Fundamentals of Computer Systems

A Single Cycle MIPS Processor

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Let’s Build a Simple Processor

Supported instructions:

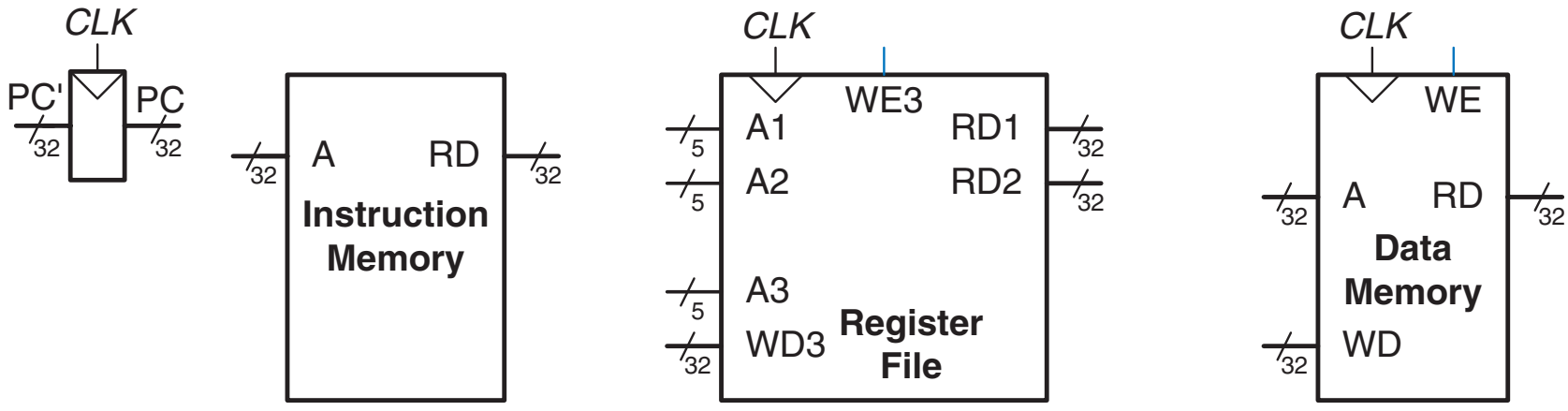
- R-type: and, or, addu, subu, slt
- Memory instructions: lw, sw
- Branch instructions: beq

Version 2.0:

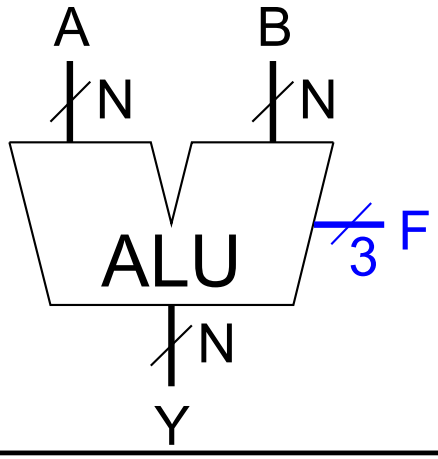
- I-type: addiu
- J-type: j

MIPS State Elements

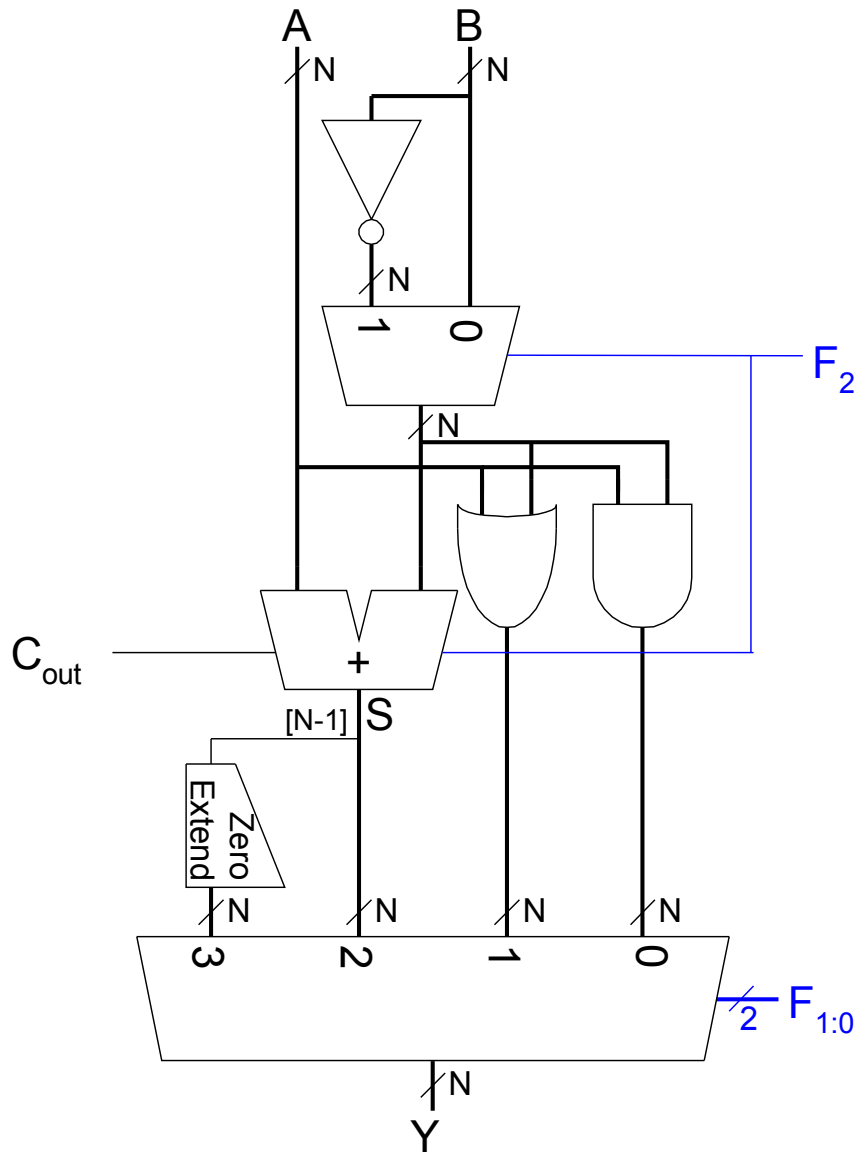
This is the programmer-visible state in the ISA



ALU Interface and Implementation

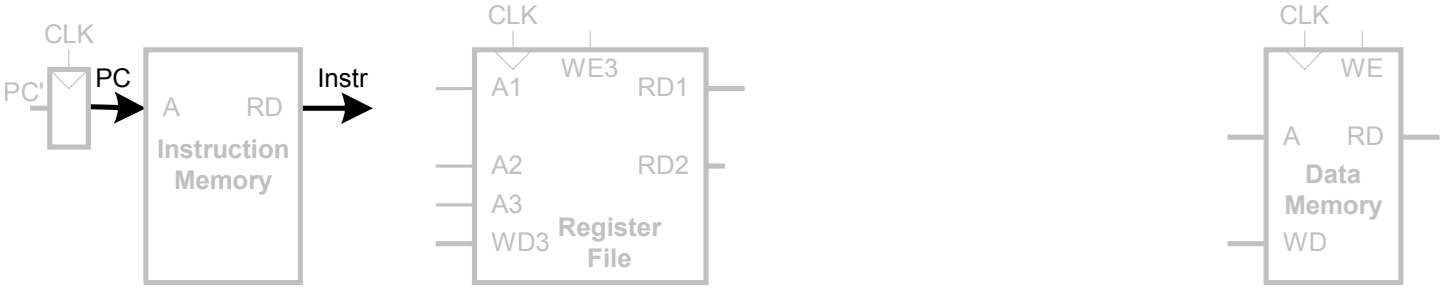


F2	F1	F0	Func.
0	0	0	A & B
0	0	1	A | B
0	1	0	A + B
0	1	1	
1	0	0	A & $\overline{B}$
1	0	1	A | $\overline{B}$
1	1	0	A − B
1	1	1	A < B (slt)



Datapath Elements for the `lw` Instruction

Fetch instruction from instruction memory:
Send the PC to the instruction memory's address

