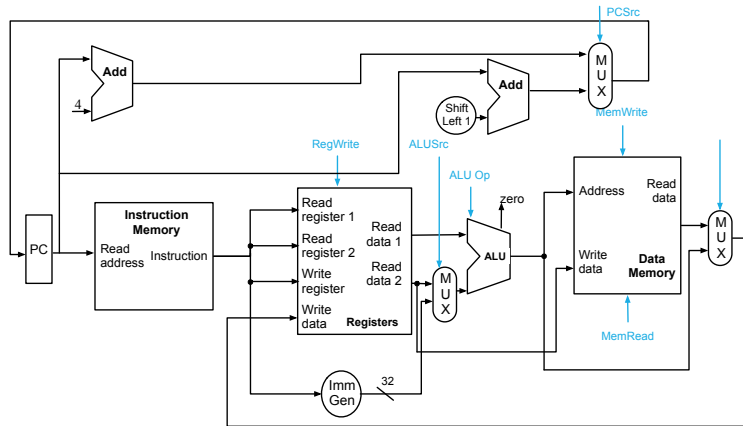
- **compute** a memory address by adding the base register (in `rs1`) to the **12-bit** signed offset field in the instruction
 - base register was read from the Register File during decode
 - offset value in the low order 12 bits of the instruction must be **sign extended** to create a **32-bit** signed value
- **store** value, read from the Register File during decode, must be written to the Data Memory
- **load** value, read from the Data Memory, must be stored in the Register File



Note:

- lw: I-type
- sw: S-type

Executing Load and Store Operations (cont.)





Note:

- ImmGen: signed extension from 12 bits to 32 bits



imm[12]	imm[10:5]	rs2	rs1	funct3	imm[4:1]	imm[11]	opcode	B-type
---------	-----------	-----	-----	--------	----------	---------	--------	--------

Branch operations have to

- compare the operands read from the Register File during decode (`rs1` and `rs2` values) for equality (zero ALU output)
- The 12-bit B-immediate encodes **signed offsets in multiples of one byte**.
- The 12-bit immediate offset is sign-extended and added to the address of the branch instruction to give the target address.

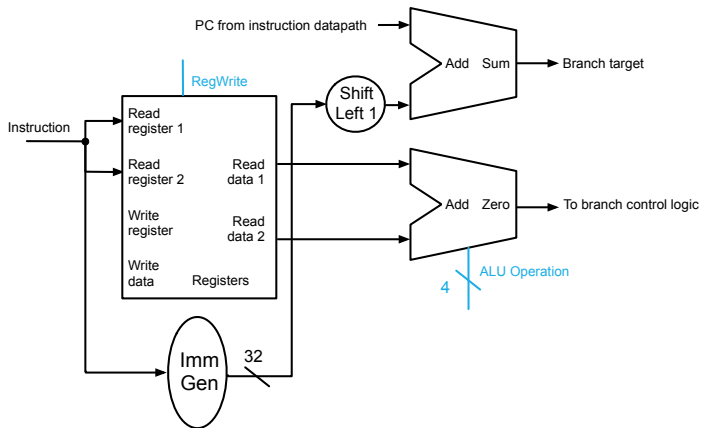


imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode	S-type
imm[12]	imm[10:5]	rs2	rs1	funct3	imm[4:1] imm[11]	opcode B-type

The only difference between S and B formats:

the 12-bit immediate field is used to encode branch offsets in multiples of 2 in the B format

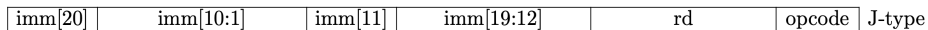
Executing Branch Operations (cont.)





Note:

- Textbook is about [RV64](#): 64-bit memory space
- Our course is about [RV32](#): 32-bit memory space
- RV32 is better suited to very low-cost processors
- Therefore, “Imm Gen” module outputs 32-bits.

