Lecture 22
Single-cycle CPU Control

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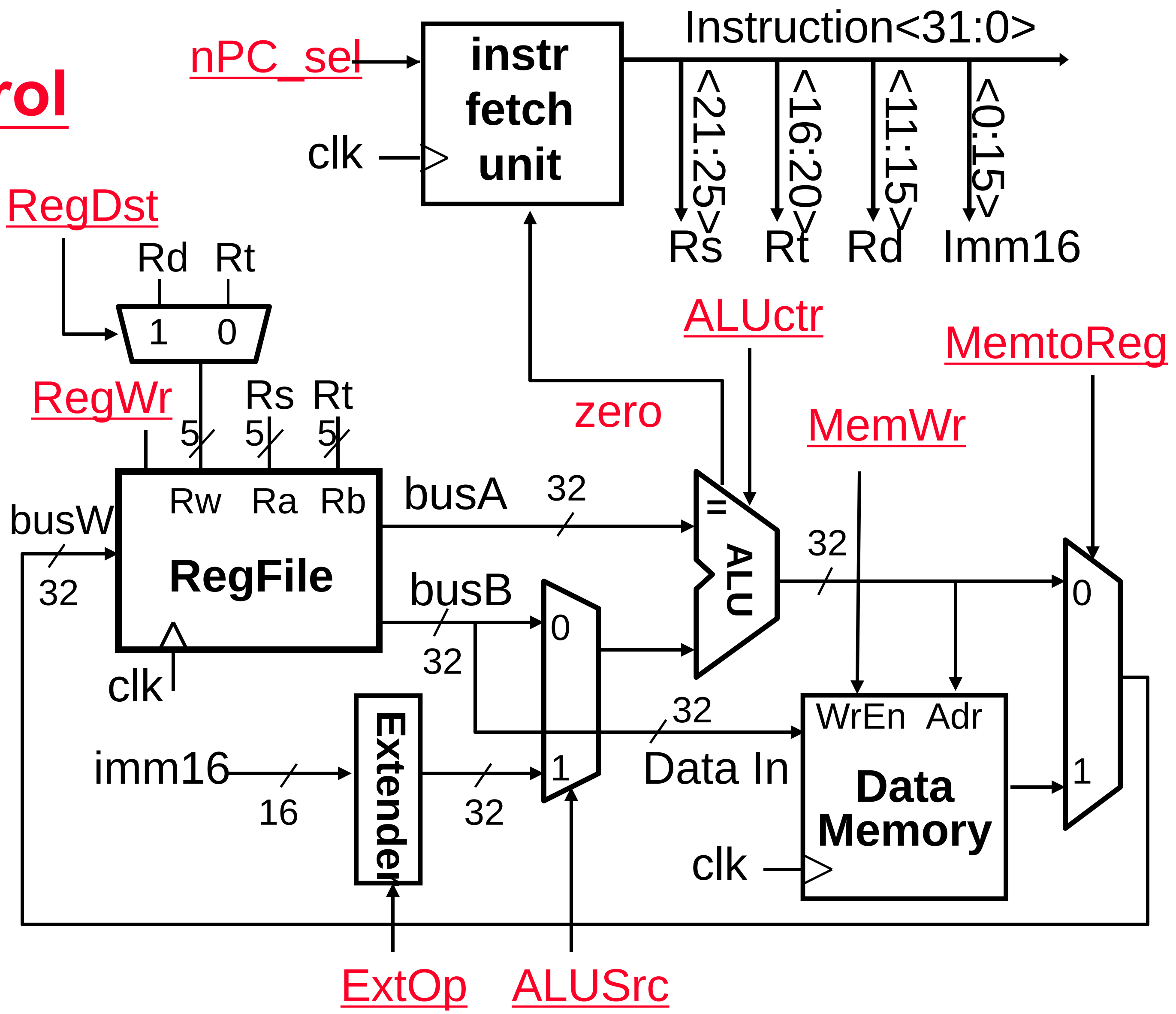
TSMC Sees HPC As Next Inflection Point

Review: A Single Cycle Datapath

- We have everything except control signals

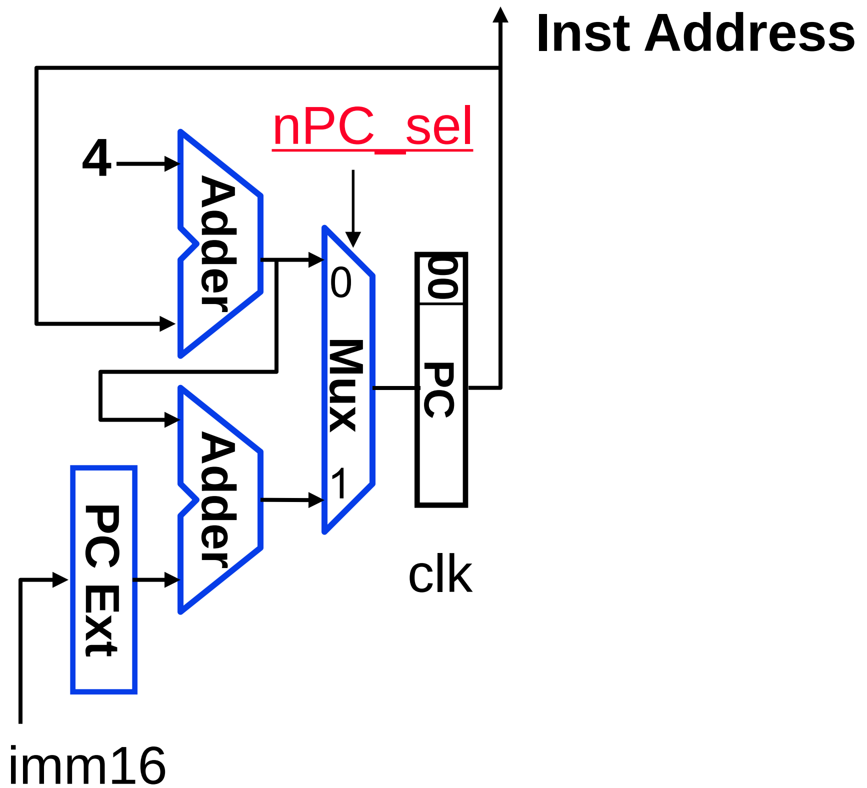


Recap: Meaning of the Control Signals

- **nPC_sel:** “+4” 0 ⇒ PC <– PC + 4
  “br” 1 ⇒ PC <– PC + 4 + {SignExt(Im16) , 00 }

  “n”=next

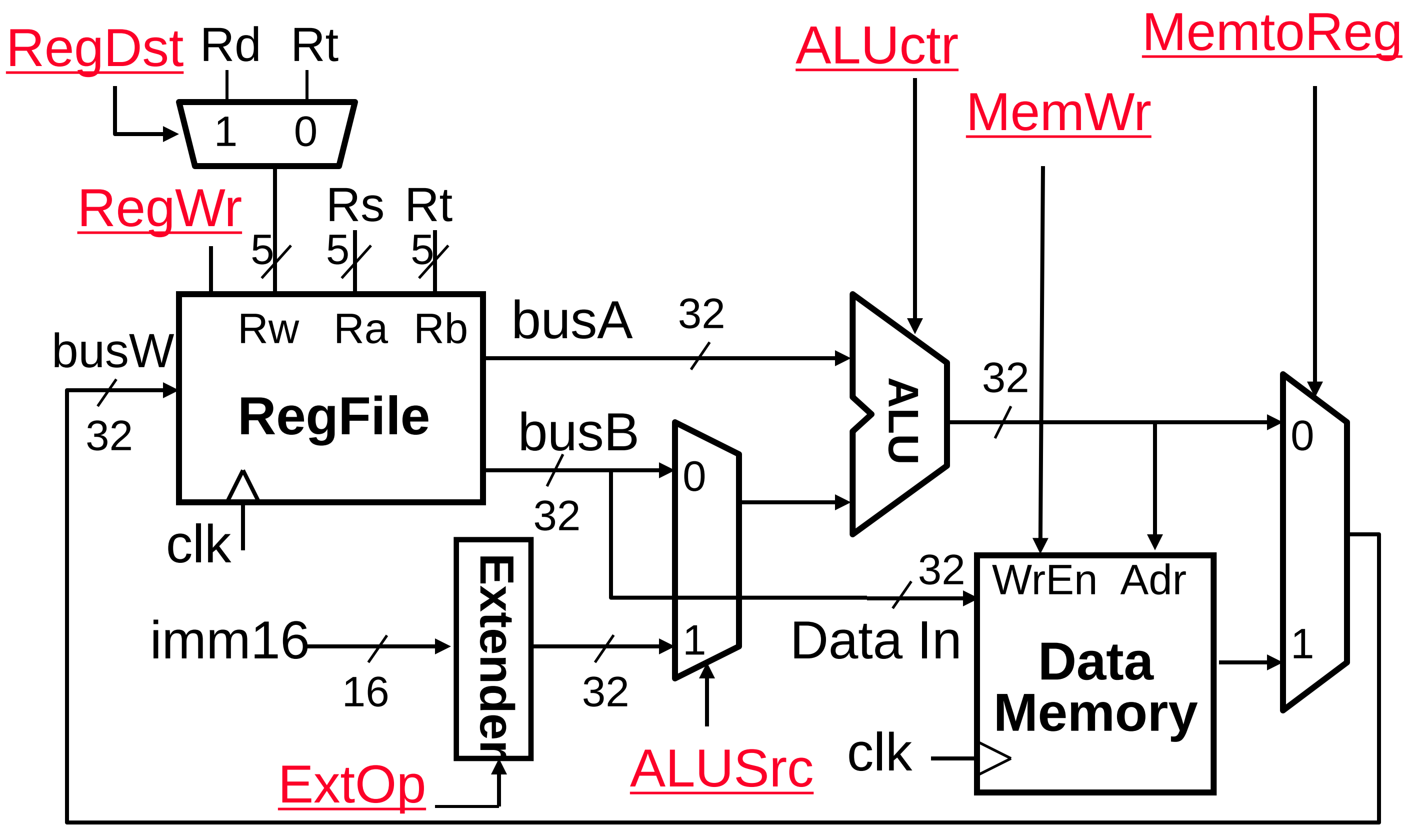
- **Later in lecture: higher-level connection between mux and branch condition**



Recap: Meaning of the Control Signals

- **ExtOp:** "zero", "sign"
- **ALUsrc:** 0 ⇒ regB; 1 ⇒ immed
- **ALUctr:** "ADD", "SUB", "OR"

- **MemWr:** 1 ⇒ write memory
- **MemtoReg:** 0 ⇒ ALU; 1 ⇒ Mem
- **RegDst:** 0 ⇒ "rt"; 1 ⇒ "rd"
- **RegWr:** 1 ⇒ write register