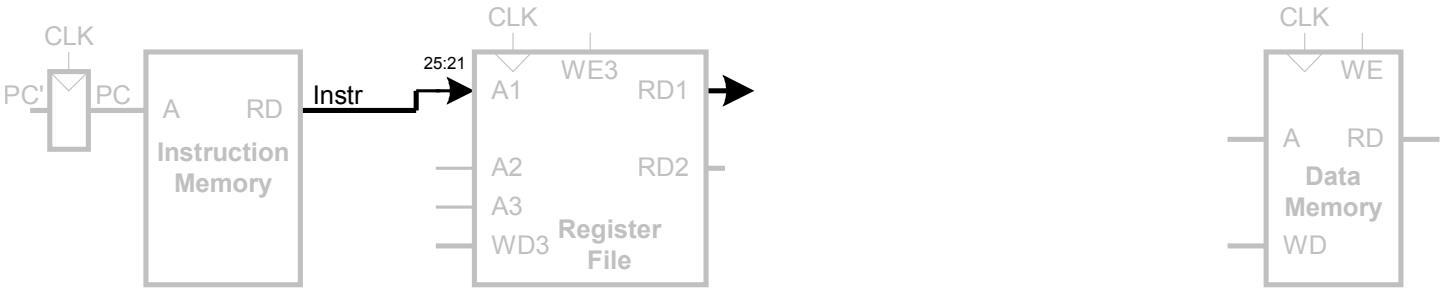


`lw rt, offset(base)`

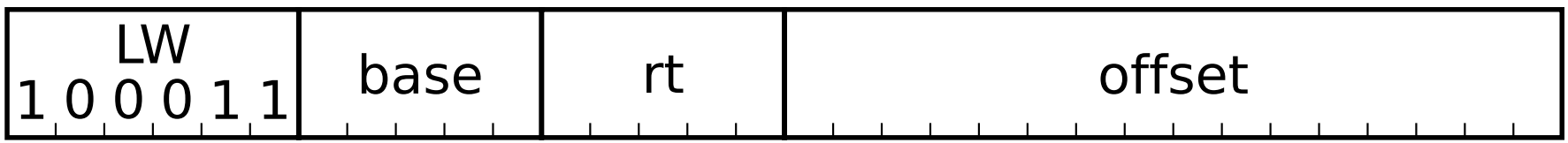
LW 1 0 0 0 1 1	base	rt	offset

Datapath Elements for the `lw` Instruction

Read the base register

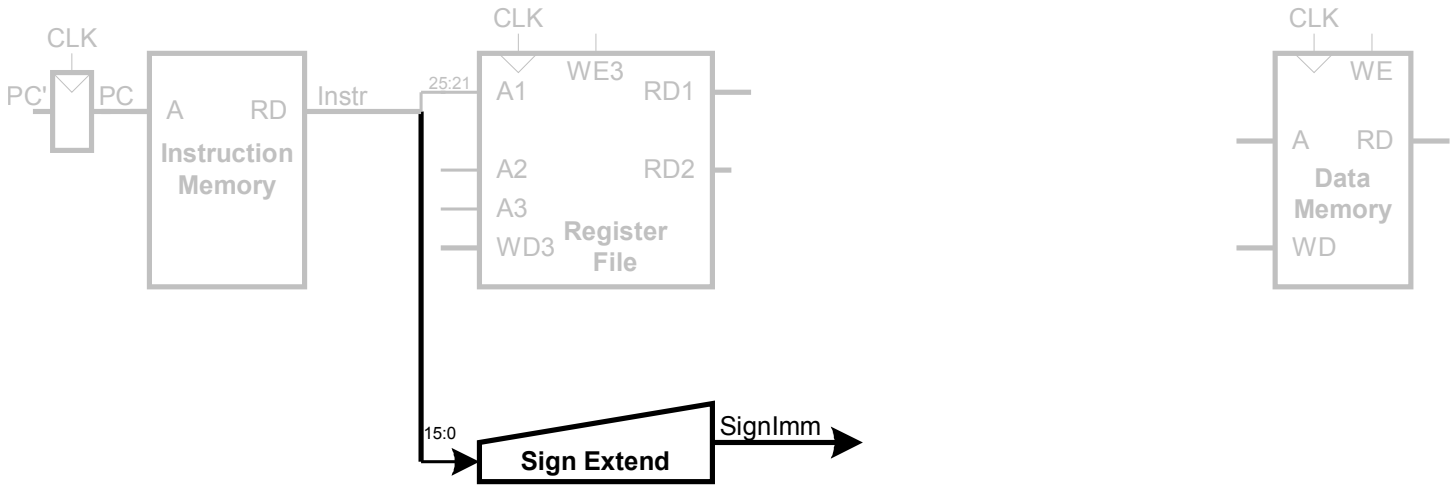


`lw rt, offset(base)`



Datapath Elements for the `lw` Instruction

Sign-extend the immediate

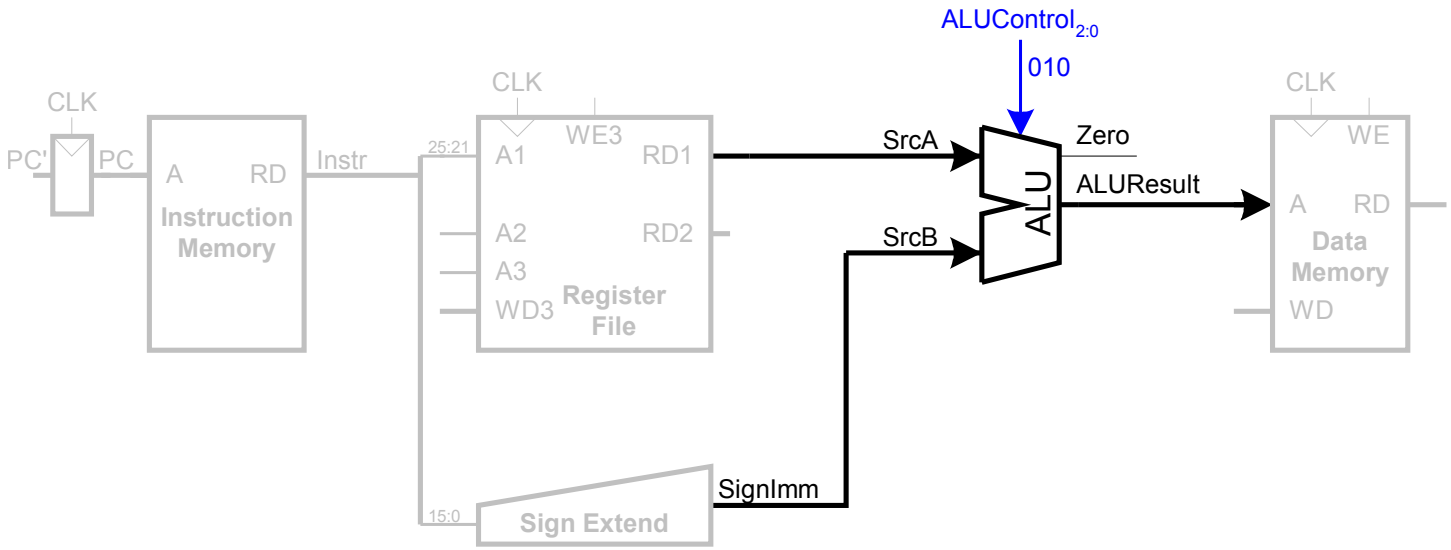


`lw rt, offset(base)`

LW 1 0 0 0 1 1	base	rt	offset

Datapath Elements for the `lw` Instruction

Add the base register and the sign-extended immediate to compute the data memory address