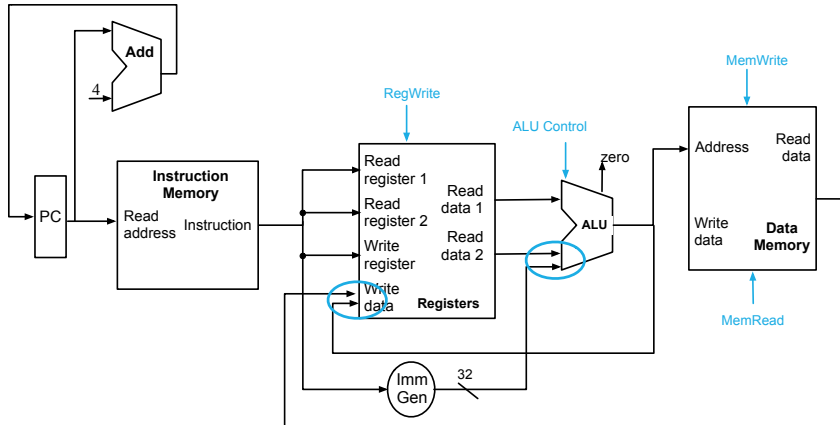


- jal
- The J-immediate encodes a signed offset in multiples of 2 bytes.
- The offset is sign-extended and added to the address of the jump instruction to form the jump target address.

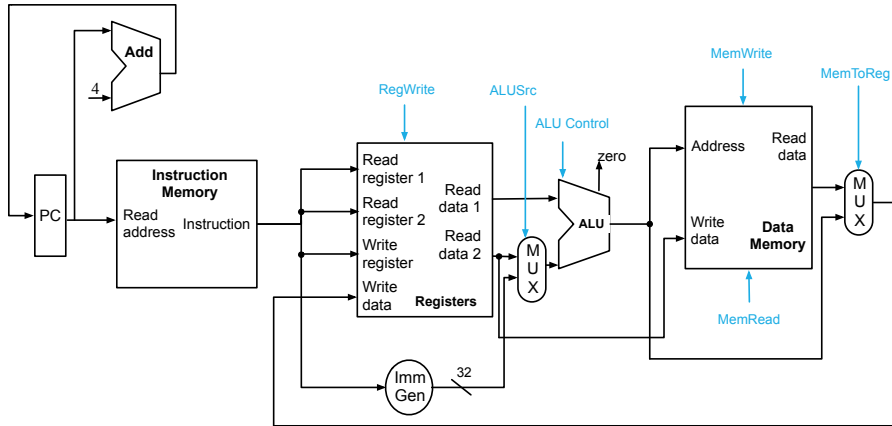


- Assemble the datapath elements, add control lines as needed, and design the control path
- Fetch, decode and execute each instruction in one clock cycle – **single cycle** design
 - **no** datapath resource can be used more than once per instruction, so some must be duplicated (e.g., why we have a separate Instruction Memory and Data Memory)
 - to share datapath elements between two different instruction classes will need **multiplexors** at the input of the shared elements with control lines to do the selection
- **Cycle** time is determined by length of the longest path

Multiplex Insertion



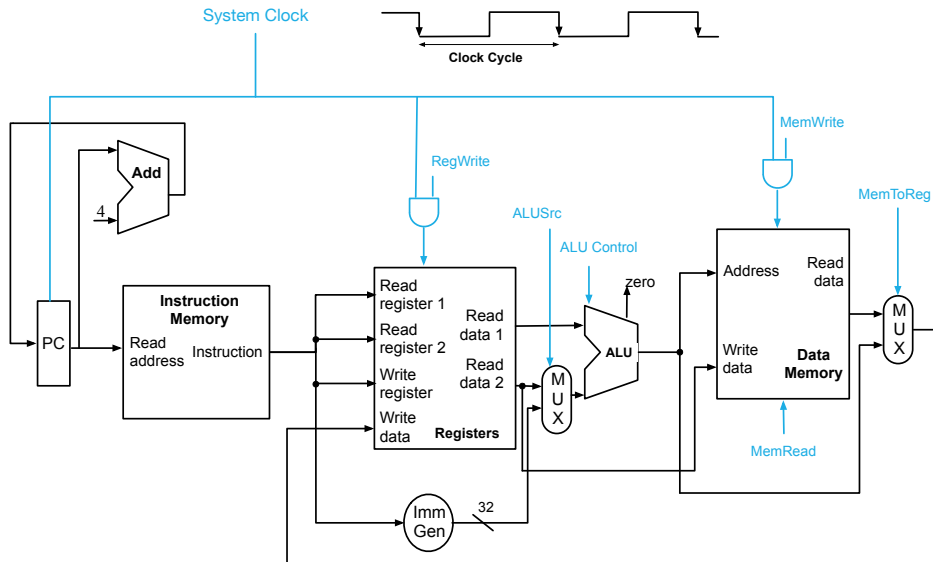
Multiplex Insertion





Note:

