Chapter 7: Microarchitecture

Multicycle RISC-V Processor

Single- vs. Multicycle Processor

- **Single-cycle:**
  - + simple
  - - cycle time limited by longest instruction (`lw`)
  - - separate memories for instruction and data
  - - 3 adders/ALUs
- **Multicycle processor** addresses these issues by breaking instruction into **shorter steps**
  - shorter instructions take fewer steps
  - can re-use hardware
  - cycle time is faster

Single- vs. Multicycle Processor

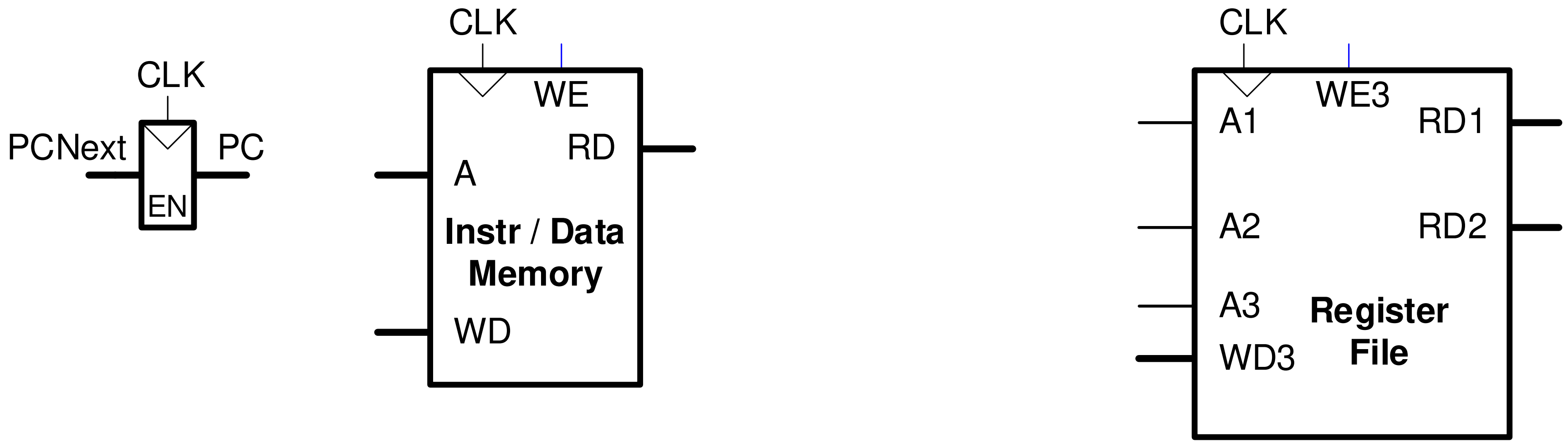
- **Single-cycle:**
  - + simple
  - - cycle time limited by longest instruction (`lw`)
  - - separate memories for instruction and data
  - - 3 adders/ALUs
- **Multicycle:**
  - + higher clock speed
  - + simpler instructions run faster
  - + reuse expensive hardware on multiple cycles
  - - sequencing overhead paid many times

Same design steps as single-cycle:

- **first datapath**
- **then control**

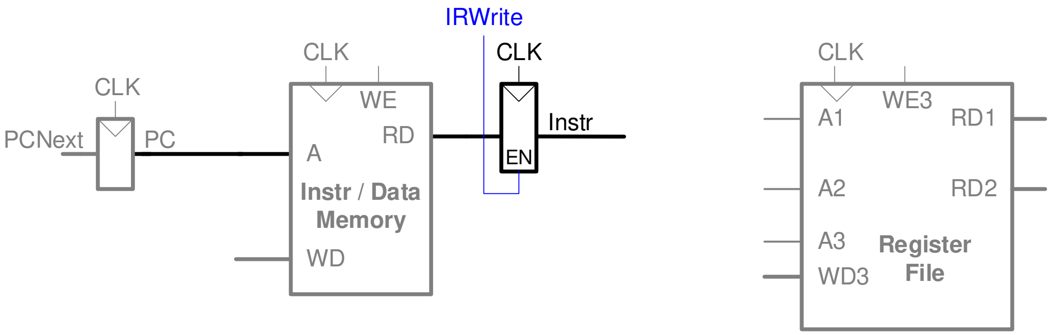
Multicycle State Elements

Replace separate Instruction and Data memories with a **single unified memory** – more realistic



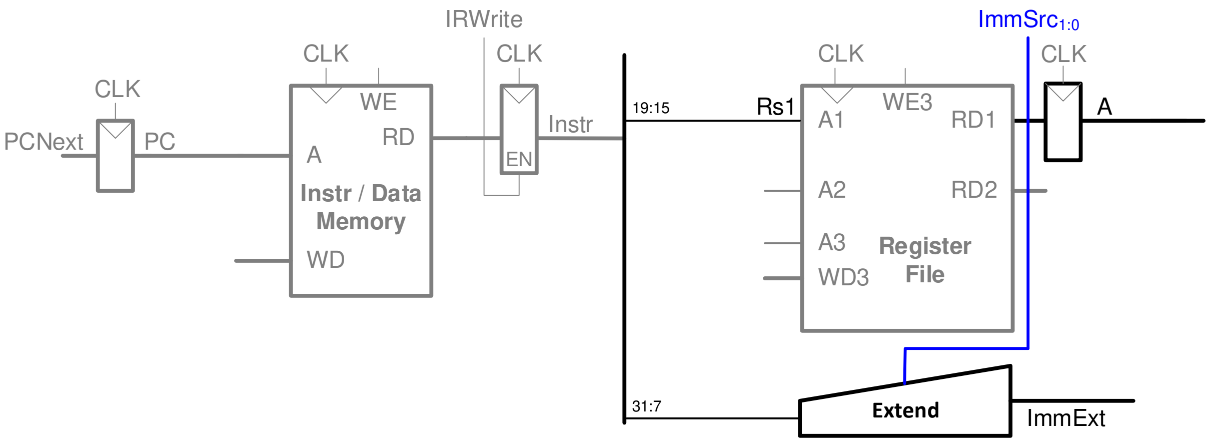
Multicycle Datapath: Instruction Fetch

STEP 1: Fetch instruction



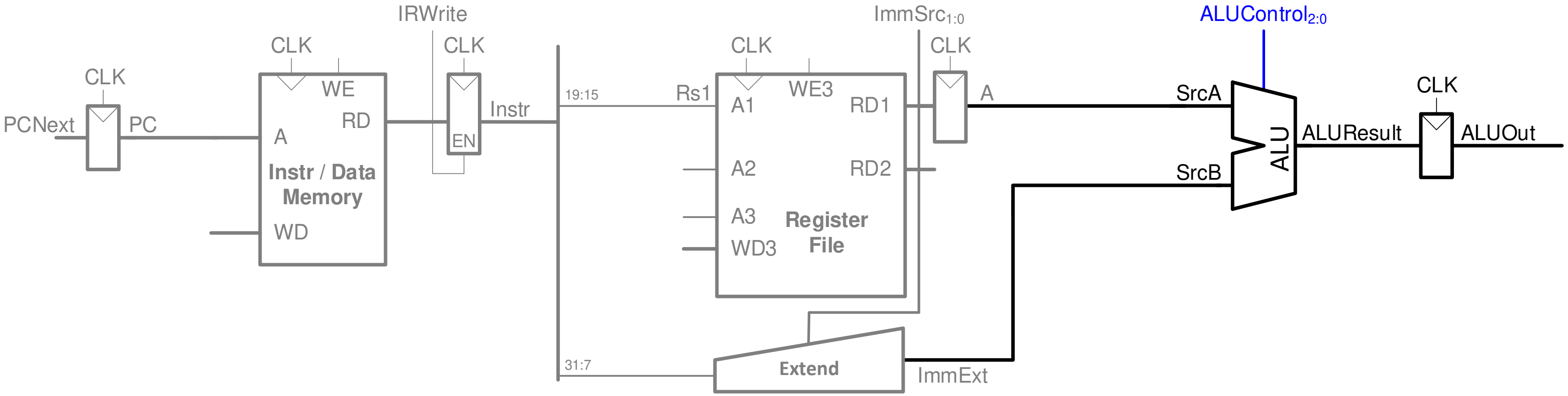
Multicycle Datapath: `lw` Get Sources

STEP 2: Read source operand from RF and extend immediate



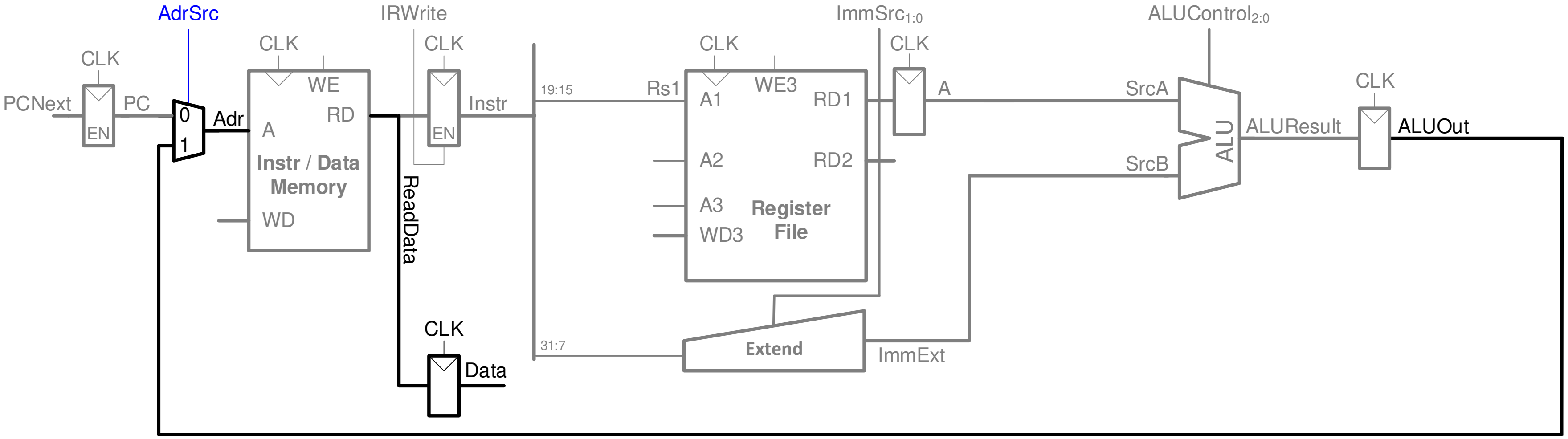
Multicycle Datapath: `lw` Address

STEP 3: Compute the memory address



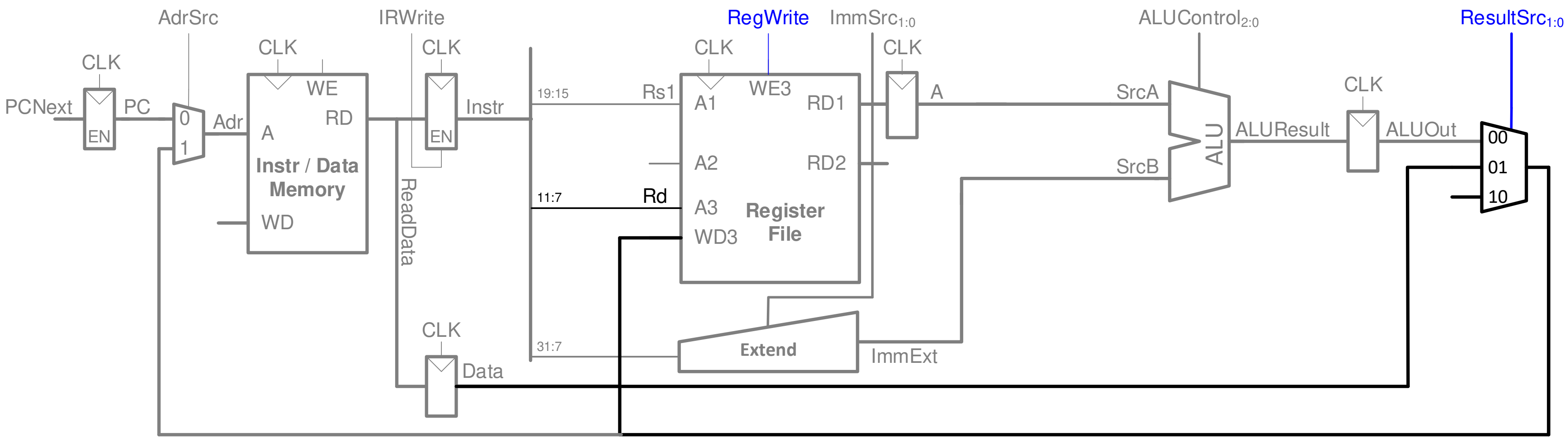
Multicycle Datapath: `lw` Memory Read

STEP 4: Read data from memory



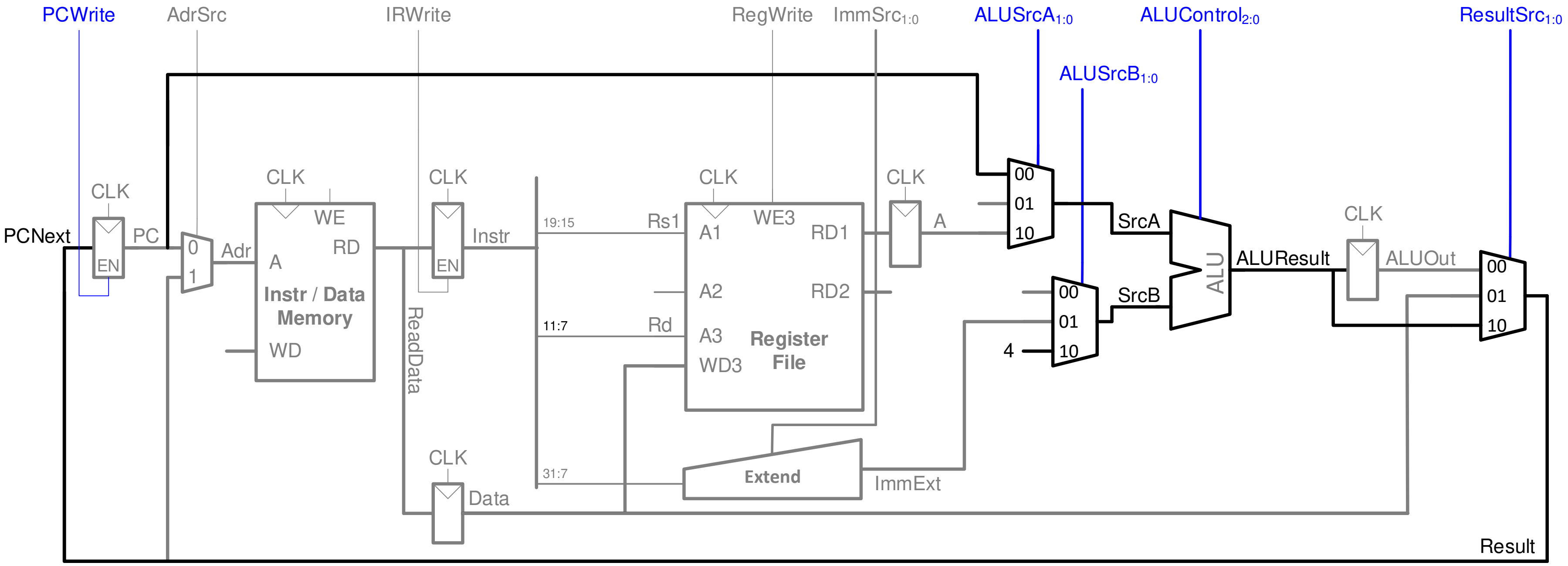
Multicycle Datapath: `lw` Write Register