RTL: The `Add` Instruction

31 26 21 16 11 6 0

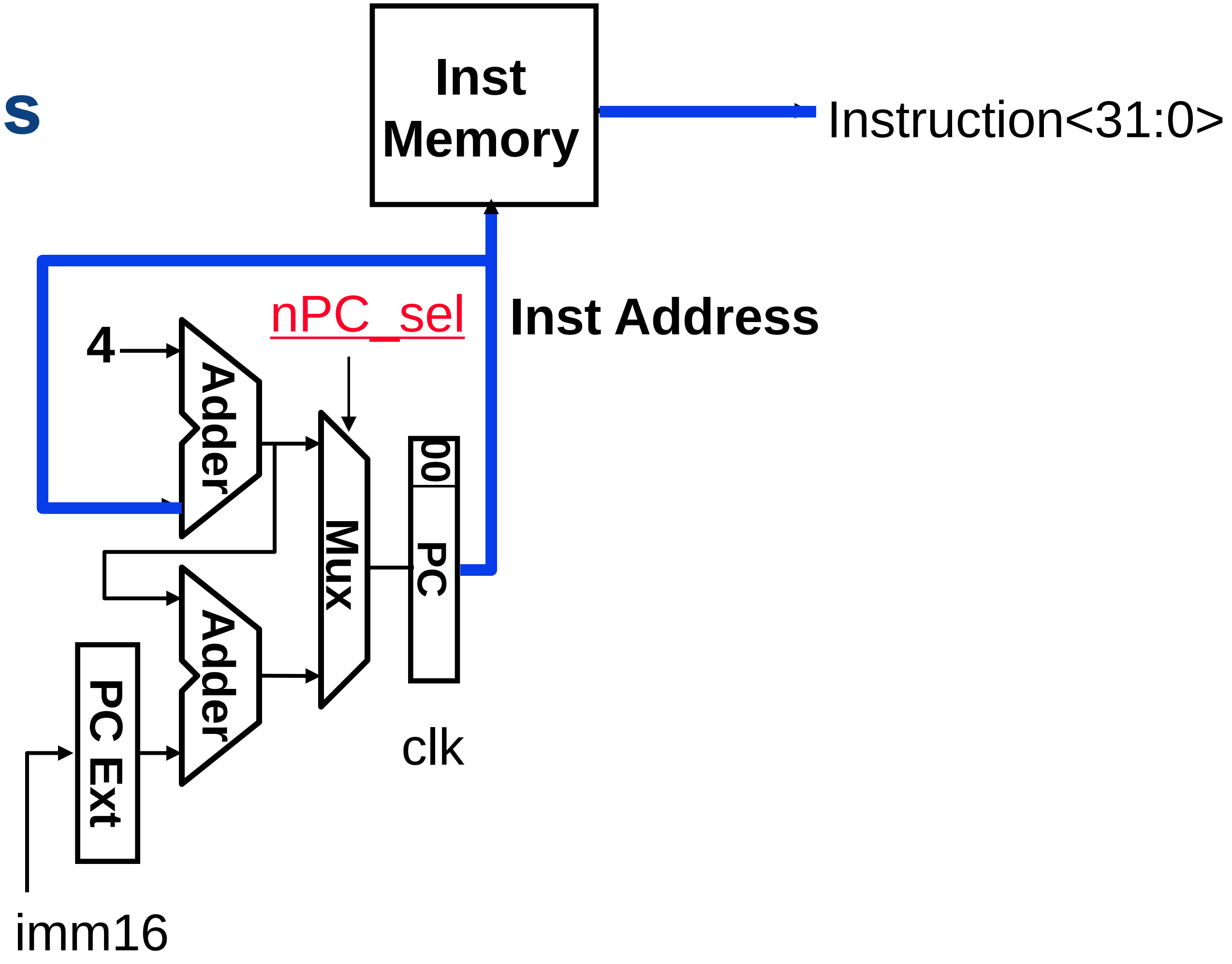
op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

`add rd,rs,rt`

- MEM[PC] Fetch the instruction from memory
- R[rd] = R[rs] + R[rt] The actual operation
- PC = PC + 4 Calculate the next instruction's address

Instruction Fetch Unit at the Beginning of Add

- Fetch the instruction from Instruction memory: Instruction = MEM[PC]
  - same for all instructions

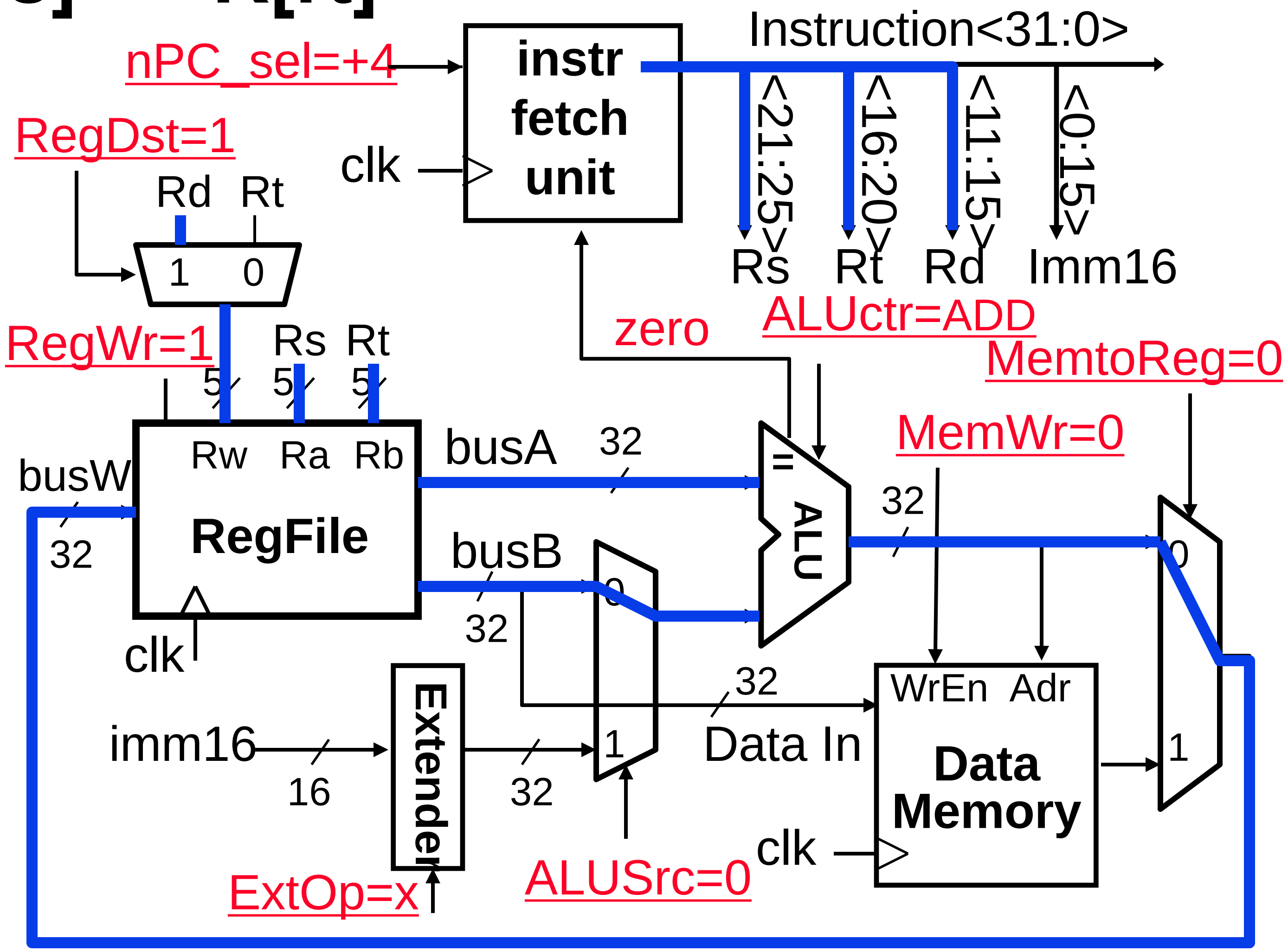


The Single Cycle Datapath during Add

31 26 21 16 11 6 0

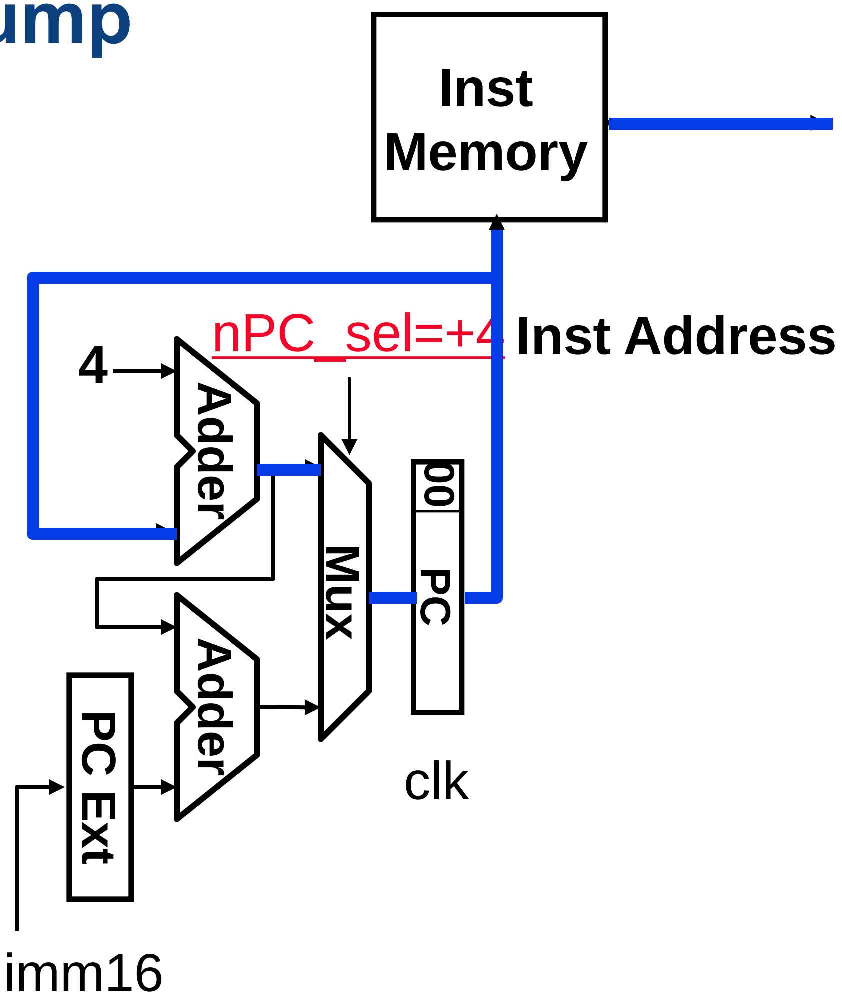
op	rs	rt	rd	shamt	funct

R[rd] = R[rs] + R[rt]