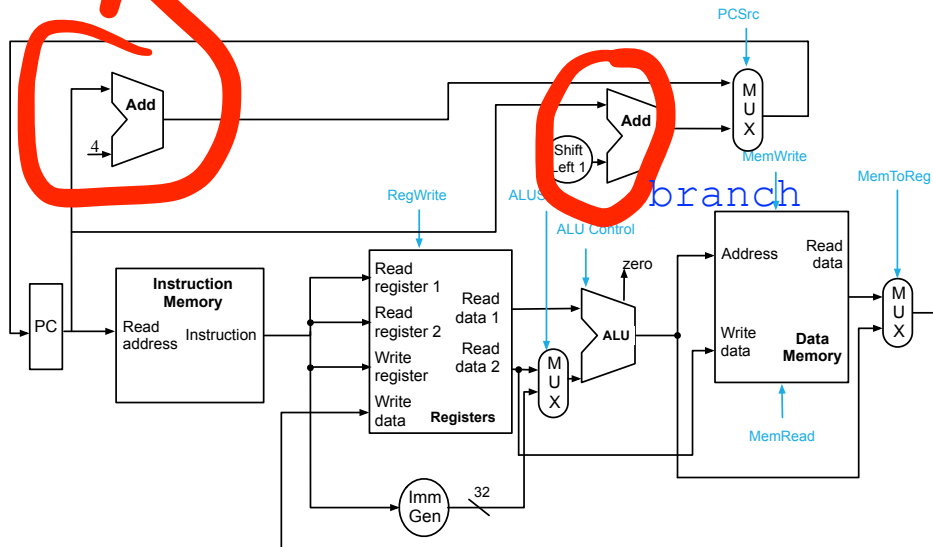
- ALUSrc: determine second ALU operand
- MemtoReg: whether feed memory data into register file



Adding the Branch Portion



By default, $PC += 4$





Note:

- `PCSrc`: The PC is replaced by the output of the adder that computes the branch target.



- We wait for everything to settle down
 - ALU might not produce "right answer" right away
 - Memory and RegFile reads are **combinational** (as are ALU, adders, muxes, shifter, signextender)
 - Use write signals along with the clock edge to determine when to write to the **sequential** elements (to the PC, to the Register File and to the Data Memory)
- The clock cycle time is determined by the logic delay through the **longest** path
- (We are ignoring some details like register setup and hold times)



Which operation involves a **sequential** logic?

- A: Read data memory
- B: Write data memory
- C: Compute $a+b$ in the ALU
- D: Set the overflow bit



Which operation involves a sequential logic?

- A: Read data memory
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Answer: B