STEP 5: Write data back to register file



Multicycle Datapath: Increment PC

STEP 6: Increment PC: PC = PC+4



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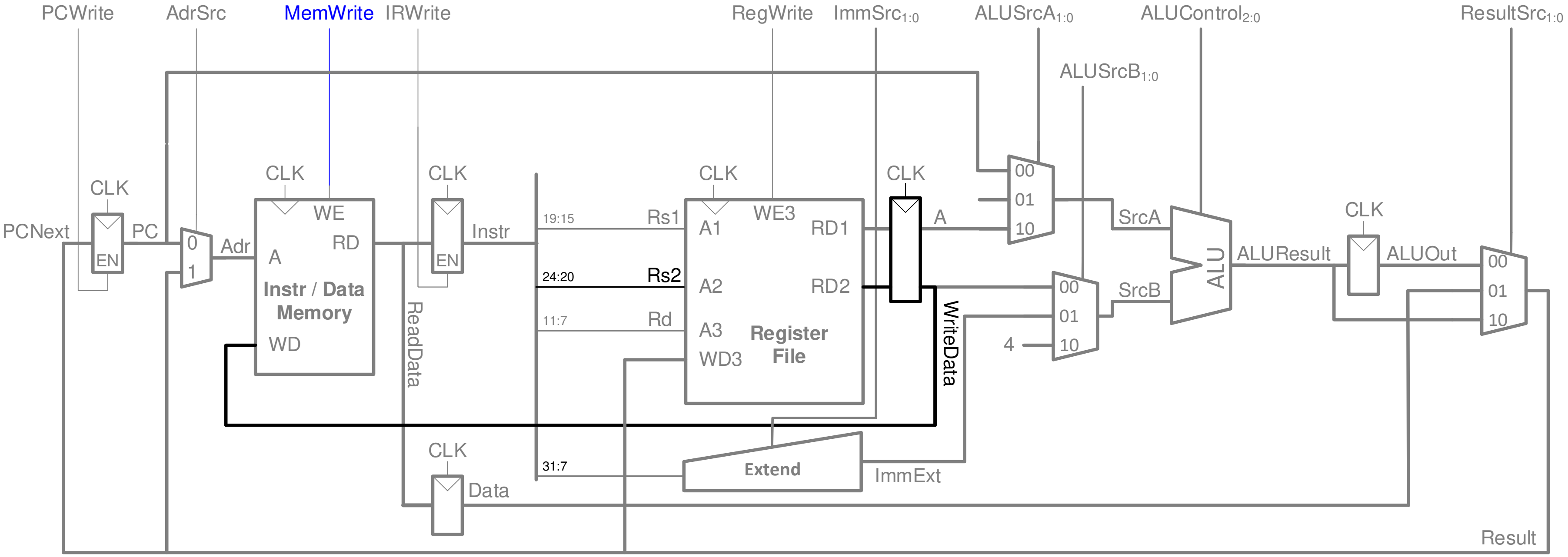
Multicycle Datapath: Other Instructions

