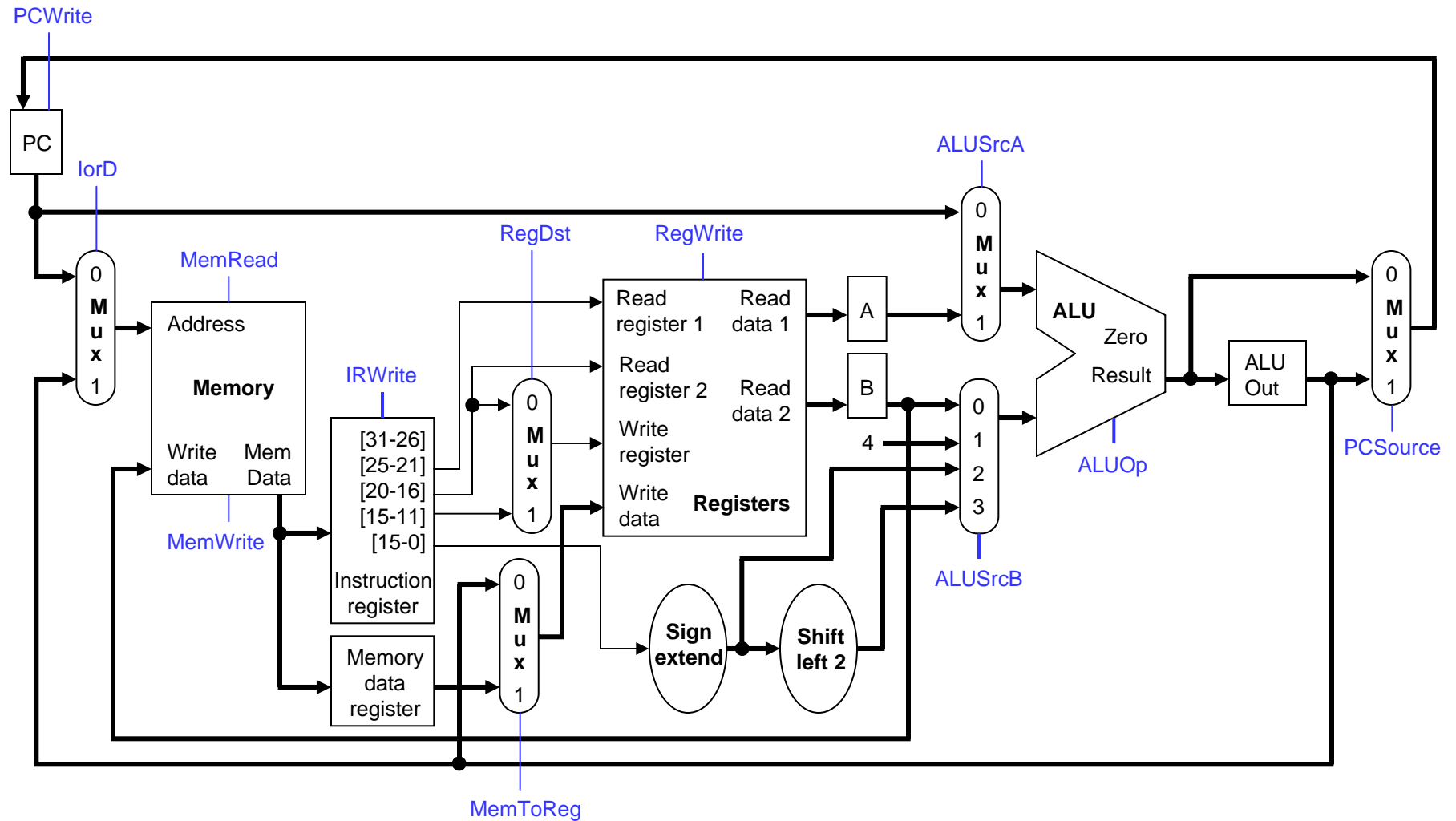


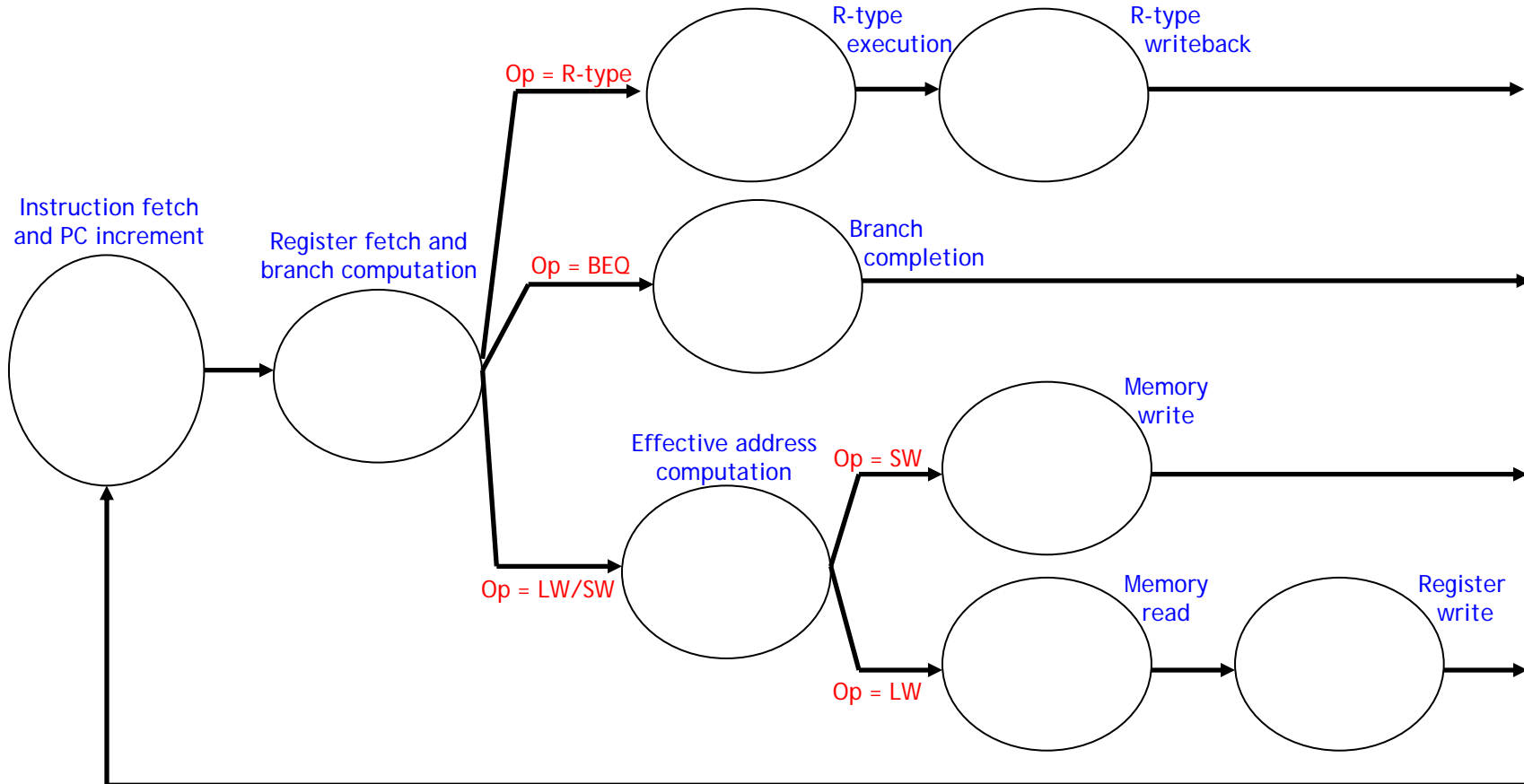
The multicycle datapath



Multicycle control unit

- ❑ The control unit is responsible for producing all of the control signals.
- ❑ Each instruction requires a *sequence* of control signals, generated over multiple clock cycles.
 - This implies that we need a **state machine**.
 - The datapath control signals will be **outputs** of the state machine.
- ❑ Different instructions require different sequences of steps.
 - This implies the instruction word is an **input** to the state machine.
 - The **next state** depends upon the exact instruction being executed.
- ❑ After we finish executing one instruction, we'll have to repeat the entire process again to execute the next instruction.