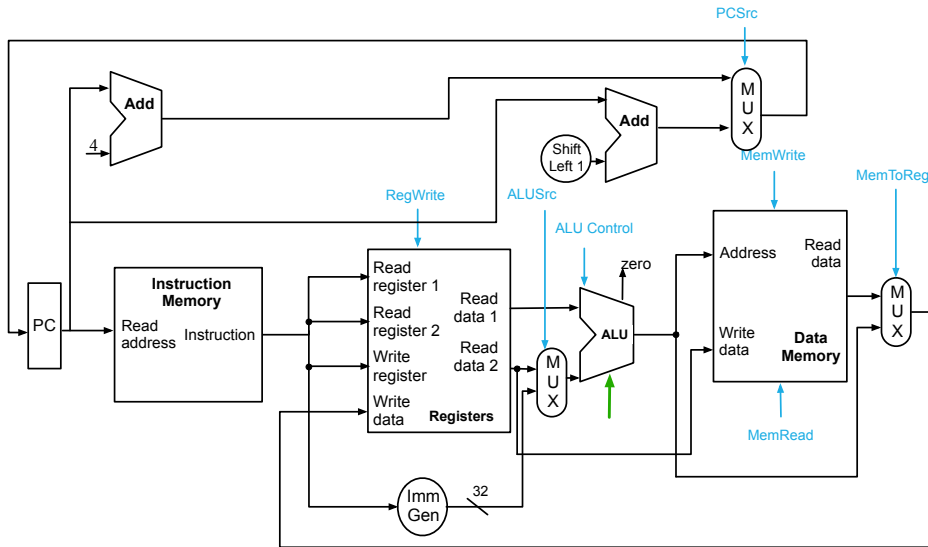
- Selecting the operations to perform (ALU, Register File and Memory read/write)
- Controlling the flow of data (multiplexor inputs)
- Information comes from the 32 bits of the instruction

31	25 24	20 19	15 14	12 11	7 6	0	
funct7		rs2	rs1	funct3	rd	opcode	R-type
imm[11:0]			rs1	funct3	rd	opcode	I-type

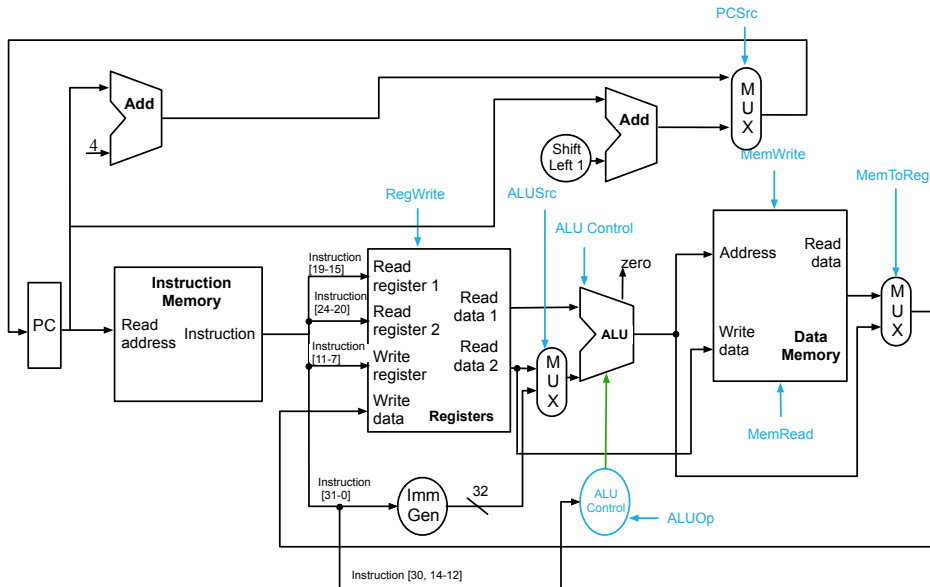
Observations:

- opcode field always in bits 6-0
- address of two registers to be read are **always** specified by the rs1 and rs2 fields (bits 19–15 and 24–20)
- **base register** for lw and sw always in rs1 (bits 19–15)

(Almost) Complete Single Cycle Datapath



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Which path decodes the instruction?

- A: PC => Add
- B: PC => Instruction Memory
- C: Instruction Memory => Registers
- D: Registers => ALU