Instruction Fetch Unit at the End of `Add`

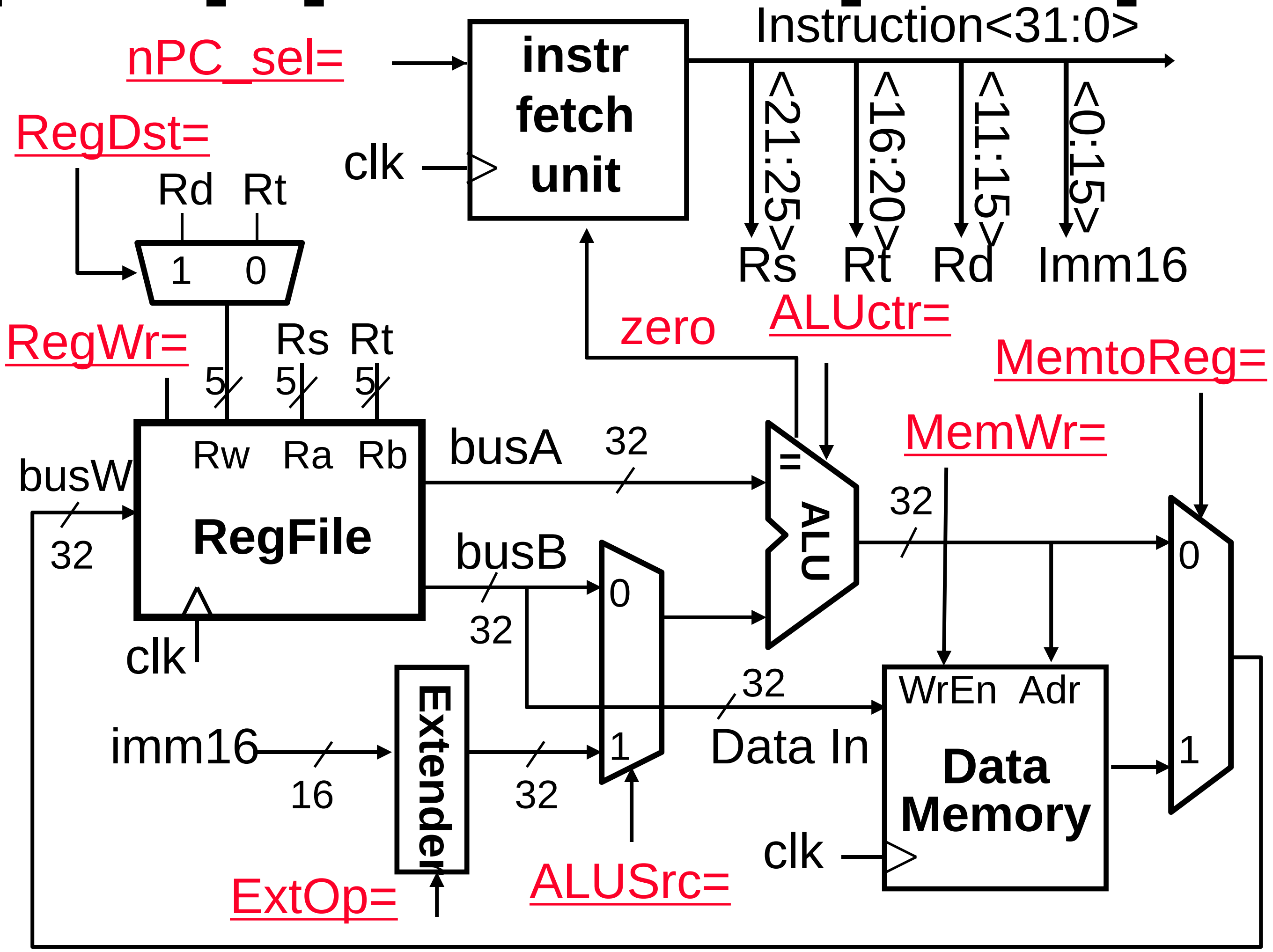
- **PC = PC + 4**
  - **This is the same for all instructions except: Branch and Jump**



Single Cycle Datapath during Or Immediate?

31	26	21	16	0
op	rs	rt	immediate	

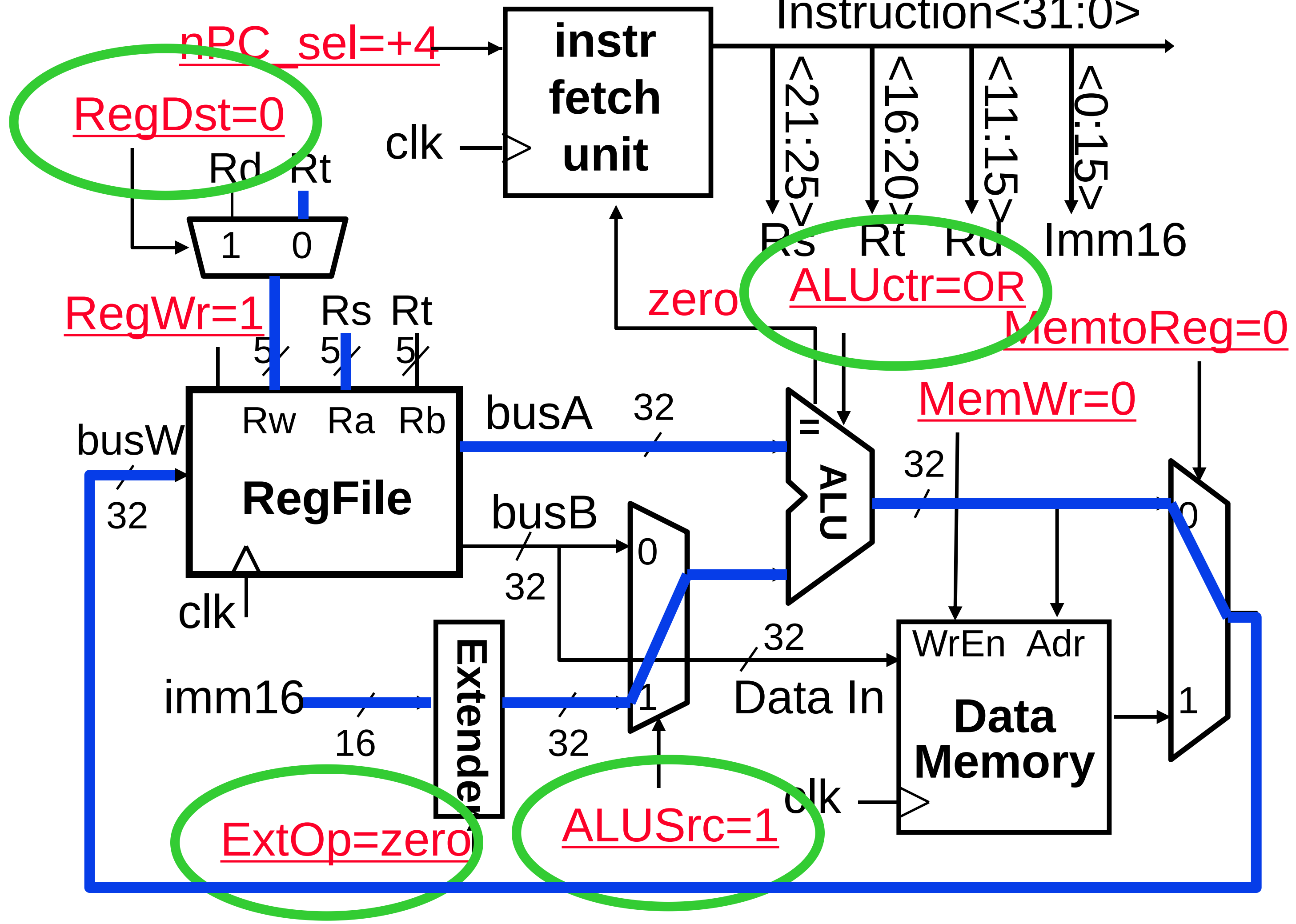
- R[rt] = R[rs] OR ZeroExt[Imm16]



Single Cycle Datapath during Or Immediate?

31	26	21	16	0
op	rs	rt	immediate	

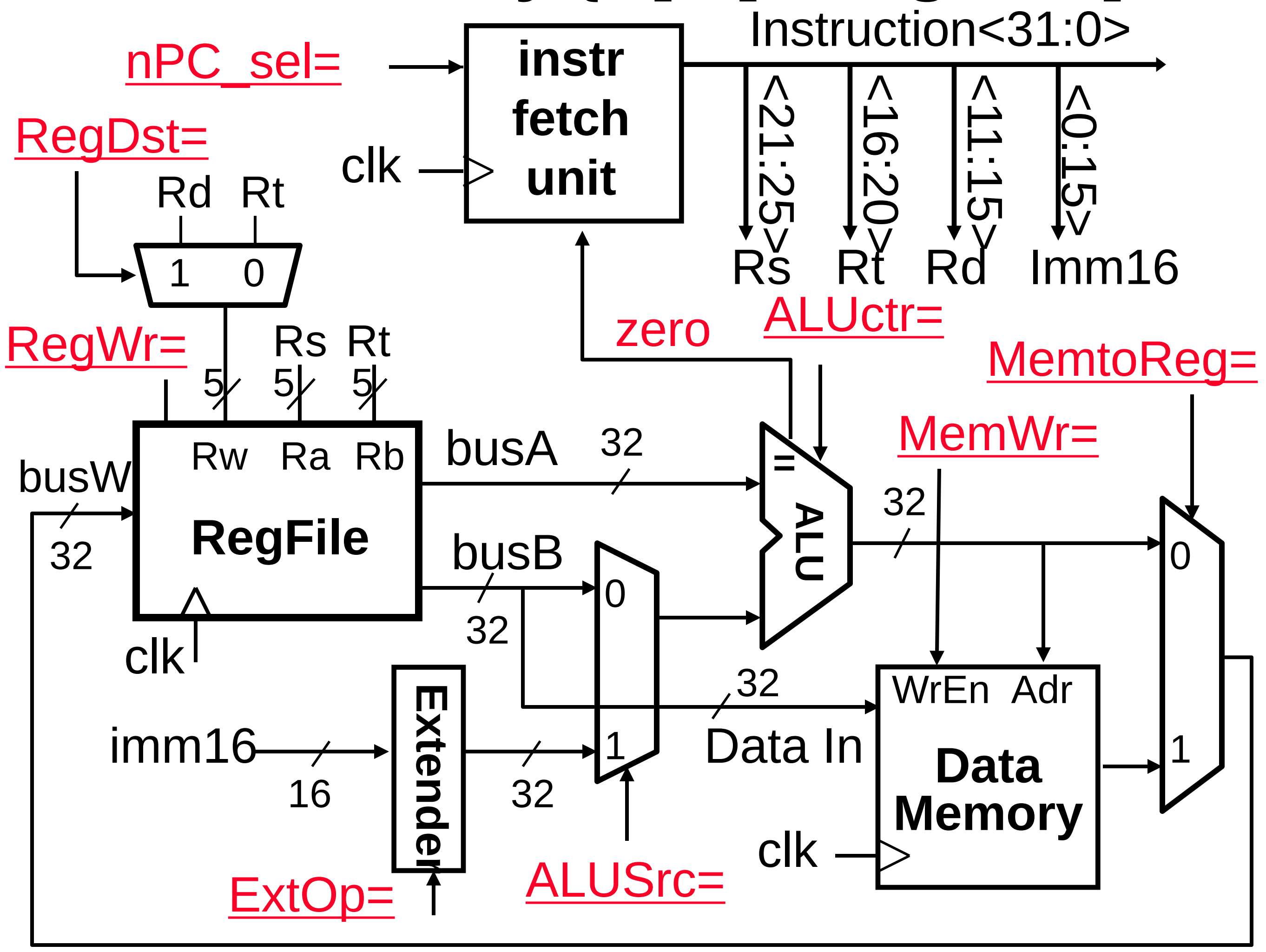
- **R[rt] = R[rs] OR ZeroExt[Imm16]**



The Single Cycle Datapath during Load?