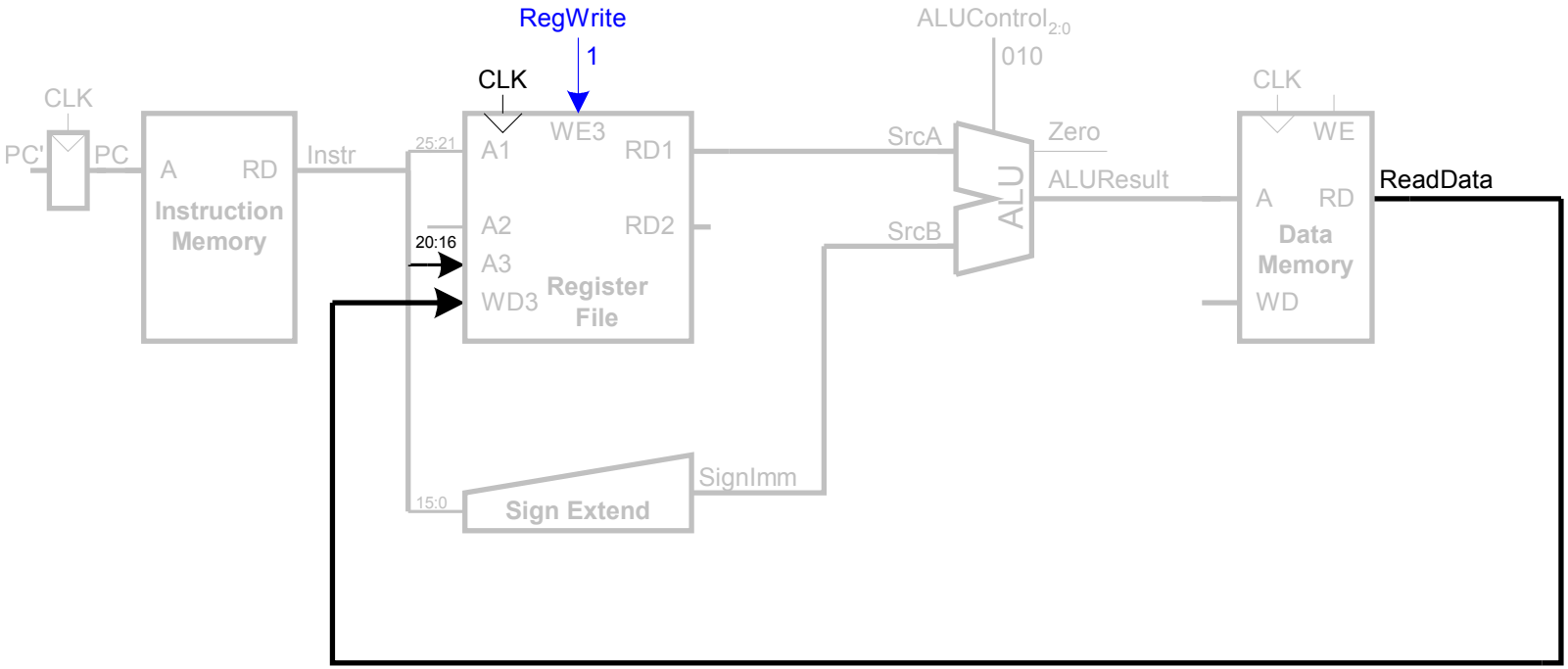


`lw rt, offset(base)`

LW 1 0 0 0 1 1	base	rt	offset

Datapath Elements for the `lw` Instruction

Read data from memory and write it back to rt in the register file

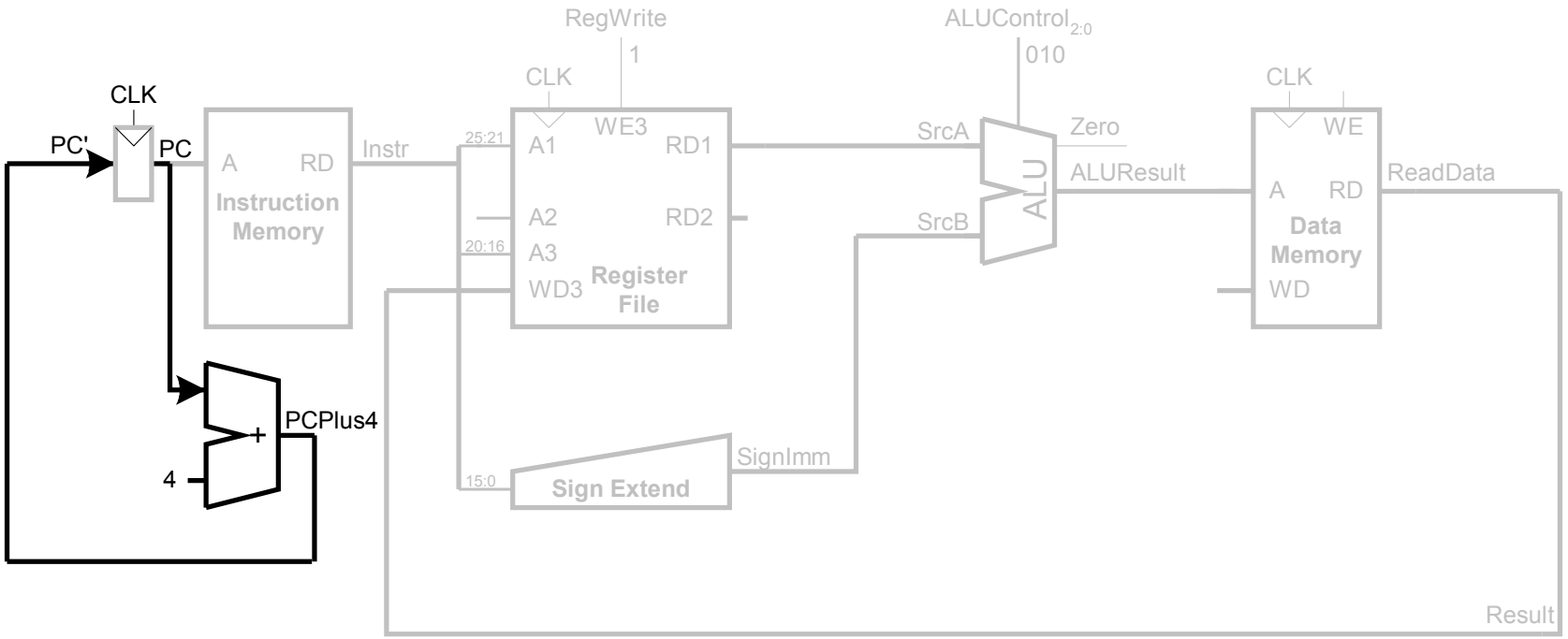


`lw rt, offset(base)`

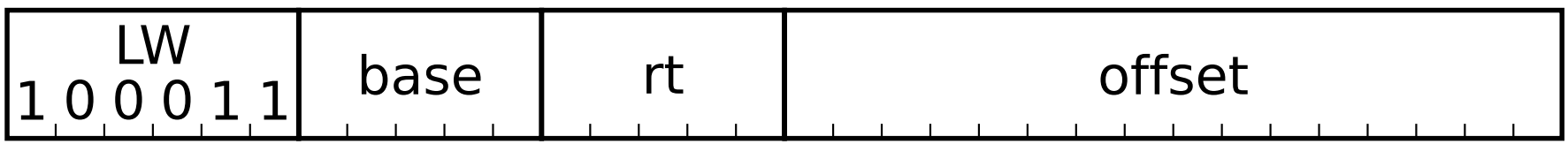
LW 100011	base	rt	offset

Datapath Elements for the `lw` Instruction

Add four to the program counter to determine address of the the next instruction to execute

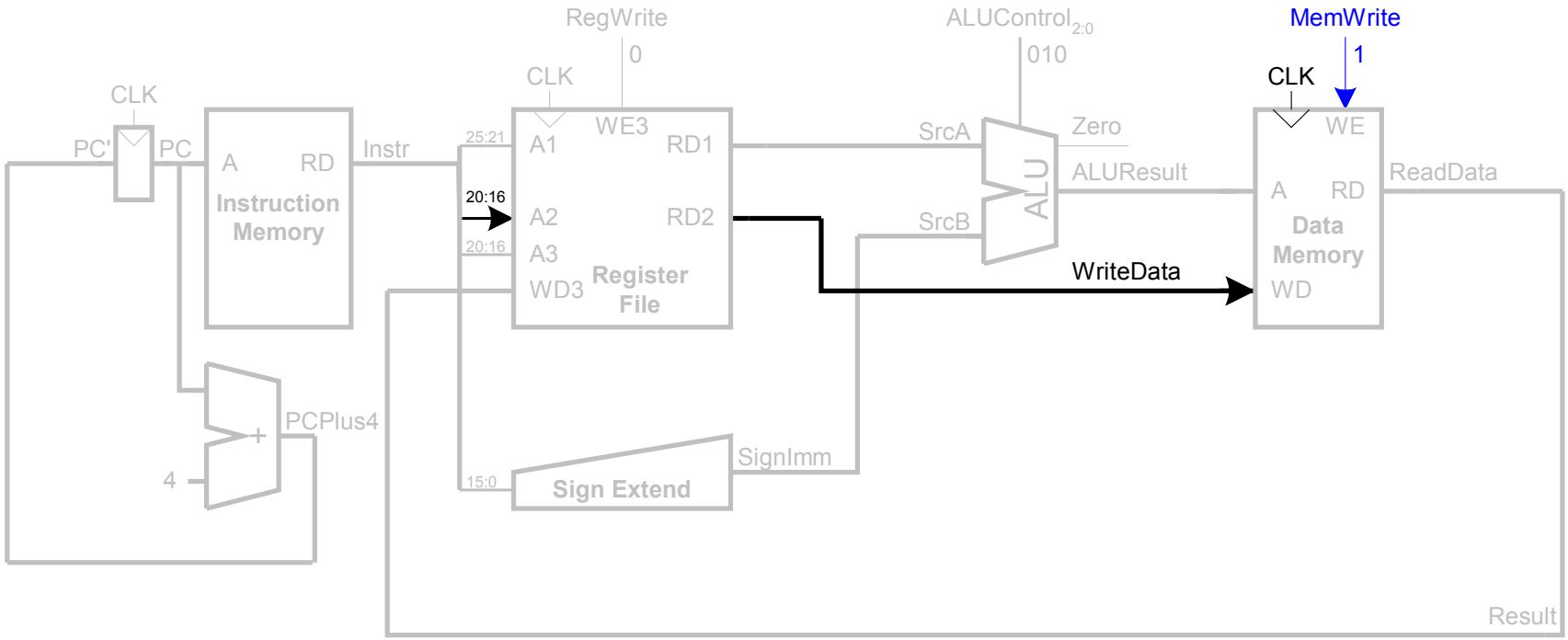


`lw rt, offset(base)`



Additional Elements for sw

Read rt from the register file and write it to data memory



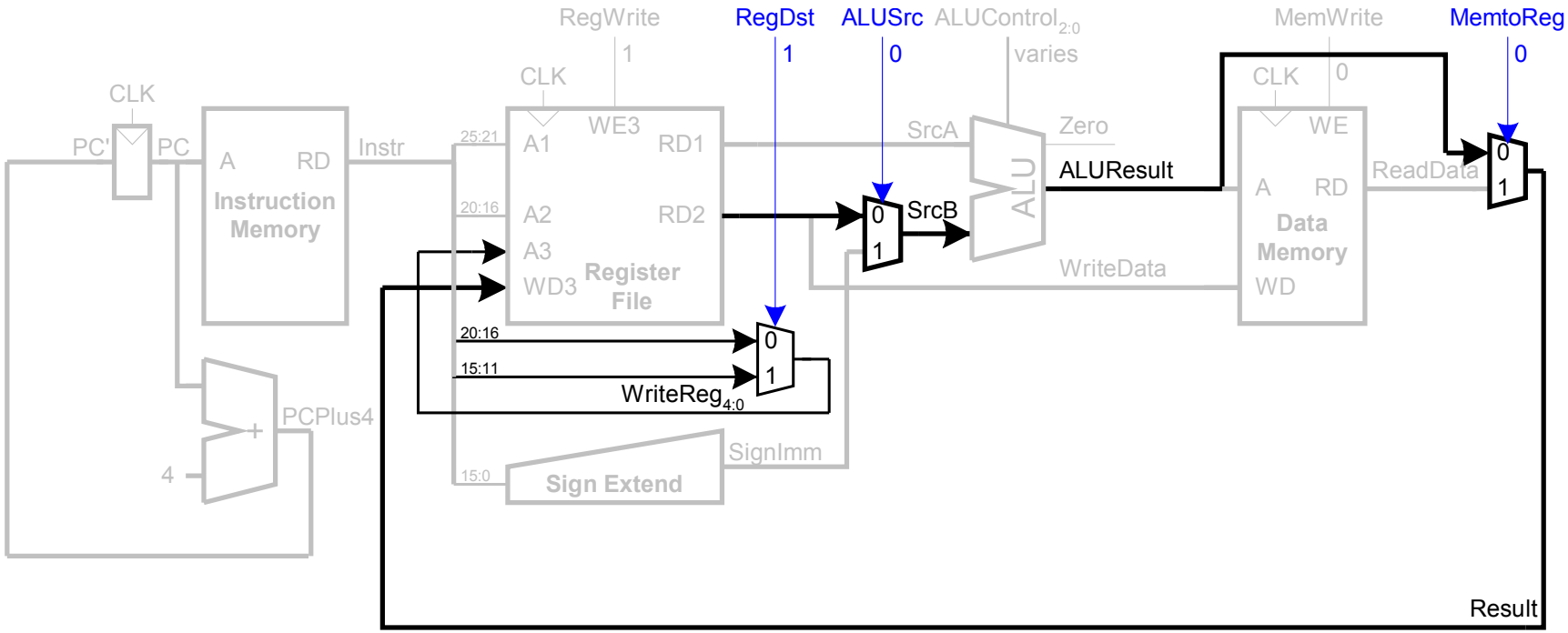
`sw rt, offset(base)`

SW 1 0 1 0 1 1	base	rt	offset

Additional Elements for R-Type Instructions

Read from rs and rt

Write ALUResult to rd (instead of rt)



