Single Cycle Processor Design

ICS 233

Computer Architecture and Assembly Language

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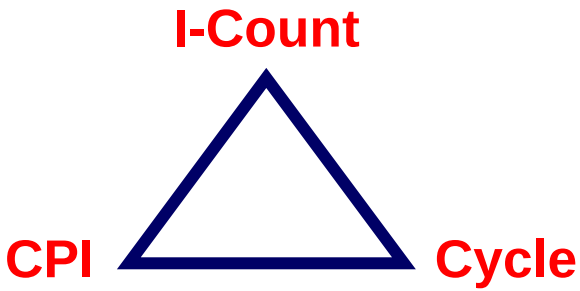
[Adapted from slides of Dr. M. Mudawar, ICS 233, KFUPM]

Outline

- Designing a Processor: Step-by-Step
- Datapath Components and Clocking
- Assembling an Adequate Datapath
- Controlling the Execution of Instructions
- The Main Controller and ALU Controller
- Drawback of the single-cycle processor design

The Performance Perspective

- Recall, performance is determined by:
  - Instruction count
  - Clock cycles per instruction (CPI)
  - Clock cycle time



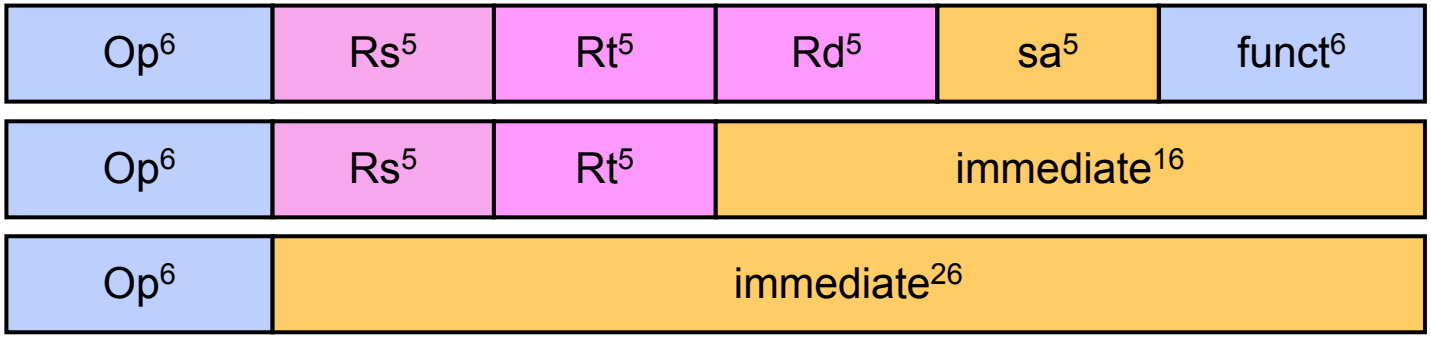
- Processor design will affect
  - Clock cycles per instruction
  - Clock cycle time
- Single cycle datapath and control design:
  - Advantage: One clock cycle per instruction
  - Disadvantage: long cycle time

Designing a Processor: Step-by-Step

- Analyze instruction set => datapath requirements
  - The meaning of each instruction is given by the register transfers
  - Datapath must include storage elements for ISA registers
  - Datapath must support each register transfer
- Select datapath components and clocking methodology
- Assemble datapath meeting the requirements
- Analyze implementation of each instruction
  - Determine the setting of control signals for register transfer
- Assemble the control logic

Review of MIPS Instruction Formats

- All instructions are 32-bit wide
- Three instruction formats: R-type, I-type, and J-type



  - Op^6: 6-bit opcode of the instruction
  - Rs^5, Rt^5, Rd^5: 5-bit source and destination register numbers
  - sa^5: 5-bit shift amount used by shift instructions
  - $funct^6$: 6-bit function field for R-type instructions
  - $immediate^{16}$: 16-bit immediate value or address offset
  - $immediate^{26}$: 26-bit target address of the jump instruction

MIPS Subset of Instructions

- Only a subset of the MIPS instructions are considered
  - ALU instructions (R-type): **add, sub, and, or, xor, slt**
  - Immediate instructions (I-type): **addi, slti, andi, ori, xori**
  - Load and Store (I-type): **lw, sw**
  - Branch (I-type): **beq, bne**
  - Jump (J-type): **j**
- This subset does not include all the integer instructions
- But sufficient to illustrate design of datapath and control
- Concepts used to implement the MIPS subset are used to construct a broad spectrum of computers

Details of the MIPS Subset

Instruction		Meaning	Format					
add	rd, rs, rt	addition	$op^6 = 0$	rs^5	rt^5	rd^5	0	0x20
sub	rd, rs, rt	subtraction	$op^6 = 0$	rs^5	rt^5	rd^5	0	0x22
and	rd, rs, rt	bitwise and	$op^6 = 0$	rs^5	rt^5	rd^5	0	0x24
or	rd, rs, rt	bitwise or	$op^6 = 0$	rs^5	rt^5	rd^5	0	0x25
xor	rd, rs, rt	exclusive or	$op^6 = 0$	rs^5	rt^5	rd^5	0	0x26
slt	rd, rs, rt	set on less than	$op^6 = 0$	rs^5	rt^5	rd^5	0	0x2a
addi	rt, rs, im^{16}	add immediate	0x08	rs^5	rt^5	im^{16}		
slti	rt, rs, im^{16}	slt immediate	0x0a	rs^5	rt^5	im^{16}		
andi	rt, rs, im^{16}	and immediate	0x0c	rs^5	rt^5	im^{16}		
ori	rt, rs, im^{16}	or immediate	0x0d	rs^5	rt^5	im^{16}		
xori	rt, im^{16}	xor immediate	0x0e	rs^5	rt^5	im^{16}		
lw	rt, im^{16}(rs)	load word	0x23	rs^5	rt^5	im^{16}		
sw	rt, im^{16}(rs)	store word	0x2b	rs^5	rt^5	im^{16}		
beq	rs, rt, im^{16}	branch if equal	0x04	rs^5	rt^5	im^{16}		
bne	rs, rt, im^{16}	branch not equal	0x05	rs^5	rt^5	im^{16}		
j	im^{26}	jump	0x02	im^{26}				

Register Transfer Level (RTL)

- RTL is a description of data flow between registers
- RTL gives a meaning to the instructions
- All instructions are fetched from memory at address PC

Instruction	RTL Description	
ADD	Reg(Rd) ← Reg(Rs) + Reg(Rt);	PC ← PC + 4
SUB	Reg(Rd) ← Reg(Rs) – Reg(Rt);	PC ← PC + 4
ORI	Reg(Rt) ← Reg(Rs) | zero_ext(Im16);	PC ← PC + 4
LW	Reg(Rt) ← MEM[Reg(Rs) + sign_ext(Im16)];	PC ← PC + 4
SW	MEM[Reg(Rs) + sign_ext(Im16)] ← Reg(Rt);	PC ← PC + 4
BEQ	if (Reg(Rs) == Reg(Rt)) PC ← PC + 4 + 4 × sign_extend(Im16) else PC ← PC + 4	

Instructions are Executed in Steps

- **R-type**

Fetch instruction:	Instruction ← MEM[PC]
Fetch operands:	data1 ← Reg(Rs), data2 ← Reg(Rt)
Execute operation:	ALU_result ← func(data1, data2)
Write ALU result:	Reg(Rd) ← ALU_result
Next PC address:	PC ← PC + 4

- **I-type**

Fetch instruction:	Instruction ← MEM[PC]
Fetch operands:	data1 ← Reg(Rs), data2 ← Extend(imm16)
Execute operation:	ALU_result ← op(data1, data2)
Write ALU result:	Reg(Rt) ← ALU_result
Next PC address:	PC ← PC + 4

- **BEQ**

Fetch instruction:	Instruction ← MEM[PC]
Fetch operands:	data1 ← Reg(Rs), data2 ← Reg(Rt)
Equality:	zero ← subtract(data1, data2)
Branch:	if (zero) PC ← PC + 4 + 4×sign_ext(imm16)
	else PC ← PC + 4

Instruction Execution – cont'd

- **LW**

Fetch instruction:	Instruction ← MEM[PC]
Fetch base register:	base ← Reg(Rs)
Calculate address:	address ← base + sign_extend(imm16)
Read memory:	data ← MEM[address]
Write register Rt:	Reg(Rt) ← data
Next PC address:	PC ← PC + 4

- **SW**

Fetch instruction:	Instruction ← MEM[PC]
Fetch registers:	base ← Reg(Rs), data ← Reg(Rt)
Calculate address:	address ← base + sign_extend(imm16)
Write memory:	MEM[address] ← data
Next PC address:	PC ← PC + 4

- **Jump**

Fetch instruction:	Instruction ← MEM[PC]
Target PC address:	target ← PC[31:28] , Imm26 , '00'
Jump:	PC ← target

concatenation

Requirements of the Instruction Set

- Memory
  - Instruction memory where instructions are stored
  - Data memory where data is stored
- Registers
  - 32 × 32-bit general purpose registers, R0 is always zero
  - Read source register Rs
  - Read source register Rt
  - Write destination register Rt or Rd
- Program counter PC register and Adder to increment PC
- Sign and Zero extender for immediate constant
- ALU for executing instructions

Next . . .