Finite-state machine for the control unit



□ Each bubble is a state

- Holds the control signals for a single cycle
- **Note:** All instructions do the same things during the first two cycles

Stage 1: Instruction Fetch

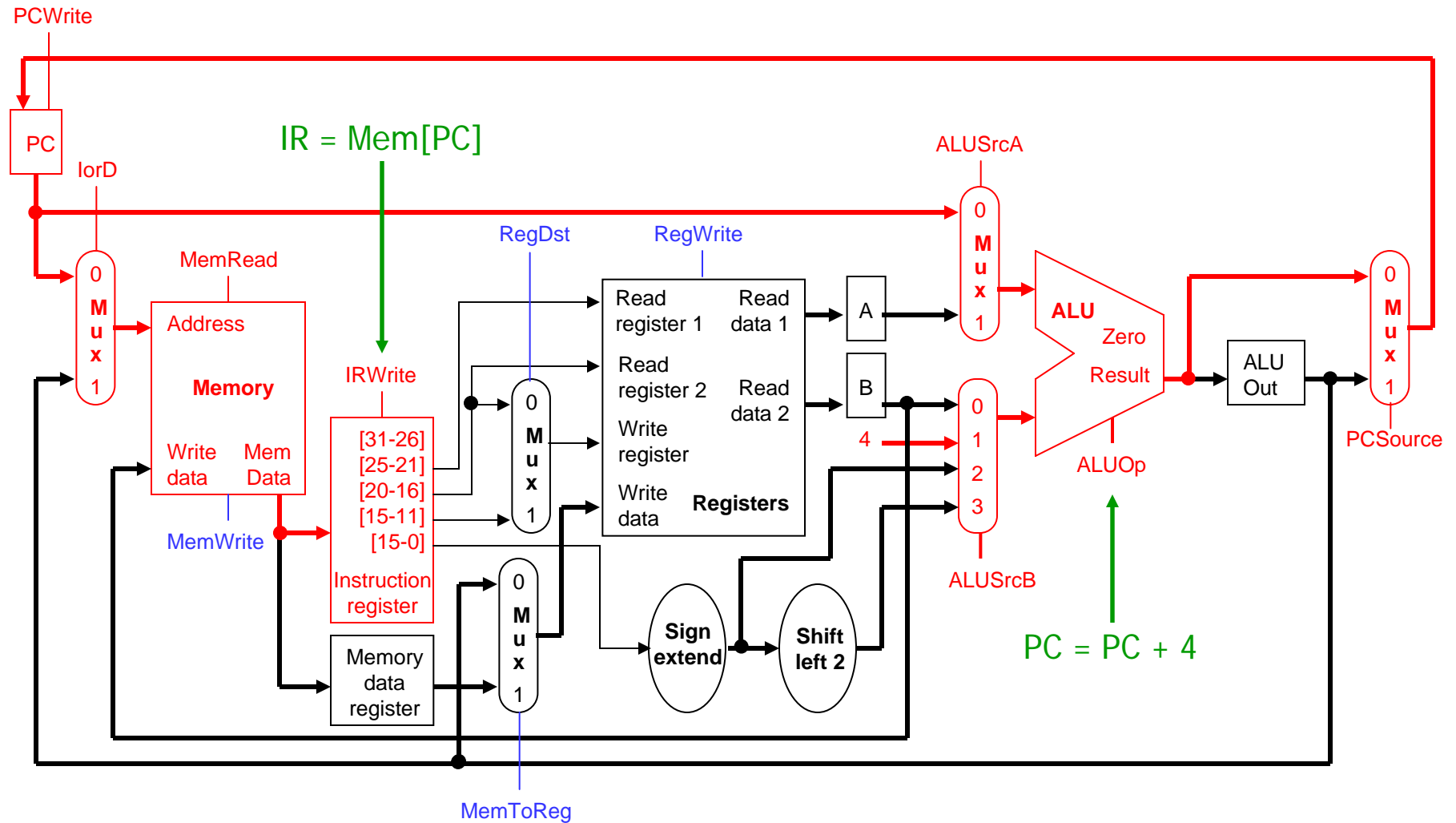
- **Stage 1** includes two actions which use two separate functional units: the memory and the ALU.
 - Fetch the instruction from memory and store it in IR.

$$\text{IR} = \text{Mem}[\text{PC}]$$

- Use the ALU to increment the PC by 4.

$$\text{PC} = \text{PC} + 4$$

Stage 1: Instruction fetch and PC increment



Stage 1 control signals

□ Instruction fetch: $IR = Mem[PC]$

Signal	Value	Description
MemRead	1	Read from memory
lrd	0	Use PC as the memory read address
IRWrite	1	Save memory contents to instruction register

□ Increment the PC: $PC = PC + 4$

Signal	Value	Description
ALUSrcA	0	Use PC as the first ALU operand
ALUSrcB	01	Use constant 4 as the second ALU operand
ALUOp	ADD	Perform addition
PCWrite	1	Change PC
PCSource	0	Update PC from the ALU output

□ We'll assume that all control signals not listed are implicitly set to 0.

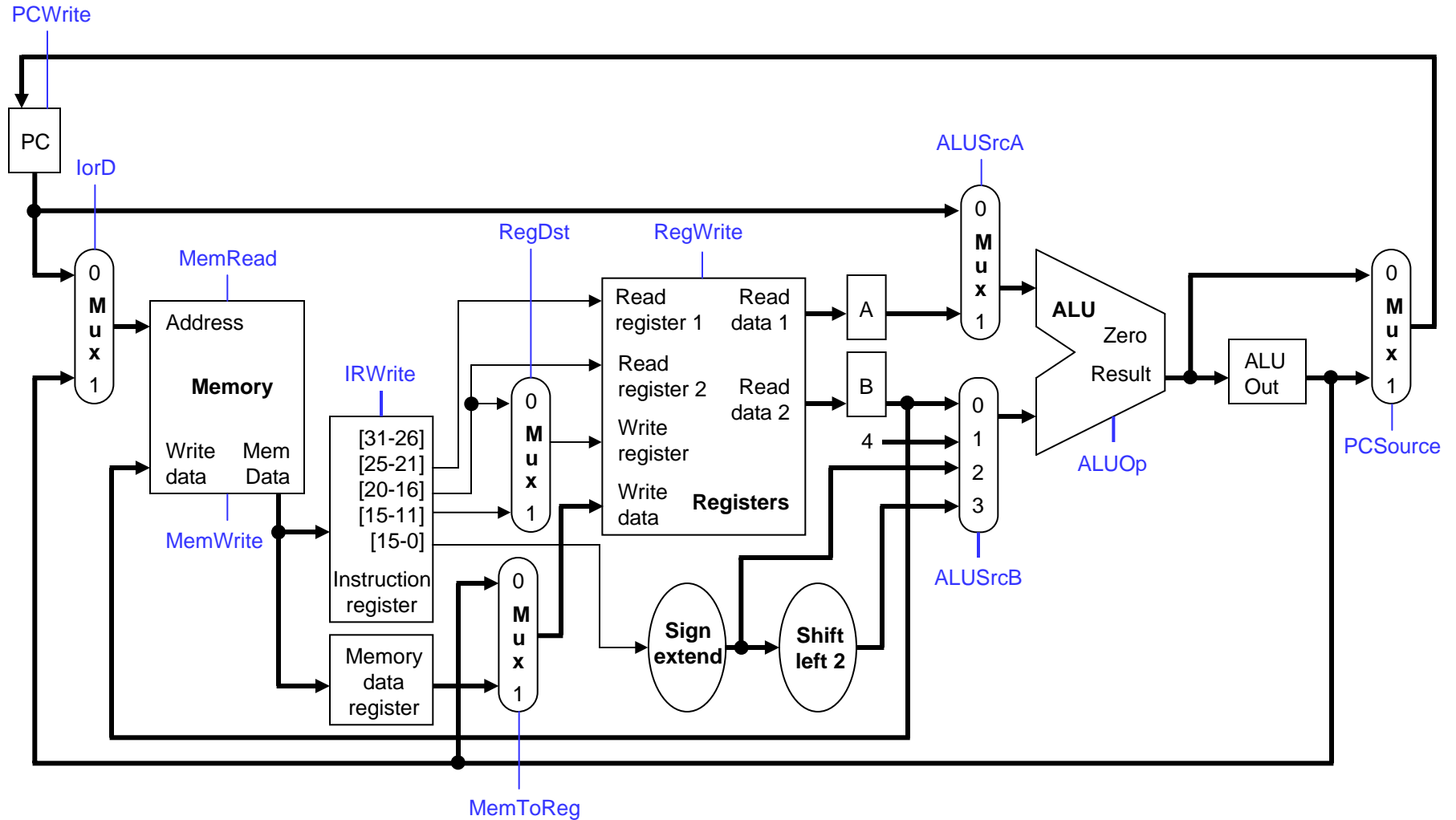
Stage 2: Read registers for non-branches