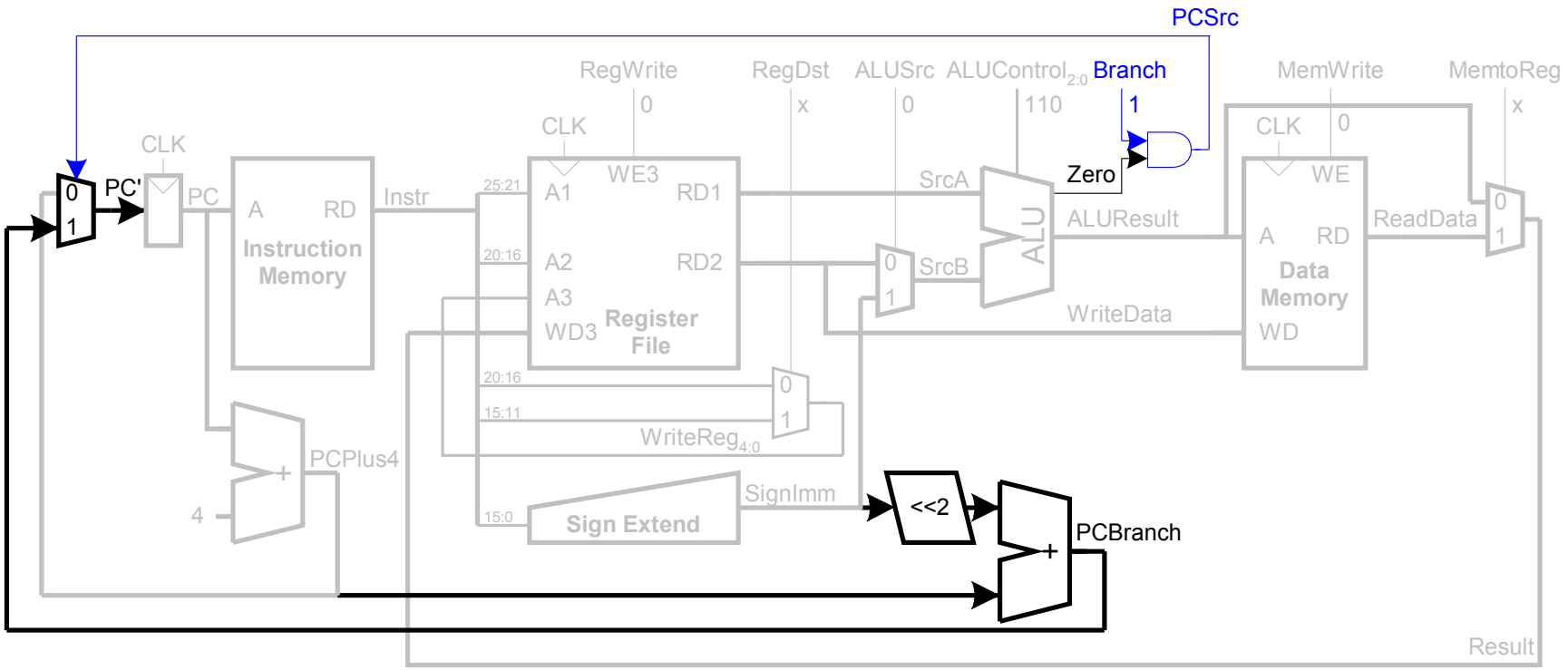
`addu rd, rs, rt`

SPECIAL 0 0 0 0 0 0	rs	rt	rd	0 0 0 0 0	ADDU 1 0 0 0 0 1

Additional Elements for beq

Determine whether rs and rt are equal

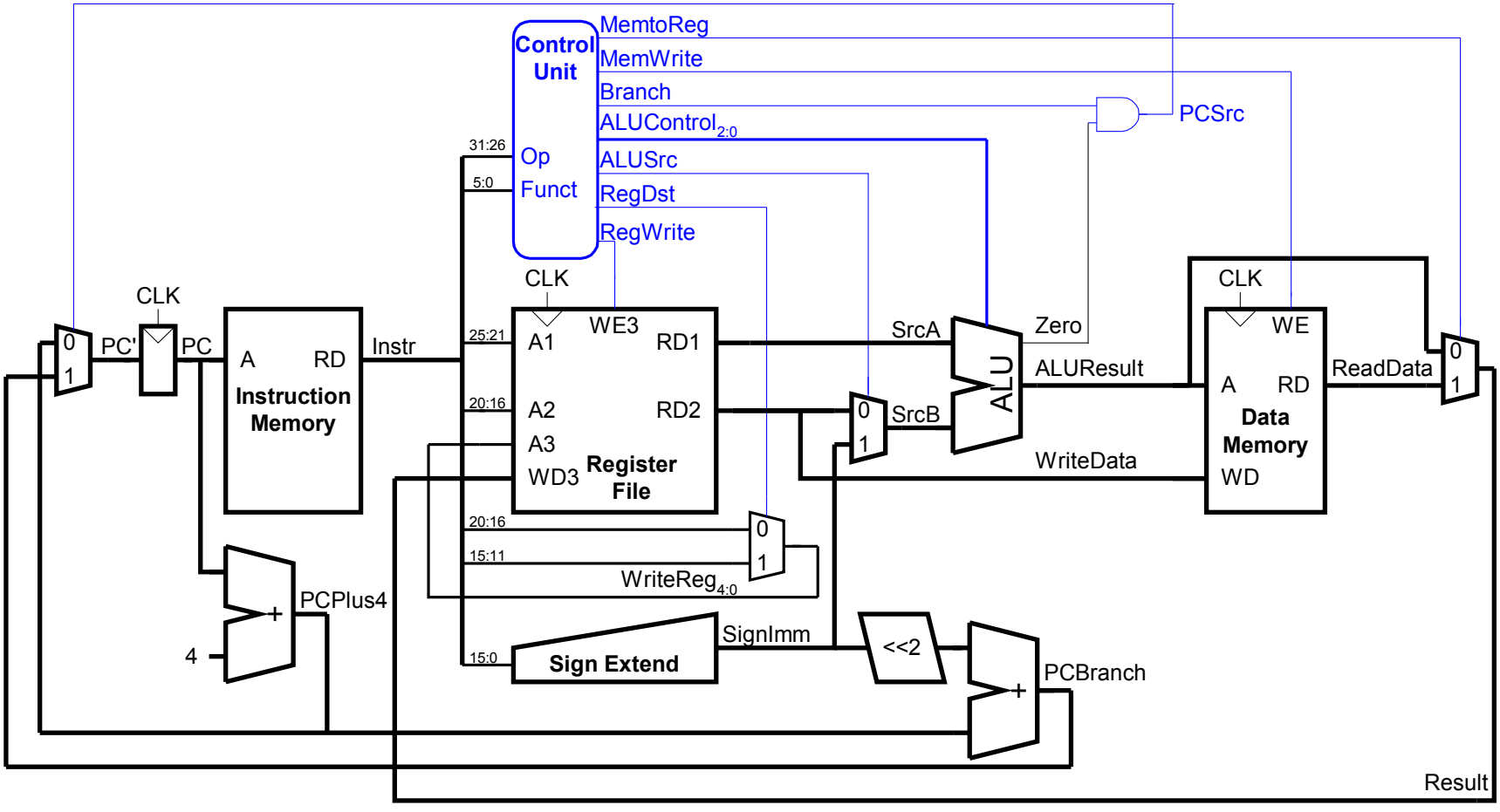
Calculate branch target address

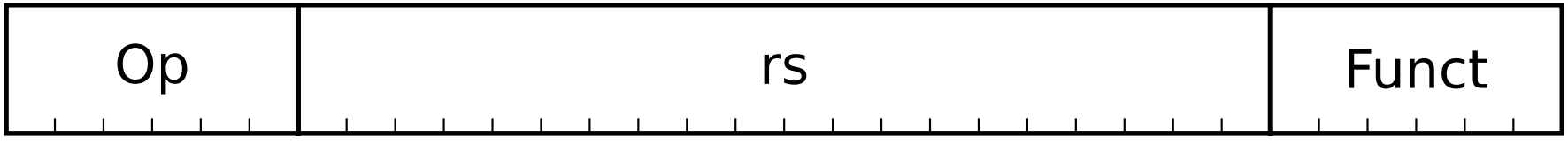



```
beq rs, rt, offset
```

BEQ 0 0 0 1 0 0	rs	rt	offset

Add a controller to complete it





R-Type Instruction Encoding

`addu rd, rs, rt`

SPECIAL 0 0 0 0 0 0	rs	rt	rd	0 0 0 0 0	ADDU 1 0 0 0 0 1

`subu rd, rs, rt`

SPECIAL 0 0 0 0 0 0	rs	rt	rd	0 0 0 0 0	SUBU 1 0 0 0 1 1

`and rd, rs, rt`

SPECIAL 0 0 0 0 0 0	rs	rt	rd	0 0 0 0 0	AND 1 0 0 1 0 0