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- Datapath Components and Clocking
- Assembling an Adequate Datapath
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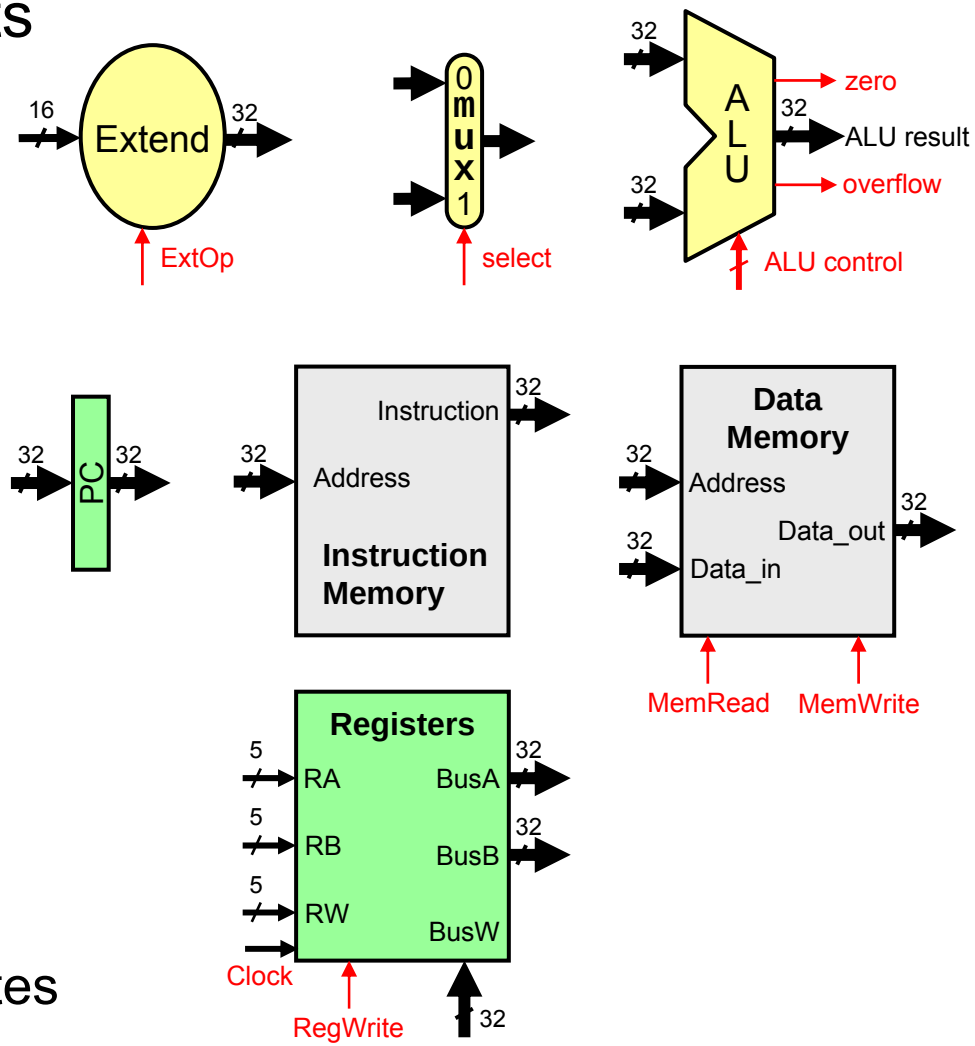
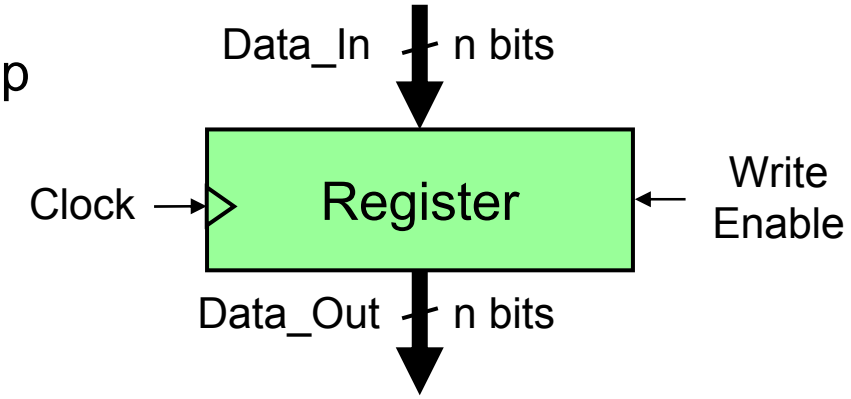
Components of the Datapath

- Combinational Elements
  - ALU, Adder
  - Immediate extender
  - Multiplexers
- Storage Elements
  - Instruction memory
  - Data memory
  - PC register
  - Register file
- Clocking methodology
  - Timing of reads and writes



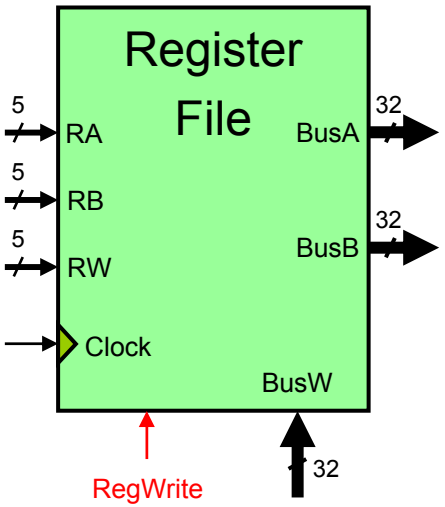
Register Element

- Register
  - Similar to the D-type Flip-Flop
- n-bit input and output
- Write Enable:
  - Enable / disable writing of register
  - Negated (0): Data_Out will not change
  - Asserted (1): Data_Out will become Data_In after clock edge
- Edge triggered Clocking
  - Register output is modified at clock edge



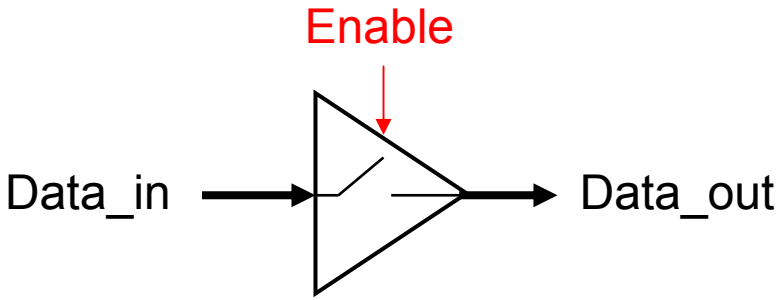
MIPS Register File

- Register File consists of 32 × 32-bit registers
  - BusA and BusB: 32-bit output busses for reading 2 registers
  - BusW: 32-bit input bus for writing a register when RegWrite is 1
  - Two registers read and one written in a cycle
- Registers are selected by:
  - RA selects register to be read on BusA
  - RB selects register to be read on BusB
  - RW selects the register to be written
- Clock input
  - The clock input is used ONLY during write operation
  - During read, register file behaves as a combinational logic block
    - RA or RB valid => BusA or BusB valid after access time