- **Stage 2 is much simpler.**
 - Read the contents of source registers *rs* and *rt*, and store them in the intermediate registers *A* and *B*. (Remember the *rs* and *rt* fields come from the instruction register *IR*.)

$A = \text{Reg}[\text{IR}[25-21]]$

$B = \text{Reg}[\text{IR}[20-16]]$

Stage 2: Register File Read



Stage 2 control signals

- **No control signals need to be set for the register reading operations $A = \text{Reg}[\text{IR}[25-21]]$ and $B = \text{Reg}[\text{IR}[20-16]]$.**
 - **IR[25-21] and IR[20-16] are already applied to the register file.**
 - **Registers A and B are already written on every clock cycle.**

Executing Arithmetic Instructions: Stages 3 & 4

- ❑ We'll start with R-type instructions like **add \$t1, \$t1, \$t2?**
- ❑ **Stage 3** for an arithmetic instruction is simply ALU computation.

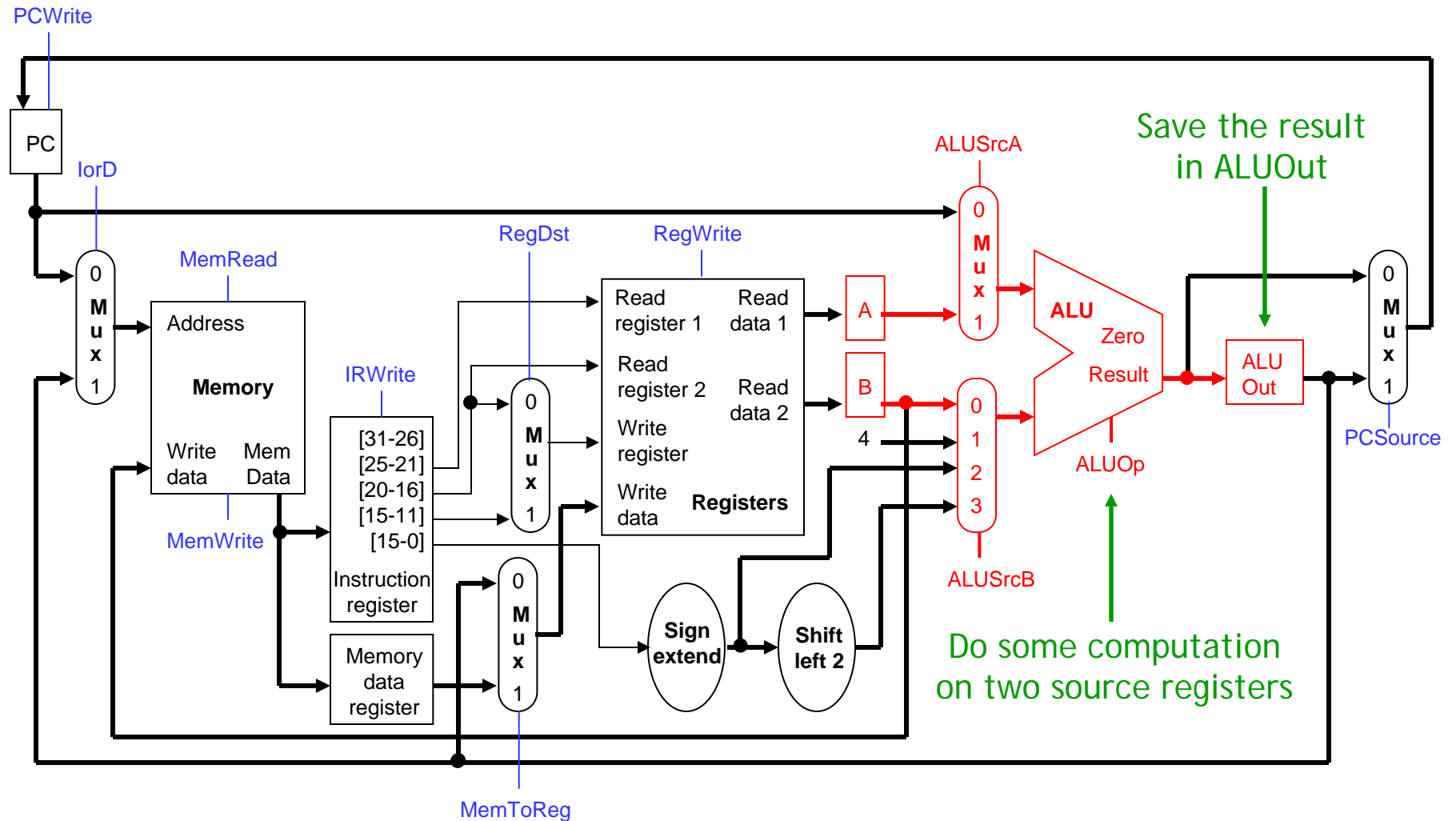
$$\text{ALUOut} = A \text{ op } B$$

- A and B are the intermediate registers holding the source operands.
 - The ALU operation is determined by the instruction's "func" field and could be one of add, sub, and, or, slt.
-
- ❑ **Stage 4**, the final R-type stage, is to store the ALU result generated in the *previous* cycle into the destination register rd.