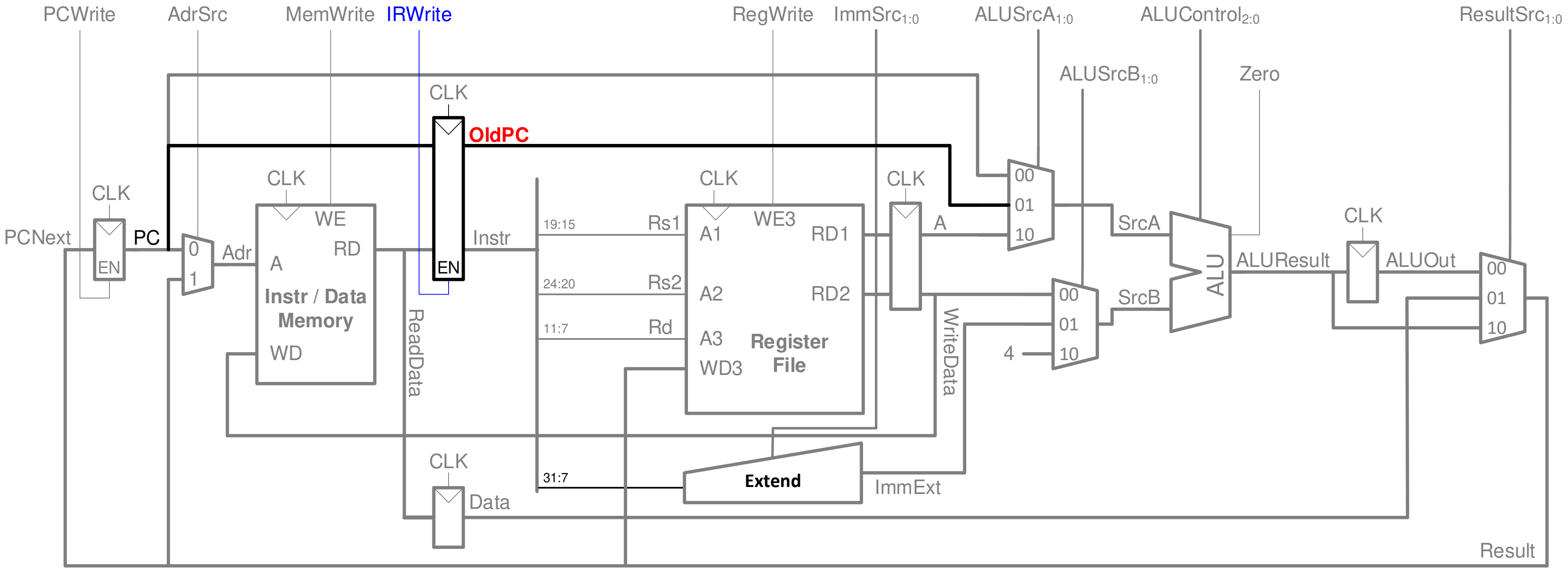
Multicycle Datapath: `sw`

Write data in **rs2** to memory



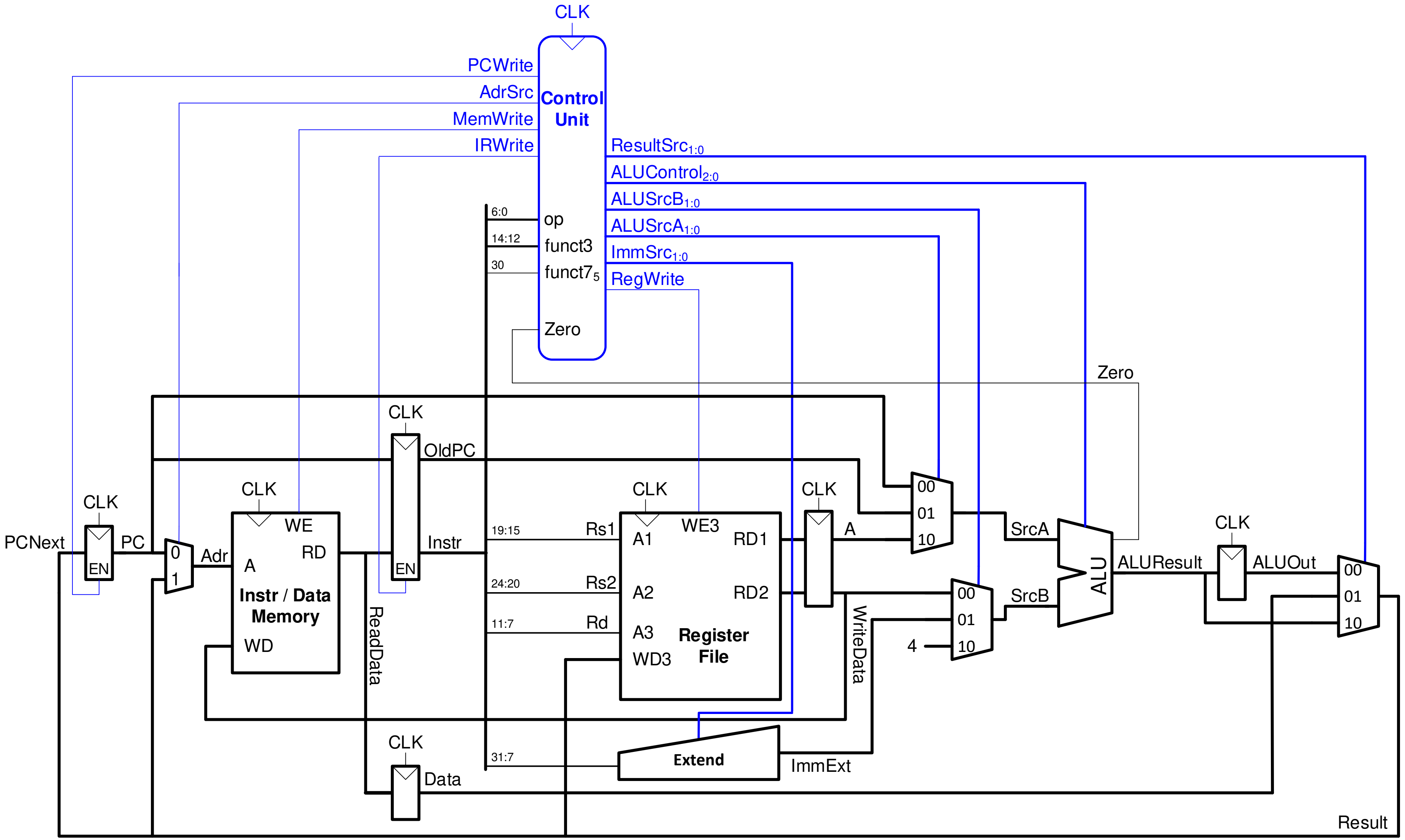
Multicycle Datapath: beq

Calculate branch target address:
BTA = PC + imm



PC is updated in Fetch stage, so need to save **old (current) PC**

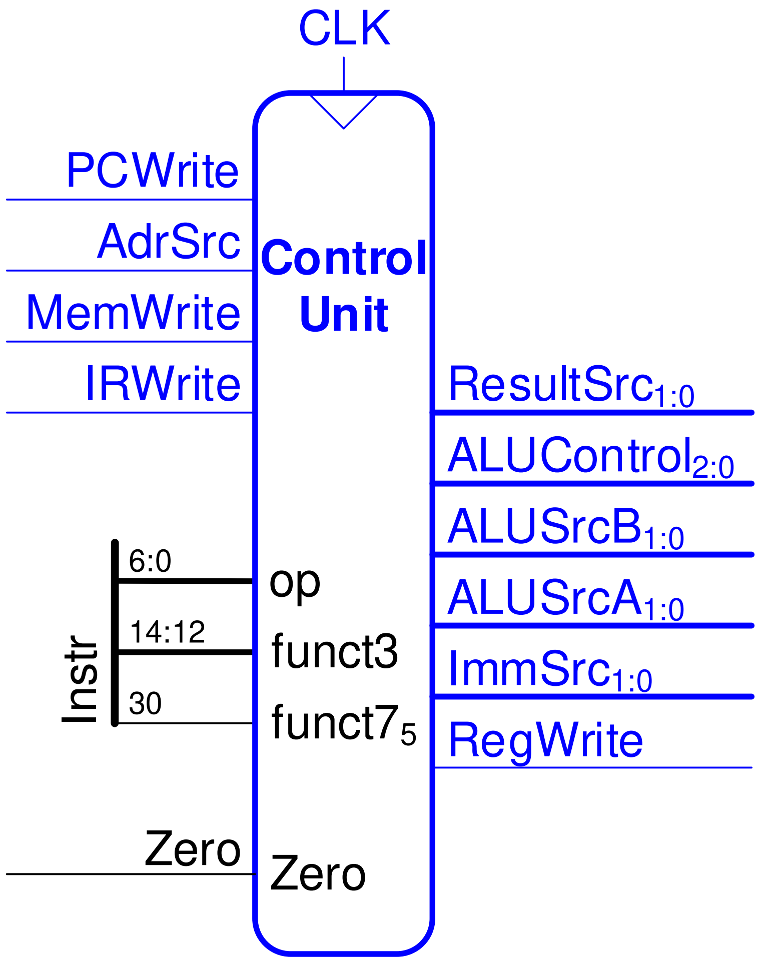
Multicycle RISC-V Processor



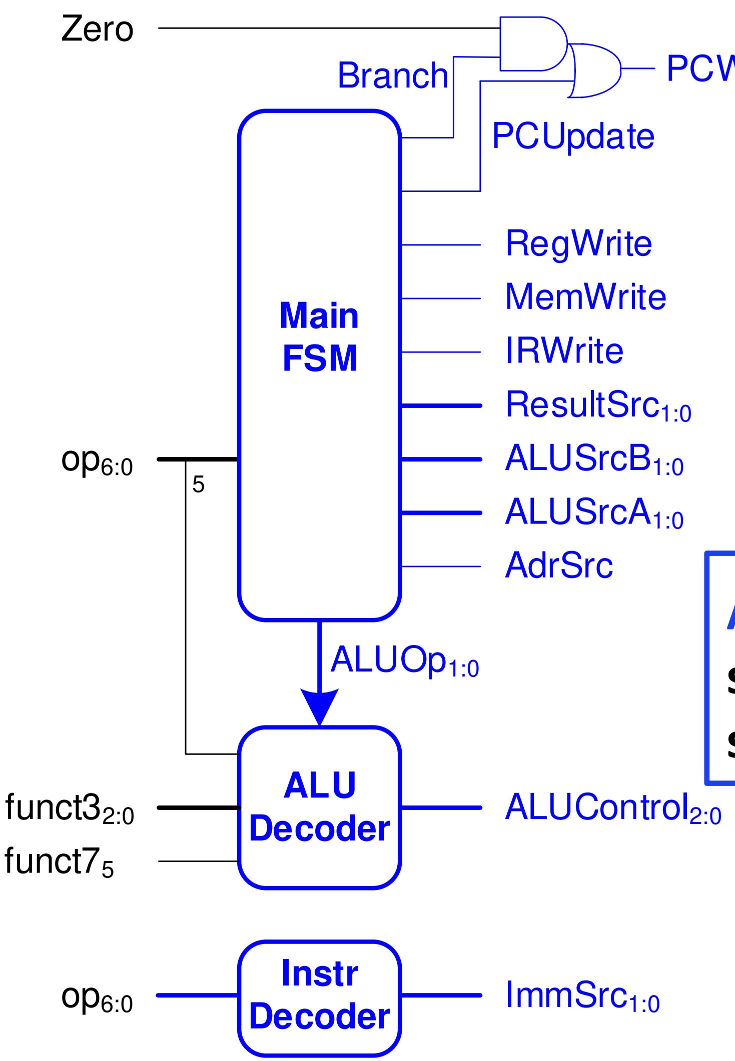
Multicycle Control

Multicycle Control

High-Level View

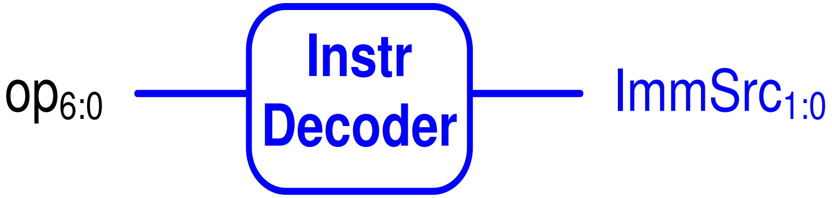


Low-Level View



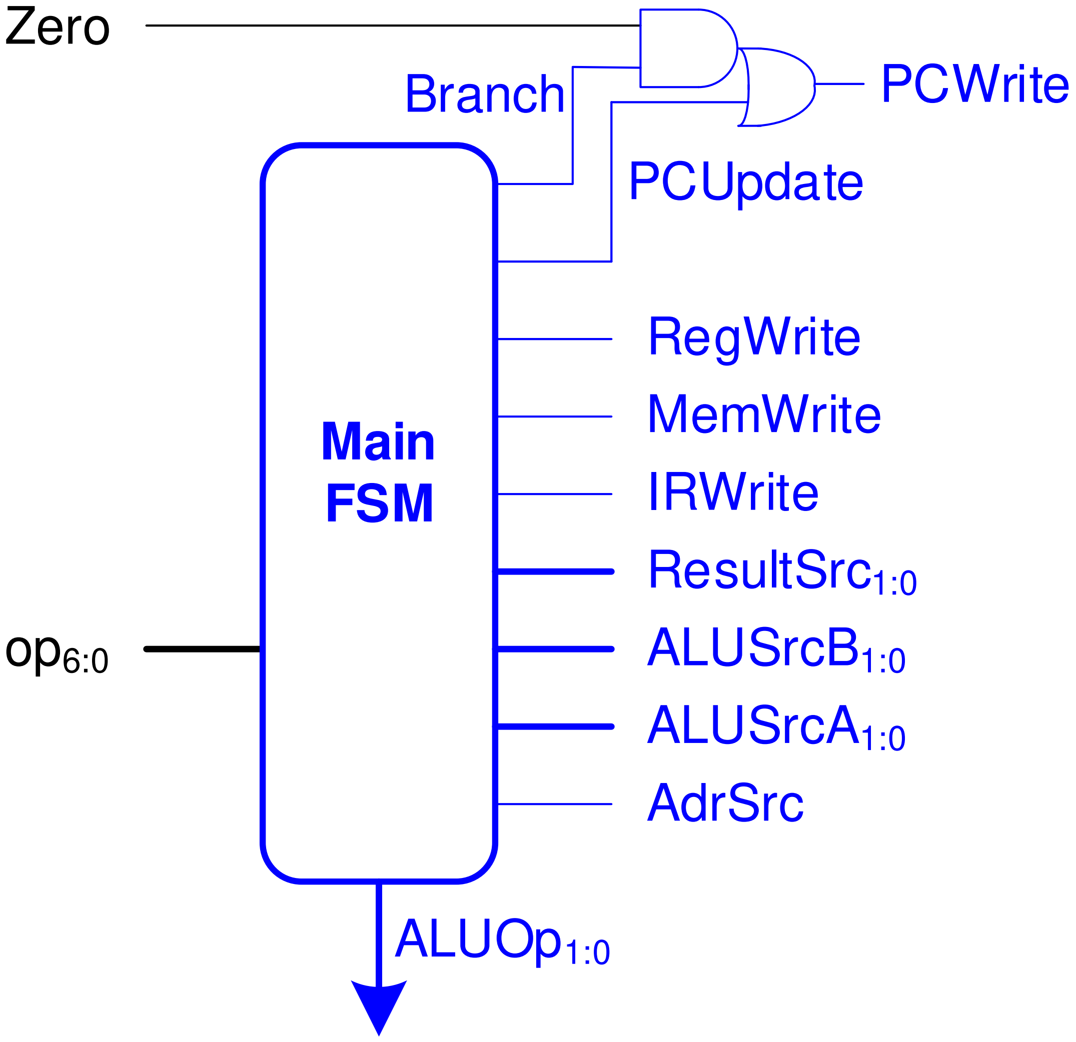
ALU Decoder same as single-cycle

Multicycle Control: Instruction Decoder



op	Instruction	ImmSrc
3	`lw`	00
35	`sw`	01
51	R-type	XX
99	`beq`	10

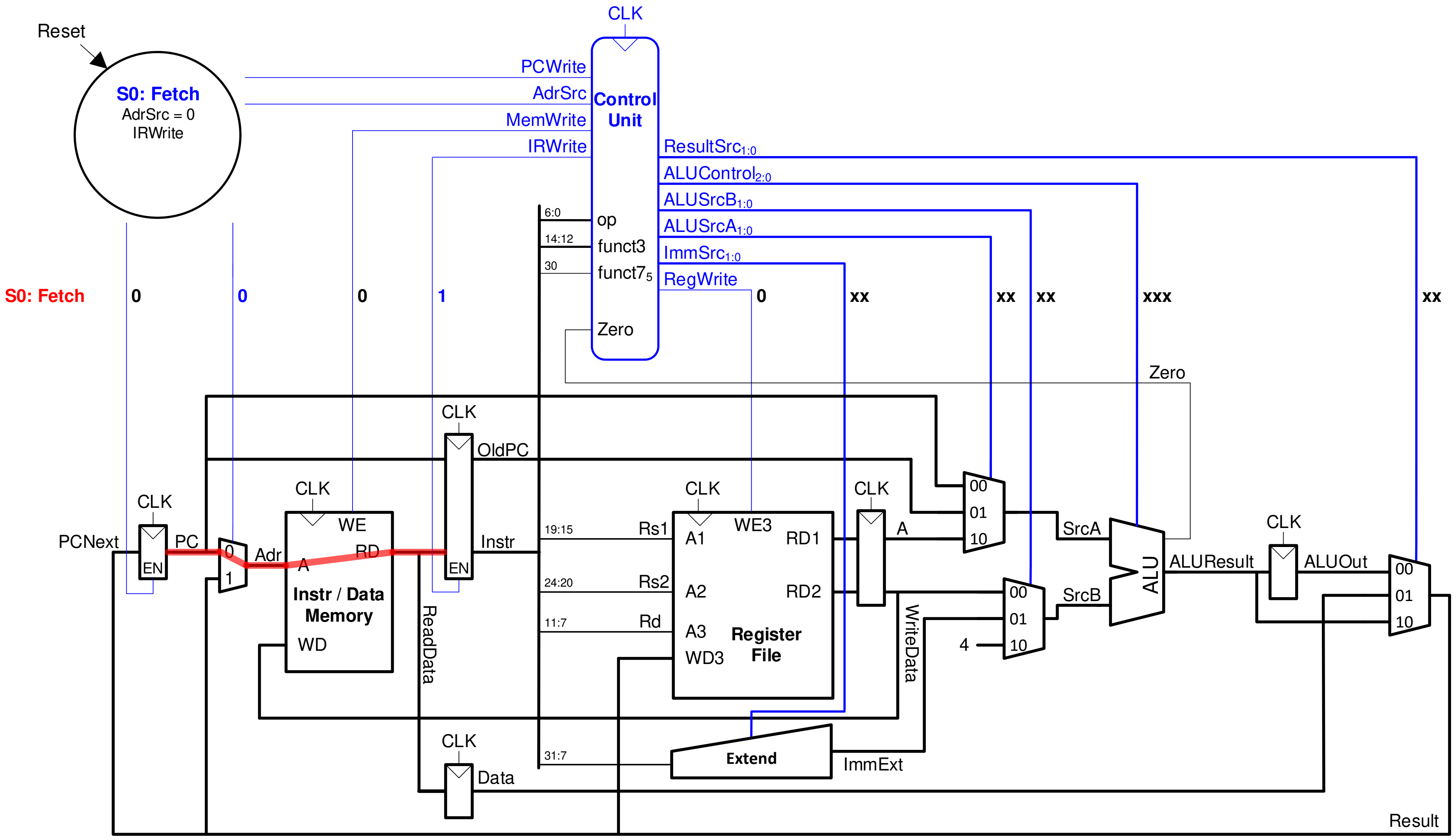
Multicycle Control: Main FSM



To declutter FSM:

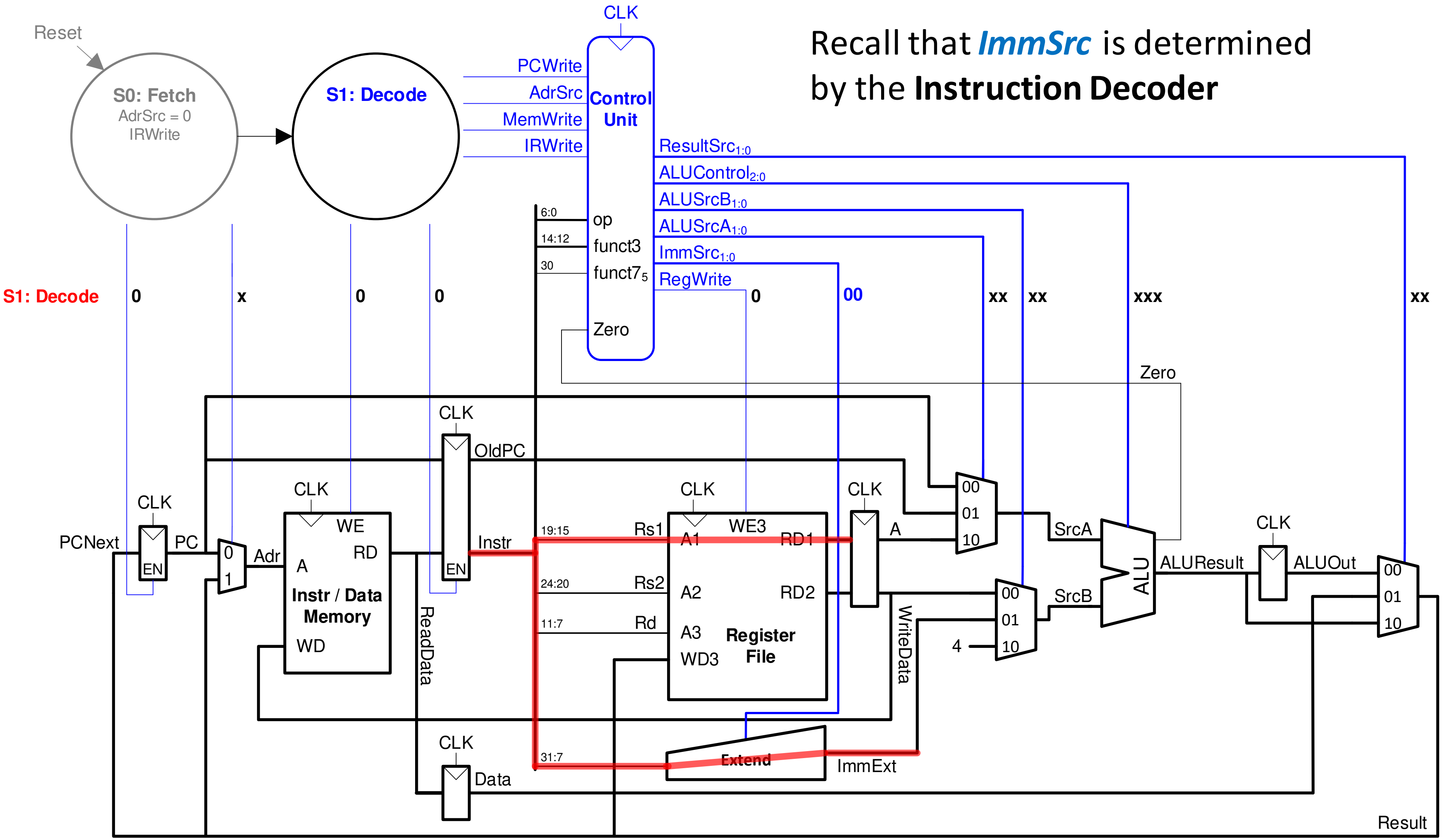
- **Write enable signals** (RegWrite, MemWrite, IRWrite, PCUpdate, and Branch) are **0** if not listed in a state.
- **Other signals are don't care** if not listed in a state

Main FSM: Fetch

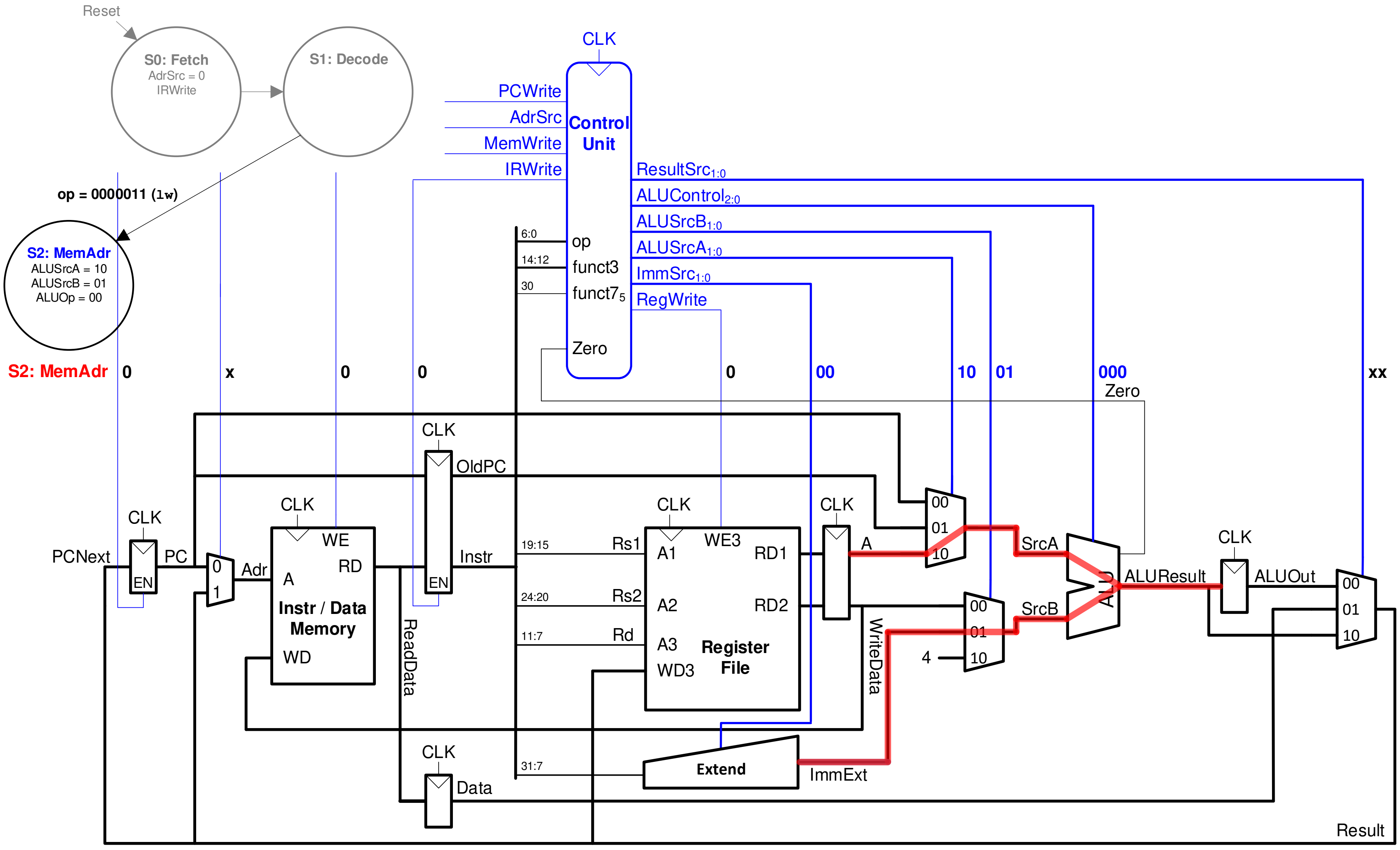


Main FSM: Decode

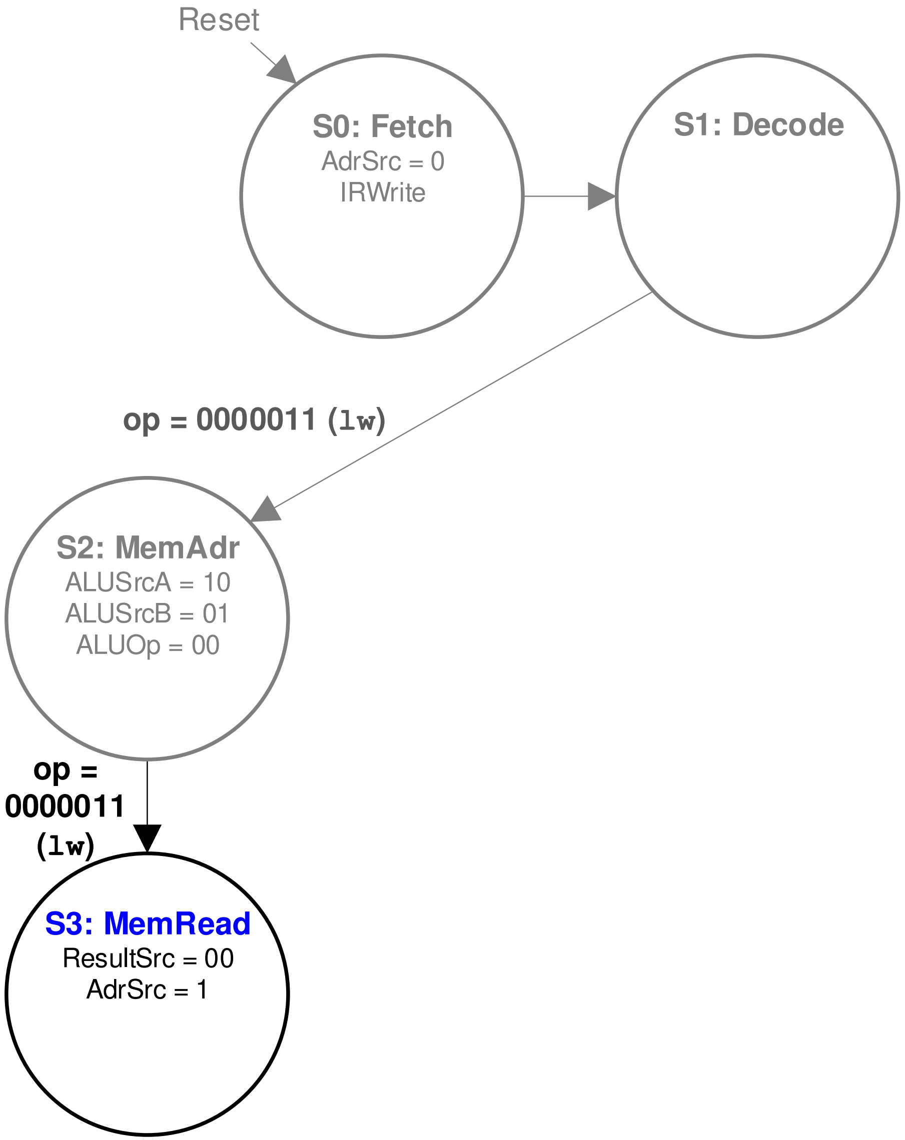
Recall that ***ImmSrc*** is determined by the **Instruction Decoder**