Tri-State Buffers

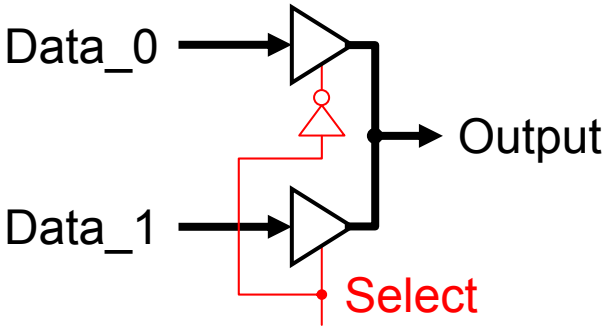
- Allow multiple sources to drive a single bus
- Two Inputs:
  - Data signal (data_in)
  - Output enable



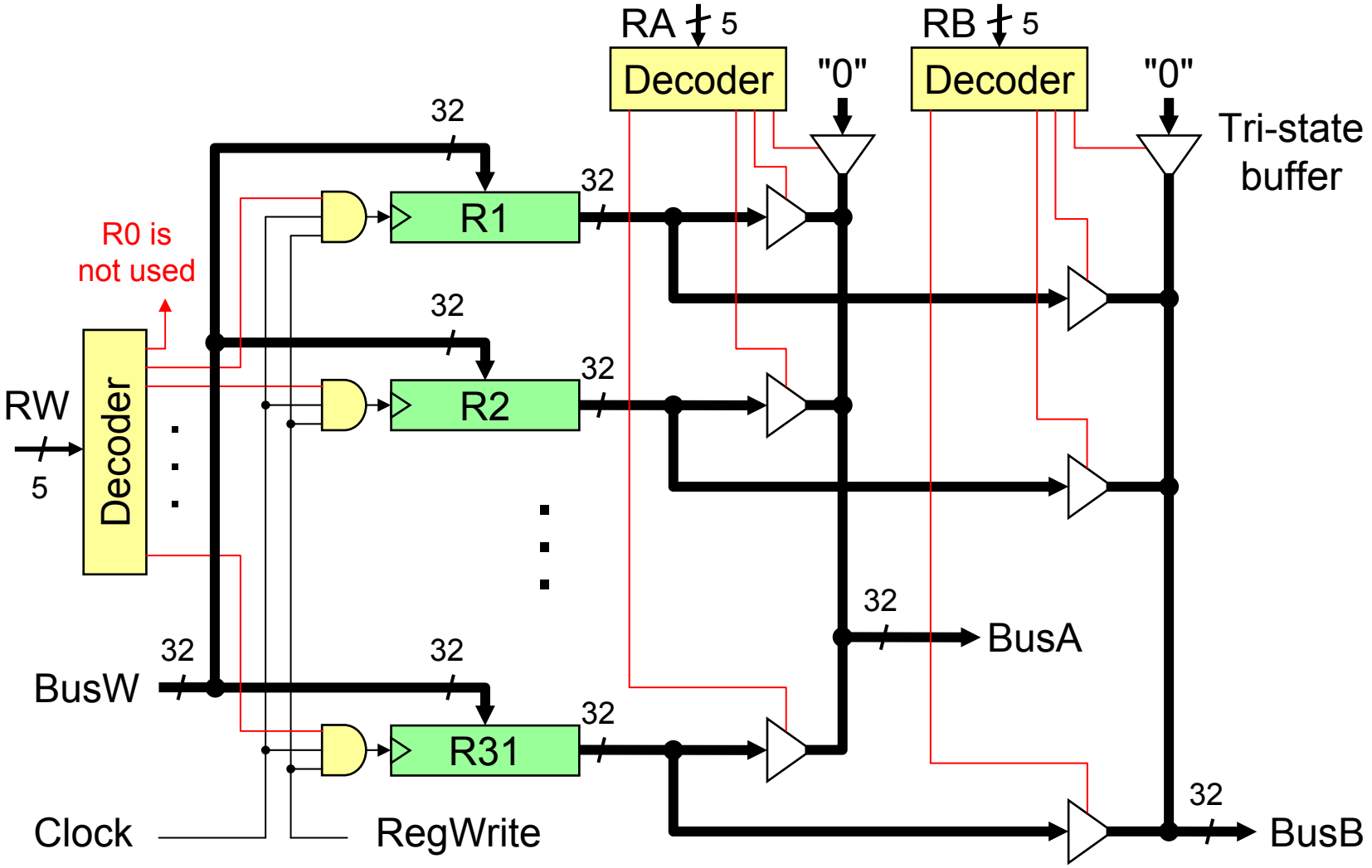
- One Output (data_out):
  - If (Enable) Data_out = Data_in

    else Data_out = High Impedance state (output is disconnected)

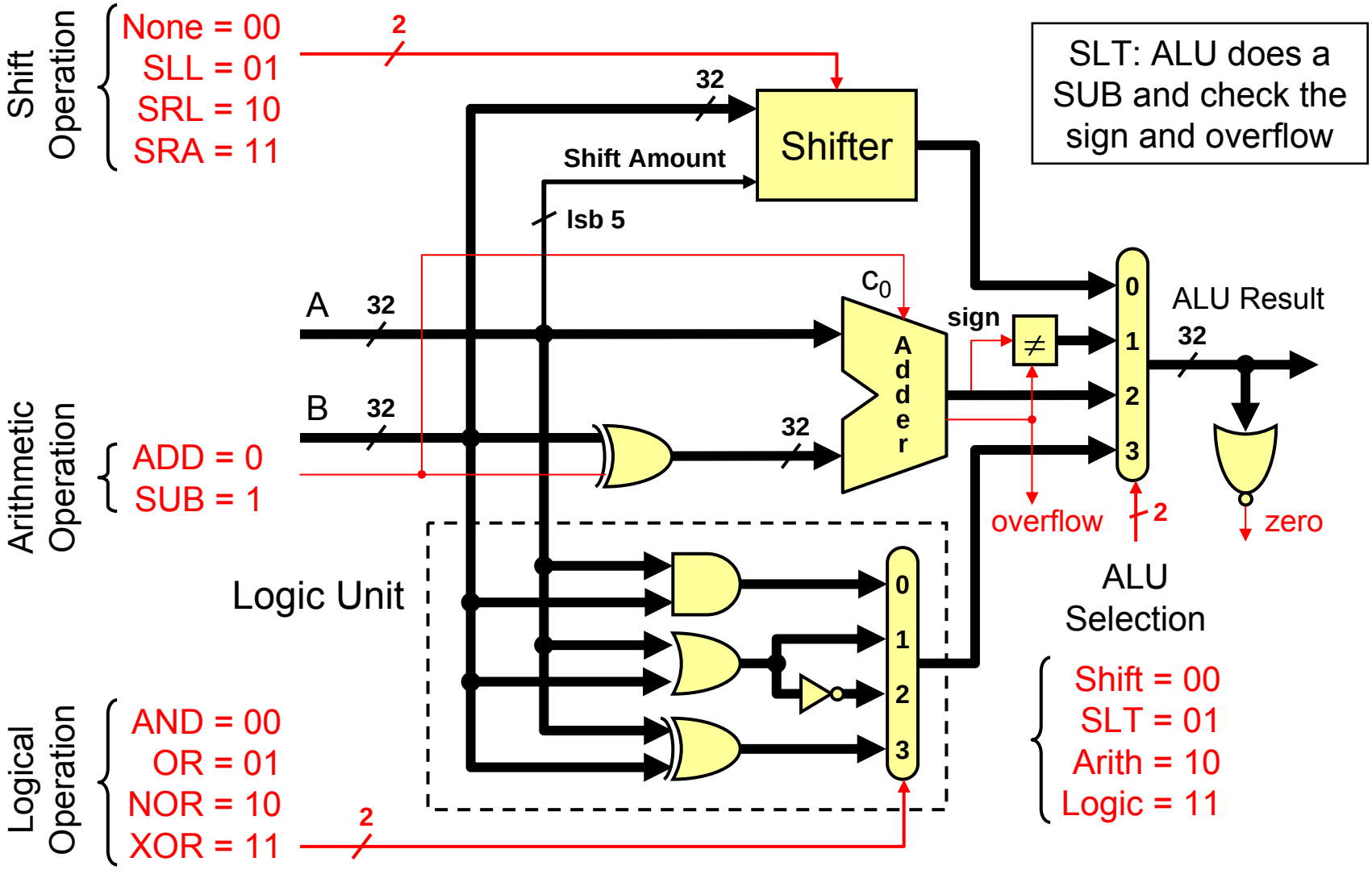
- Tri-state buffers can be used to build multiplexors