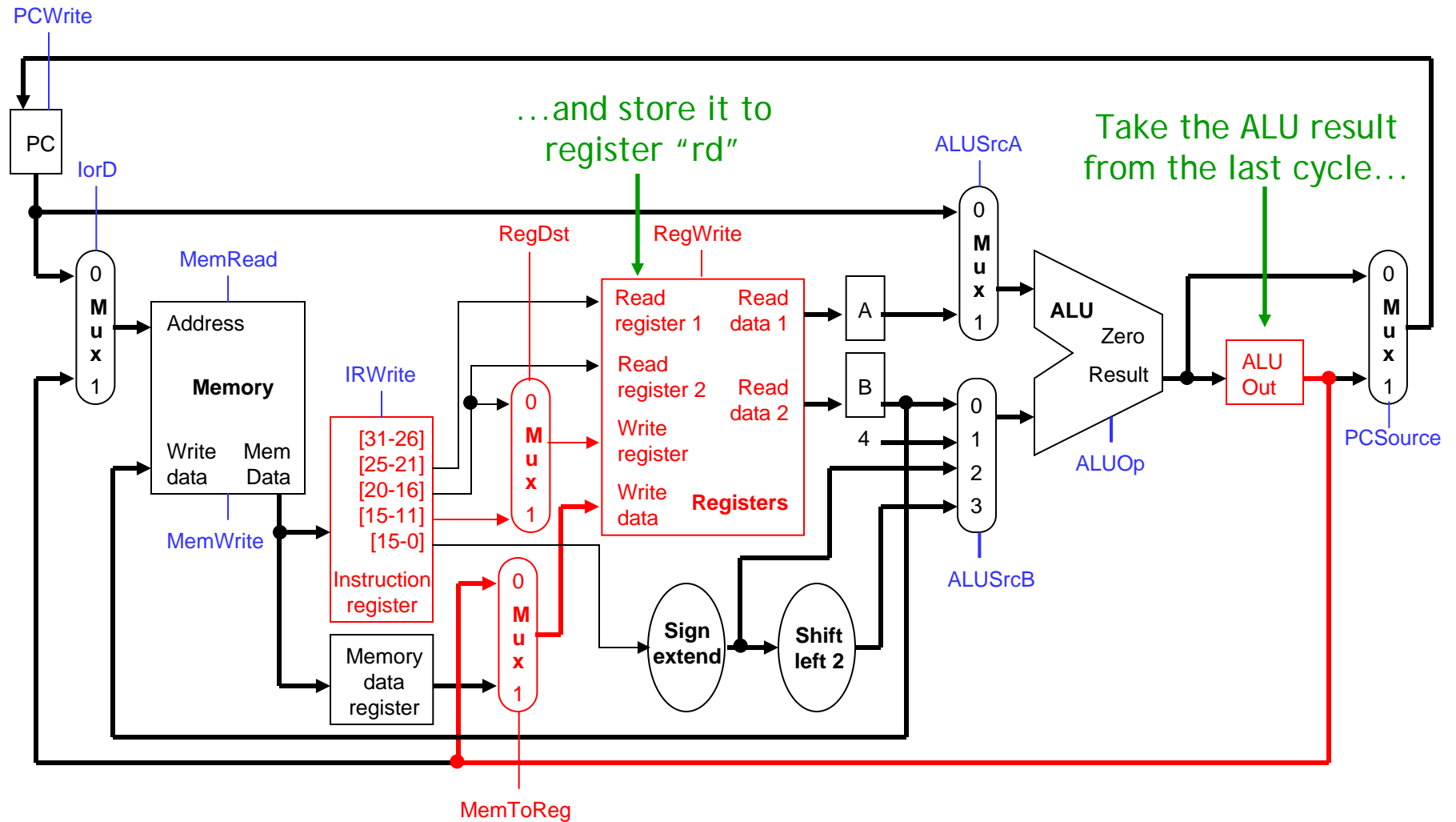
$$\text{Reg}[\text{IR}[15-11]] = \text{ALUOut}$$



Stage 3 (R-type): instruction execution



Stage 4 (R-type): write back



Stages 3-4 (R-type) control signals

□ Stage 3 (execution): $ALUOut = A \text{ op } B$

Signal	Value	Description
ALUSrcA	1	Use A as the first ALU operand
ALUSrcB	00	Use B as the second ALU operand
ALUOp	func	Do the operation specified in the “func” field

□ Stage 4 (writeback): $Reg[IR[15-11]] = ALUOut$

Signal	Value	Description
RegWrite	1	Write to the register file
RegDst	1	Use field rd as the destination register
MemToReg	0	ALUOut contains the data to write

Executing a beq instruction

- We can execute a branch instruction in three stages or clock cycles.
 - But it requires a little cleverness...
 - **Stage 1** involves instruction fetch and PC increment.

$IR = Mem[PC]$
 $PC = PC + 4$

- **Stage 2** is register fetch and branch target computation.

$A = Reg[IR[25-21]]$
 $B = Reg[IR[20-16]]$

- **Stage 3** is the final cycle needed for executing a branch instruction.
 - Assuming we have the branch target available
if (A == B) then
PC = branch_target

When should we compute the branch target?

- We need the ALU to do the computation.
 - When is the ALU not busy?

Cycle	ALU
1	PC = PC + 4
2	Compute target
3	Comparing A & B

Optimistic execution

- ❑ But, we don't know whether or not the branch is taken in cycle 2!!
- ❑ That's okay.... we can still go ahead and compute the branch target first. The book calls this **optimistic execution**.
 - The ALU is otherwise free during this clock cycle.
 - Nothing is harmed by doing the computation early. If the branch is not taken, we can just ignore the ALU result.
- ❑ This idea is also used in more advanced CPU design techniques.
 - Modern CPUs perform branch prediction, which we'll discuss in a few weeks in the context of pipelining (hopefully!)
 - The Intel IA-64 architecture and the Itanium processors go one step further with branch predication and data speculation.

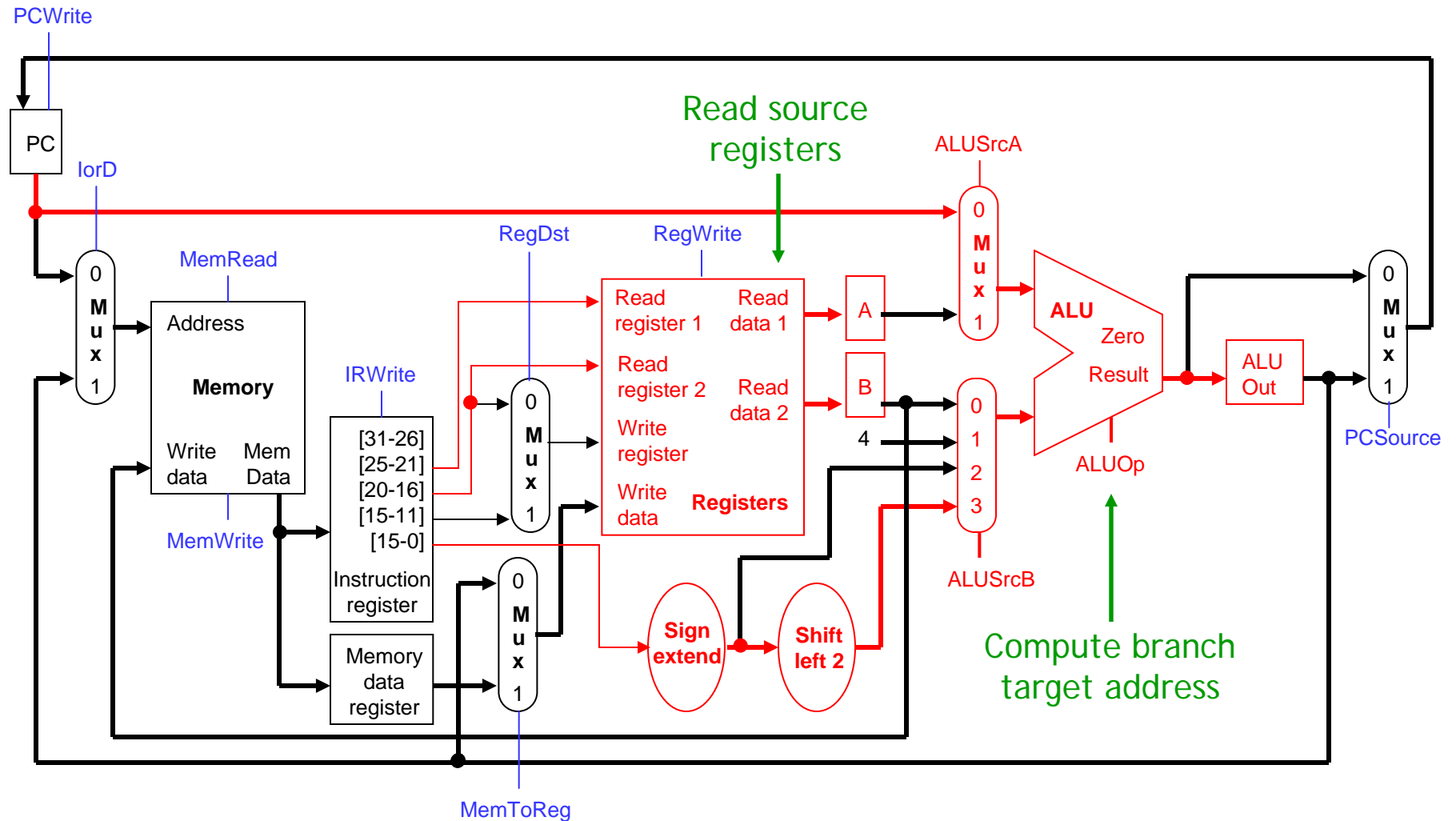
Stage 2 Revisited: Compute the branch target