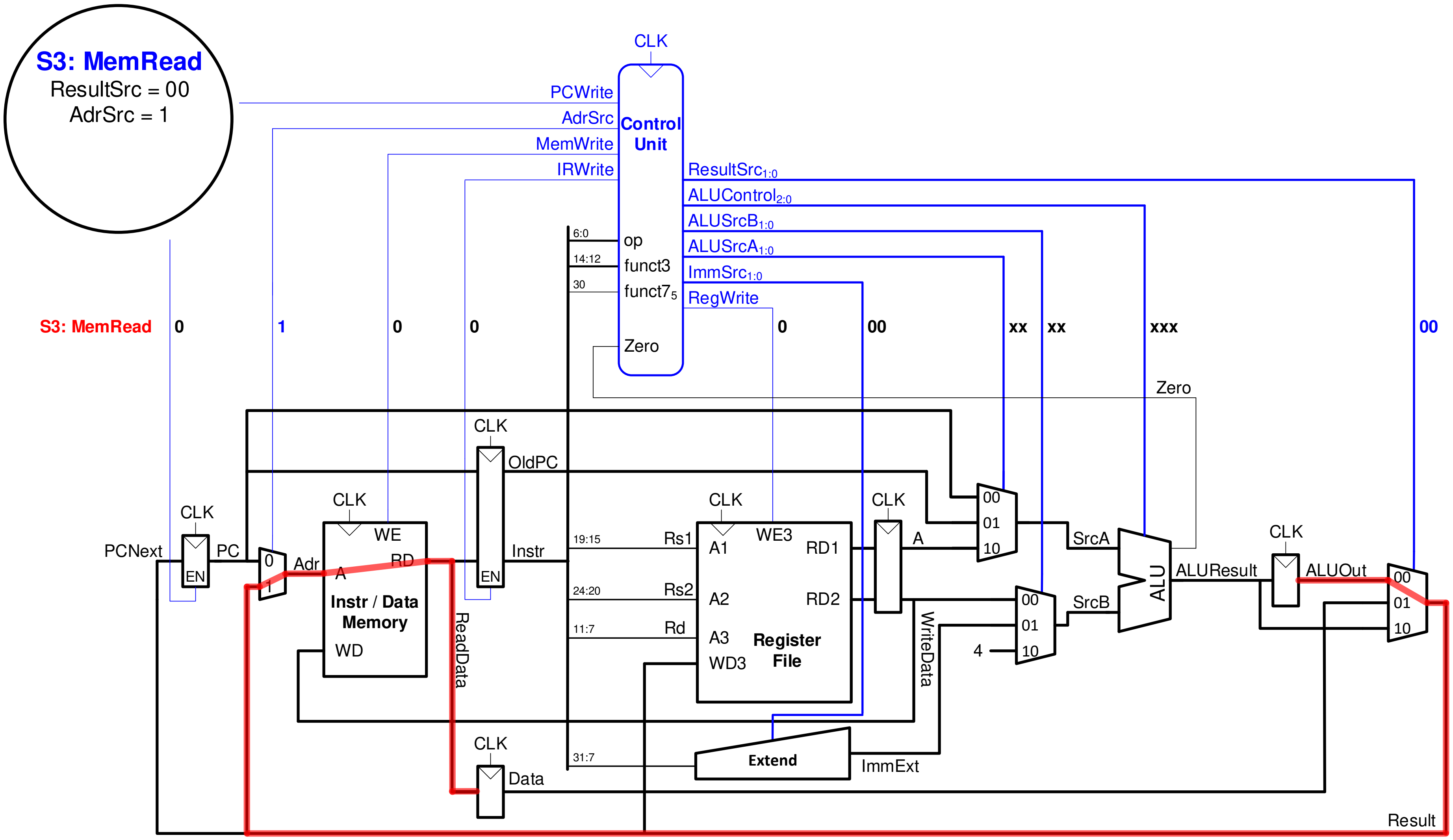
Main FSM: Address



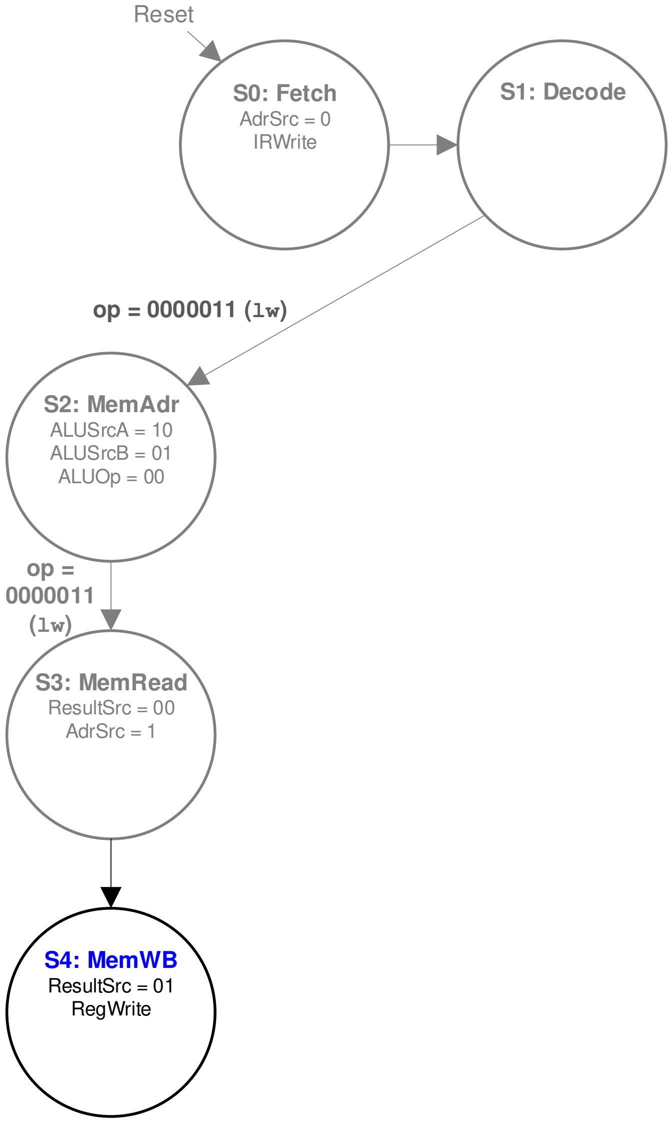
Main FSM: Read Memory



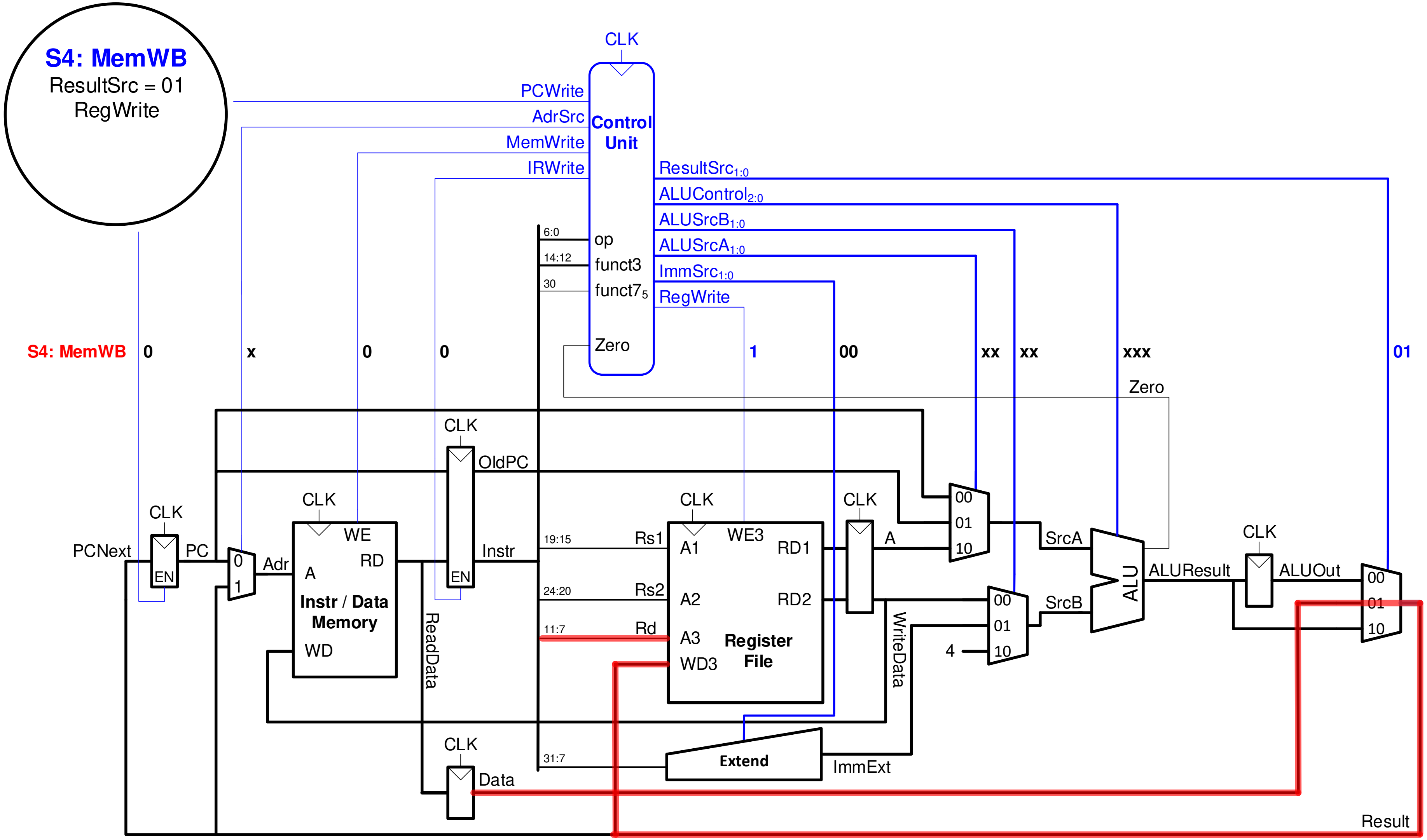
Main FSM: Read Memory Datapath



Main FSM: Write RF

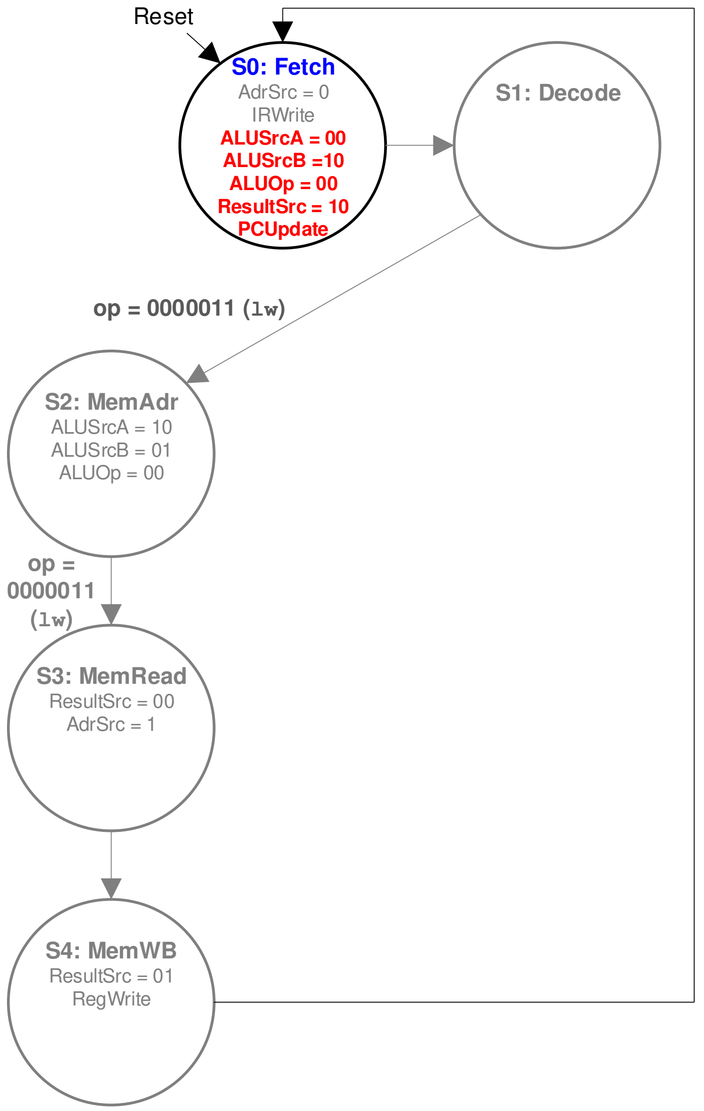


Main FSM: Write RF Datapath



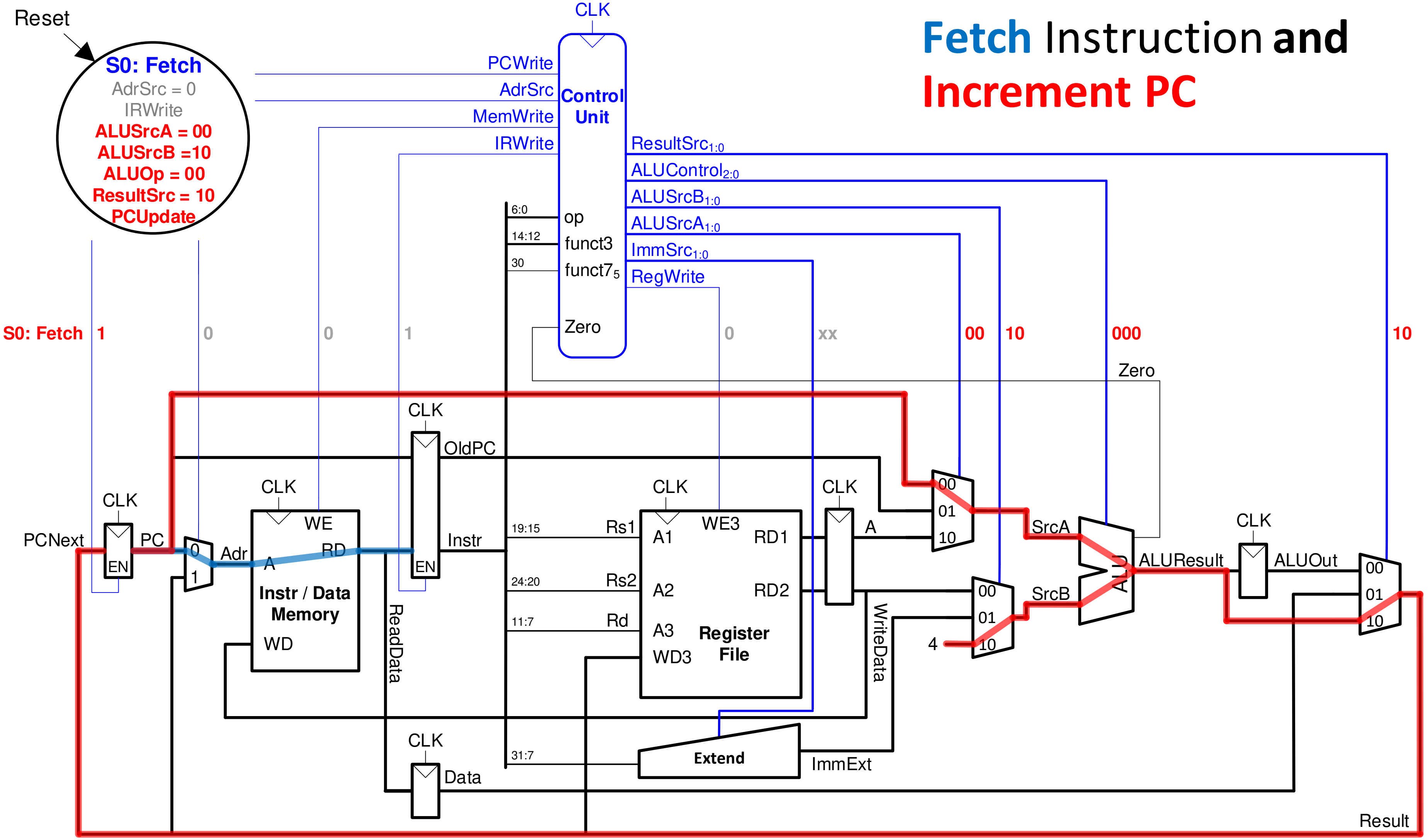
Main FSM: Fetch Revisited

Calculate **PC+4** during Fetch stage (ALU isn't being used)