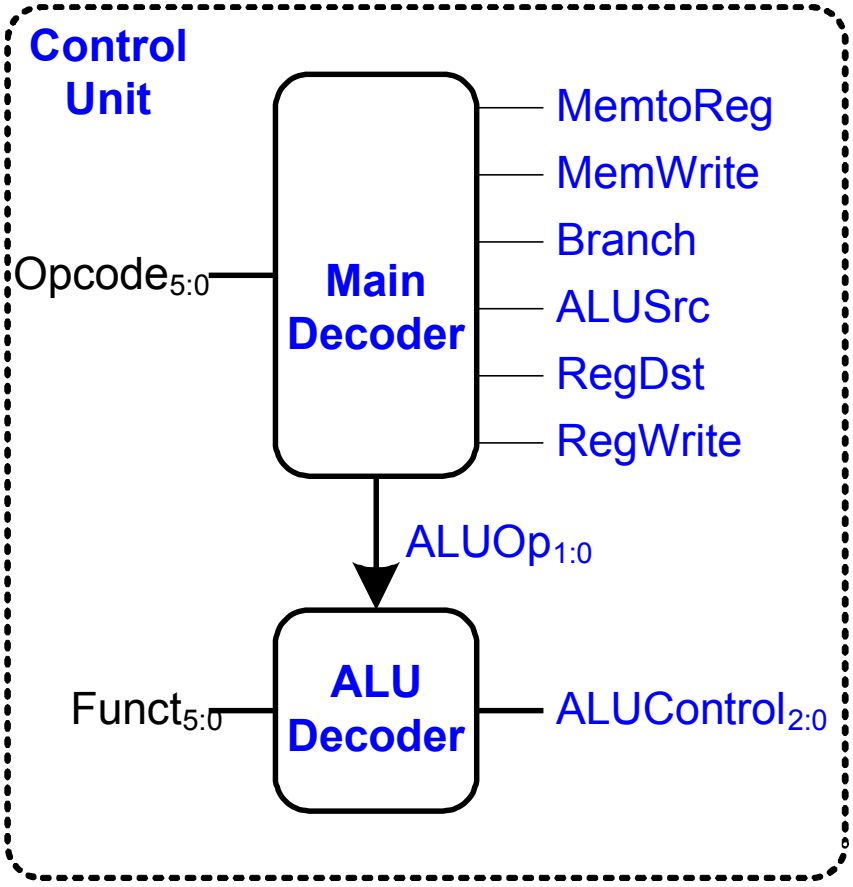
`or rd, rs, rt`

SPECIAL 0 0 0 0 0 0	rs	rt	rd	0 0 0 0 0	OR 1 0 0 1 0 1

`slt rd, rs, rt`

SPECIAL 0 0 0 0 0 0	rs	rt	rd	0 0 0 0 0	SLT 1 0 1 0 1 0

The ALU Decoder

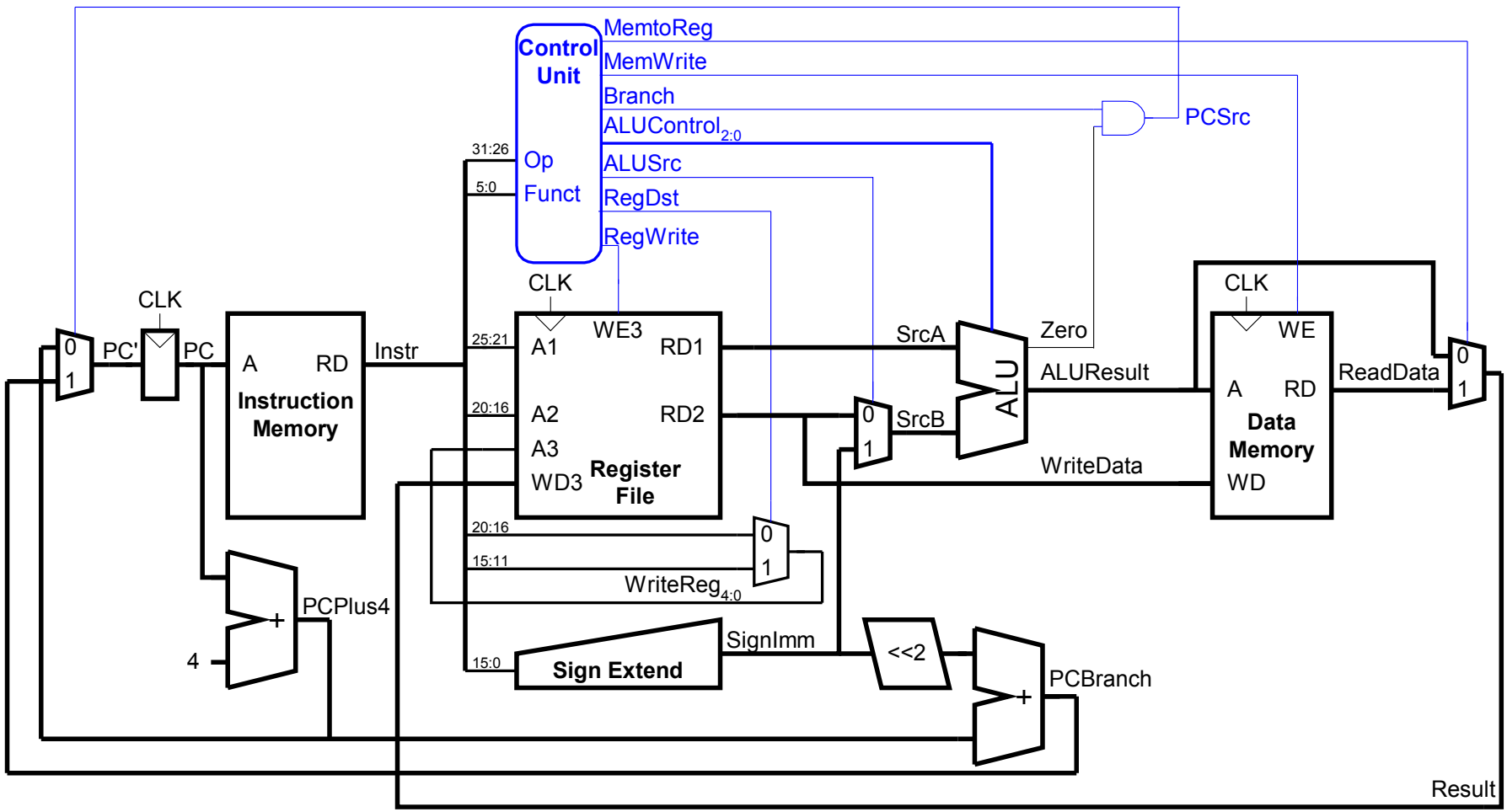


Part of the control unit responsible for implementing the opcode *Funct* field.

ALU Op	Funct	ALU Ctrl.	ALU Function
00	—	010	Add
-1	—	110	Subtract
1-	100001	010	Add
1-	100011	110	Subtract
1-	100100	000	AND
1-	100101	001	OR
1-	101010	111	Slt

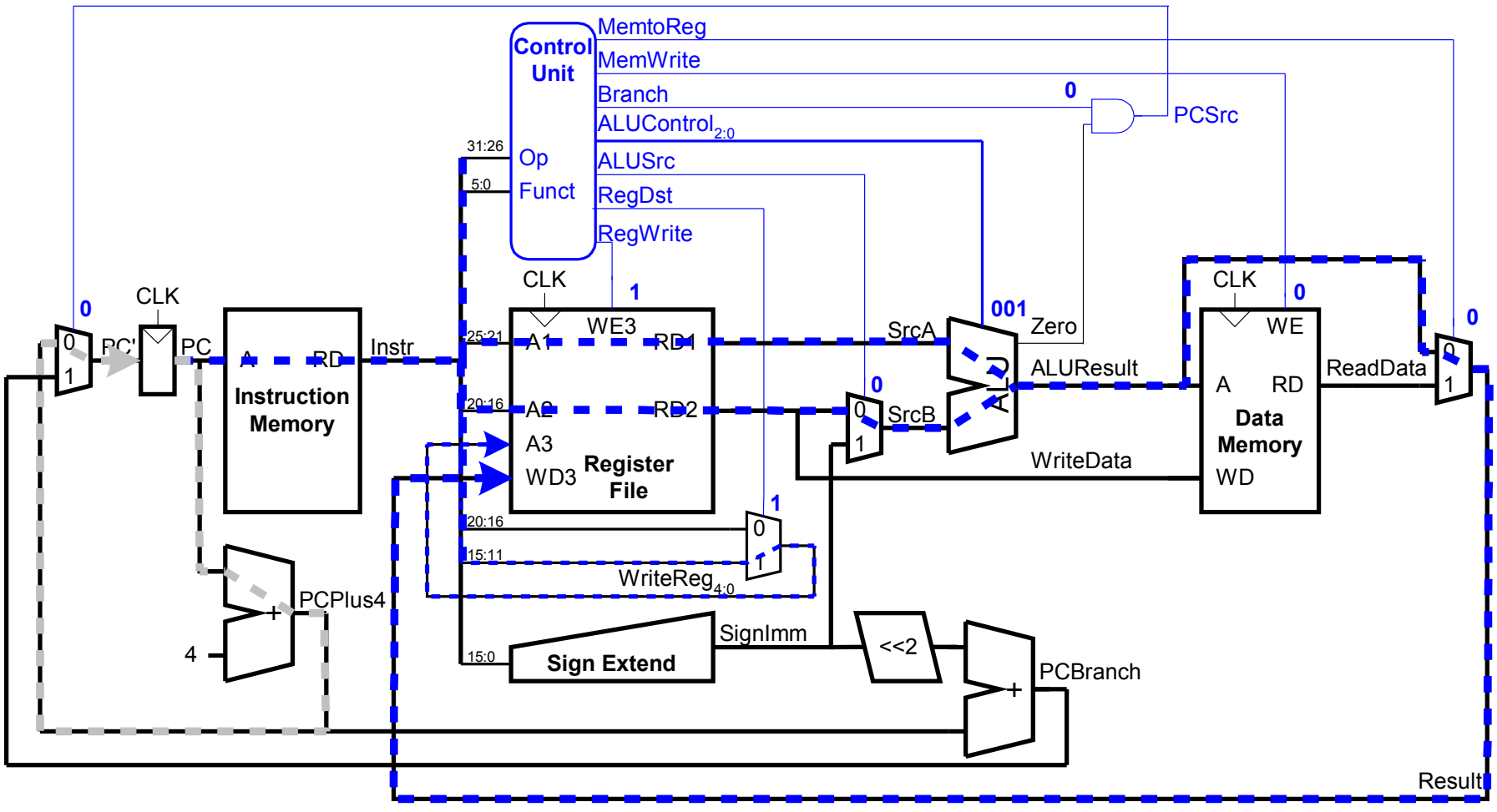
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000							
lw	100011							
sw	101011							
beq	000100							