- ❑ To **Stage 2**, we'll add the computation of the branch target.
 - Compute the branch target address by adding the new PC (the original PC + 4) to the sign-extended, shifted constant from IR.

$$\text{ALUOut} = \text{PC} + (\text{sign-extend}(\text{IR}[15-0]) \ll 2)$$

We save the target address in ALUOut for now, since we don't know yet if the branch should be taken.

Stage 2: Register fetch & branch target computation



Stage 2 control signals

- ❑ No control signals need to be set for the register reading operations $A = \text{Reg}[\text{IR}[25-21]]$ and $B = \text{Reg}[\text{IR}[20-16]]$.
 - $\text{IR}[25-21]$ and $\text{IR}[20-16]$ are already applied to the register file.
 - Registers A and B are already written on every clock cycle.
- ❑ Branch target computation: $\text{ALUOut} = \text{PC} + (\text{sign-extend}(\text{IR}[15-0]) \ll 2)$

Signal	Value	Description
ALUSrcA	0	Use PC as the first ALU operand
ALUSrcB	11	Use $(\text{sign-extend}(\text{IR}[15-0]) \ll 2)$ as second operand
ALUOp	ADD	Add and save the result in ALUOut

ALUOut is also written automatically on each clock cycle.

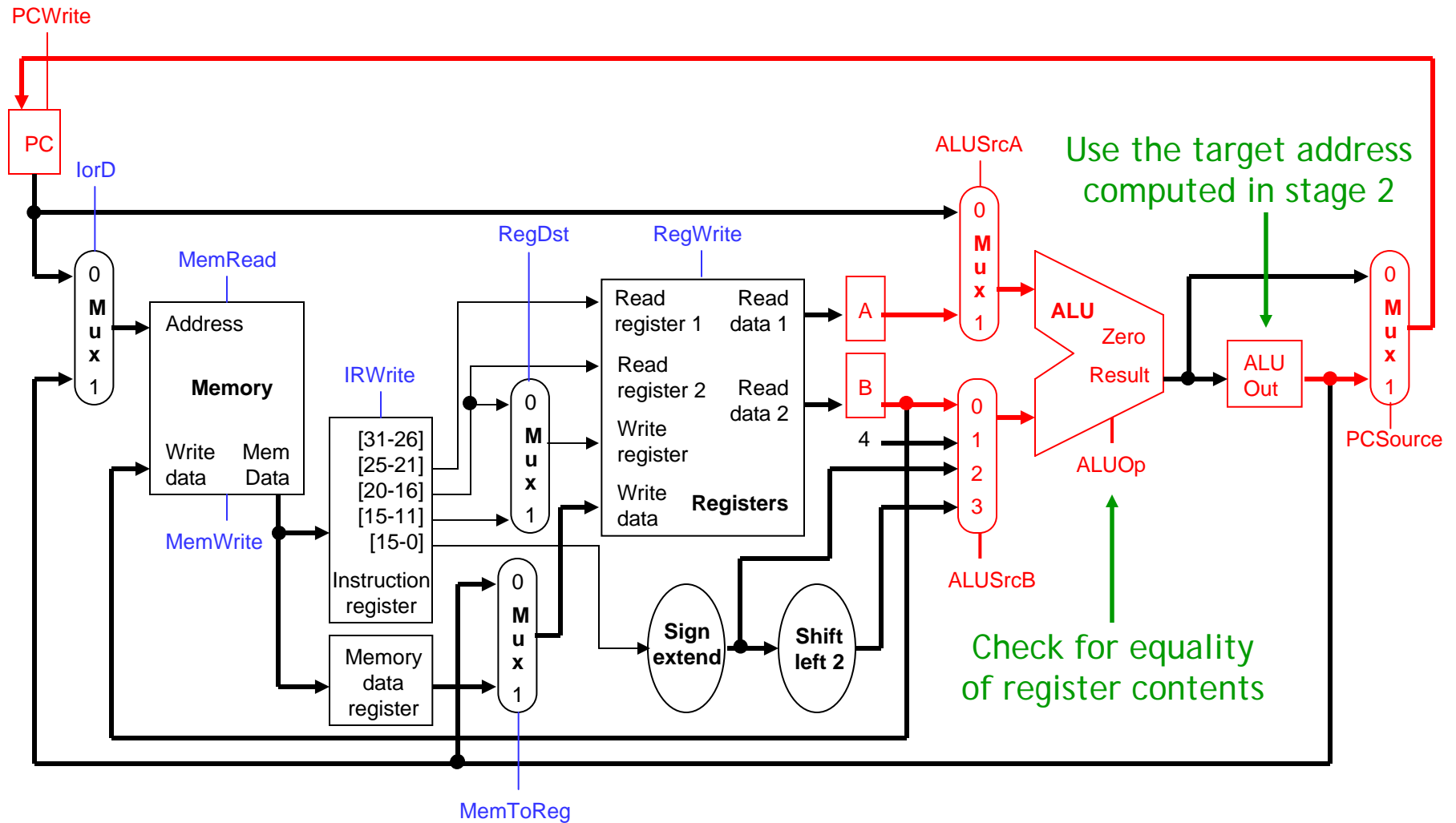
Branch completion

- ❑ **Stage 3** is the final cycle needed for executing a branch instruction.

if (A == B) then
PC = ALUOut

- ❑ Remember that A and B are compared by subtracting and testing for a result of 0, so we must use the ALU again in this stage.

Stage 3 (beq): Branch completion



Stage 3 (beq) control signals

- ❑ Comparison: if (A == B) ...

Signal	Value	Description
ALUSrcA	1	Use A as the first ALU operand
ALUSrcB	00	Use B as the second ALU operand
ALUOp	SUB	Subtract, so Zero will be set if A = B

- ❑ Branch: ...then PC = ALUOut

Signal	Value	Description
PCWrite	Zero	Change PC only if Zero is true (i.e., A = B)
PCSource	1	Update PC from the ALUOut register

- ❑ ALUOut contains the ALU result from the *previous* cycle, which would be the branch target. We can write that to the PC, even though the ALU is doing something different (comparing A and B) during the *current* cycle.