Main FSM: Fetch (PC+4) Datapath

Fetch Instruction **and**
Increment PC



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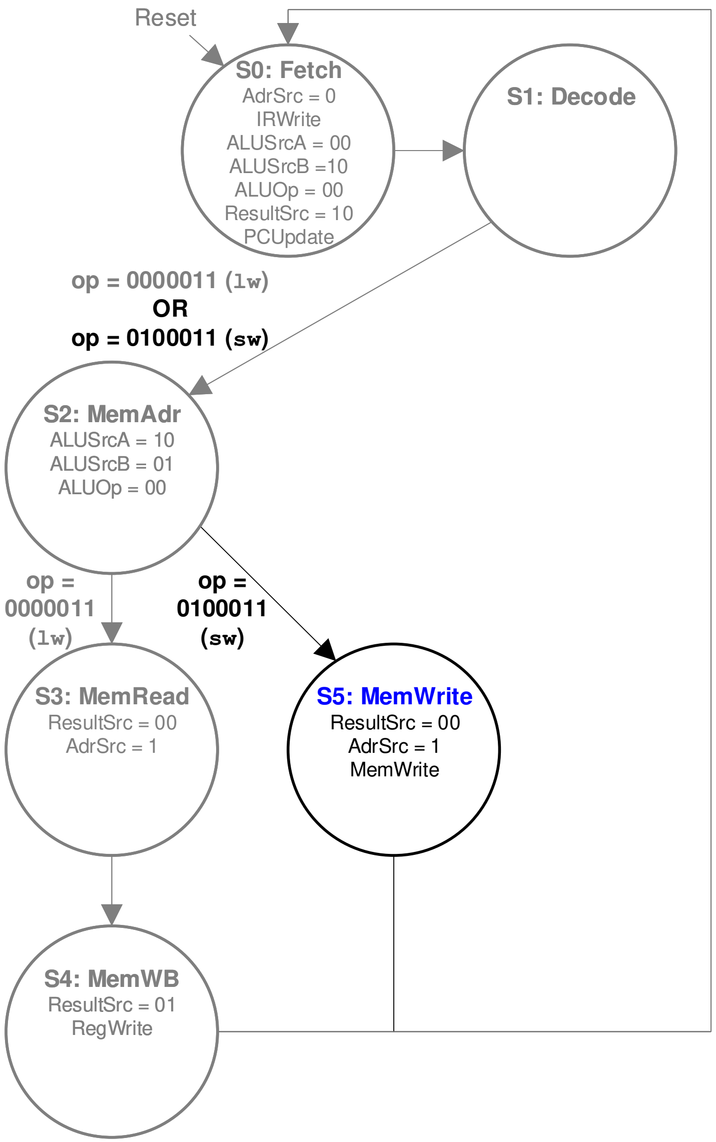
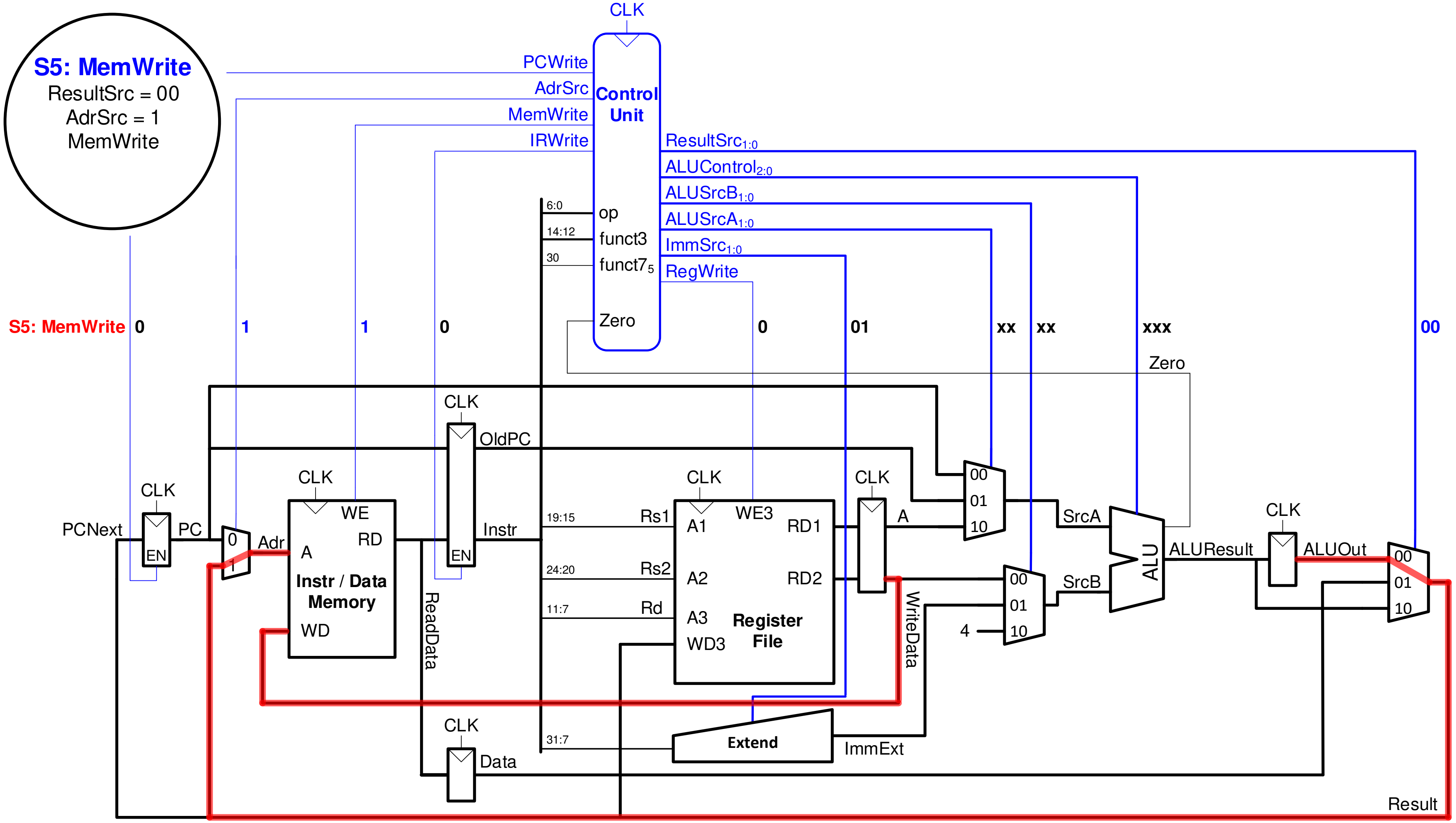
Multicycle Control: Other Instructions

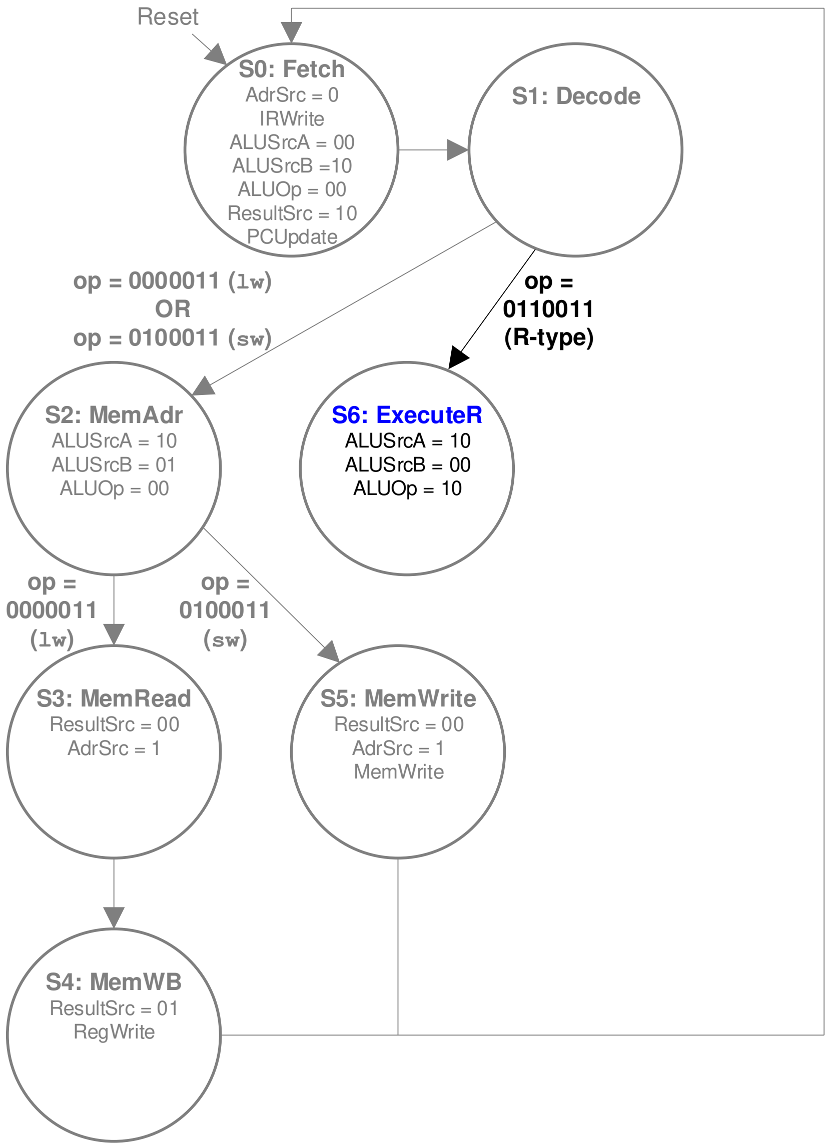
Main FSM: sw


Reset
S0: Fetch
AdrSrc = 0
IRWrite
ALUSrcA = 00
ALUSrcB =10
ALUOp = 00
ResultSrc = 10
PCUpdate
S1: Decode
op = 0000011 (lw)
OR
op = 0100011 (sw)
S2: MemAdr
ALUSrcA = 10
ALUSrcB = 01
ALUOp = 00
op = 0000011 (lw)
op = 0100011 (sw)
S3: MemRead
ResultSrc = 00
AdrSrc = 1
S5: MemWrite
ResultSrc = 00
AdrSrc = 1
MemWrite
S4: MemWB
ResultSrc = 01
RegWrite