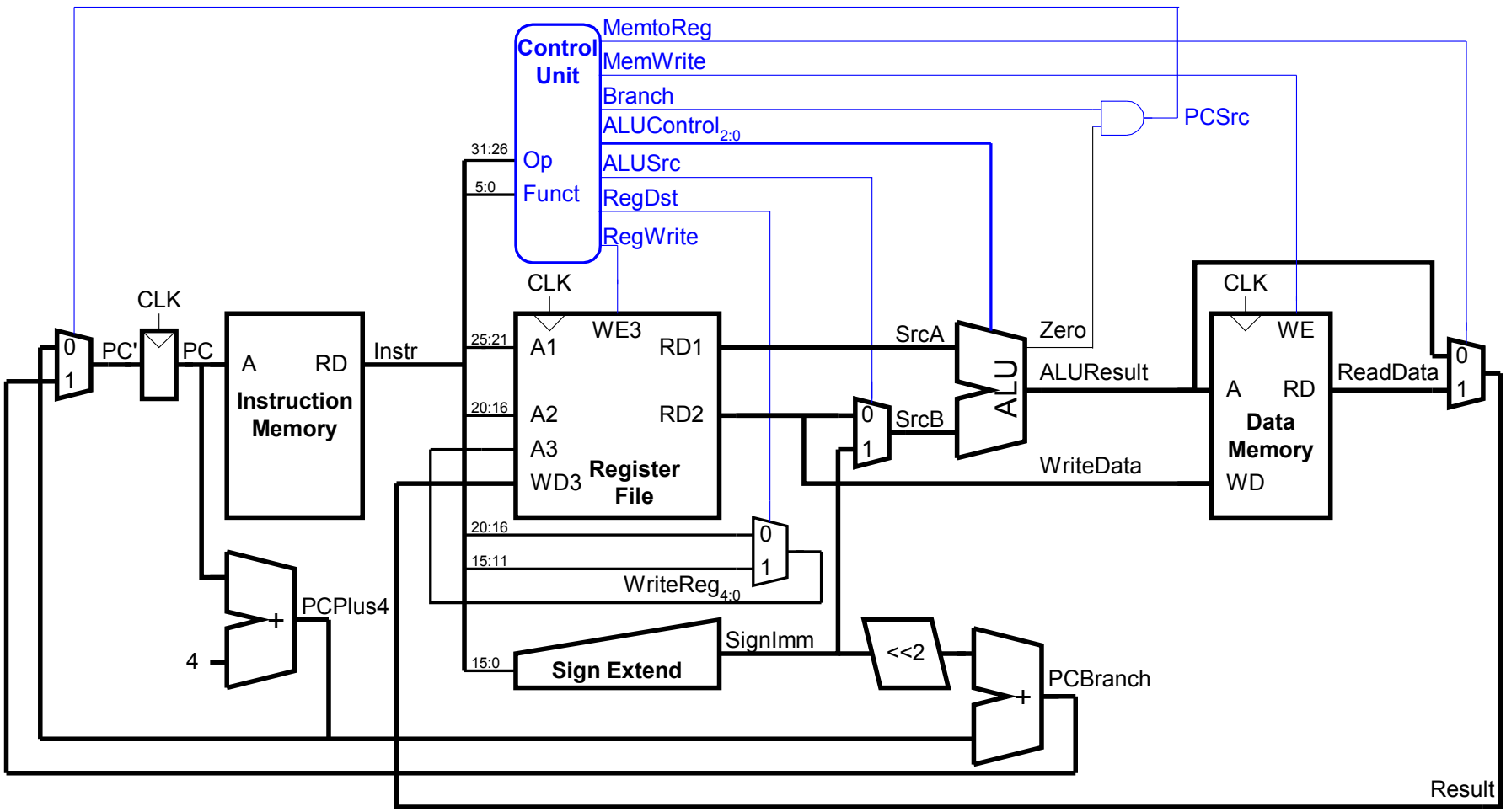
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000	1	1	0	0	0	0	1-
lw	100011							
sw	101011							
beq	000100							



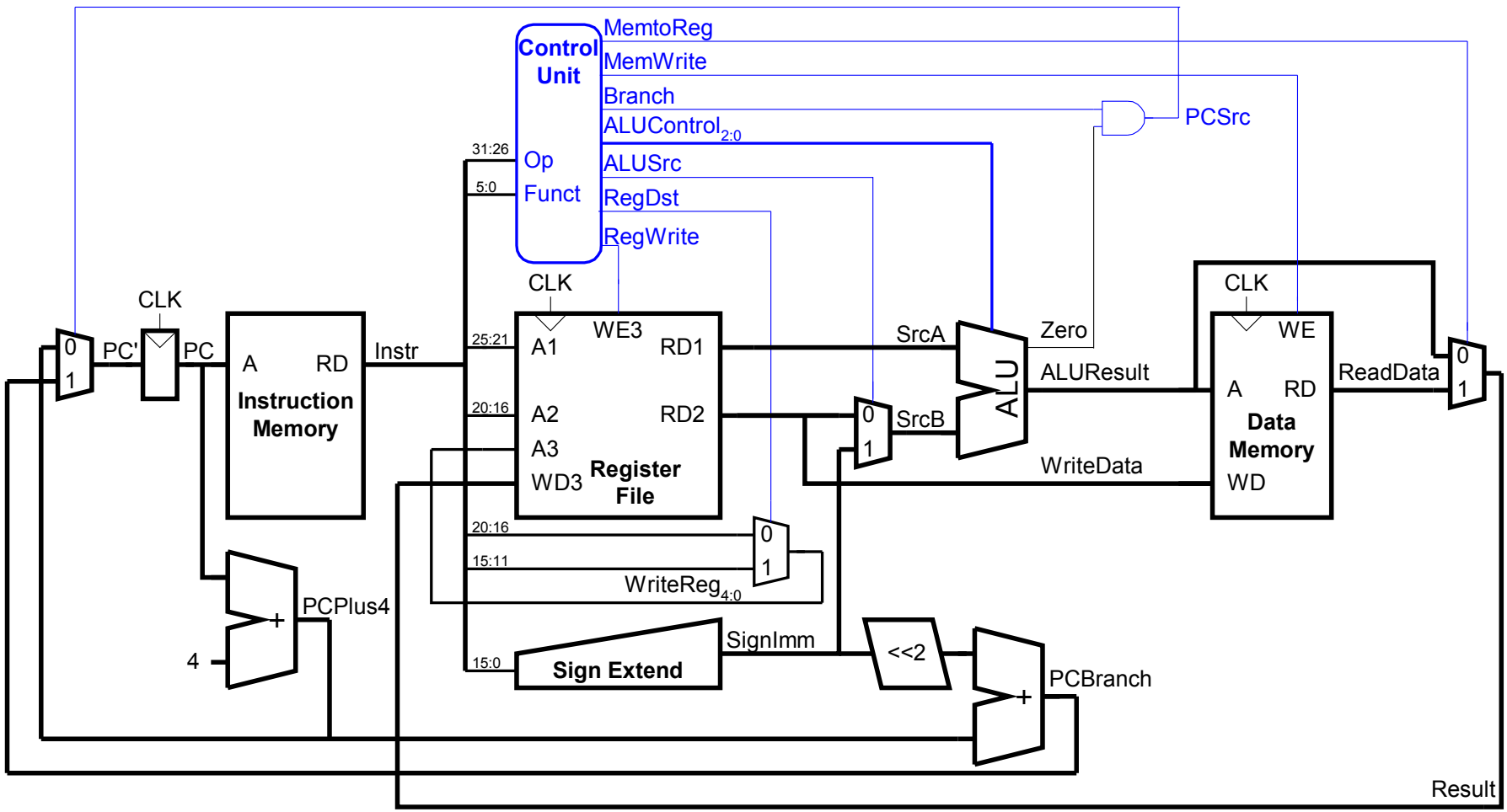
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000	1	1	0	0	0	0	1-
lw	100011	1	0	1	0	0	1	00
sw	101011							
beq	000100							



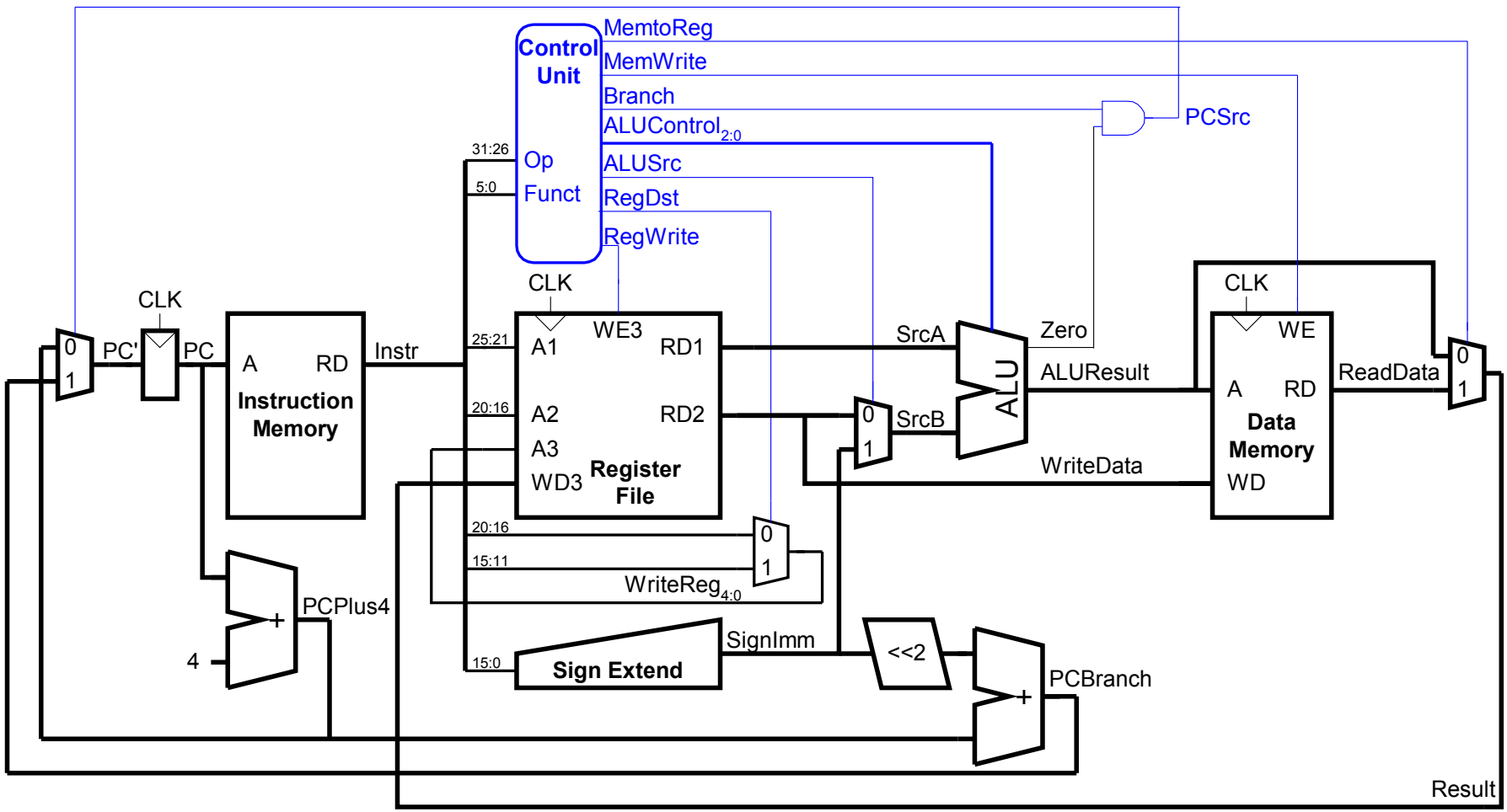
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000	1	1	0	0	0	0	1-
lw	100011	1	0	1	0	0	1	00
sw	101011	0	-	1	0	1	-	00
beq	000100							