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- D: Registers => ALU

Answer: C



ALU's operation based on instruction type and function code

ALU Control	Function
0000	and
0001	or
0010	add
0110	subtract



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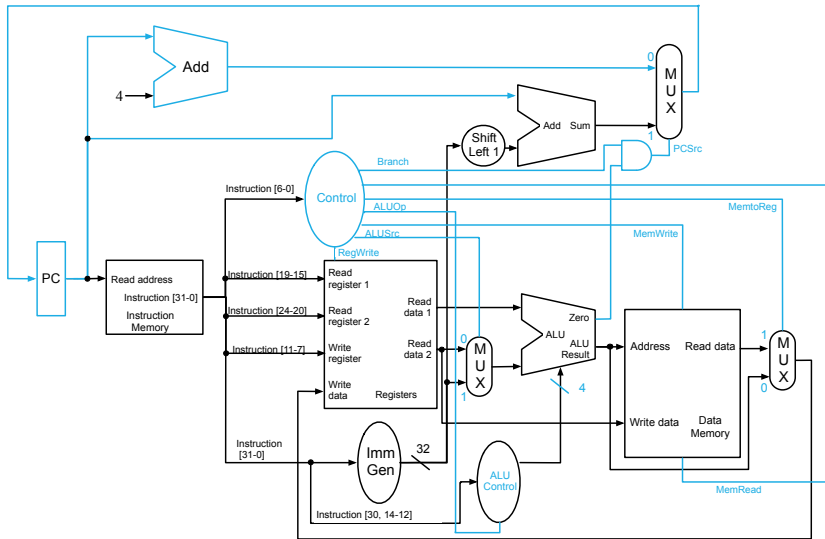


Controlling the ALU uses of multiple decoding levels

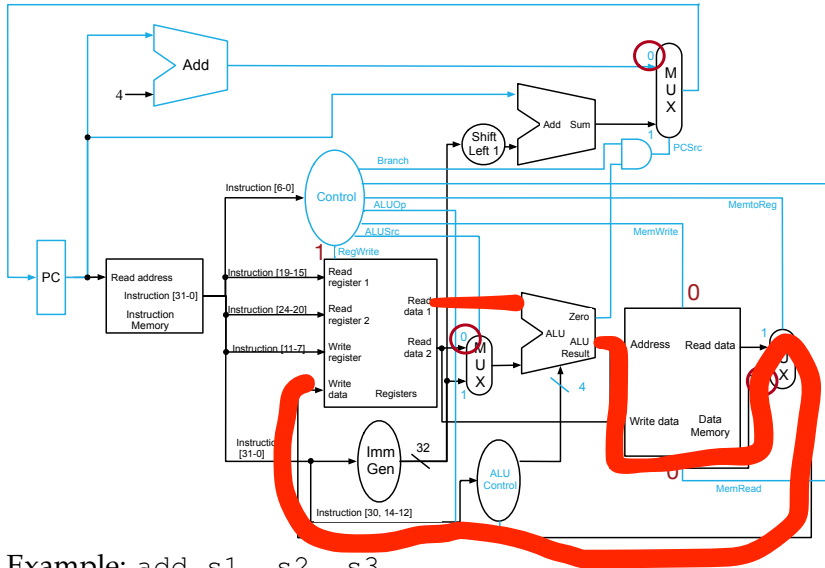
- main control unit generates the `ALUOp` bits
 - `ALUOp`: add (00), subtract (01), determined by `funct` field (10),
- ALU control unit generates `ALUcontrol` bits

Instruction	Function	ALUOp	funct7	funct3	ALUcontrol
lw	add	00	xxxxxxx	xxx	0010
sw	add	00	xxxxxxx	xxx	0010
beq	subtract	01	xxxxxxx	xxx	0110
add	add	10	0000000	000	0010
sub	subtract	10	0100000	000	0110
and	and	10	0000000	111	0000
or	or	10	0000000	110	0001