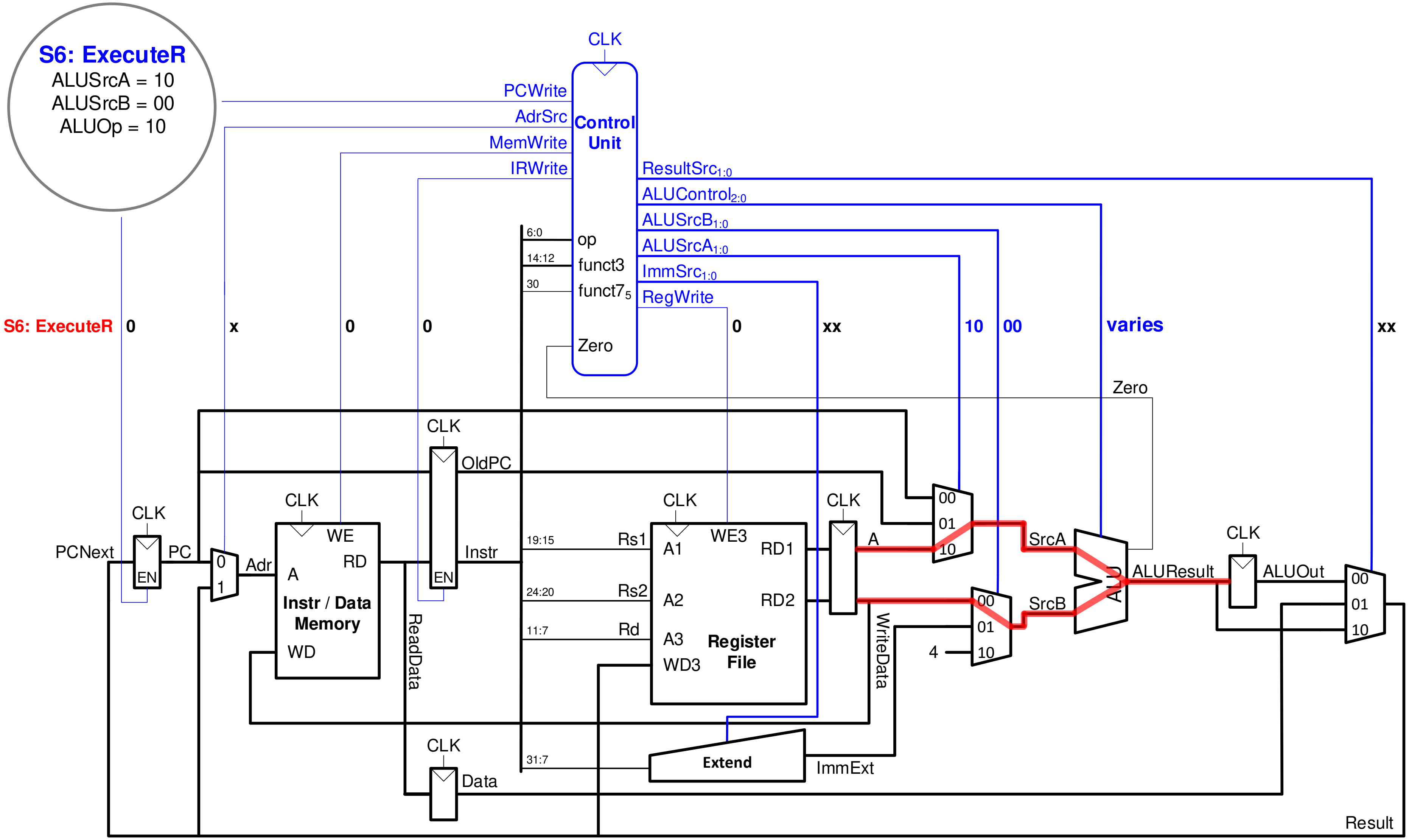
Main FSM: `sw` Datapath



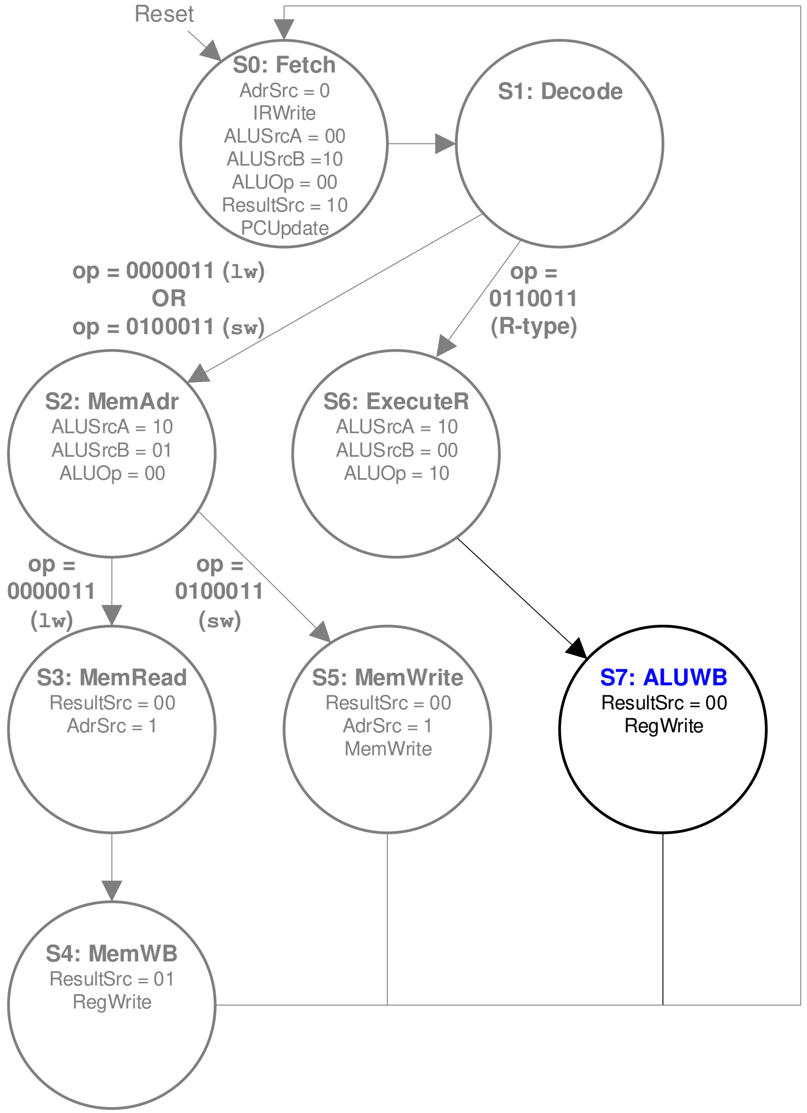
Main FSM: R-Type Execute



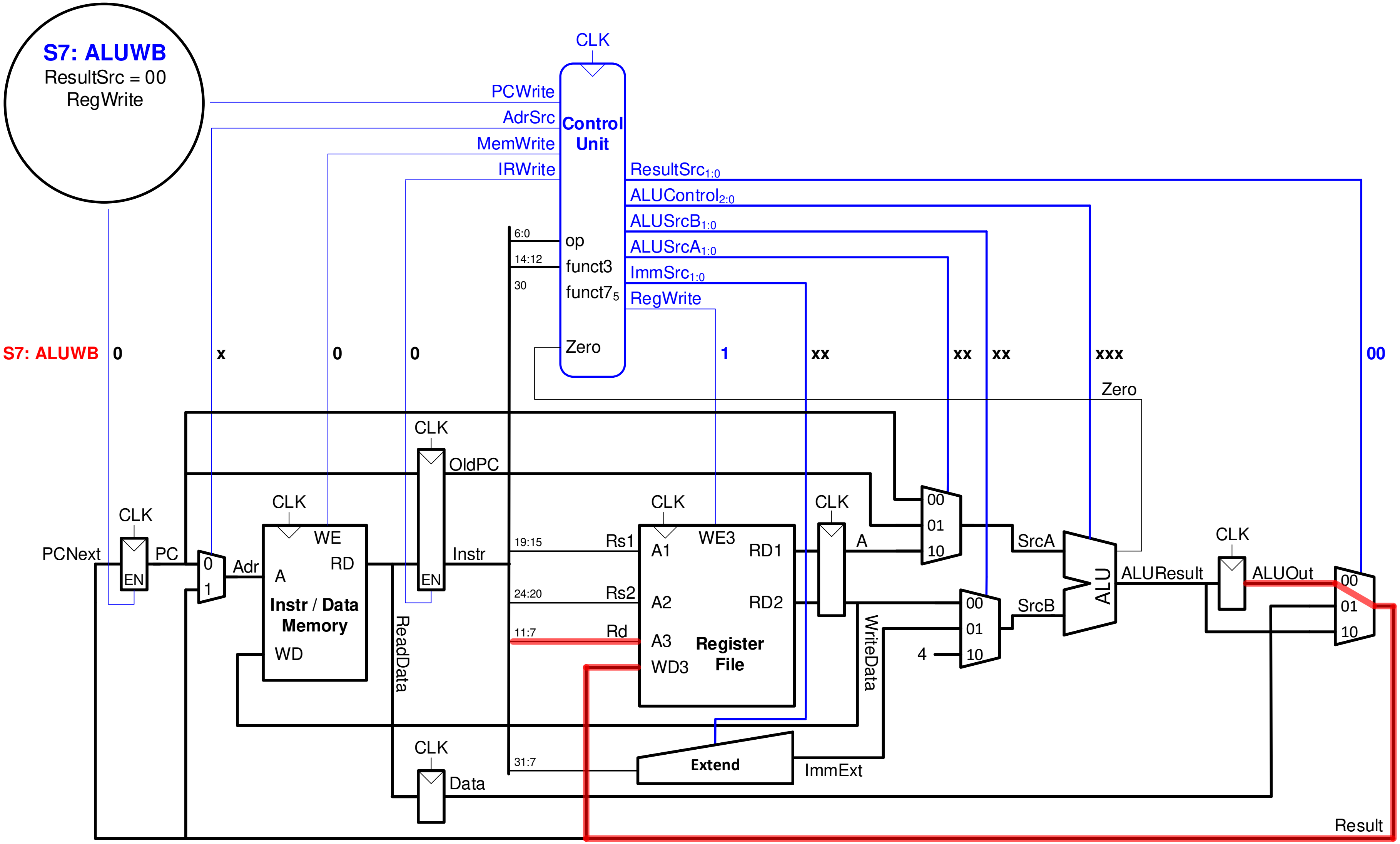
Main FSM: R-Type Execute Datapath



Main FSM: R-Type ALU Write Back



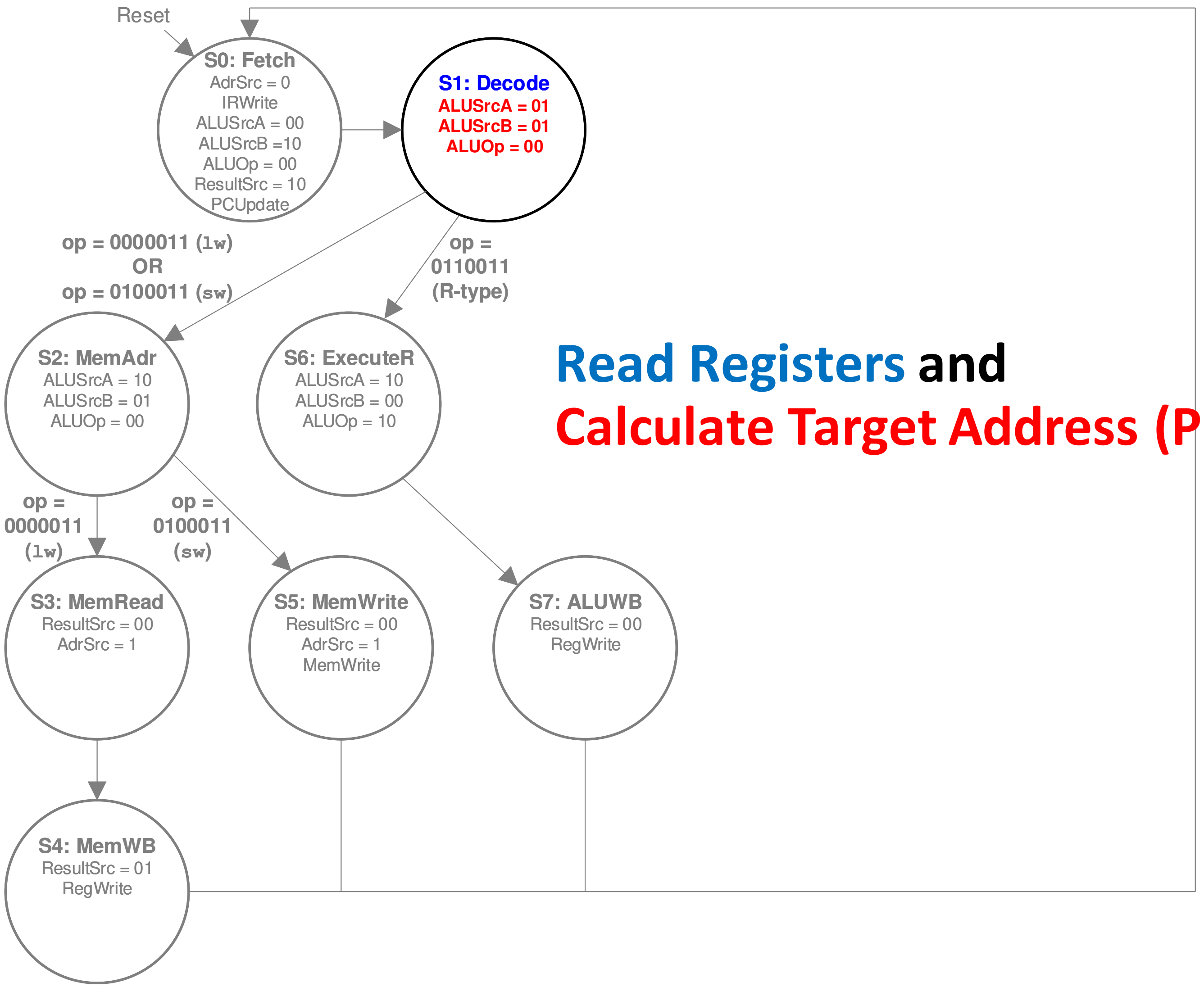
Main FSM: R-Type ALU Write Back



Main FSM: beq

- **Need to calculate:**
  - Branch Target Address
  - **rs1** - **rs2** (to see if equal)
- **ALU** isn't being used in Decode stage
  - Use it to calculate Target Address (PC + imm)

Main FSM: Decode Revisited

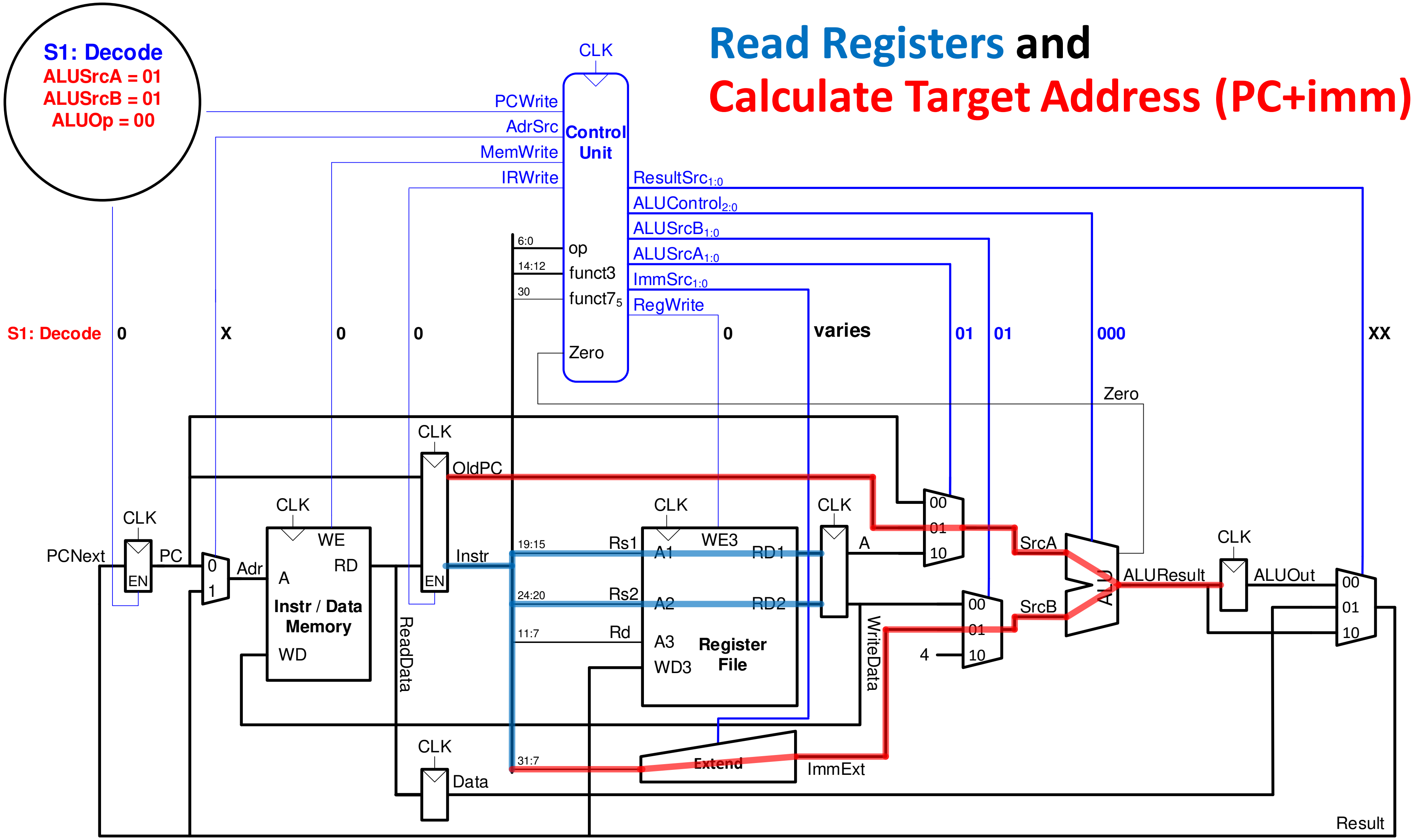


Read Registers and
Calculate Target Address (PC+imm)

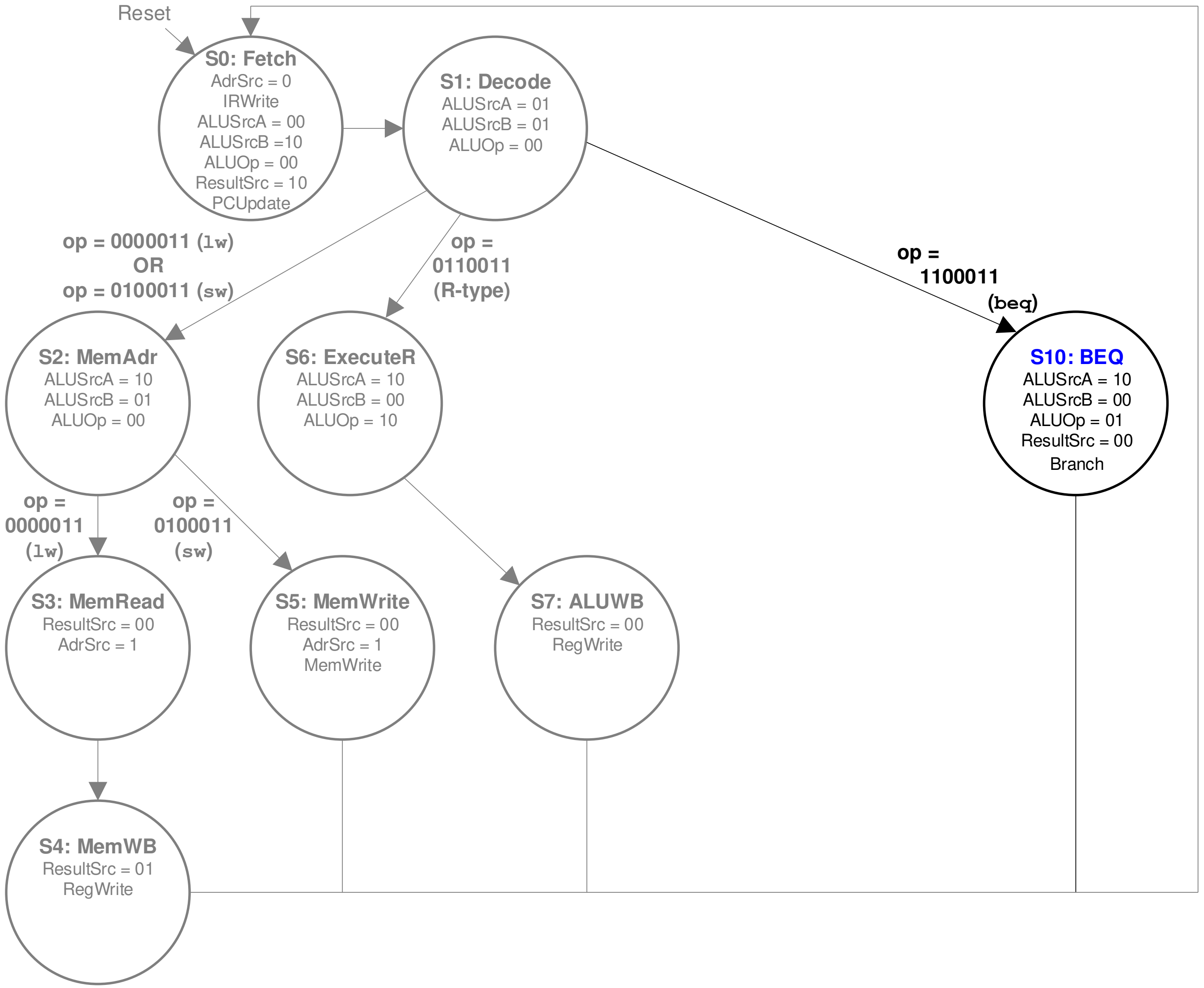
Main FSM: Decode (Target Address)

Read Registers and

Calculate Target Address (PC+imm)