Executing a sw instruction

- ❑ A store instruction, like `sw $a0, 16($sp)`, also shares the same first two stages as the other instructions.
 - **Stage 1**: instruction fetch and PC increment.
 - **Stage 2**: register fetch and branch target computation.
- ❑ **Stage 3** computes the effective memory address using the ALU.

$$\text{ALUOut} = A + \text{sign-extend}(\text{IR}[15-0])$$

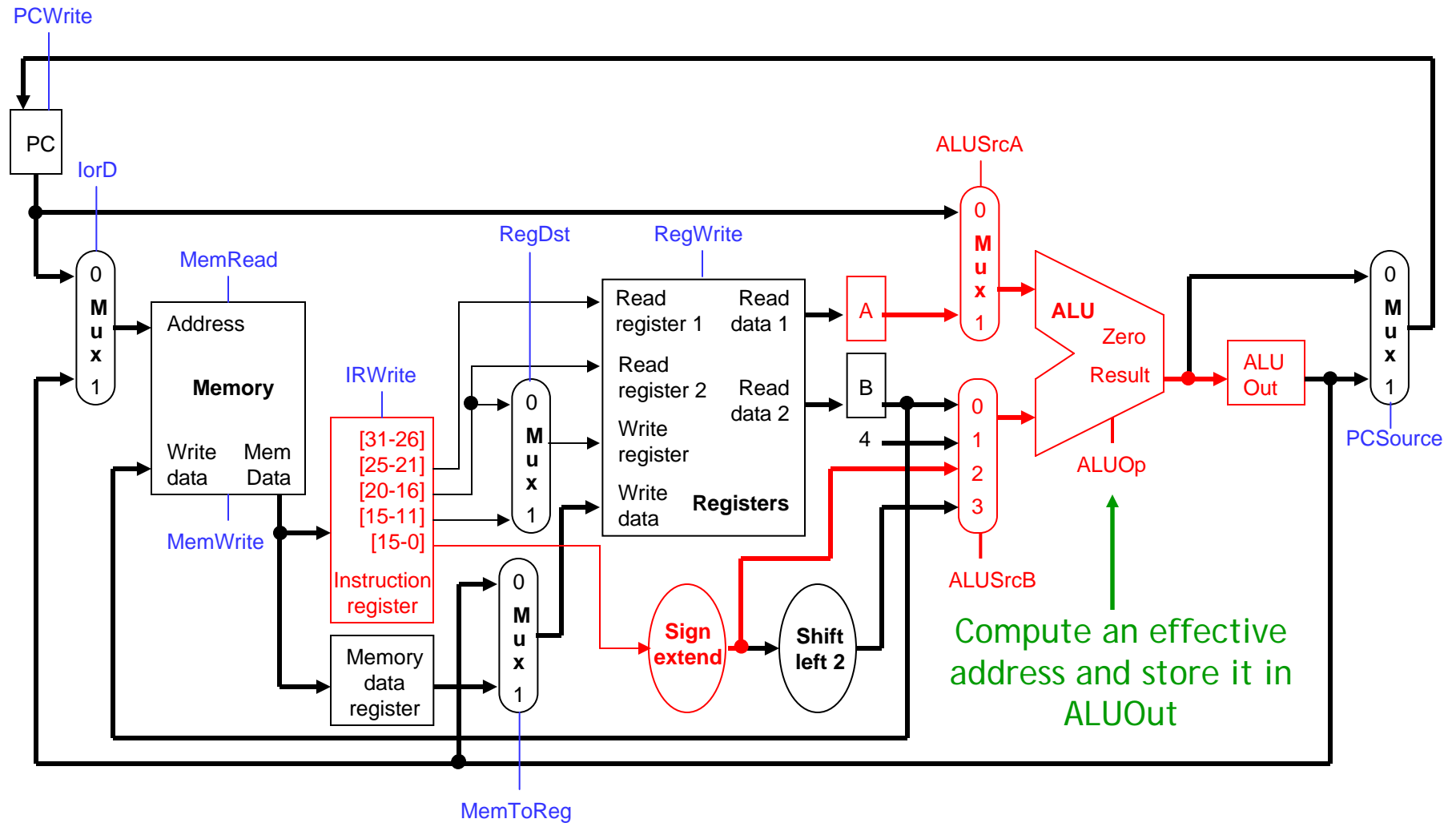
A contains the base register (like `$sp`), and `IR[15-0]` is the 16-bit constant offset from the instruction word, which is *not* shifted.

- ❑ **Stage 4** saves the register contents (here, `$a0`) into memory.

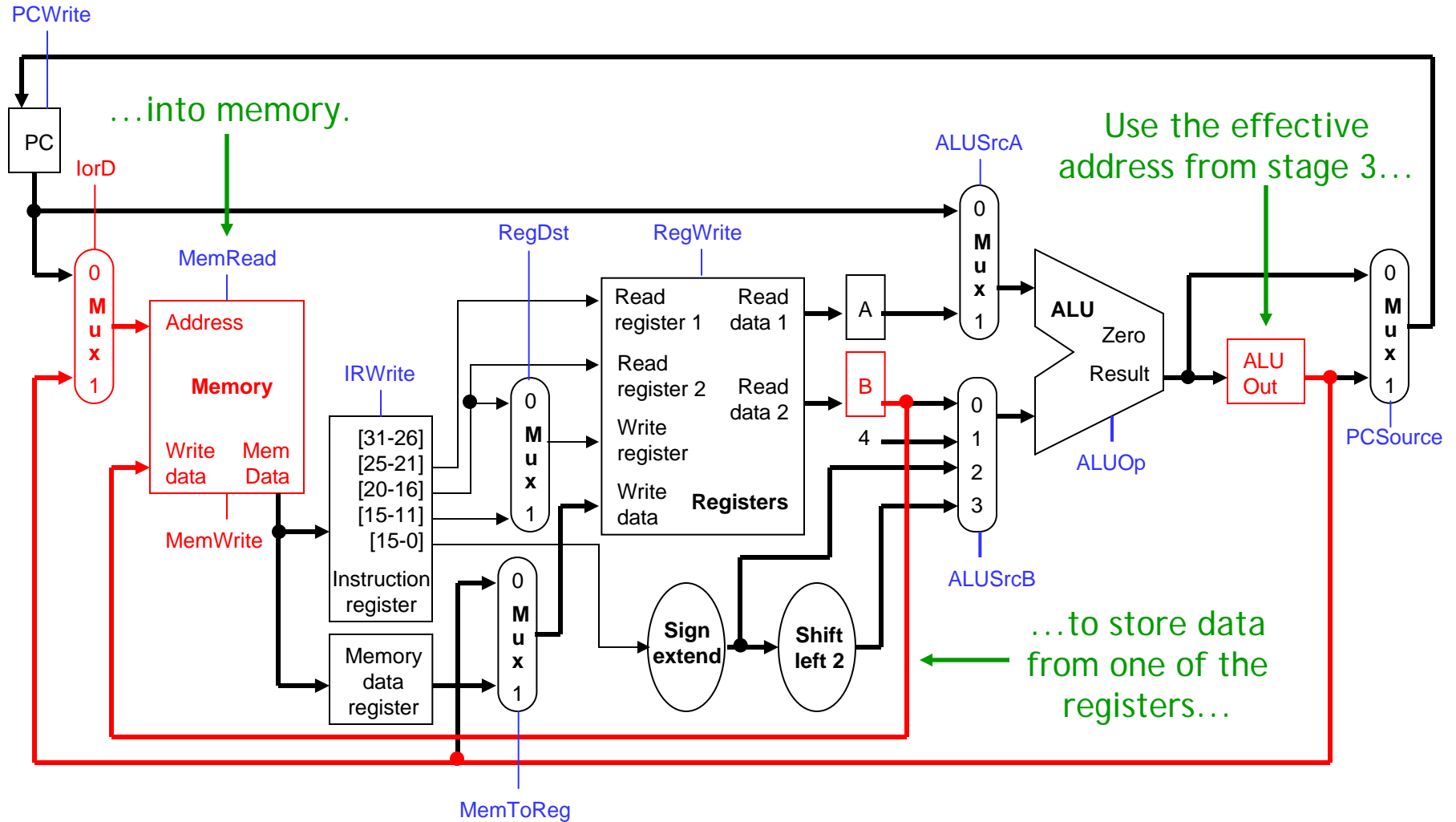
$$\text{Mem}[\text{ALUOut}] = B$$

Remember that the second source register `rt` was already read in Stage 2 (and again in Stage 3), and its contents are in intermediate register B.