Details of the Register File

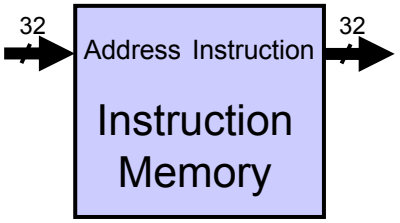


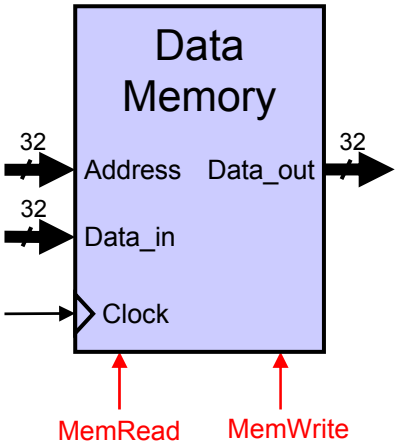
Building a Multifunction ALU



Instruction and Data Memories

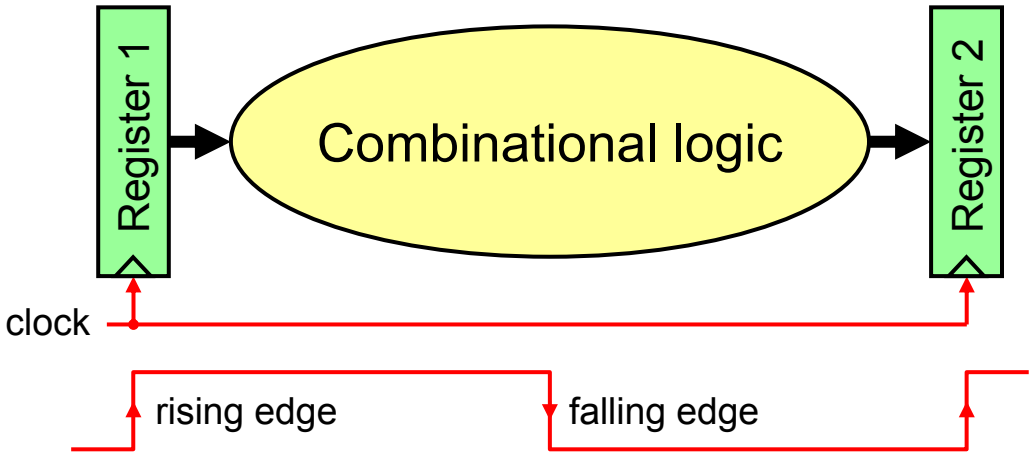
- Instruction memory needs only provide read access
  - Because datapath does not write instructions
  - Behaves as combinational logic for read
  - Address selects Instruction after access time
- Data Memory is used for load and store
  - MemRead: enables output on Data_out
    - Address selects the word to put on Data_out
  - MemWrite: enables writing of Data_in
    - Address selects the memory word to be written
    - The Clock synchronizes the write operation
- Separate instruction and data memories
  - Later, we will replace them with caches





Clocking Methodology

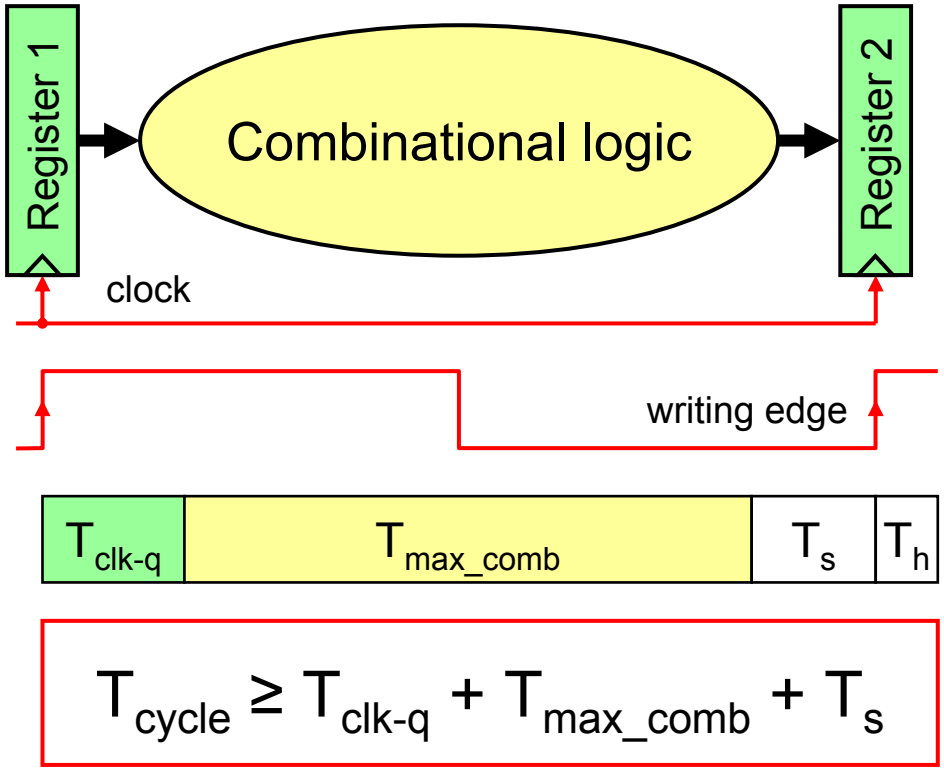
- Clocks are needed in a sequential logic to decide when a state element (register) should be updated
- To ensure correctness, a clocking methodology defines when data can be written and read



- We assume edge-triggered clocking
- All state changes occur on the same clock edge
- Data must be valid and stable before arrival of clock edge
- Edge-triggered clocking allows a register to be read and written during same clock cycle

Determining the Clock Cycle

- With edge-triggered clocking, the clock cycle must be long enough to accommodate the path from one register through the combinational logic to another register



- T_{clk-q} : clock to output delay through register
- T_{max_comb} : longest delay through combinational logic
- T_s : setup time that input to a register must be stable before arrival of clock edge
- T_h: hold time that input to a register must hold after arrival of clock edge
- Hold time (T_h) is normally satisfied since $T_{clk-q} > T_h$

Clock Skew

- Clock skew arises because the clock signal uses different paths with slightly different delays to reach state elements
- Clock skew is the difference in absolute time between when two storage elements see a clock edge
- With a clock skew, the clock cycle time is increased

$$T_{cycle} \geq T_{clk\text{-}q} + T_{max\_combinational} + T_{setup} + T_{skew}$$

- Clock skew is reduced by balancing the clock delays

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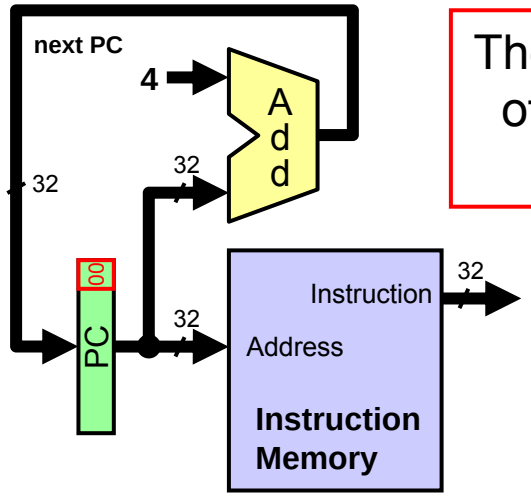
Instruction Fetching Datapath

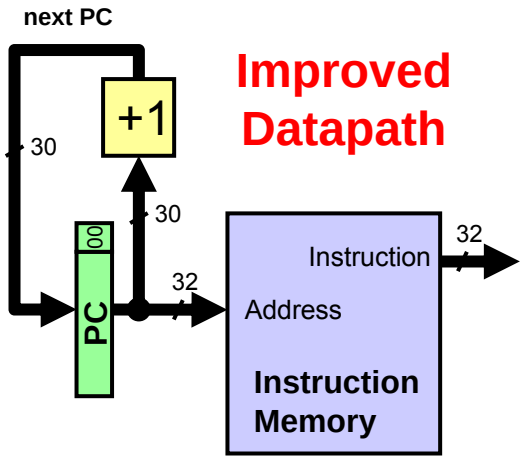
- We can now assemble the datapath from its components
- For instruction fetching, we need …
  - Program Counter (PC) register
  - Instruction Memory
  - Adder for incrementing PC