(Almost) Complete Datapath with Control Unit

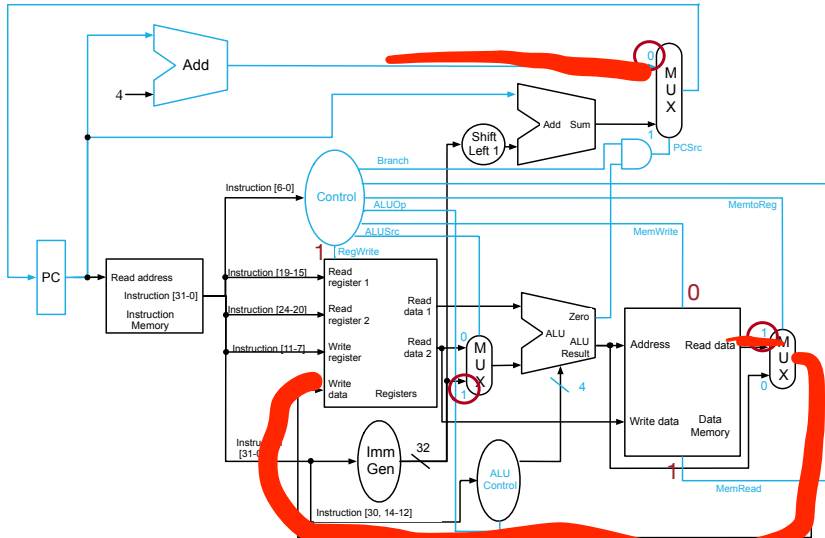


(Almost) Complete Datapath with Control Unit



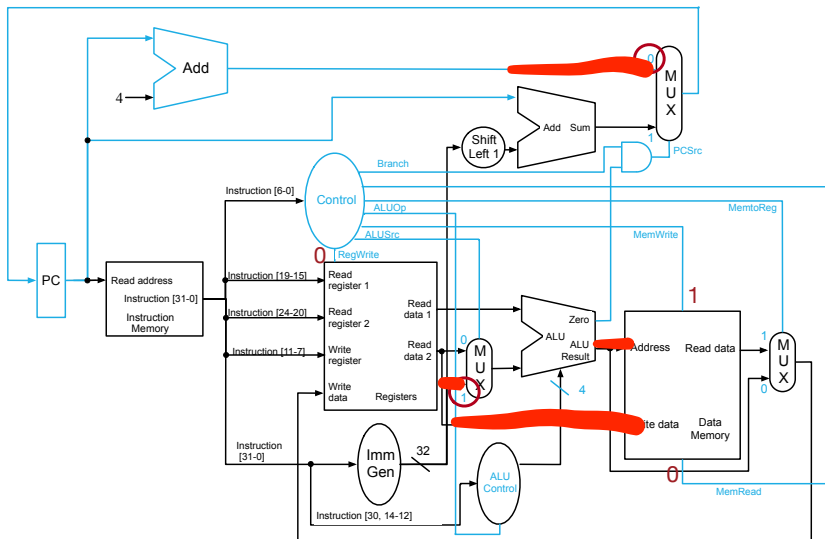
Example: `add s1, s2, s3`

(Almost) Complete Datapath with Control Unit



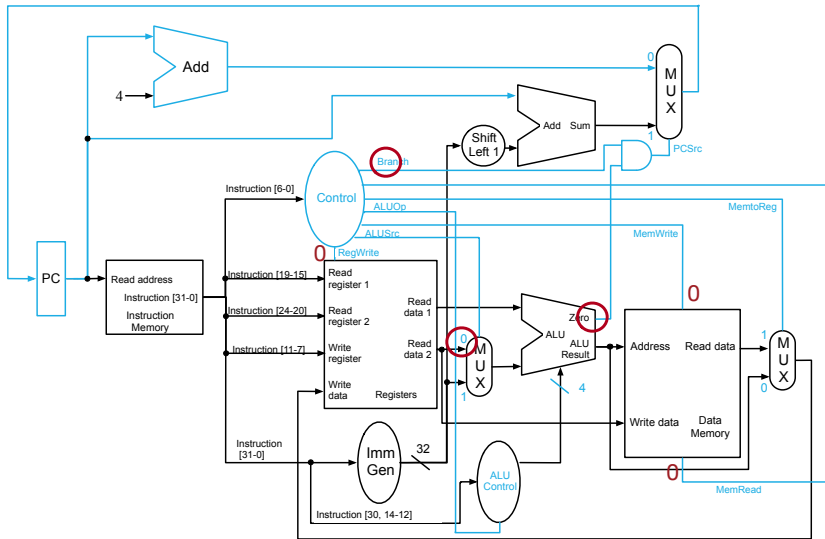
Example: `lw s1, 2(s2)`

(Almost) Complete Datapath with Control Unit



Example: `sw s1, 2(s2)`

(Almost) Complete Datapath with Control Unit





Which instruction might the previous picture correspond to?

- ① add
- ② lw
- ③ sw
- ④ beq



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- ③ sw
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Answer: D (RegWrite=0, MemRead=0, MemWrite=0)