Stage 3 (sw): effective address computation



Stage 4 (sw): memory write



Stages 3-4 (sw) control signals

- **Stage 3** (address computation): $ALUOut = A + \text{sign-extend}(IR[15-0])$

Signal	Value	Description
ALUSrcA	1	Use A as the first ALU operand
ALUSrcB	10	Use sign-extend(IR[15-0]) as the second operand
ALUOp	010	Add and store the resulting address in ALUOut

- **Stage 4** (memory write): $Mem[ALUOut] = B$

Signal	Value	Description
MemWrite	0	Write to the memory
lorD	0	Use ALUOut as the memory address

The memory's "Write data" input *always* comes from the B intermediate register, so no selection is needed.

Executing a lw instruction

- ❑ Finally, lw is the most complex instruction, requiring five stages.
- ❑ The first two are like all the other instructions.
 - **Stage 1**: instruction fetch and PC increment.
 - **Stage 2**: register fetch and branch target computation.
- ❑ The third stage is the same as for sw, since we have to compute an effective memory address in both cases.
 - **Stage 3**: compute the effective memory address.

Stages 4-5 (lw): memory read and register write

- **Stage 4** is to read from the effective memory address, and to store the value in the intermediate register MDR (memory data register).

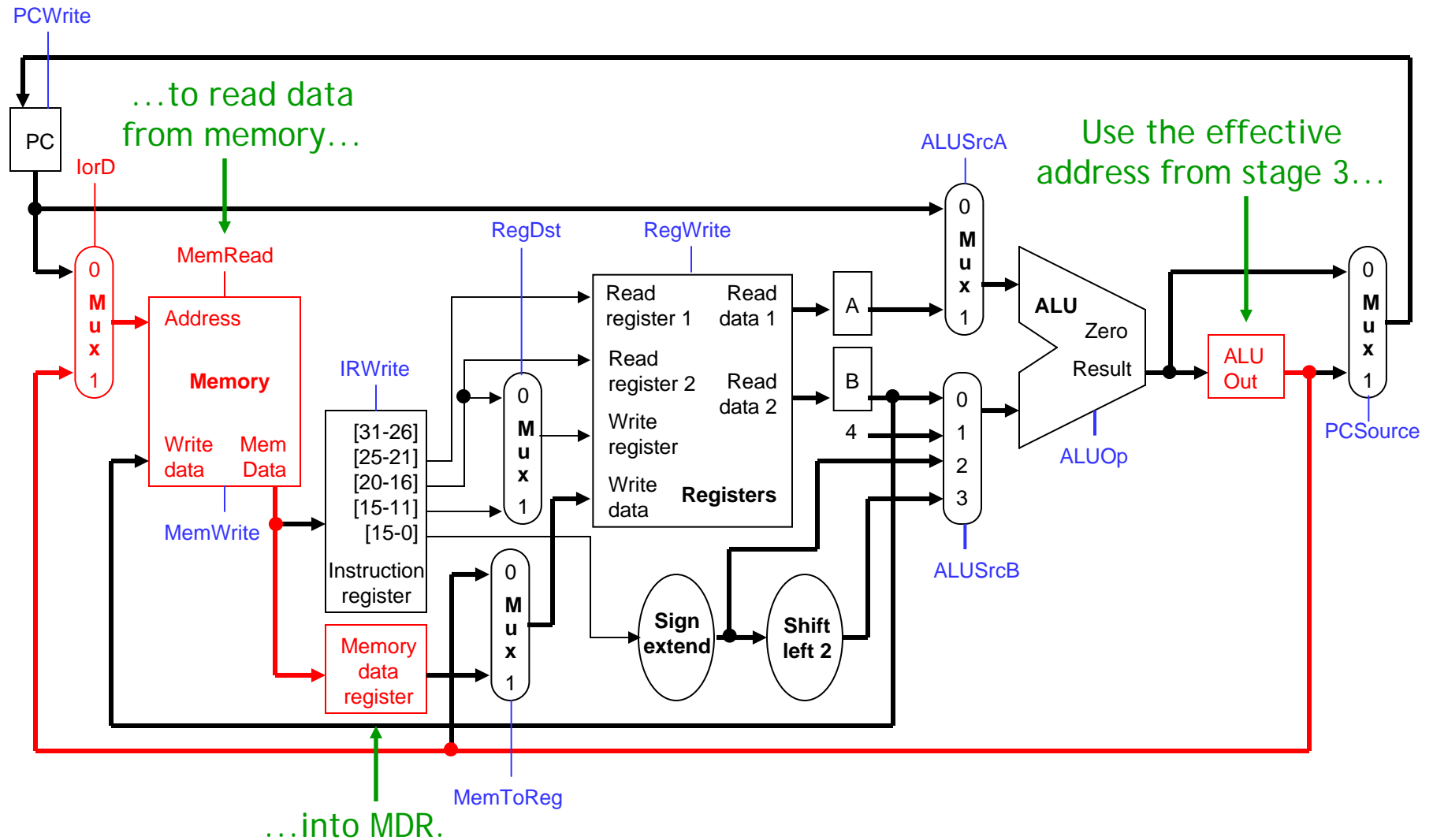
$$\text{MDR} = \text{Mem}[\text{ALUOut}]$$

- **Stage 5** stores the contents of MDR into the destination register.

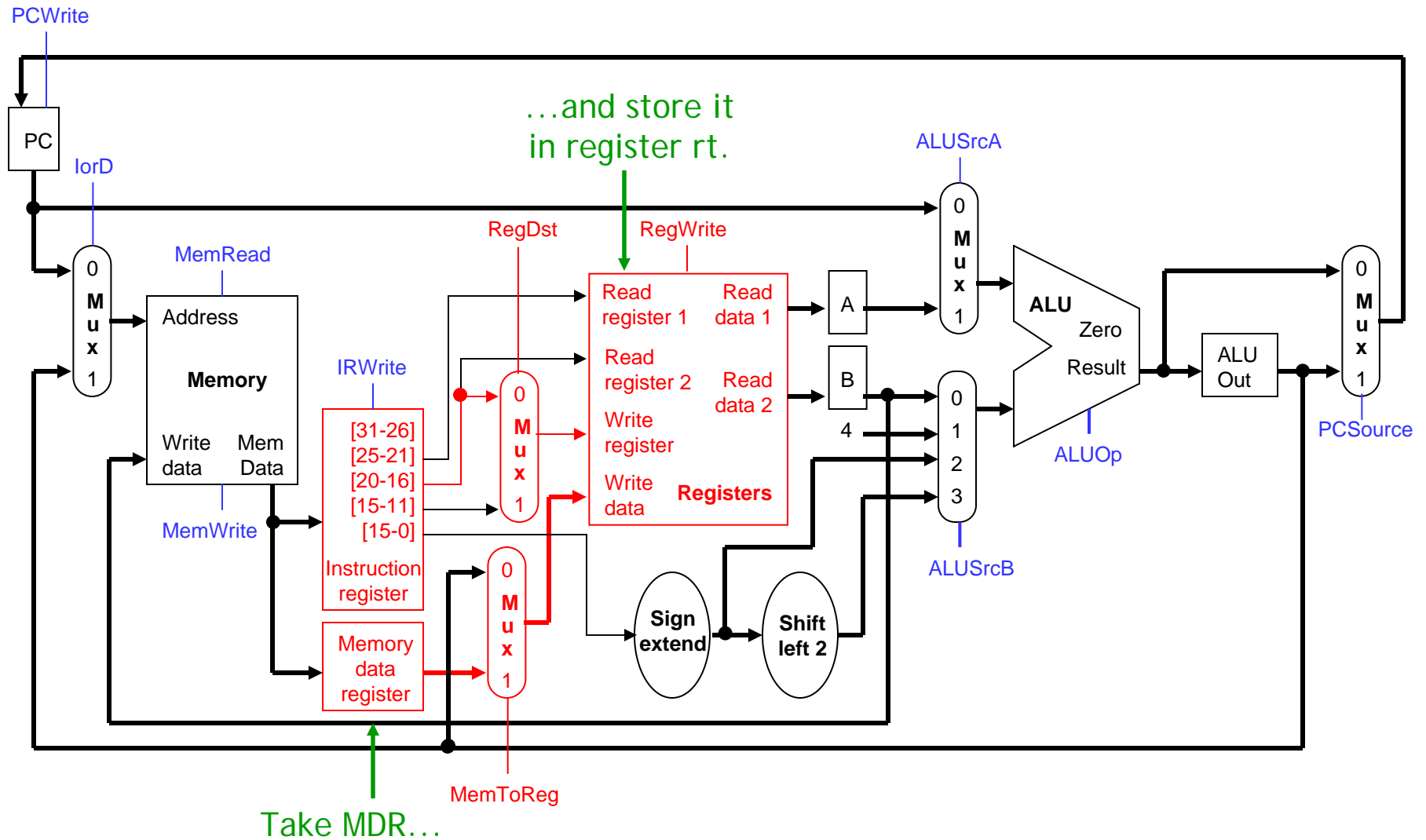
$$\text{Reg}[\text{IR}[20-16]] = \text{MDR}$$