Improved datapath increments upper 30 bits of PC by 1



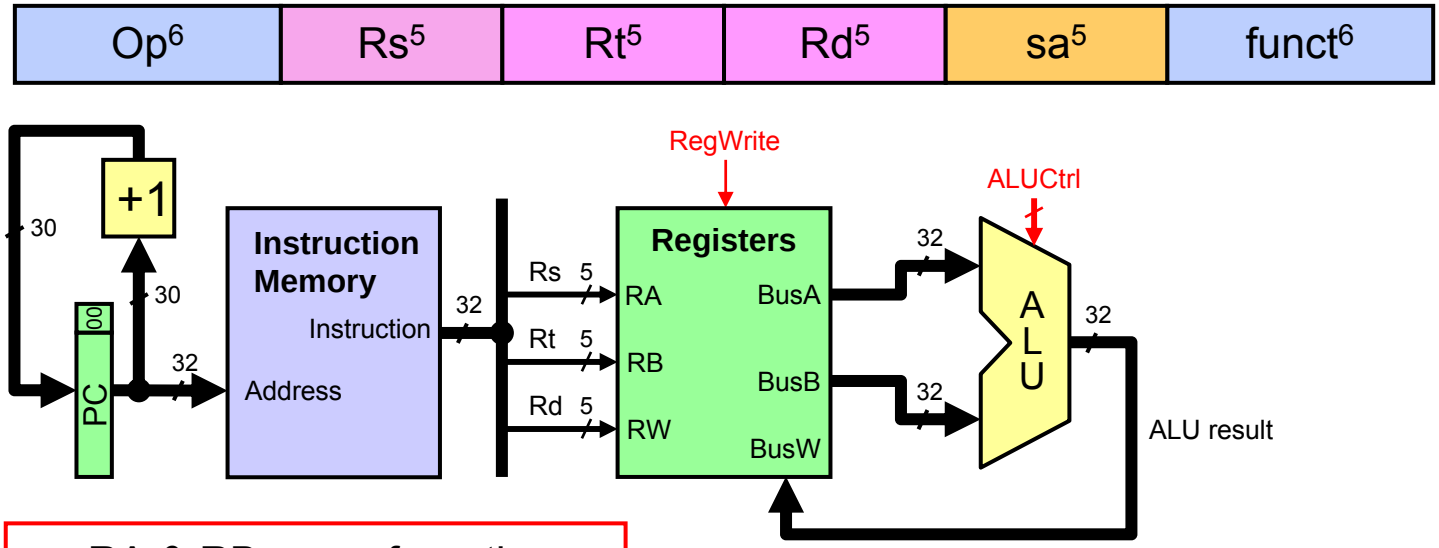
The least significant 2 bits of the PC are '00' since PC is a multiple of 4

Datapath does not handle branch or jump instructions



Improved Datapath

Datapath for R-type Instructions



RA & RB come from the instruction's Rs & Rt fields

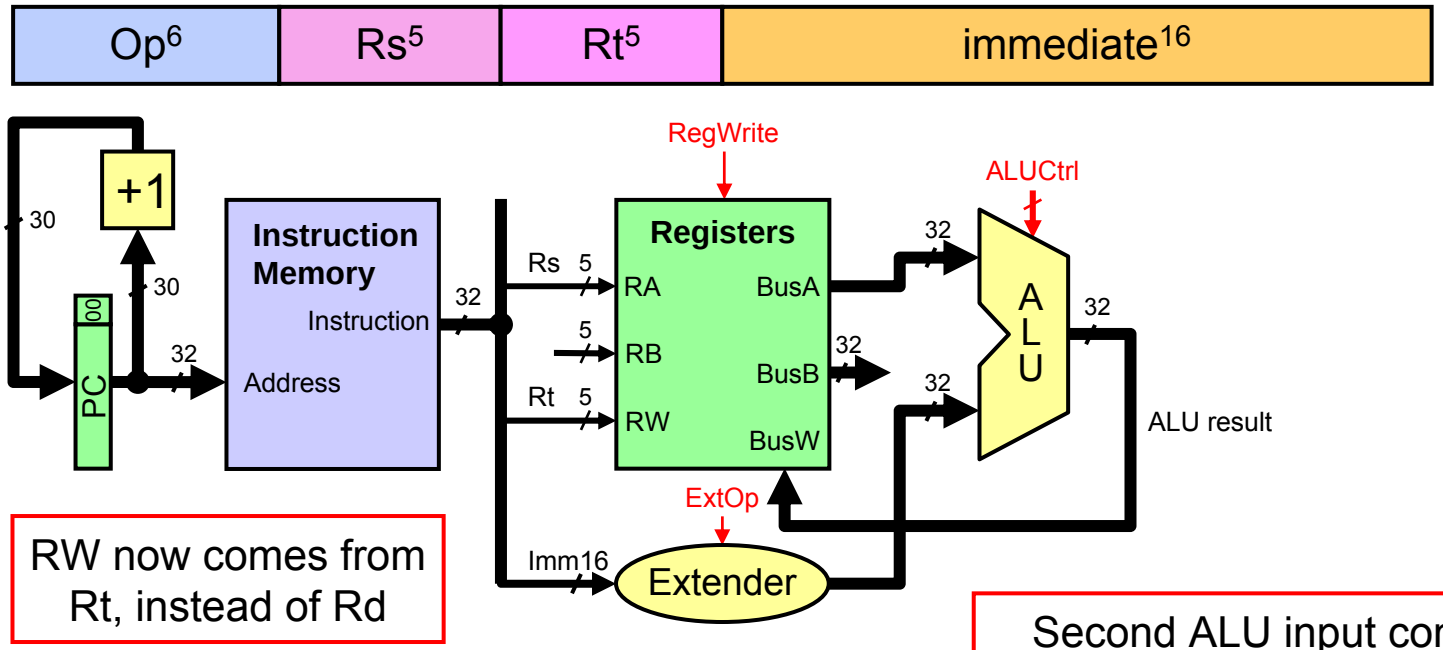
ALU inputs come from BusA & BusB

RW comes from the Rd field

ALU result is connected to BusW

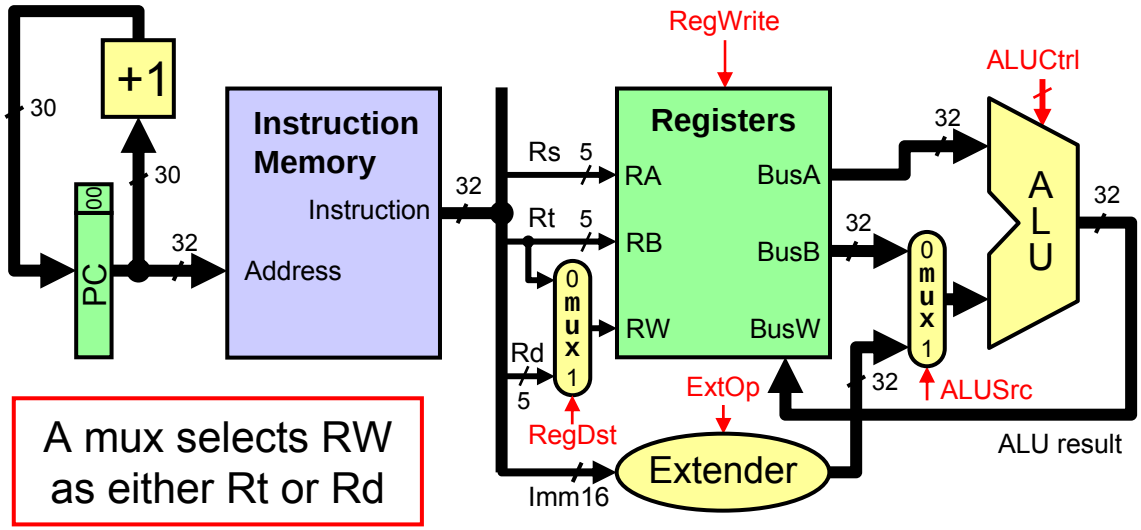
- Control signals
  - ALUCtrl is derived from the funct field because Op = 0 for R-type
  - RegWrite is used to enable the writing of the ALU result

Datapath for I-type ALU Instructions



- Control signals
  - ALUCtrl is derived from the Op field
  - RegWrite is used to enable the writing of the ALU result
  - ExtOp is used to control the extension of the 16-bit immediate