31	26	21	16 0
op	rs	rt	immediate

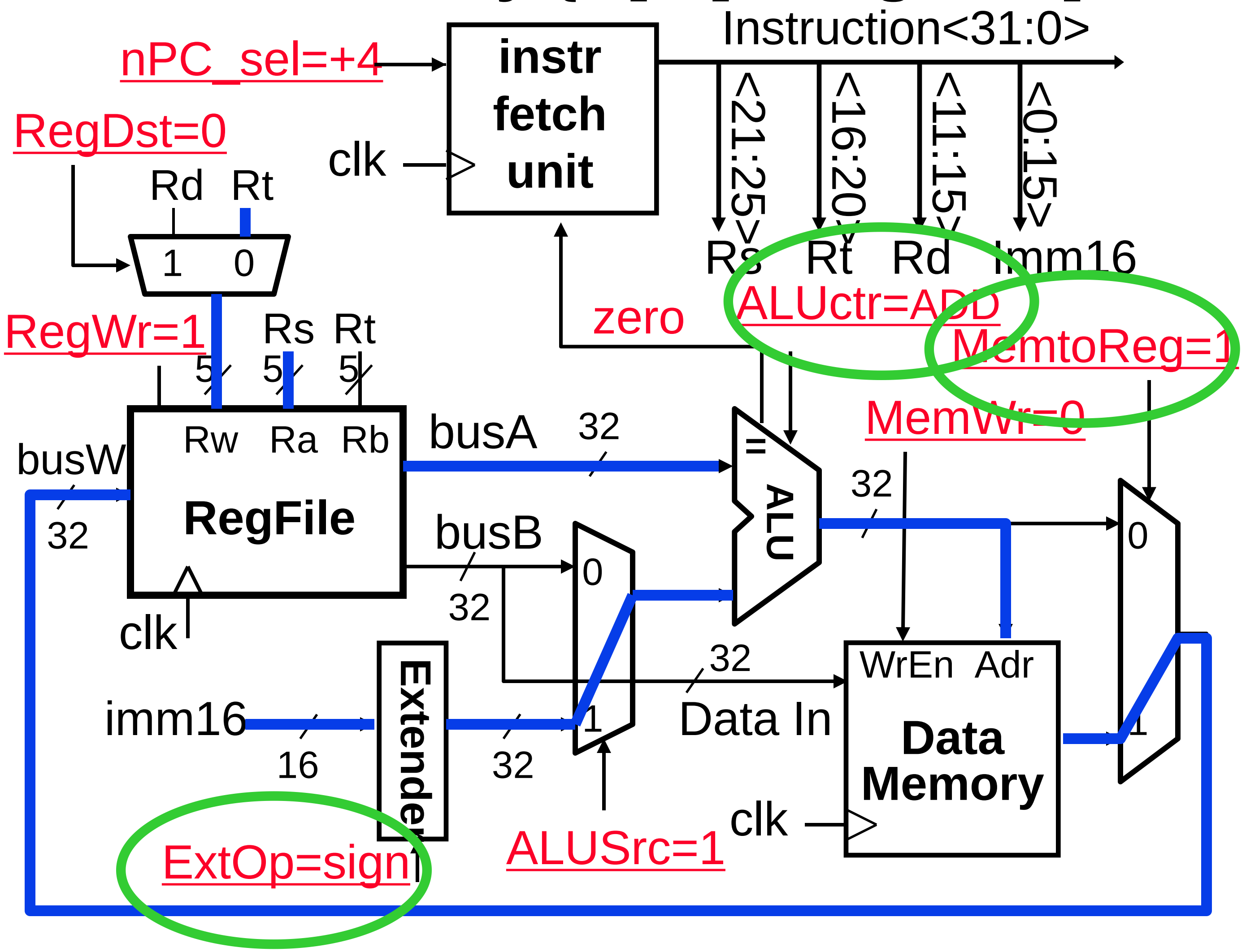
- **R[rt] = Data Memory {R[rs] + SignExt[imm16]}**



The Single Cycle Datapath during Load

31	26	21	16	0
op	**rs**	**rt**	**immediate**	

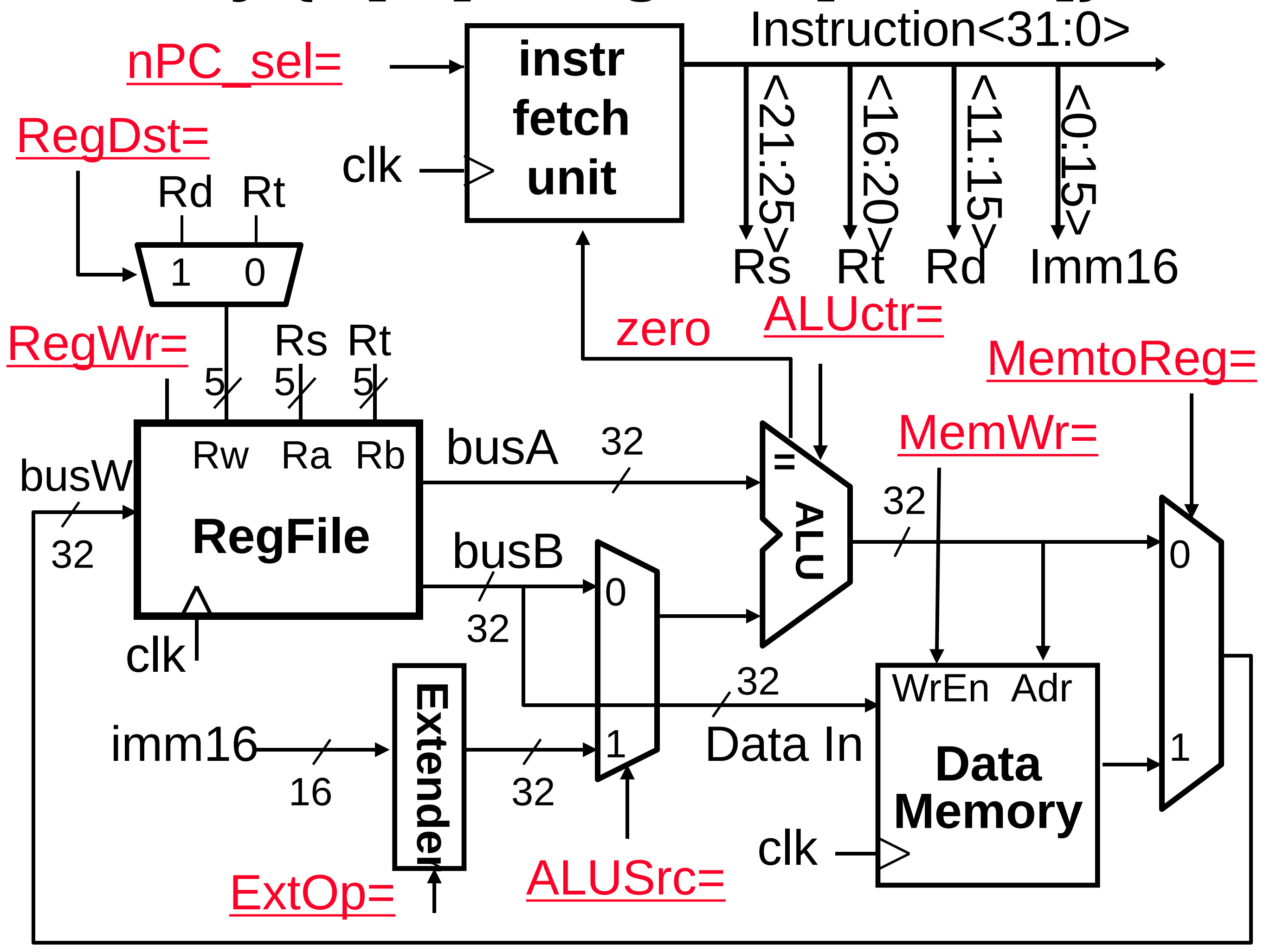
- **R[rt] = Data Memory {R[rs] + SignExt[imm16]}**



The Single Cycle Datapath during Store?

31	26	21	16	0
op	rs	rt	immediate	

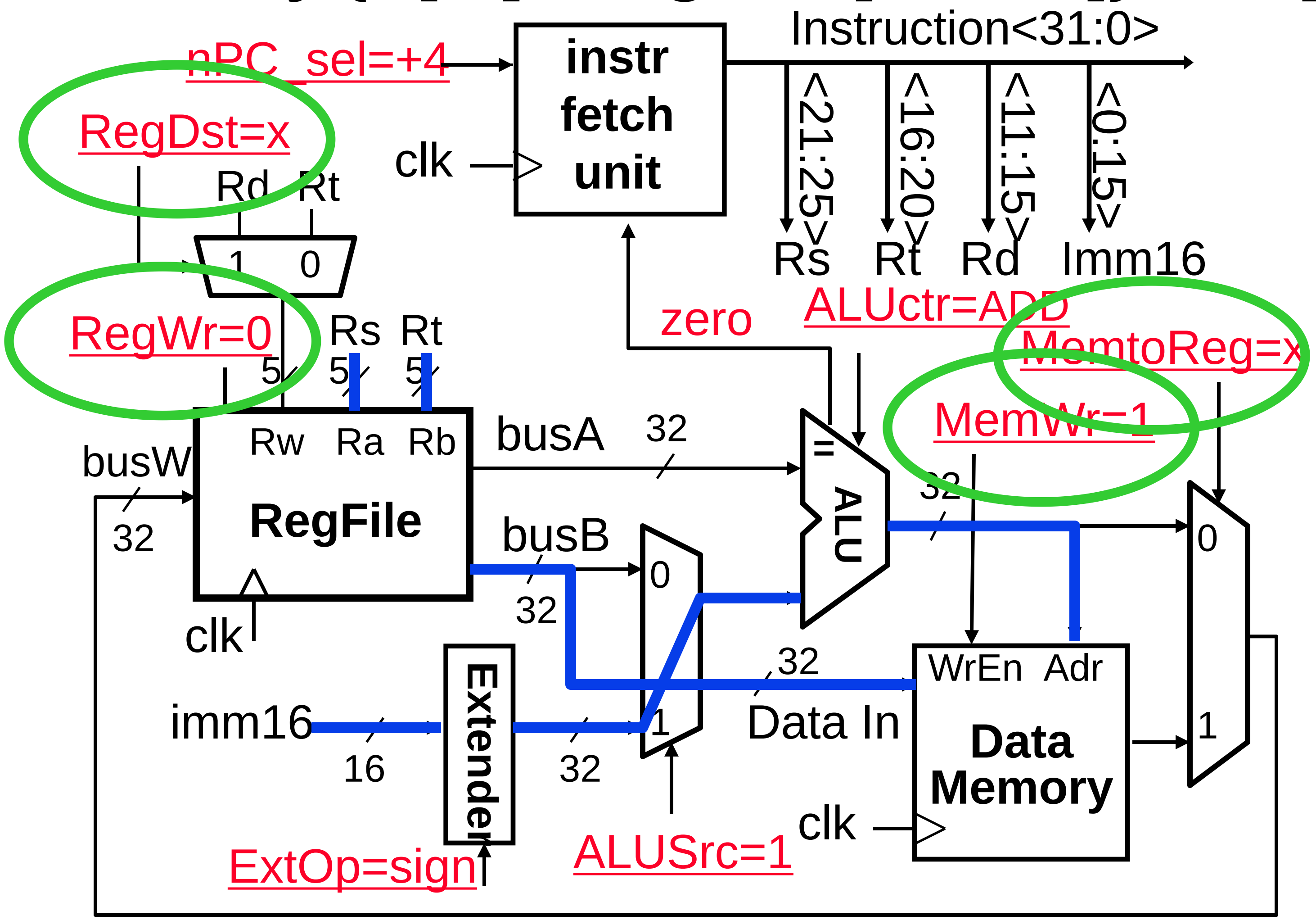
- **Data Memory {R[rs] + SignExt[imm16]} = R[rt]**