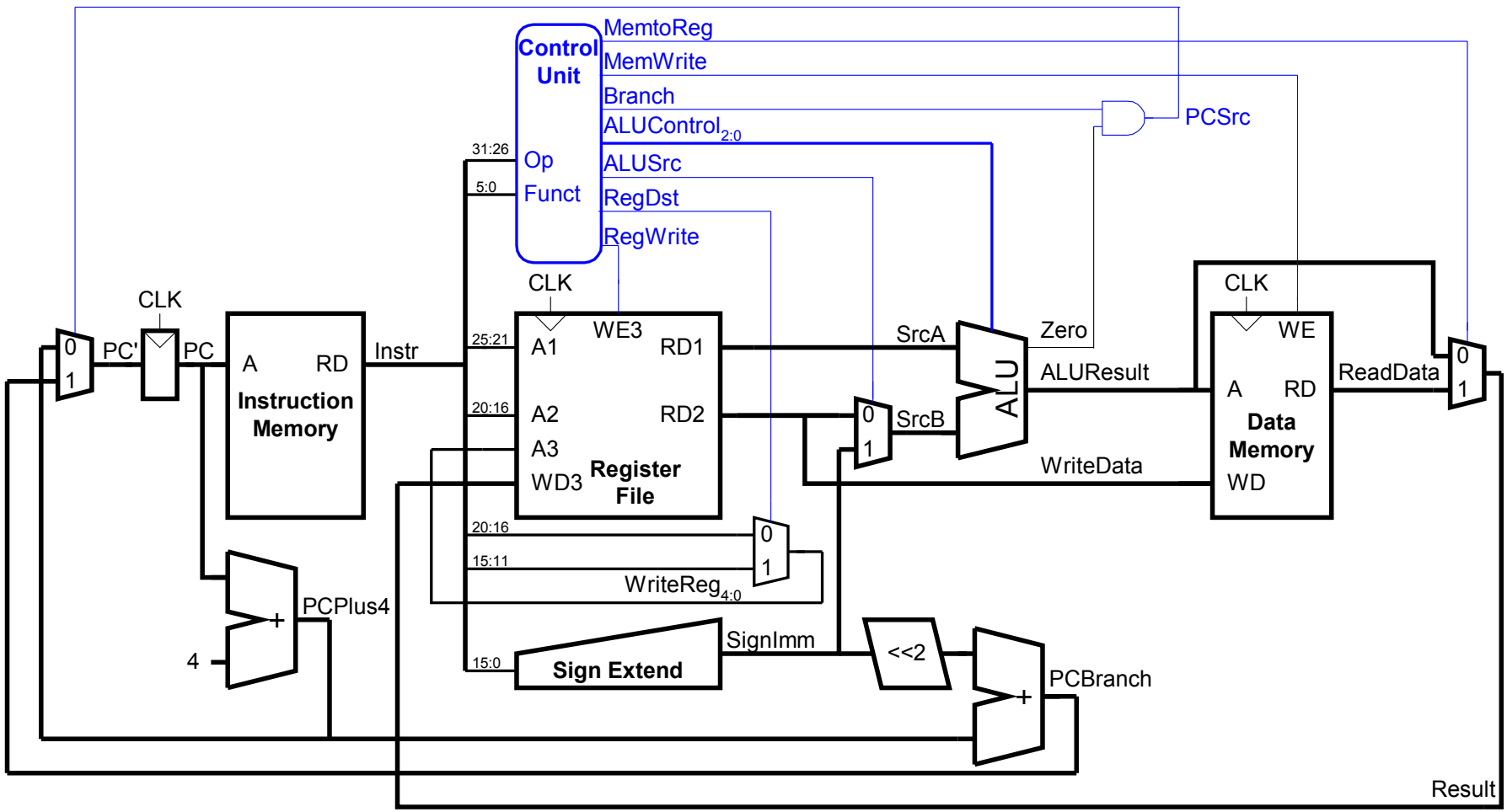
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000	1	1	0	0	0	0	1-
lw	100011	1	0	1	0	0	1	00
sw	101011	0	-	1	0	1	-	00
beq	000100	0	-	0	1	0	-	01



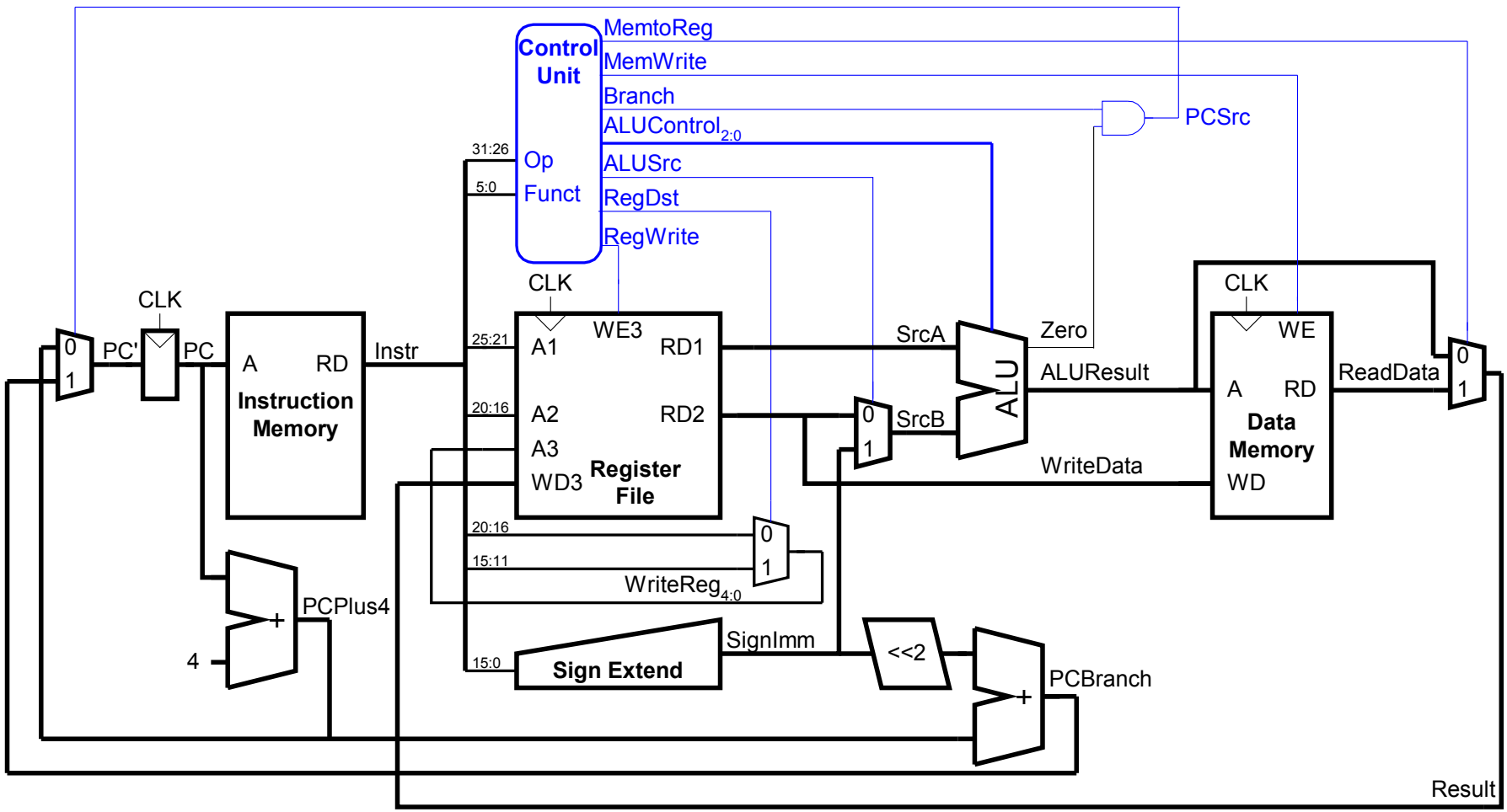
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000	1	1	0	0	0	0	1-
lw	100011	1	0	1	0	0	1	00
sw	101011	0	-	1	0	1	-	00
beq	000100	0	-	0	1	0	-	01
addiu	001001	Can we do this with our datapath?						