Combining R-type & I-type Datapaths

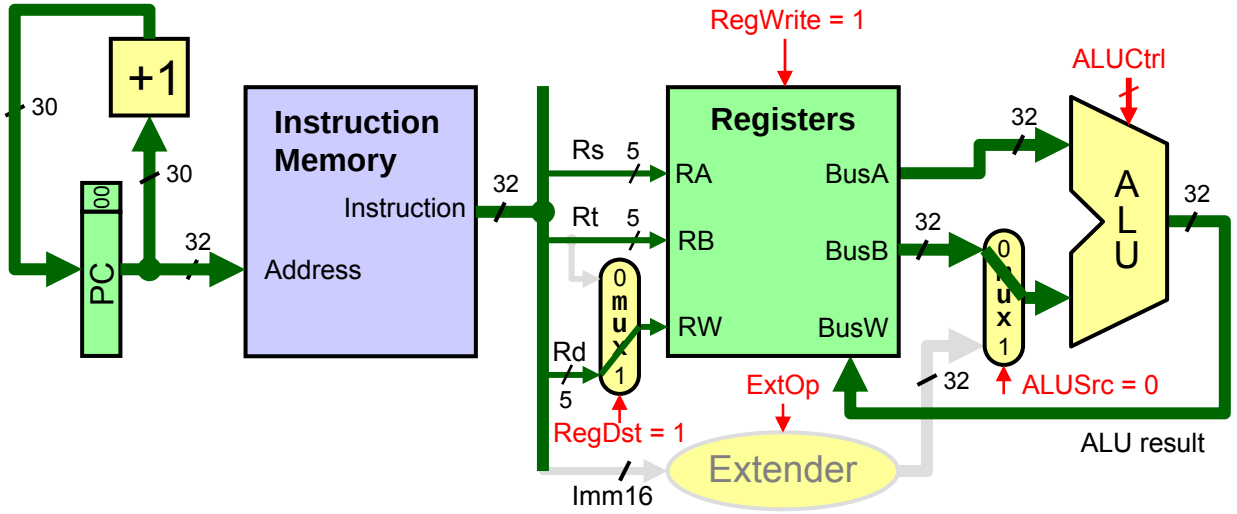


A mux selects RW as either Rt or Rd

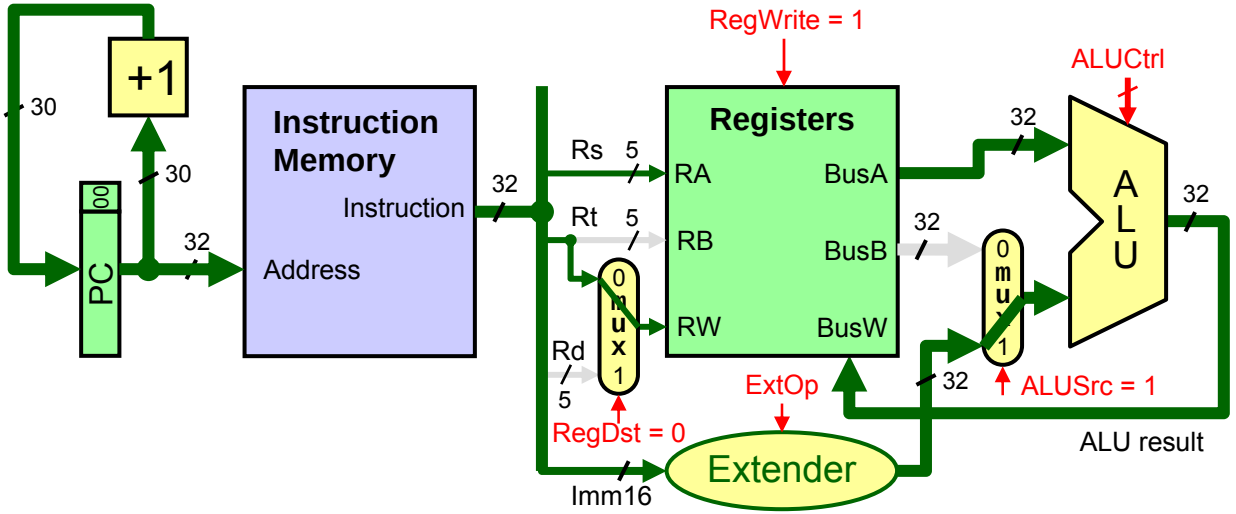
Another mux selects 2nd ALU input as either source register Rt data on BusB or the extended immediate

- Control signals
  - ALUCtrl is derived from either the Op or the funct field
  - RegWrite enables the writing of the ALU result
  - ExtOp controls the extension of the 16-bit immediate
  - RegDst selects the register destination as either Rt or Rd
  - ALUSrc selects the 2nd ALU source as BusB or extended immediate

Controlling ALU Instructions



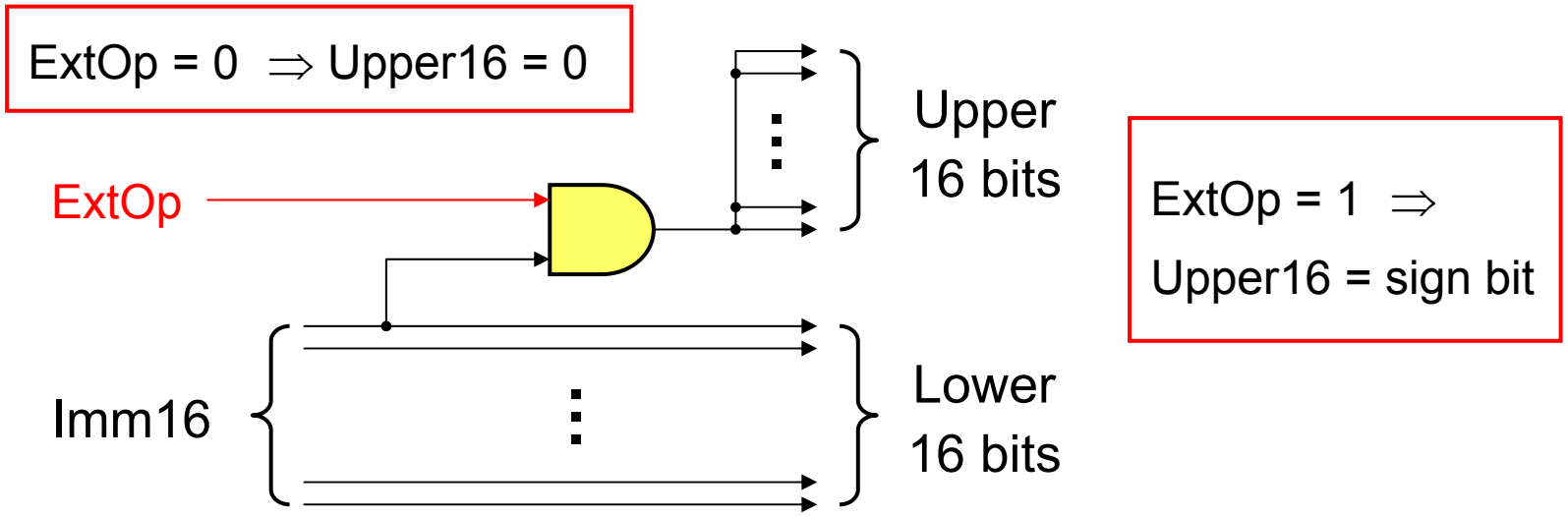
For R-type ALU instructions, RegDst is '1' to select Rd on RW and ALUSrc is '0' to select BusB as second ALU input. The active part of datapath is shown in **green**



For I-type ALU instructions, RegDst is '0' to select Rt on RW and ALUSrc is '1' to select Extended immediate as second ALU input. The active part of datapath is shown in **green**