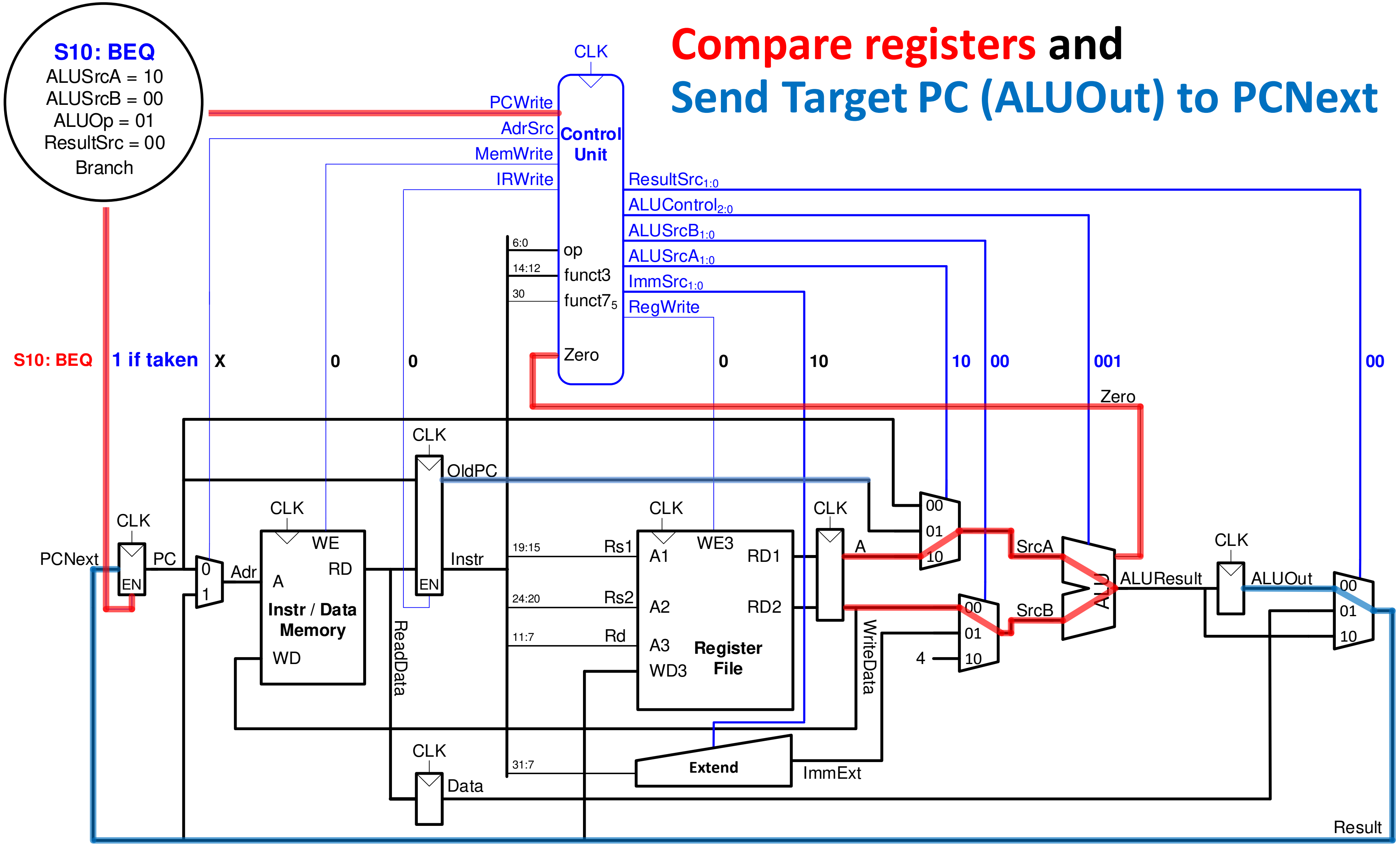
Main FSM: beq


Reset
S0: Fetch
AdrSrc = 0
IRWrite
ALUSrcA = 00
ALUSrcB =10
ALUOp = 00
ResultSrc = 10
PCUpdate
S1: Decode
ALUSrcA = 01
ALUSrcB = 01
ALUOp = 00
op = 0000011 (lw)
OR
op = 0100011 (sw)
op =
0110011
(R-type)
op =
1100011
(beq)
S2: MemAdr
ALUSrcA = 10
ALUSrcB = 01
ALUOp = 00
S6: ExecuteR
ALUSrcA = 10
ALUSrcB = 00
ALUOp = 10
S10: BEQ
ALUSrcA = 10
ALUSrcB = 00
ALUOp = 01
ResultSrc = 00
Branch
op =
0000011
(lw)
op =
0100011
(sw)
S3: MemRead
ResultSrc = 00
AdrSrc = 1
S5: MemWrite
ResultSrc = 00
AdrSrc = 1
MemWrite
S7: ALUWB
ResultSrc = 00
RegWrite
S4: MemWB
ResultSrc = 01
RegWrite

Main FSM: beq Datapath

Compare registers and

Send Target PC (ALUOut) to PCNext



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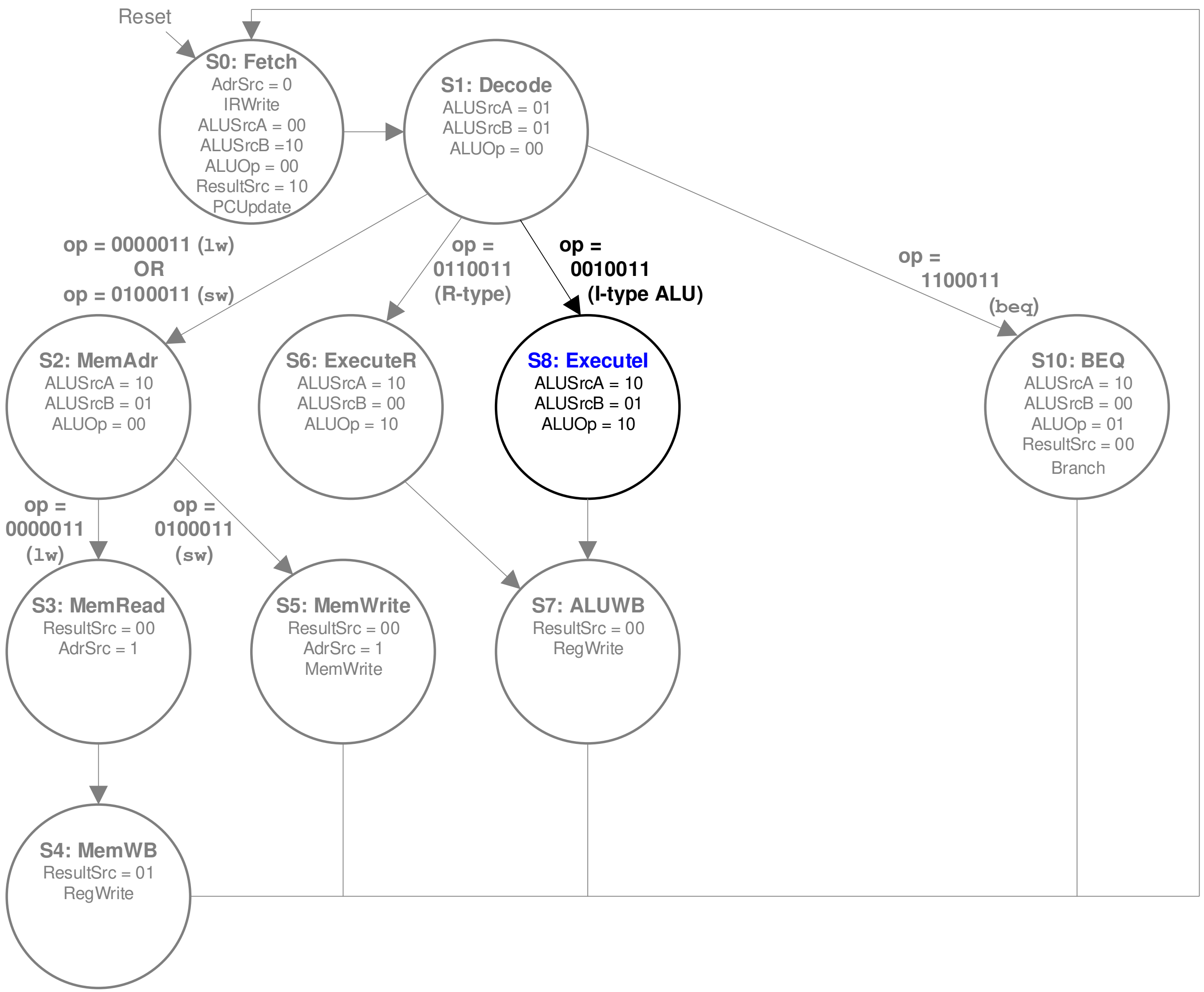
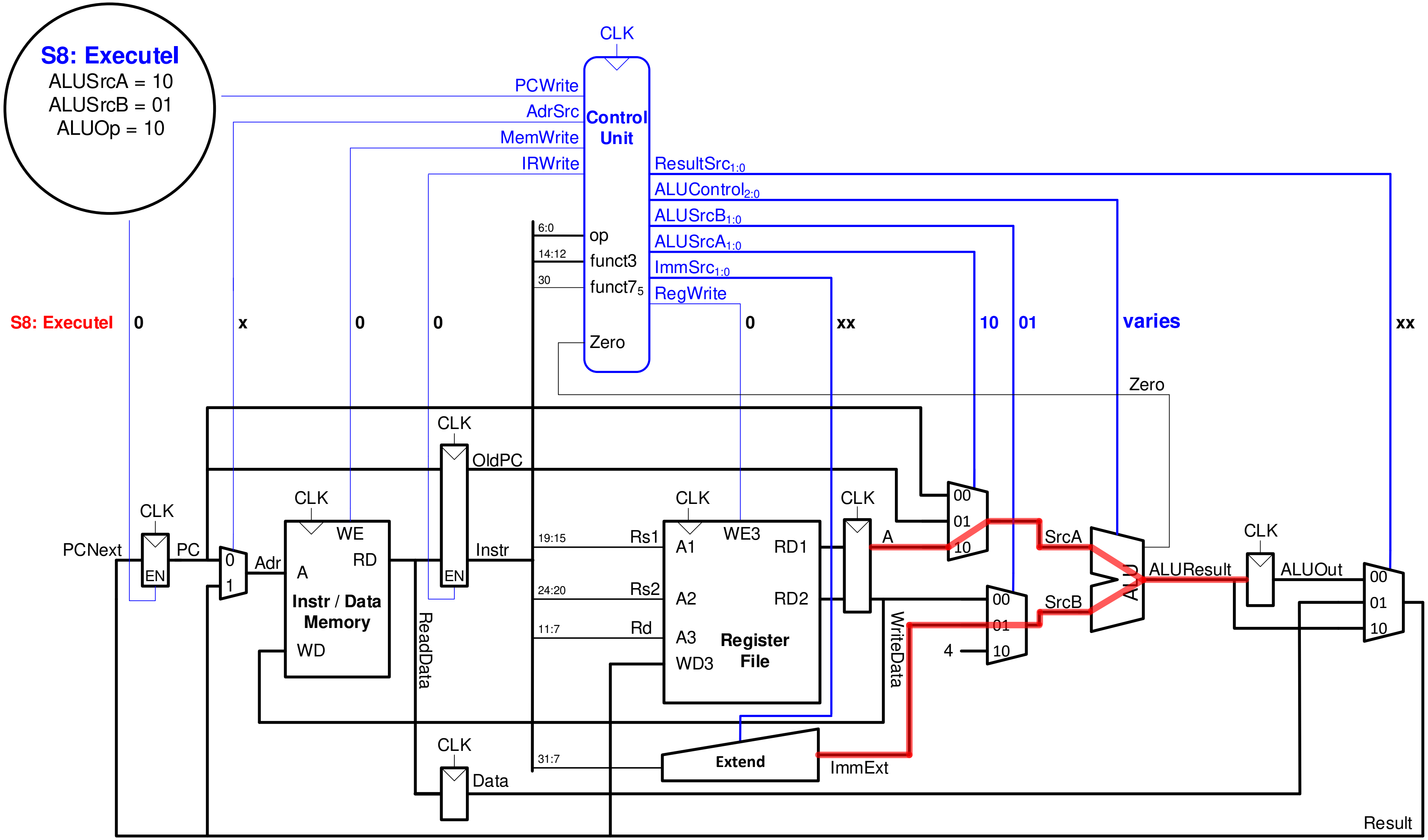
Extending the RISC-V Multicycle Processor