The Single Cycle Datapath during Store

31	26	21	16	0
op	rs	rt	immediate	

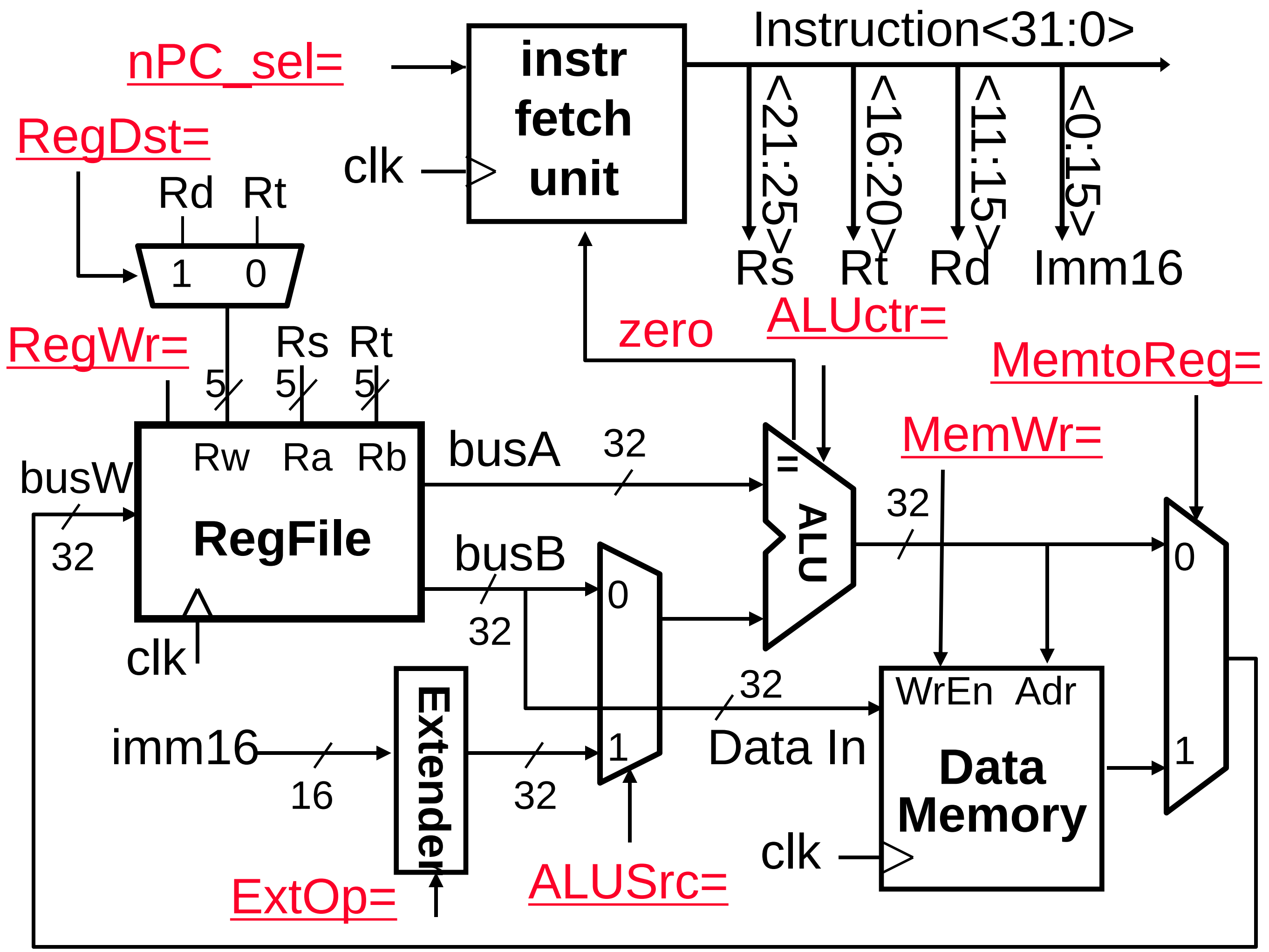
- **Data Memory {R[rs] + SignExt[imm16]} = R[rt]**



The Single Cycle Datapath during Branch?

31	26	21	16	0
op	rs	rt	immediate	

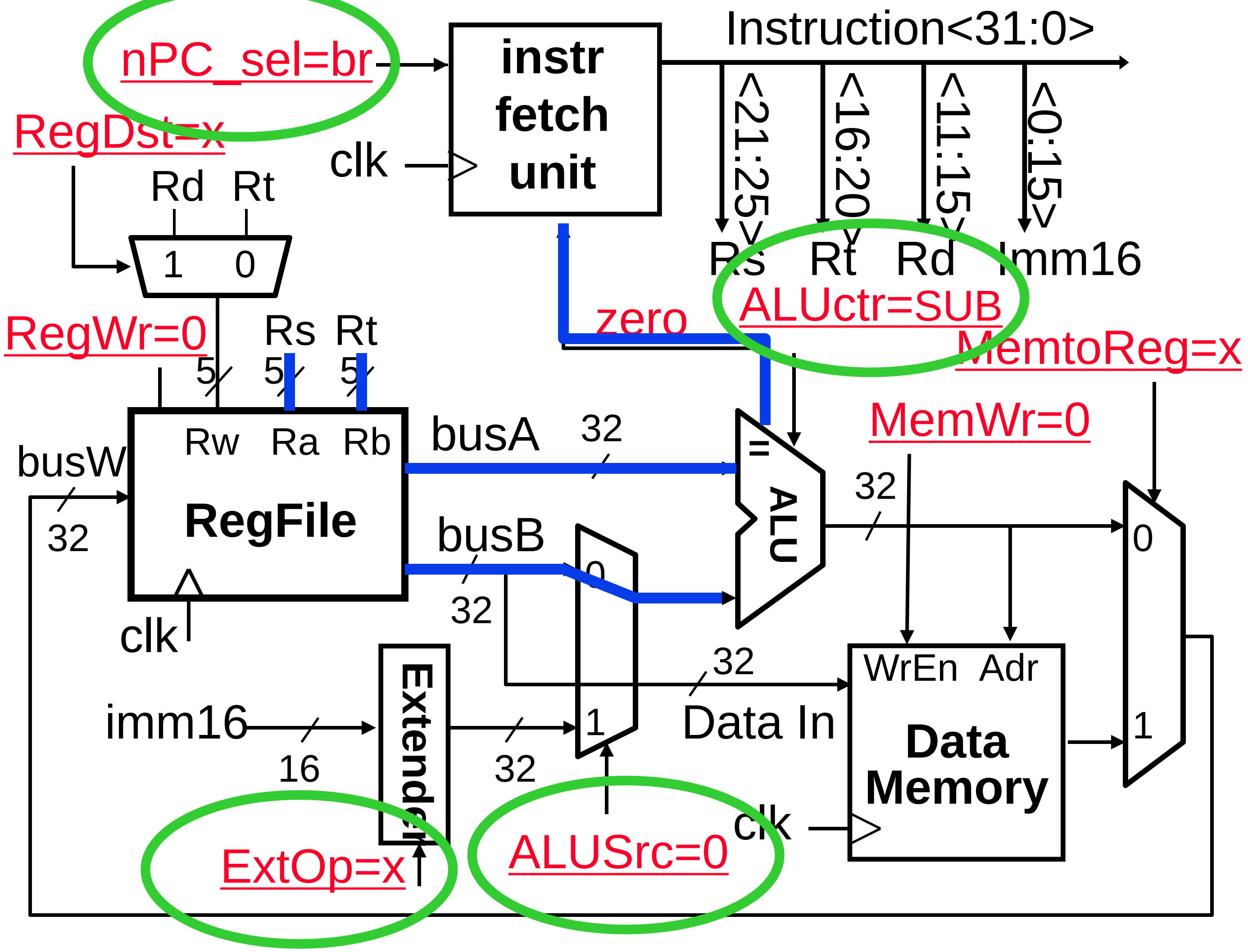
- if (R[rs] - R[rt] == 0) then Zero = 1 ; else Zero = 0



The Single Cycle Datapath during Branch

31	26	21	16	0
op	rs	rt	immediate	

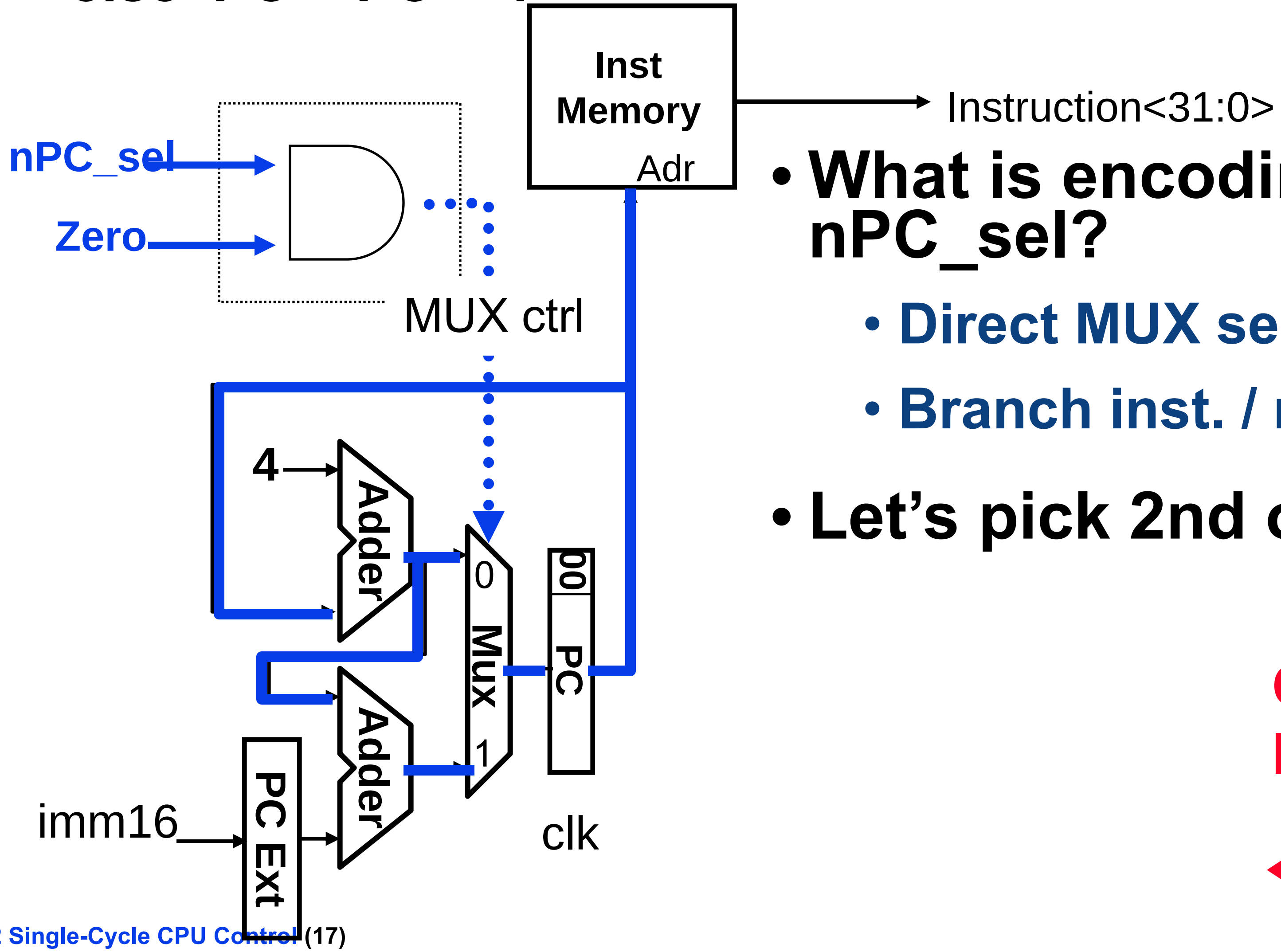
- if (R[rs] - R[rt] == 0) then Zero = 1 ; else Zero = 0