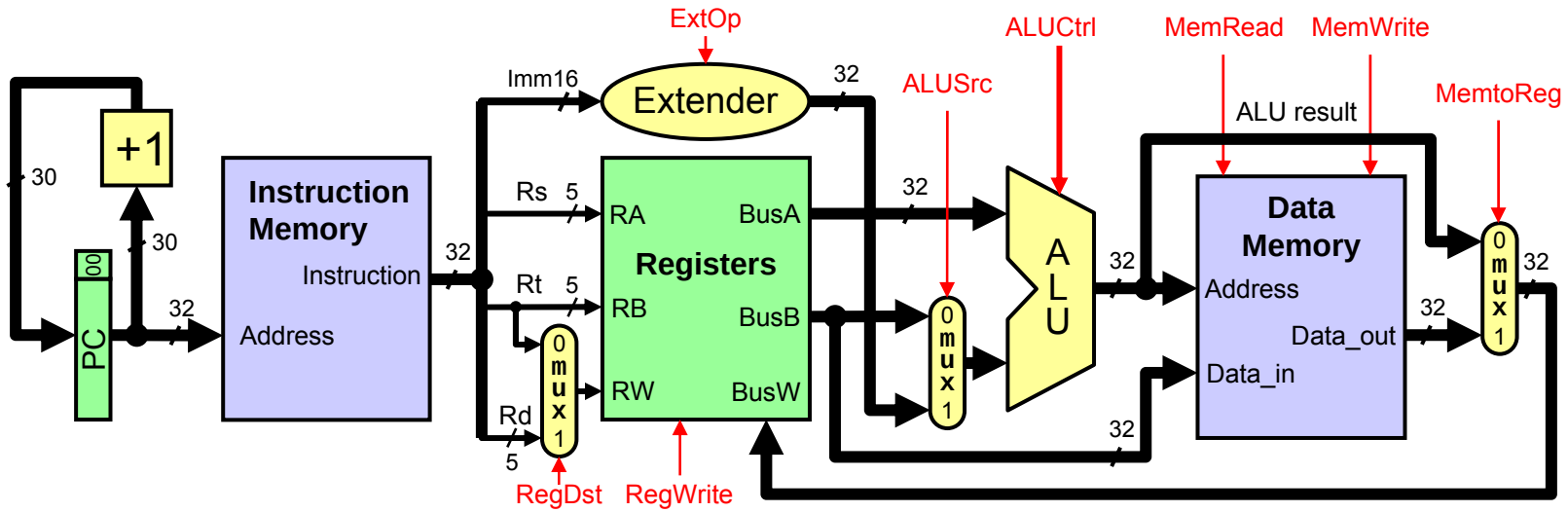
Details of the Extender

- Two types of extensions
  - Zero-extension for unsigned constants
  - Sign-extension for signed constants
- Control signal ExtOp indicates type of extension
- Extender Implementation: wiring and one AND gate



Adding Data Memory to Datapath

- A data memory is added for load and store instructions



ALU calculates data memory address

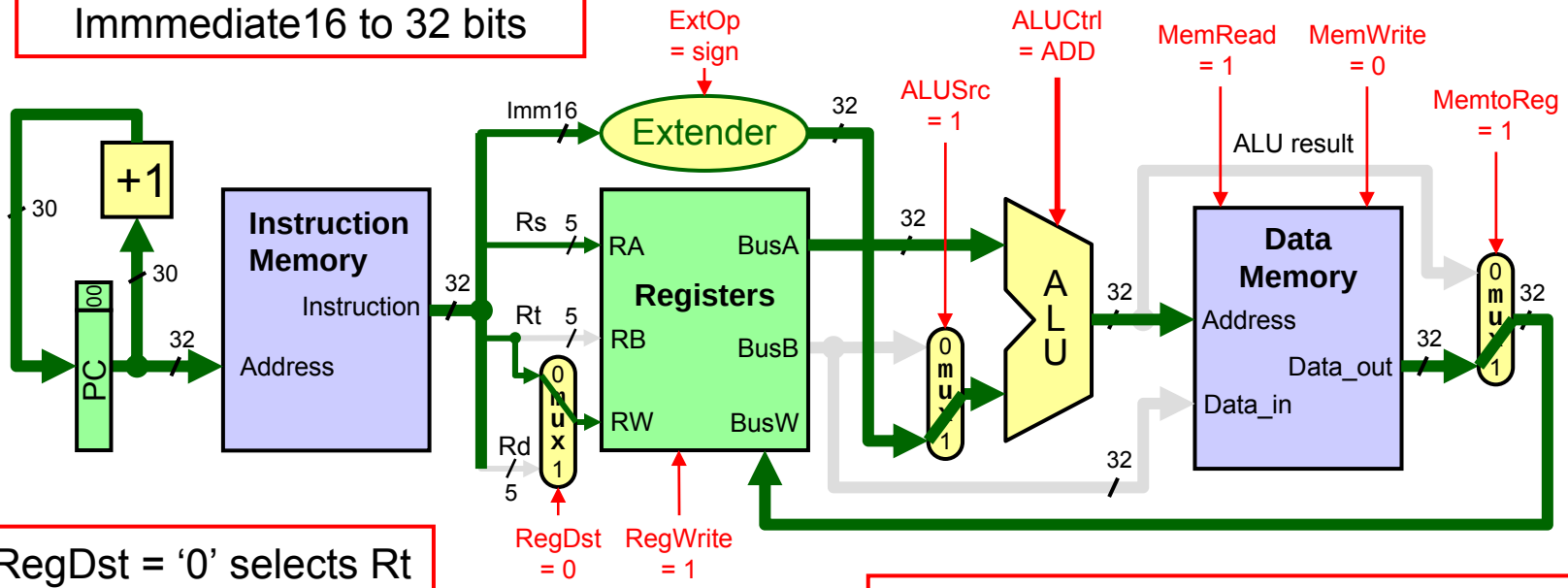
A 3rd mux selects data on BusW as either ALU result or memory data_out

- Additional Control signals
  - MemRead for load instructions
  - MemWrite for store instructions
  - MemtoReg selects data on BusW as ALU result or Memory Data_out

BusB is connected to Data_in of Data Memory for store instructions

Controlling the Execution of Load

ExtOp = 'sign' to sign-extend Immmediate16 to 32 bits



RegDst = '0' selects Rt as destination register

MemRead = '1' to read data memory

ALUSrc = '1' selects extended immediate as second ALU input

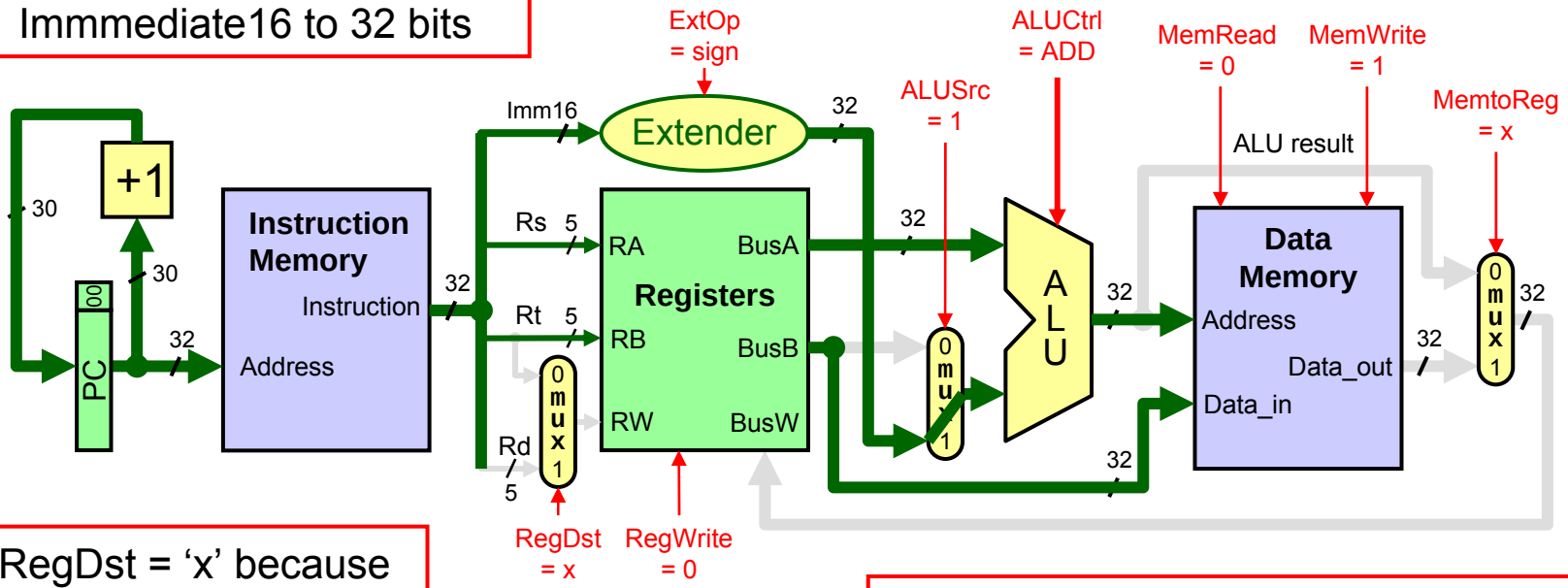
MemtoReg = '1' places the data read from memory on BusW