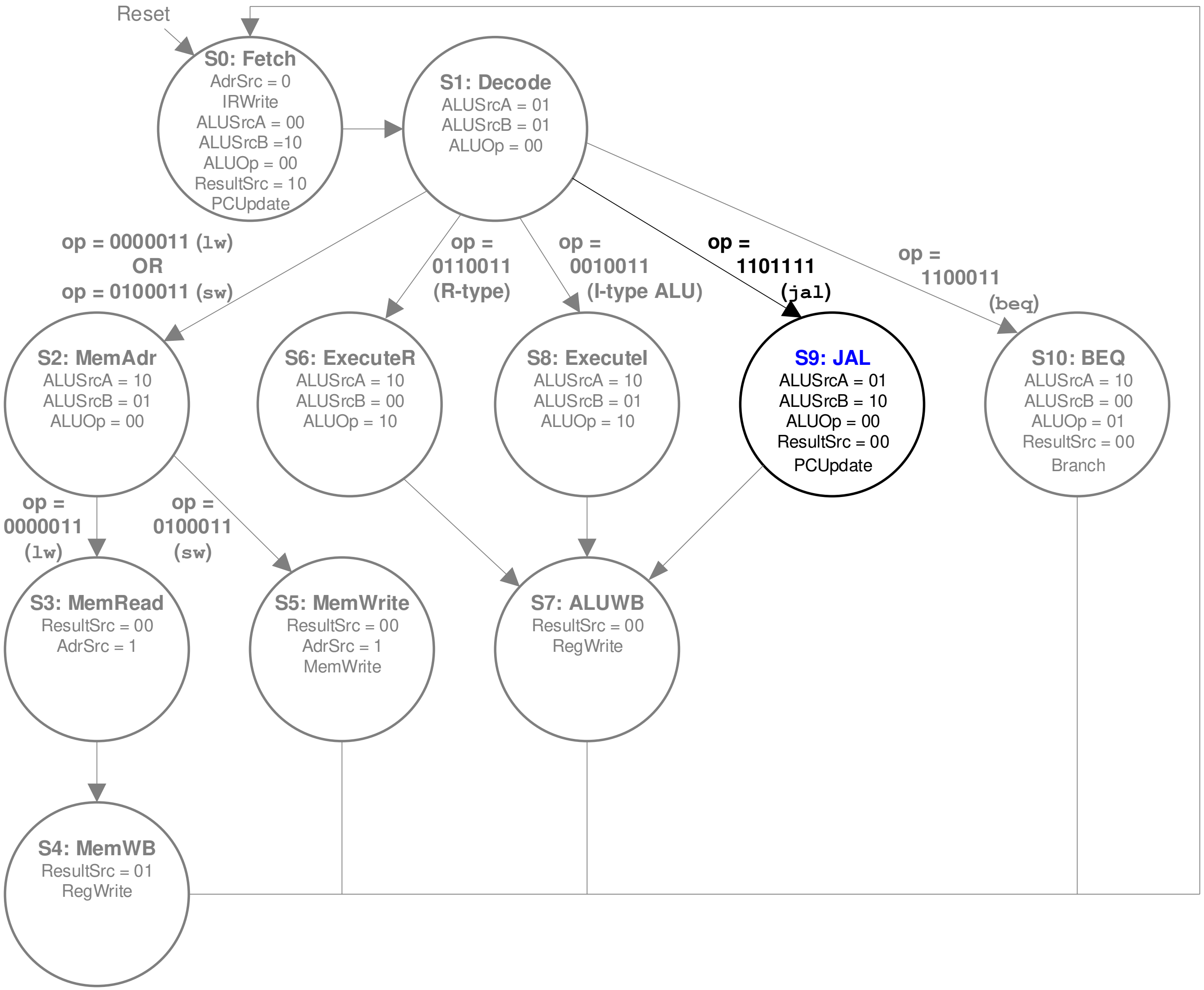
Main FSM: I-Type ALU Execute



Main FSM: I-Type ALU Exec. Datapath

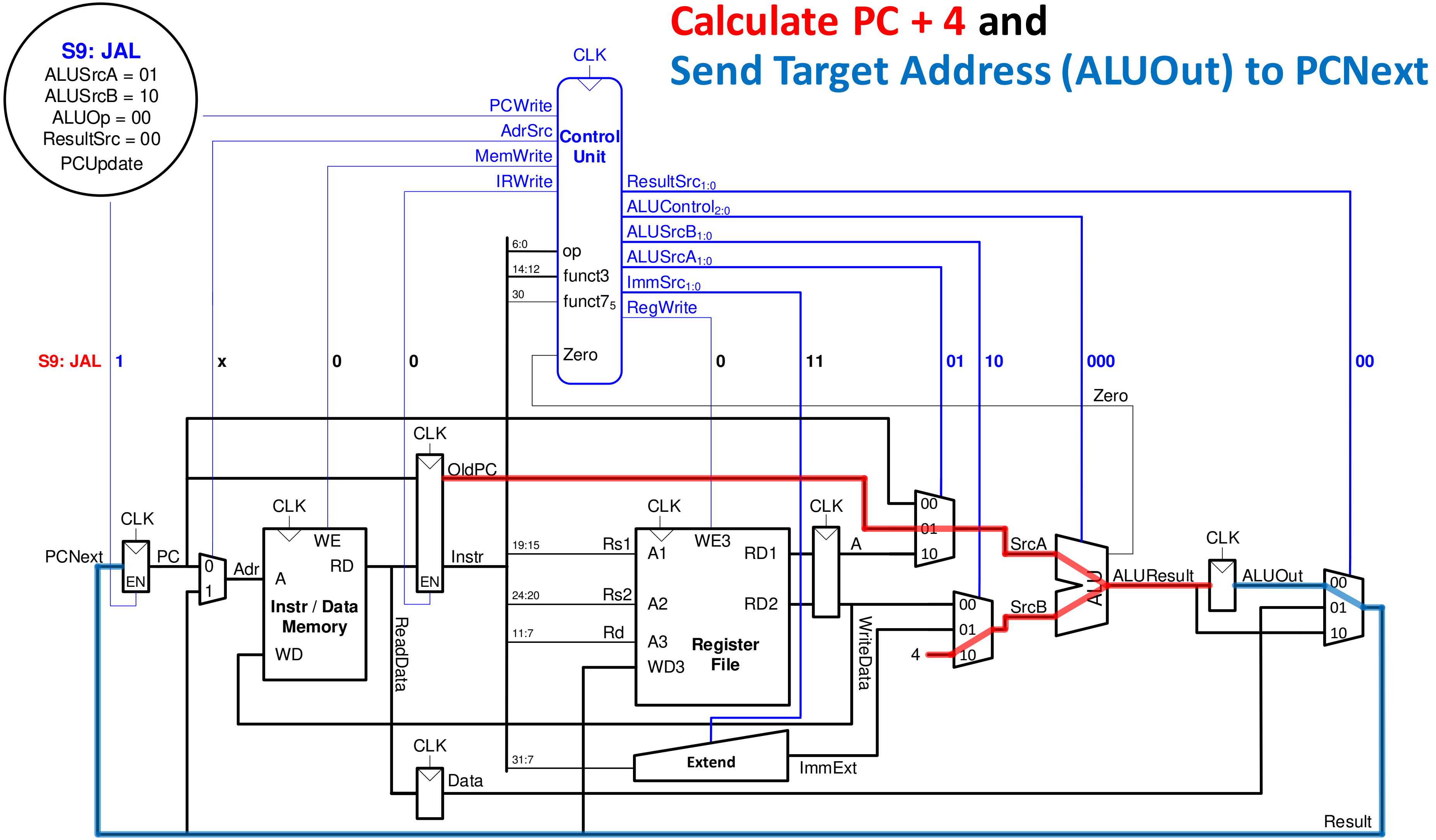


Main FSM: `jal`


Reset
S0: Fetch
AdrSrc = 0
IRWrite
ALUSrcA = 00
ALUSrcB =10
ALUOp = 00
ResultSrc = 10
PCUpdate
S1: Decode
ALUSrcA = 01
ALUSrcB = 01
ALUOp = 00
op = 0000011 (lw)
OR
op = 0100011 (sw)
op = 0110011 (R-type)
op = 0010011 (I-type ALU)
op = 1101111 (jal)
op = 1100011 (beq)
S2: MemAdr
ALUSrcA = 10
ALUSrcB = 01
ALUOp = 00
S6: ExecuteR
ALUSrcA = 10
ALUSrcB = 00
ALUOp = 10
S8: ExecuteI
ALUSrcA = 10
ALUSrcB = 01
ALUOp = 10
S9: JAL
ALUSrcA = 01
ALUSrcB = 10
ALUOp = 00
ResultSrc = 00
PCUpdate
S10: BEQ
ALUSrcA = 10
ALUSrcB = 00
ALUOp = 01
ResultSrc = 00
Branch
op = 0000011 (lw)
op = 0100011 (sw)
S3: MemRead
ResultSrc = 00
AdrSrc = 1
S5: MemWrite
ResultSrc = 00
AdrSrc = 1
MemWrite
S7: ALUWB
ResultSrc = 00
RegWrite
S4: MemWB
ResultSrc = 01
RegWrite

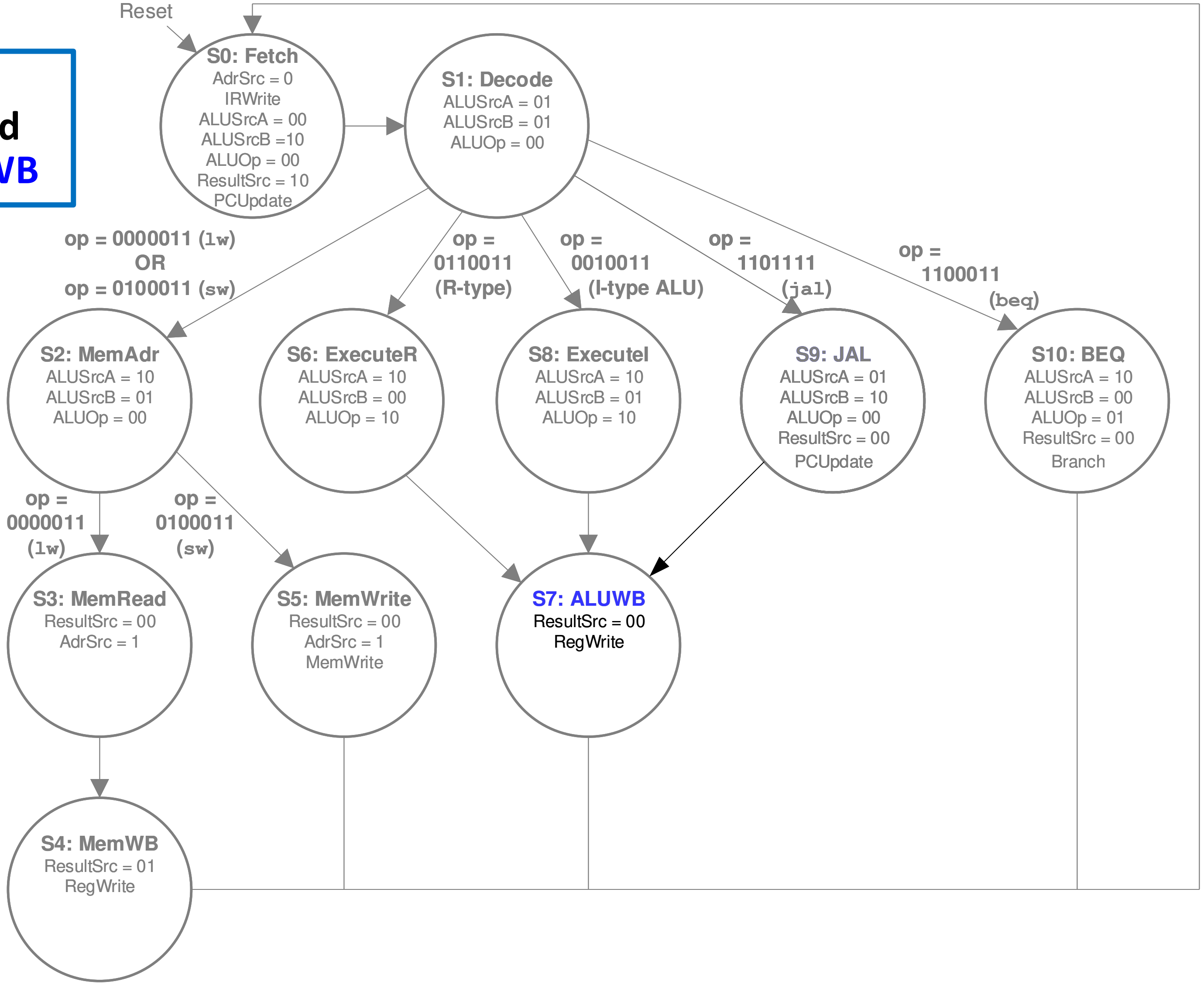
Main FSM: `jal` Datapath

Calculate PC + 4 and
Send Target Address (ALUOut) to PCNext



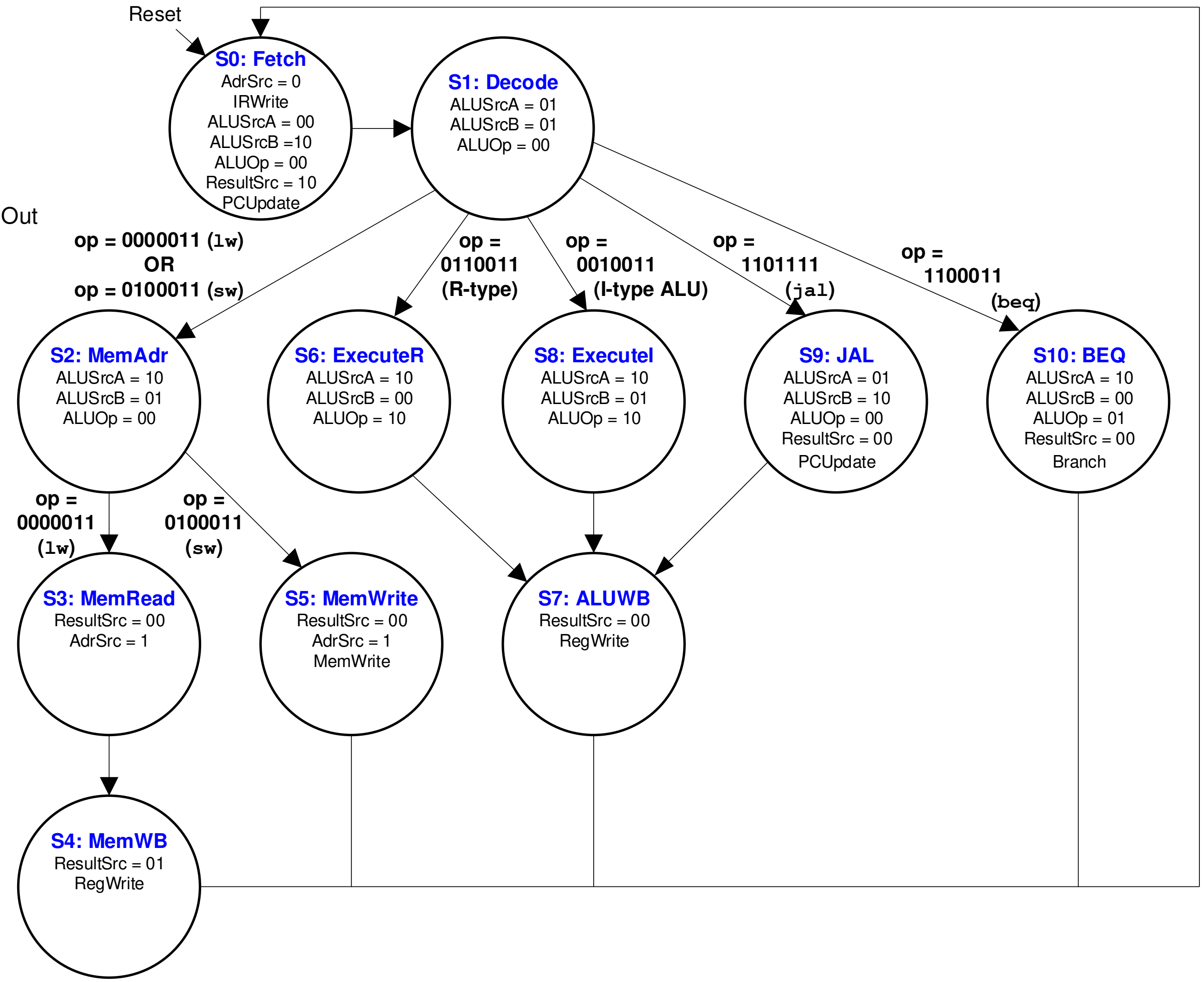
Main FSM: `jal`

PC + 4 is written to **rd** in **S7: ALUWB**



Multicycle Processor Main FSM

State	Datapath µOp
Fetch	Instr ←Mem[PC]; PC ← PC+4
Decode	ALUOut ← PCTarget
MemAdr	ALUOut ← rs1 + imm
MemRead	Data ← Mem[ALUOut]
MemWB	rd ← Data
MemWrite	Mem[ALUOut] ← rd
ExecuteR	ALUOut ← rs1 op rs2
ExecuteI	ALUOut ← rs1 op imm
ALUWB	rd ← ALUOut
BEQ	ALUResult = rs1-rs2; if Zero, PC = ALUOut
JAL	PC = ALUOut; ALUOut = PC+4



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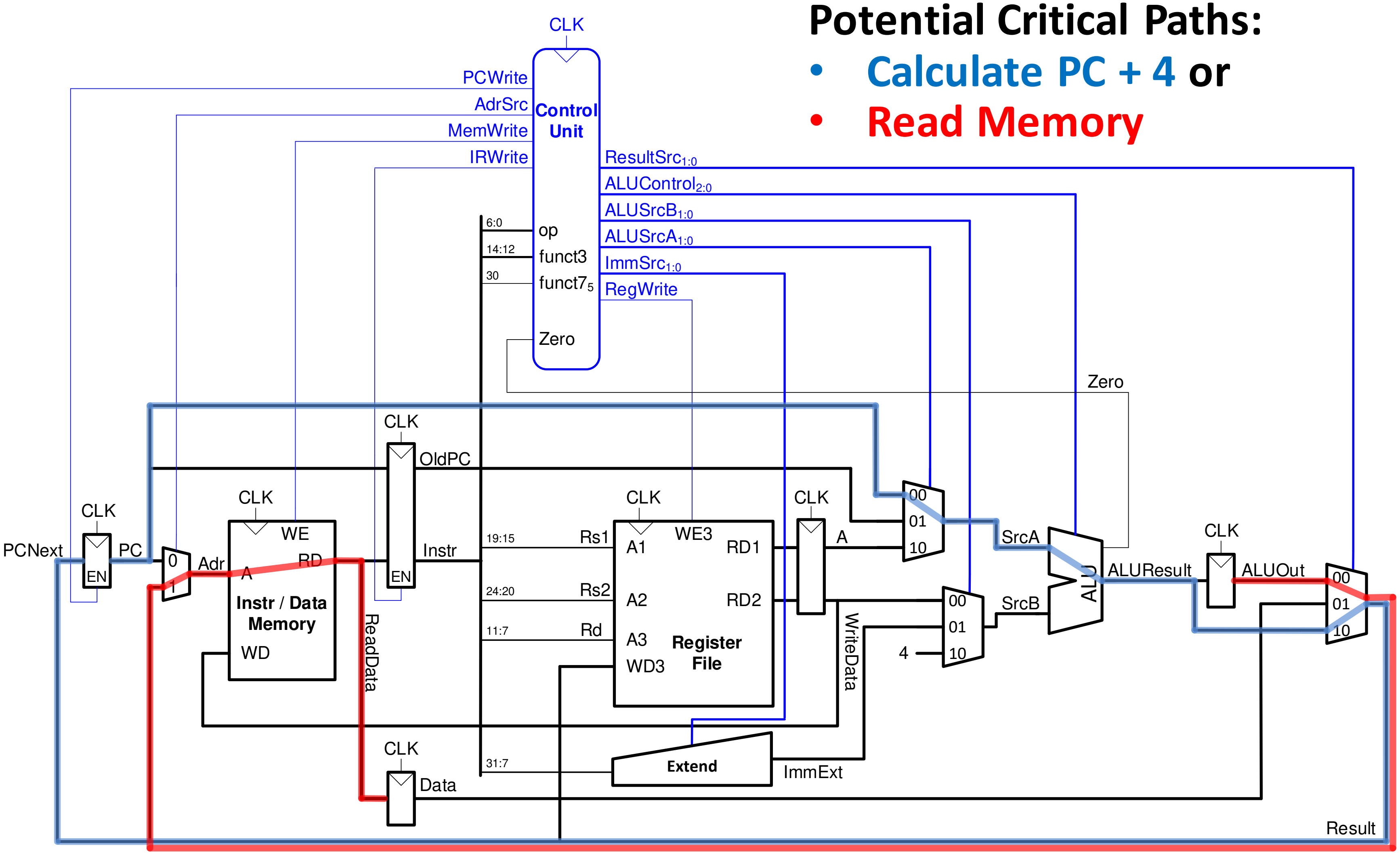
Multicycle Performance

Multicycle Processor Performance

- Instructions take different number of cycles:
  - 3 cycles: `beq`
  - 4 cycles: R-type, `addi`, `sw` , `jal`
  - 5 cycles: `lw`
- CPI is weighted average
- SPECINT2000 benchmark:
  - **25%** loads
  - **10%** stores
  - **13%** branches
  - **52%** R-type

Average CPI = (**0.13**)(3) + (**0.52 + 0.10**)(4) + (**0.25**)(5) = **4.12**

Multicycle Critical Path



Potential Critical Paths:

- Calculate PC + 4 or
- Read Memory

Multicycle Processor Performance

Multicycle critical path:

- **Assumptions:**
  - RF is faster than memory
  - Writing memory is faster than reading memory

$$T_{c\_multi} = t_{pcq} + t_{\text{dec}} + 2t_{\text{mux}} + \max(t_{\text{ALU}}, t_{\text{mem}}) + t_{\text{setup}}$$

Multicycle Performance Example

Element	Parameter	Delay (ps)
Register clock-to-Q	t_{pcq_PC}	40
Register setup	t_{setup}	50
Multiplexer	t_{mux}	30
AND-OR gate	$t_{\mathrm{AND\text{-}OR}}$	20
ALU	t_{ALU}	120
Decoder (Control Unit)	t_{dec}	25
Extend unit	t_{dec}	35
Memory read	t_{mem}	200
Register file read	$t_{RF\mathrm{read}}$	100
Register file setup	$t_{RF\mathrm{setup}}$	60

$$T_{c\_multi} = t_{pcq} + t_{\mathrm{dec}} + 2t_{\mathrm{mux}} + \max(t_{\mathrm{ALU}}, t_{\mathrm{mem}}) + t_{\mathrm{setup}}$$

$$=$$

Multicycle Performance Example

For a program with **100 billion** instructions executing on a **multicycle** RISC-V processor

- **CPI** = 4.12 cycles/instruction
- **Clock cycle time:** T_{c_multi} = 375 ps

Execution Time = (# instructions) × CPI × T_c