Instruction Fetch Unit at the End of Branch

31–26	25–21	20–16	15–0
op	rs	rt	immediate

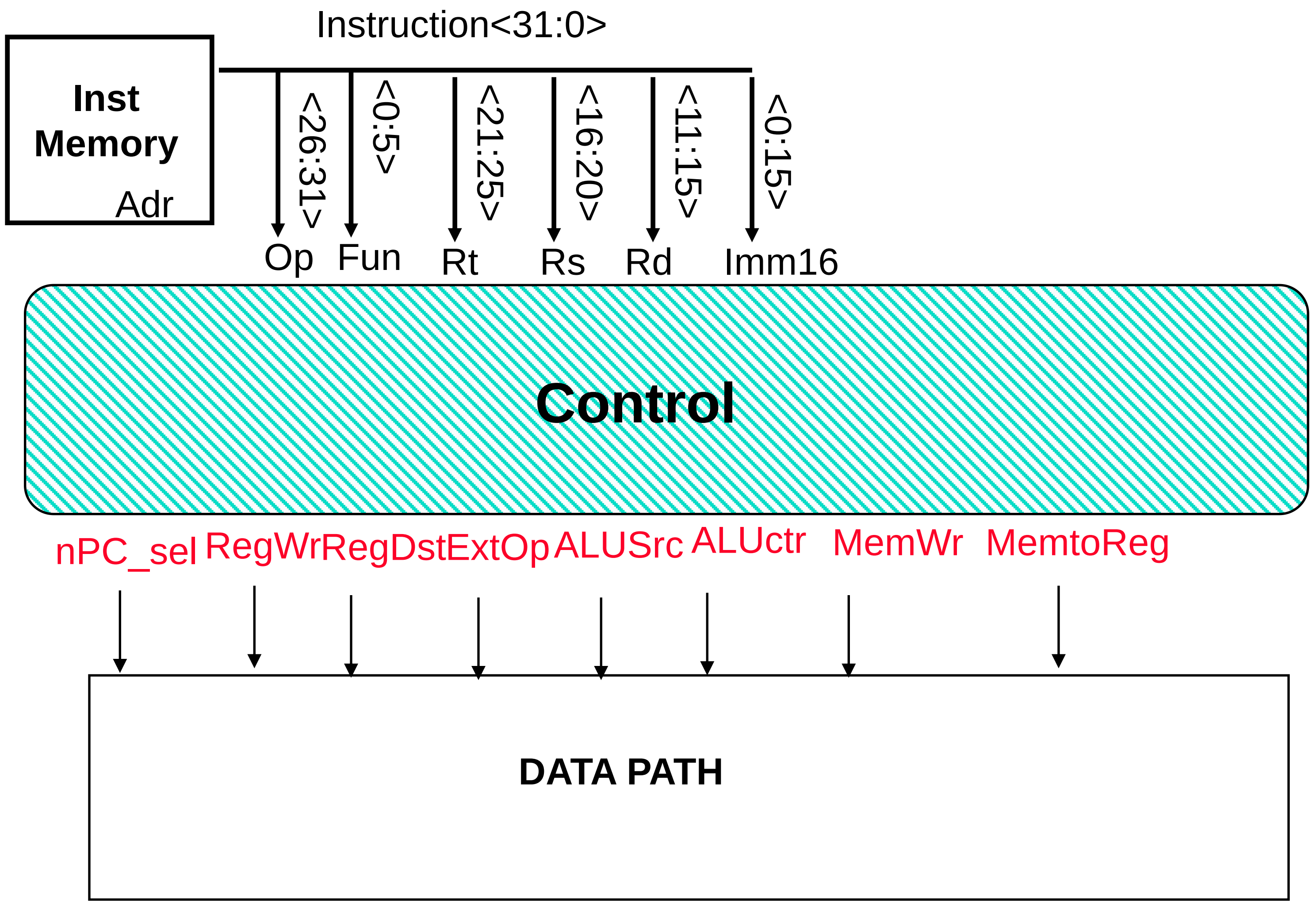
- if (Zero == 1) then PC = PC + 4 + SignExt[imm16]*4 ; else PC = PC + 4



- **What is encoding of nPC_sel?**
  - Direct MUX select?
  - Branch inst. / not branch
- **Let's pick 2nd option**

Q: What logic gate?

Step 4: Given Datapath: RTL → Control



A Summary of the Control Signals (1/2)

inst   Register Transfer

add   R[rd] ← R[rs] + R[rt];   PC ← PC + 4

ALUsrc = RegB, ALUctr = "ADD", RegDst = rd, RegWr, nPC_sel = "+4"

sub   R[rd] ← R[rs] – R[rt];   PC ← PC + 4

ALUsrc = RegB, ALUctr = "SUB", RegDst = rd, RegWr, nPC_sel = "+4"

ori   R[rt] ← R[rs] + zero_ext(Imm16);   PC ← PC + 4

ALUsrc = Im, Extop = "Z",ALUctr = "OR", RegDst = rt,RegWr, nPC_sel ="+4"

lw   R[rt] ← MEM[R[rs] + sign_ext(Imm16)];   PC ← PC + 4

ALUsrc = Im, Extop = "sn", ALUctr = "ADD",   MemtoReg, RegDst = rt, RegWr,   nPC_sel = "+4"

sw   MEM[R[rs] + sign_ext(Imm16)] ← R[rs];   PC ← PC + 4

ALUsrc = Im, Extop = "sn", ALUctr = "ADD", MemWr, nPC_sel = "+4"

beq   if (R[rs] == R[rt]) then PC ← PC + sign_ext(Imm16)] || 00 else PC ← PC + 4

A Summary of the Control Signals (2/2)

See Appendix A

func	10 0000	10 0010	We Don't Care :-)				
op	00 0000	00 0000	00 1101	10 0011	10 1011	00 0100	00 0010
	add	sub	ori	lw	sw	beq	jump
RegDst	1	1	0	0	x	x	x
ALUSrc	0	0	1	1	1	0	x
MemtoReg	0	0	0	1	x	x	x
RegWrite	1	1	1	1	0	0	0
MemWrite	0	0	0	0	1	0	0
nPCsel	0	0	0	0	0	1	?
Jump	0	0	0	0	0	0	1
ExtOp	x	x	0	1	1	x	x
ALUctr<2:0>	Add	Subtract	Or	Add	Add	Subtract	x

	31–26	26–21	21–16	16–11	11–6	6–0	
R-type	op	rs	rt	rd	shamt	funct	add, sub
I-type	op	rs	rt	immediate			ori, lw, sw, beq
J-type	op	target address					jump

Boolean Expressions for Controller

RegDst = add + sub
ALUSrc = ori + lw + sw
MemtoReg = lw
RegWrite = add + sub + ori + lw
MemWrite = sw
nPCsel = beq
Jump = jump
ExtOp = lw + sw
ALUctr[0] = sub + beq (assume ALUctr is 00 ADD, 01: SUB, 10: OR)
ALUctr[1] = or

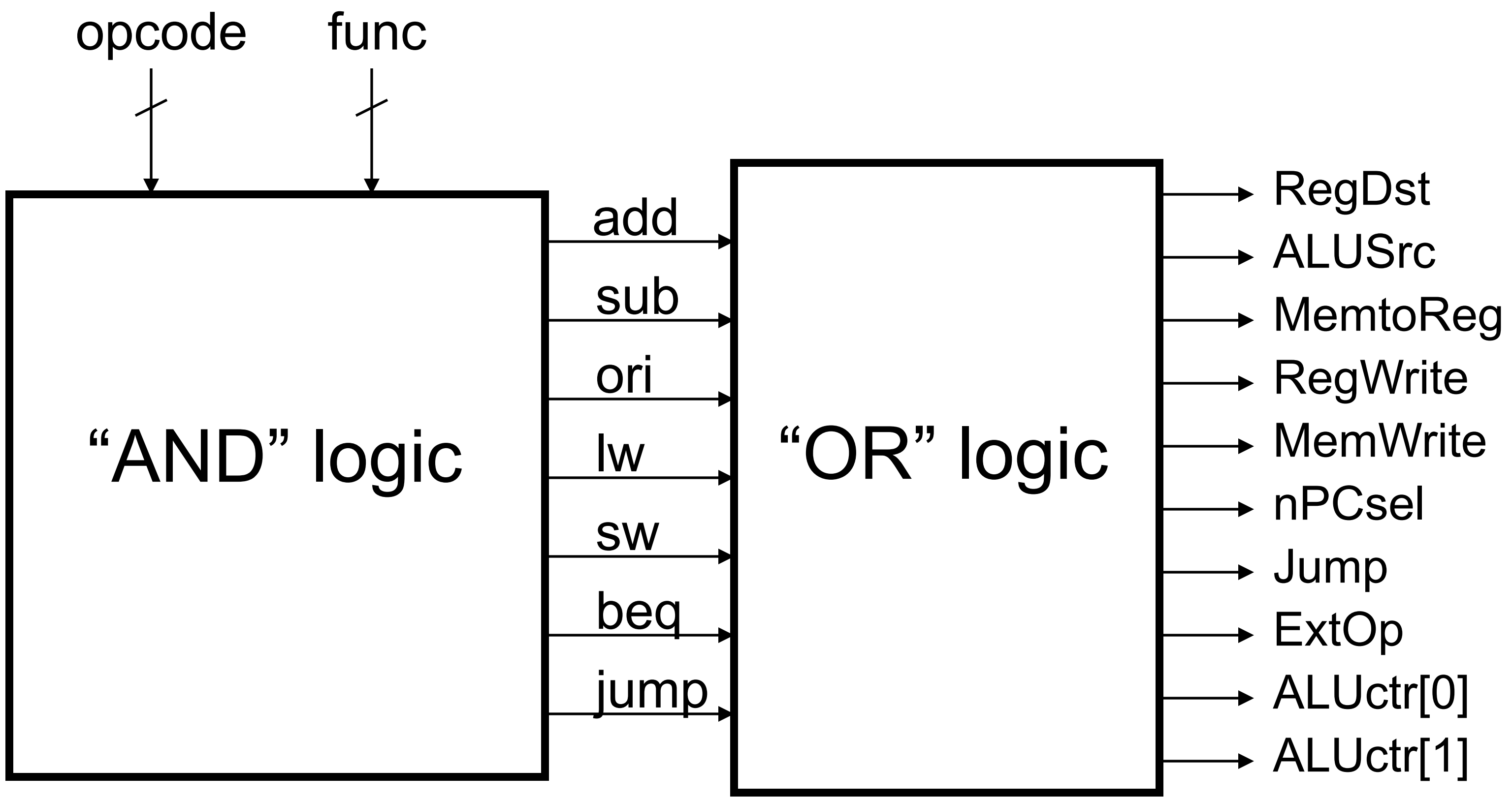
where,

rtype = $\sim op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet \sim op_2 \bullet \sim op_1 \bullet \sim op_0$,
ori = $\sim op_5 \bullet \sim op_4 \bullet op_3 \bullet op_2 \bullet \sim op_1 \bullet op_0$
lw = $op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet \sim op_2 \bullet op_1 \bullet op_0$
sw = $op_5 \bullet \sim op_4 \bullet op_3 \bullet \sim op_2 \bullet op_1 \bullet op_0$
beq = $\sim op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet op_2 \bullet \sim op_1 \bullet \sim op_0$
jump = $\sim op_5 \bullet \sim op_4 \bullet \sim op_3 \bullet \sim op_2 \bullet op_1 \bullet \sim op_0$