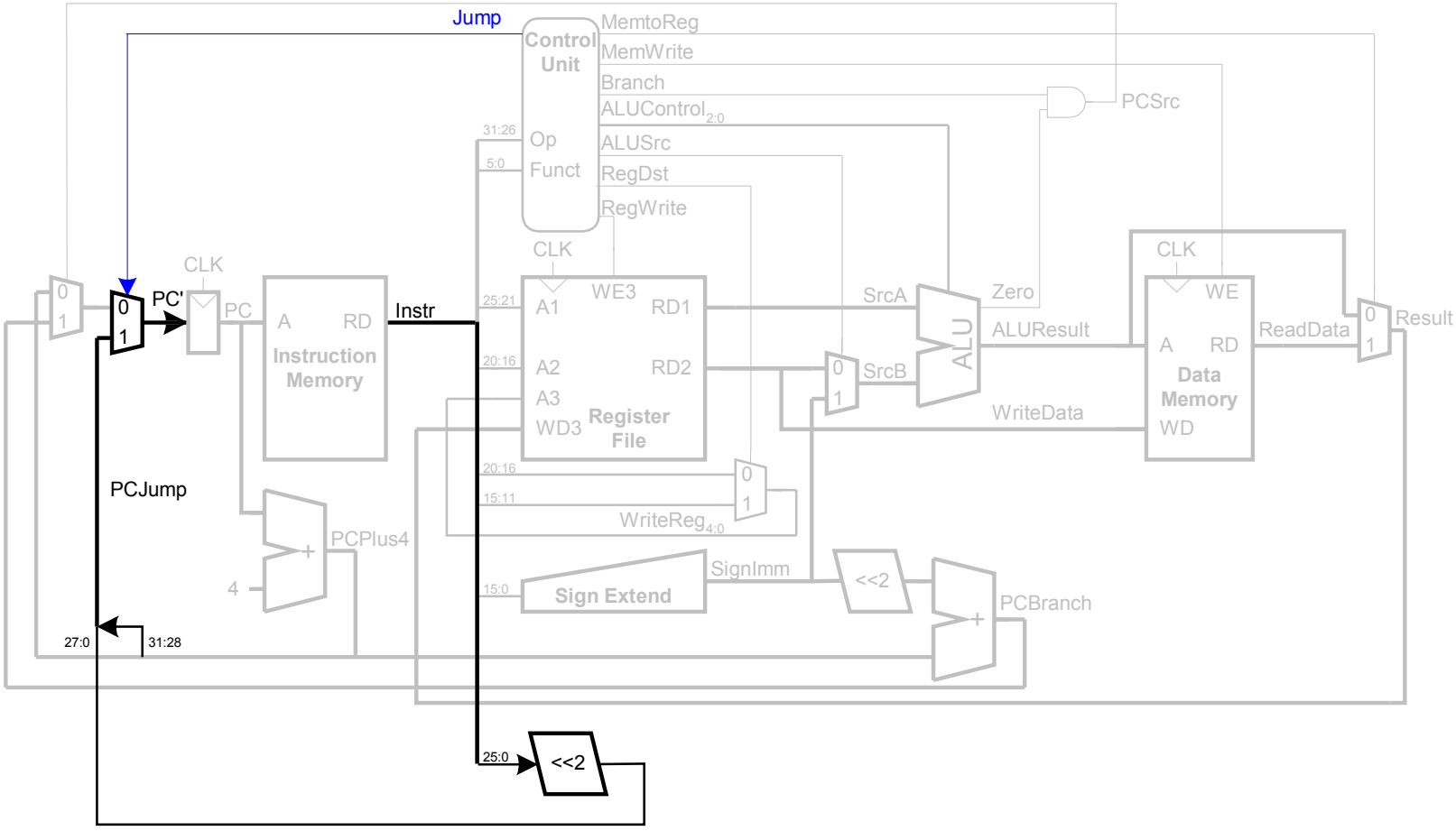
The Main Decoder

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp
R-type	000000	1	1	0	0	0	0	1-
lw	100011	1	0	1	0	0	1	00
sw	101011	0	-	1	0	1	-	00
beq	000100	0	-	0	1	0	-	01
addiu	001001	1	0	1	0	0	0	00



Additional Elements for the j Instruction

Inst.	OP	RegWrite	RegDst	ALUSrc	Branch	MemWrite	MemToReg	ALUOp	Jump
R-type	000000	1	1	0	0	0	0	1-	0
lw	100011	1	0	1	0	0	1	00	0
sw	101011	0	-	1	0	1	-	00	0
beq	000100	0	-	0	1	0	-	01	0
addiu	001001	1	0	1	0	0	0	00	0
j	000010	0	-	-	-	0	-	--	1

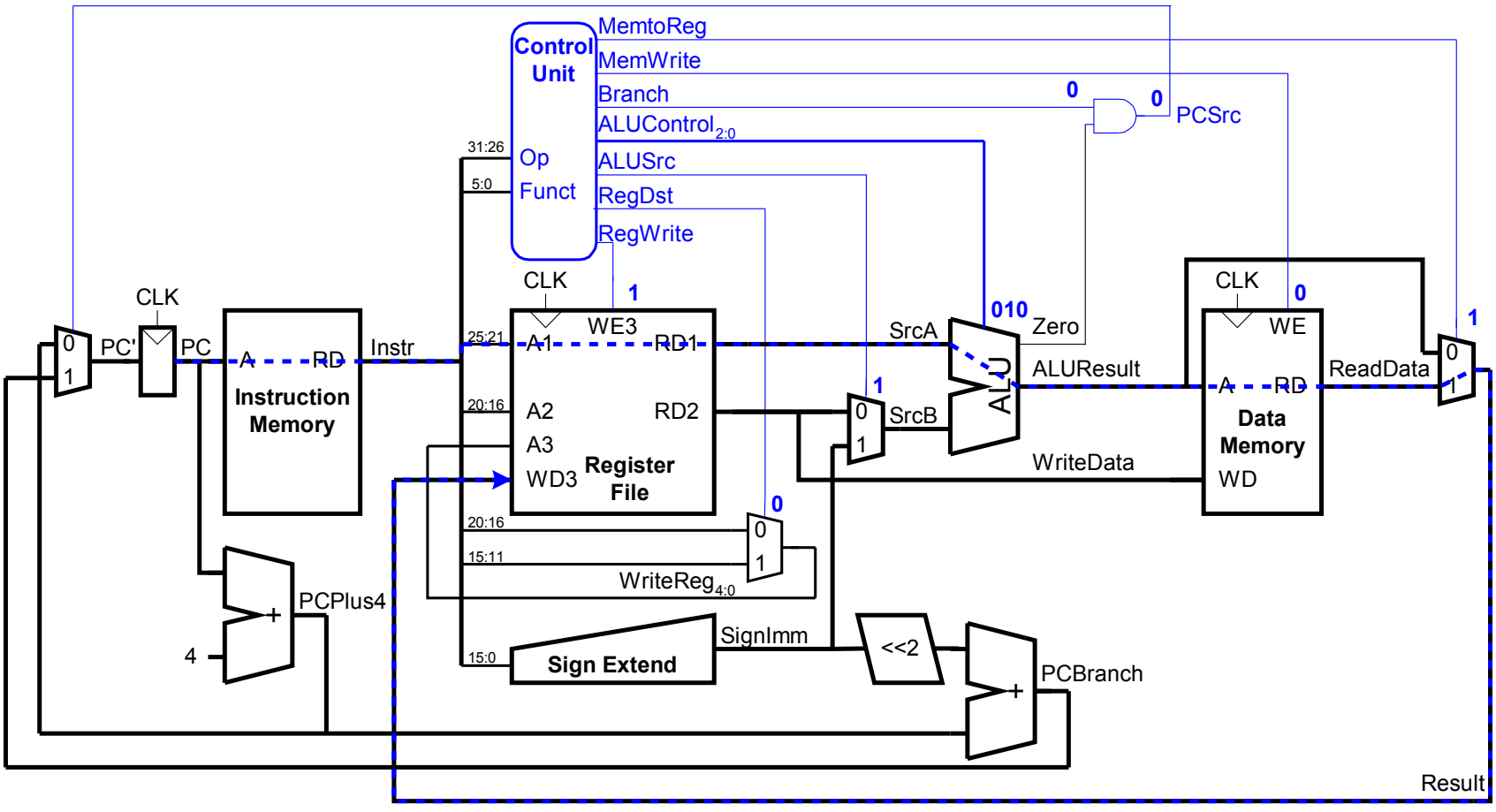


Processor Performance

$$\frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock Cycle}}$$

$\frac{\text{Seconds}}{\text{Program}}$	How long you have to wait
$\frac{\text{Instructions}}{\text{Program}}$	Number that must execute to complete the task
$\frac{\text{Clock Cycles}}{\text{Instruction}}$	CPI: Cycles per instruction
$\frac{\text{Seconds}}{\text{Clock Cycle}}$	The clock period (1/frequency)

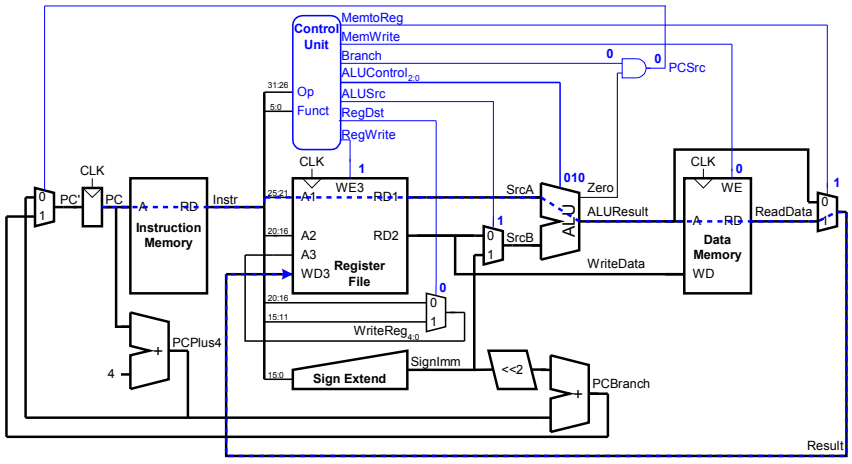
The Critical Path Here: Load from Memory



Instruction Memory to Register File to ALU to Data Memory to Register File

The Critical Path Dictates the Clock Period

Element		Delay
Register clk-to-Q	$t_{\text{pcq-PC}}$	30 ps
Register setup	t_{setup}	20
Multiplexer	t_{mux}	25
ALU	t_{ALU}	200
Memory Read	t_{mem}	250
Register file read	t_{RFread}	150
Register file setup	t_{RFsetup}	20



$$
\begin{aligned}
T_C &= t_{\text{pcq-PC}} + t_{\text{mem-I}} + t_{\text{RFread}} + t_{\text{ALU}} + t_{\text{mem-D}} + t_{\text{mux}} + t_{\text{RFsetup}} \\
&= (30 + 250 + 150 + 200 + 250 + 25 + 20)\ \text{ps} \\
&= 925\ \text{ps} \\
&= 1.08\ \text{GHz}
\end{aligned}
$$

Execution Time for Our Single-Cycle Processor

For a 100 billion-instruction task on our single-cycle processor with a 925 ps clock period,

$$\frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock Cycle}}$$

$$= 100 \times 10^9 \times 1 \times 925 \text{ ps}$$

$$= 92.5 \text{ seconds}$$