Remember that the destination register for lw is field *rt* (bits 20-16) and *not* field *rd* (bits 15-11).

Stage 4 (lw): memory read



Stage 5 (lw): register write



Stages 4-5 (lw) control signals

- **Stage 4** (memory read): $MDR = Mem[ALUOut]$

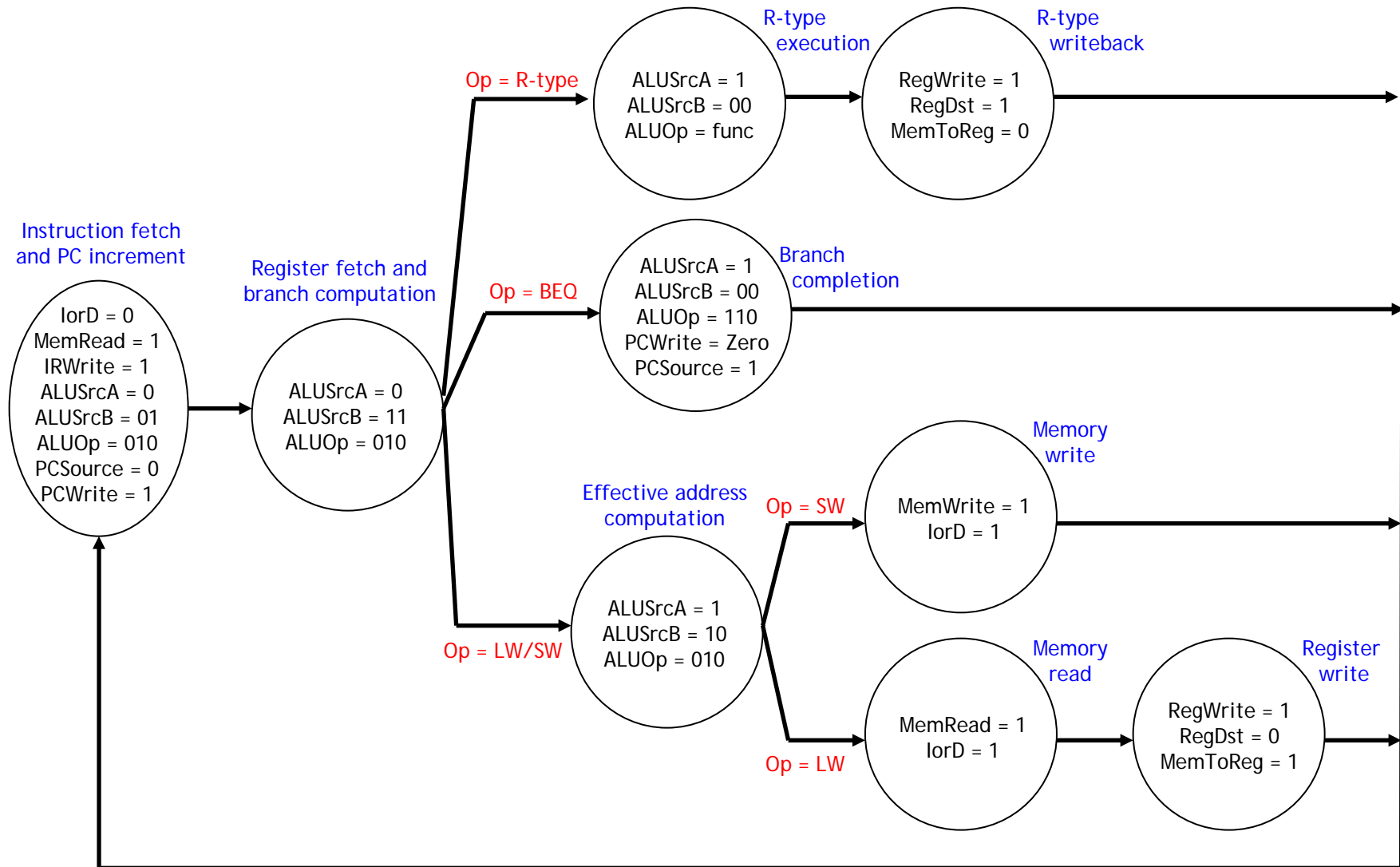
Signal	Value	Description
MemRead	1	Read from memory
lorD	1	Use ALUOut as the memory address

The memory contents will be automatically written to MDR.

- **Stage 5** (writeback): $Reg[IR[20-16]] = MDR$

Signal	Value	Description
RegWrite	1	Store new data in the register file
RegDst	0	Use field rt as the destination register
MemToReg	1	Write data from MDR (from memory)

Finite-state machine for the control unit



Implementing the FSM

- This can be translated into a state table; here are the first two states.

Current State	Input (Op)	Next State	Output (Control signals)											
			PC Write	lor D	Mem Read	Mem Write	IR Write	Reg Dst	MemToReg	Reg Write	ALU Src A	ALU Src B	ALU Op	PC Source
Instr Fetch	X	Reg Fetch	1	0	1	0	1	X	X	0	0	01	010	0
Reg Fetch	BEQ	Branch compl	0	X	0	0	0	X	X	0	0	11	010	X
Reg Fetch	R-type	R-type execute	0	X	0	0	0	X	X	0	0	11	010	X
Reg Fetch	LW/SW	Compute eff addr	0	X	0	0	0	X	X	0	0	11	010	X

- You can implement this the hard way.
 - Represent the current state using flip-flops or a register.
 - Find equations for the next state and (control signal) outputs in terms of the current state and input (instruction word).
- Or you can use the easy way.
 - Stick the whole state table into a memory, like a ROM.
 - This would be much easier, since you don't have to derive equations.

Summary

- **Now you know how to build a multicycle controller!**
 - Each instruction takes several cycles to execute.
 - Different instructions require different control signals and a different number of cycles.
 - We have to provide the control signals in the right sequence.