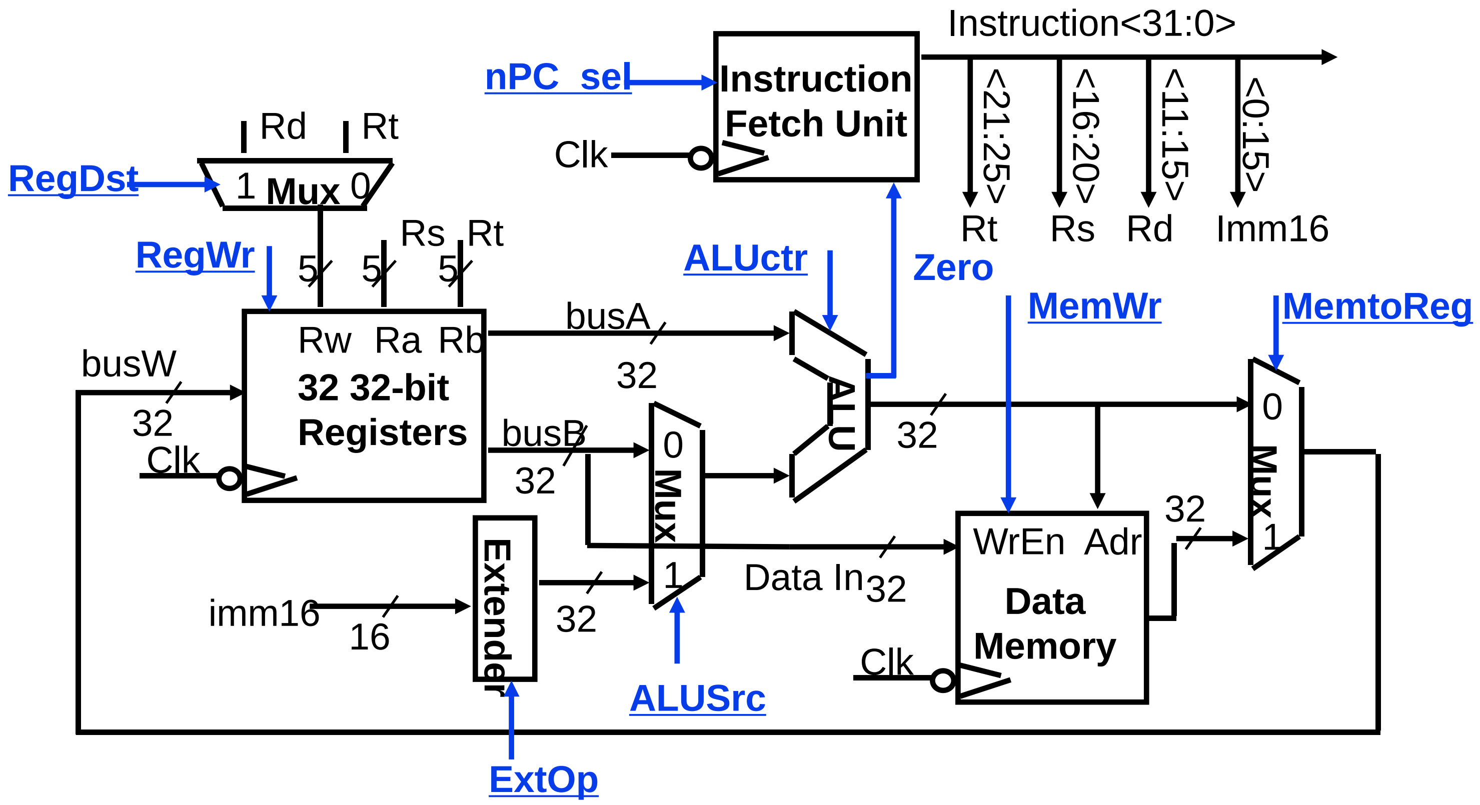
How do we implement this in gates?

add = rtype $\bullet$ $func_5 \bullet \sim func_4 \bullet \sim func_3 \bullet \sim func_2 \bullet \sim func_1 \bullet \sim func_0$
sub = rtype $\bullet$ $func_5 \bullet \sim func_4 \bullet \sim func_3 \bullet \sim func_2 \bullet func_1 \bullet \sim func_0$

Controller Implementation



Peer Instruction



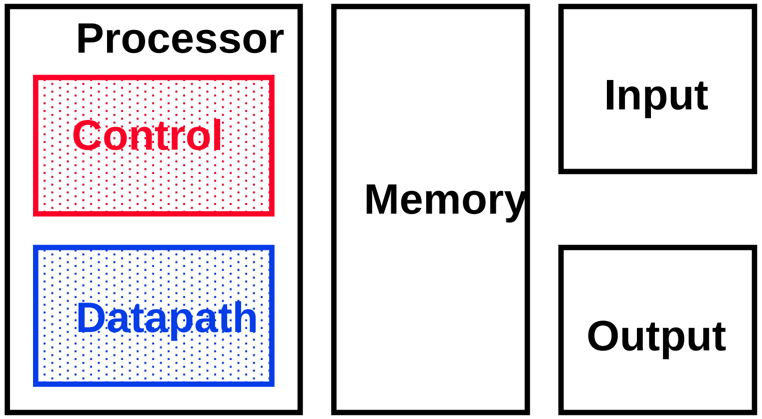
1) MemToReg='x' & ALUctr='sub'. SUB or BEQ?

2) ALUctr='add'. Which 1 signal is different for all 3 of: ADD, LW, & SW? RegDst or ExtOp?

	12
a)	SR
b)	SE
c)	BR
d)	BE

Summary: Single-cycle Processor

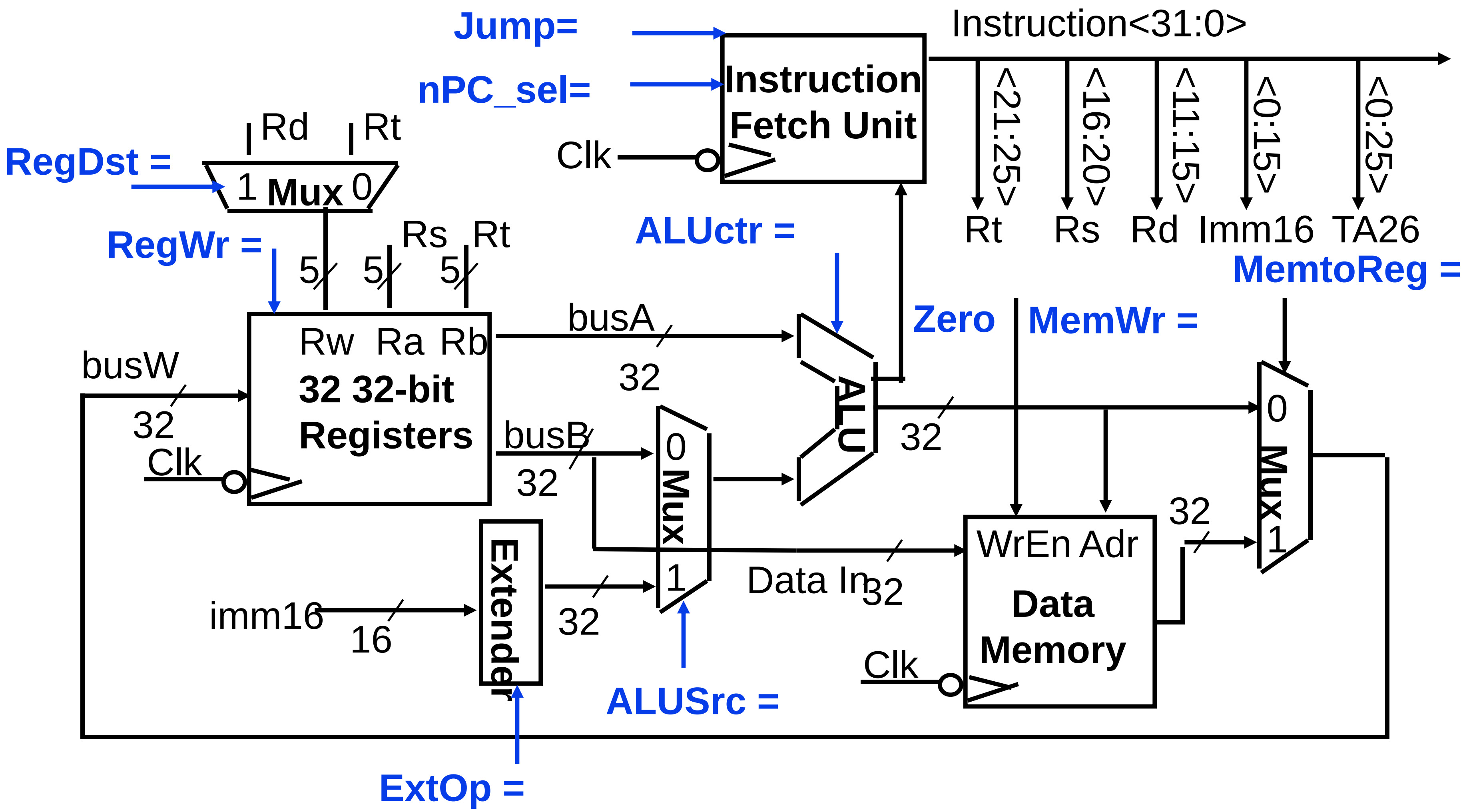
- 5 steps to design a processor
  - 1. Analyze instruction set → datapath requirements
  - 2. Select set of datapath components & establish clock methodology
  - 3. Assemble datapath meeting the requirements
  - 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
  - 5. Assemble the control logic
    - Formulate Logic Equations
    - Design Circuits



The Single Cycle Datapath during Jump

	31 … 26	25 … 0	
J-type	op	target address	jump

- **New PC = { PC[31..28], target address, 00 }**



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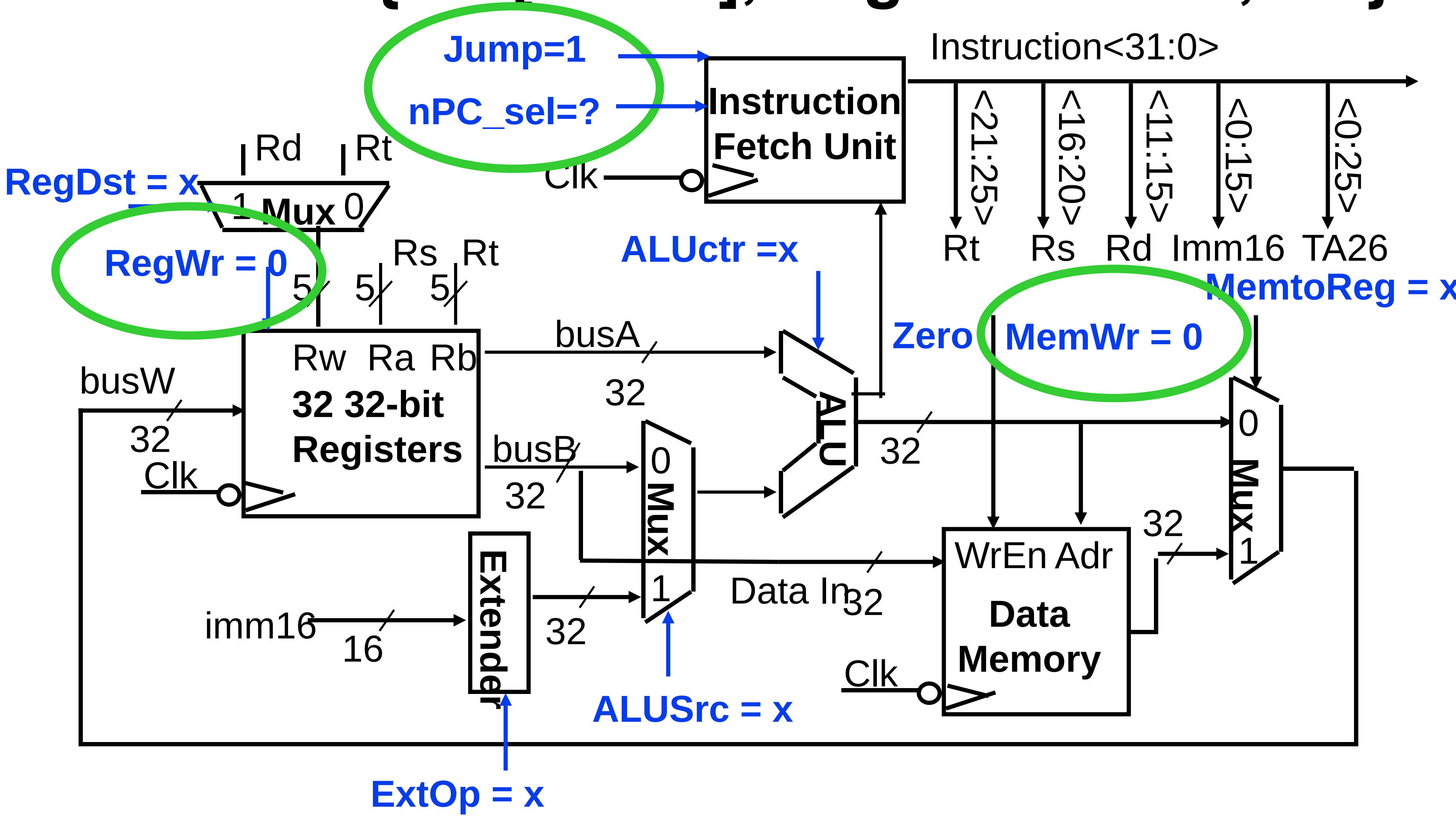
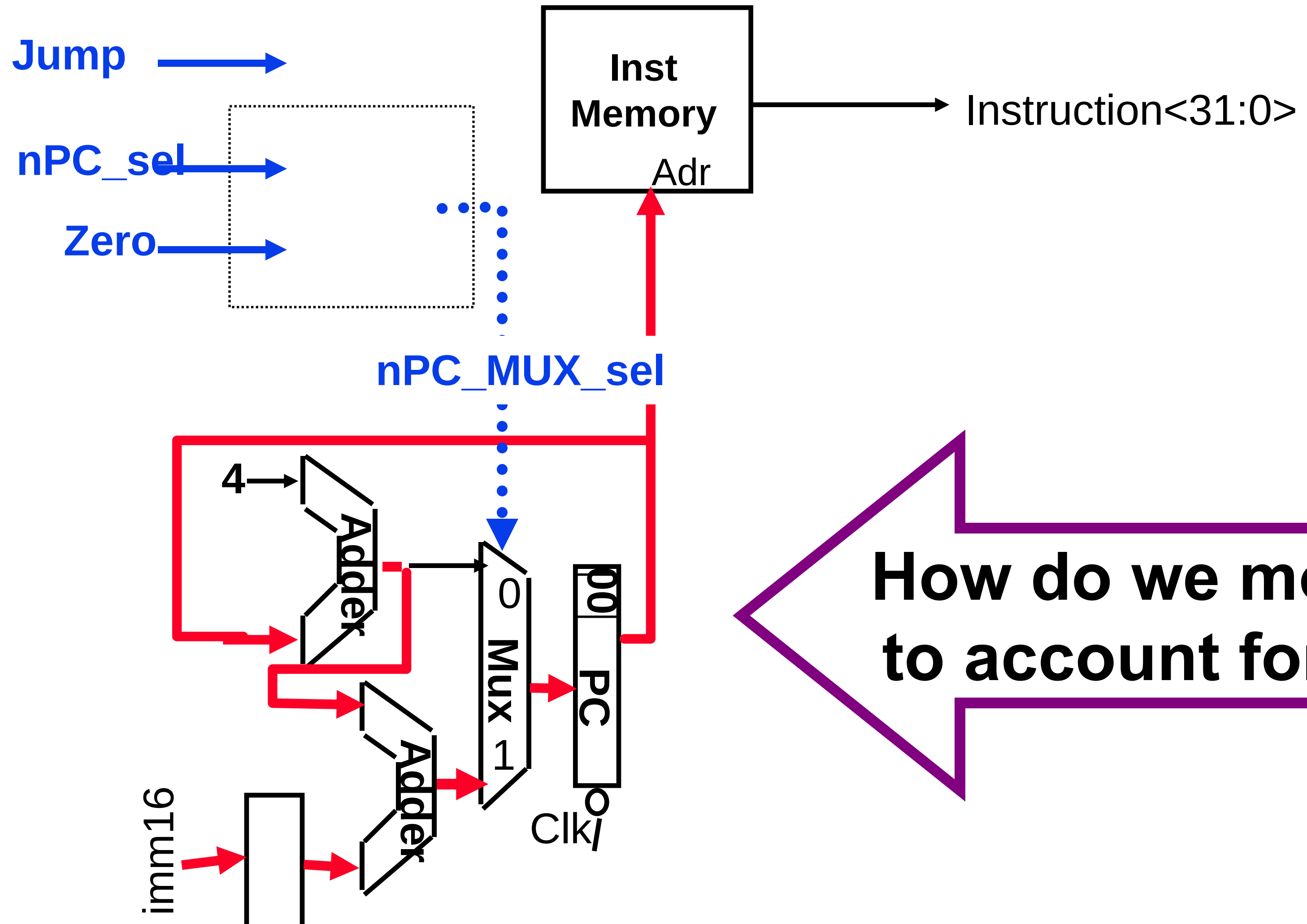


Instruction Fetch Unit at the End of Jump

	31 ... 26	25 ... 0	
J-type	op	target address	jump

- **New PC = { PC[31..28], target address, 00 }**

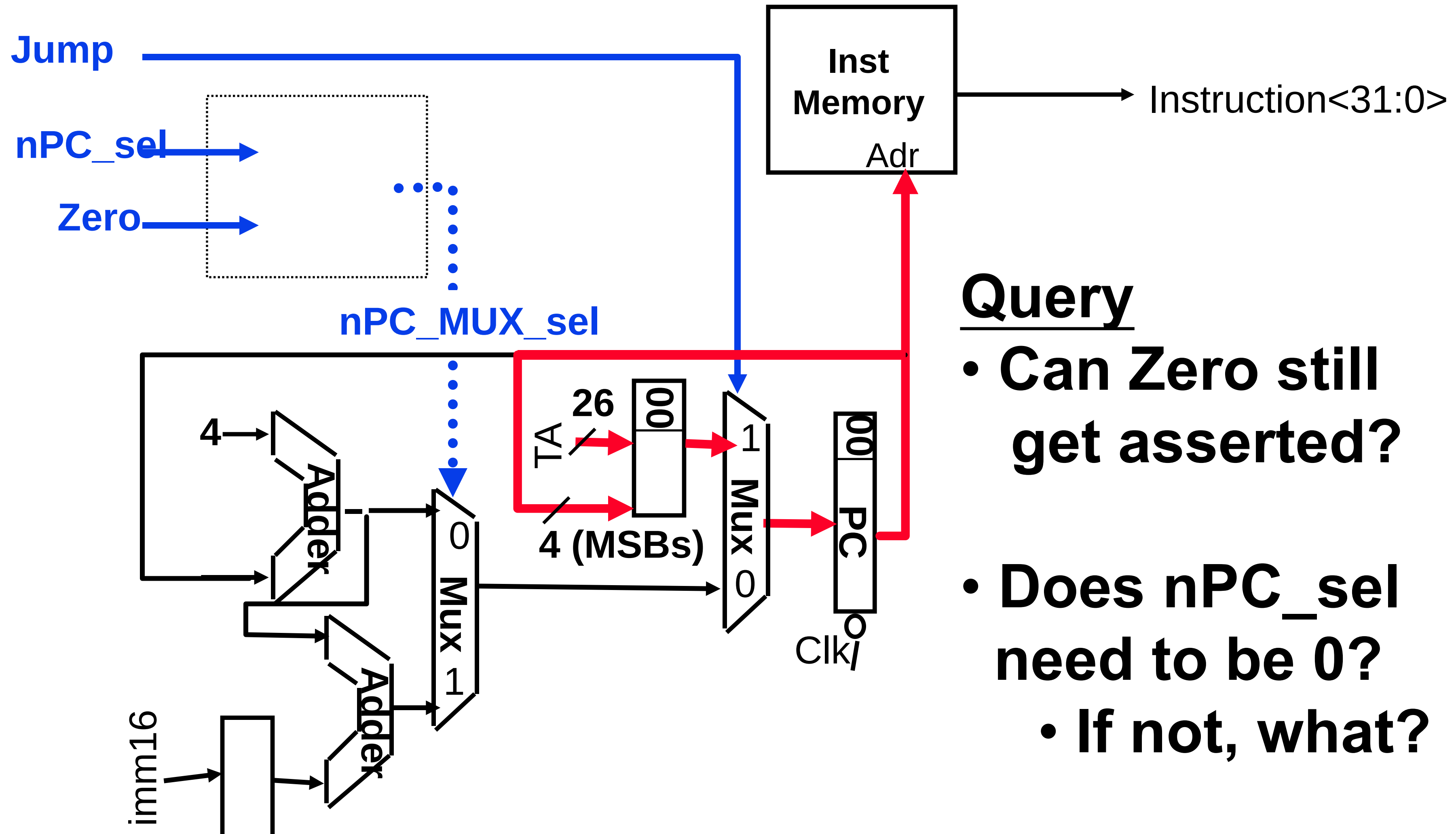


How do we modify this to account for jumps?

Instruction Fetch Unit at the End of Jump

	31	26 25	0	
J-type	op	target address		jump

- **New PC = { PC[31..28], target address, 00 }**



Query

- **Can Zero still get asserted?**
- **Does nPC_sel need to be 0?**
  - **If not, what?**