ALUCtrl = 'ADD' to calculate data memory address as Reg(Rs) + sign-extend(Imm16)

RegWrite = '1' to write the memory data on BusW to register Rt

Controlling the Execution of Store

ExtOp = 'sign' to sign-extend Immmediate16 to 32 bits



RegDst = 'x' because no destination register

MemWrite = '1' to write data memory

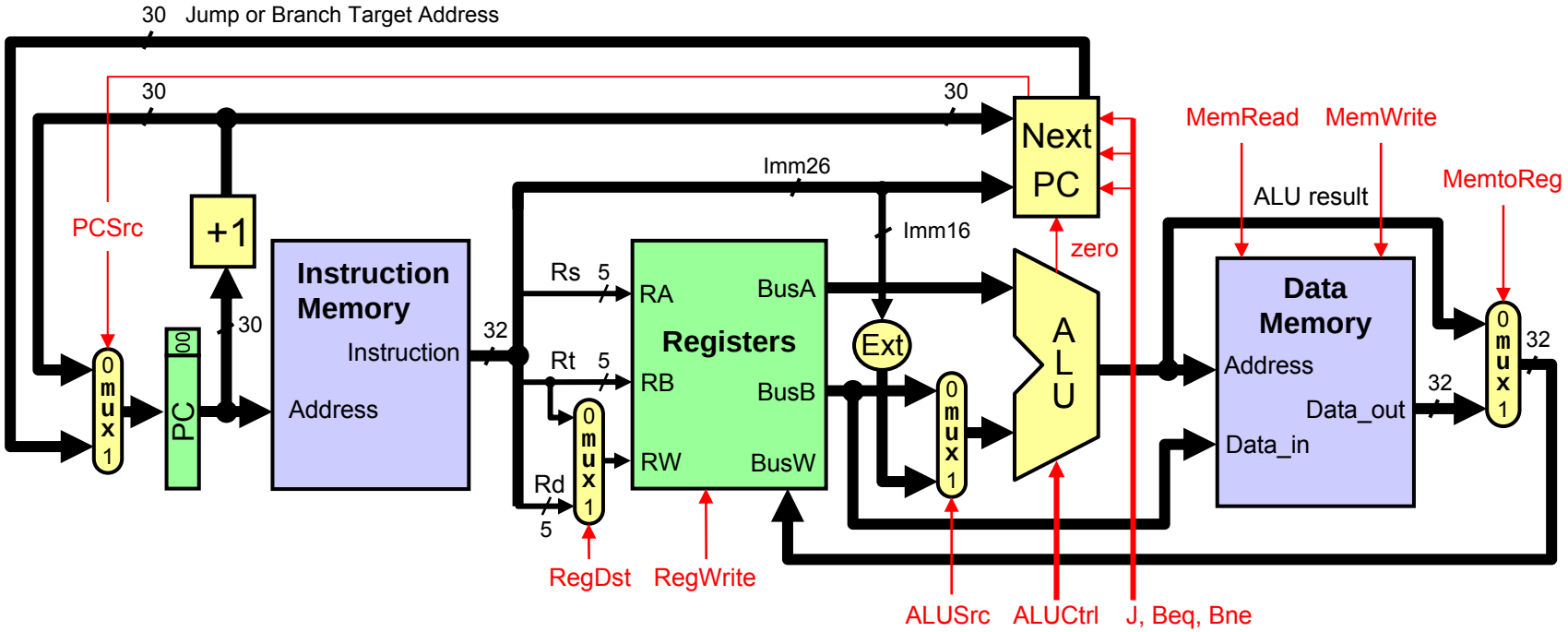
ALUSrc = '1' to select the extended immediate as second ALU input

MemtoReg = 'x' because we don't care what data is placed on BusW

ALUCtrl = 'ADD' to calculate data memory address as Reg(Rs) + sign-extend(Imm16)

RegWrite = '0' because no register is written by the store instruction

Adding Jump and Branch to Datapath

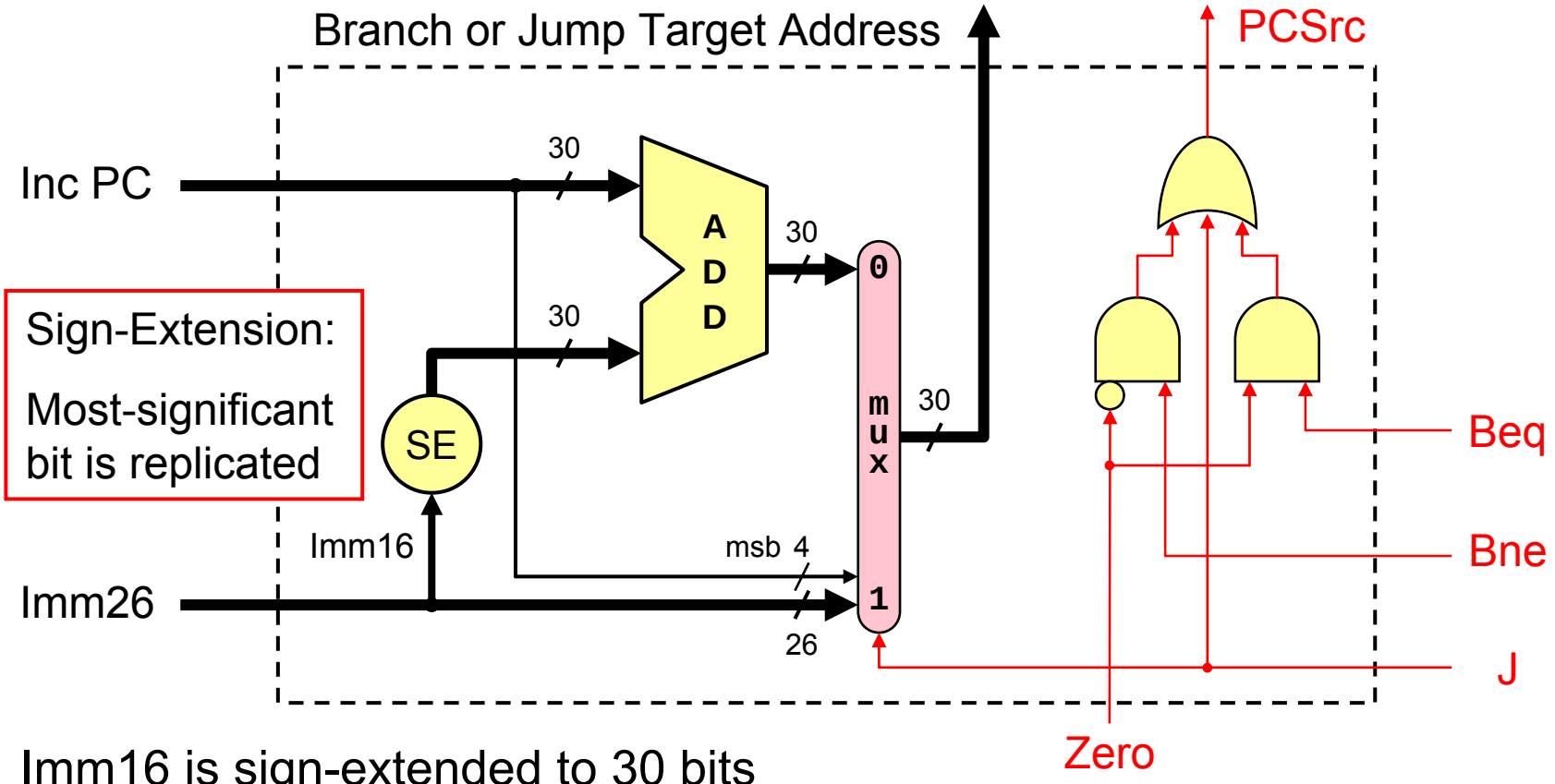


- Additional Control Signals
  - J, Beq, Bne for jump and branch instructions
  - Zero condition of the ALU is examined
  - PCSrc = 1 for Jump & taken Branch

Next PC computes jump or branch target instruction address

For Branch, ALU does a subtraction

Details of Next PC

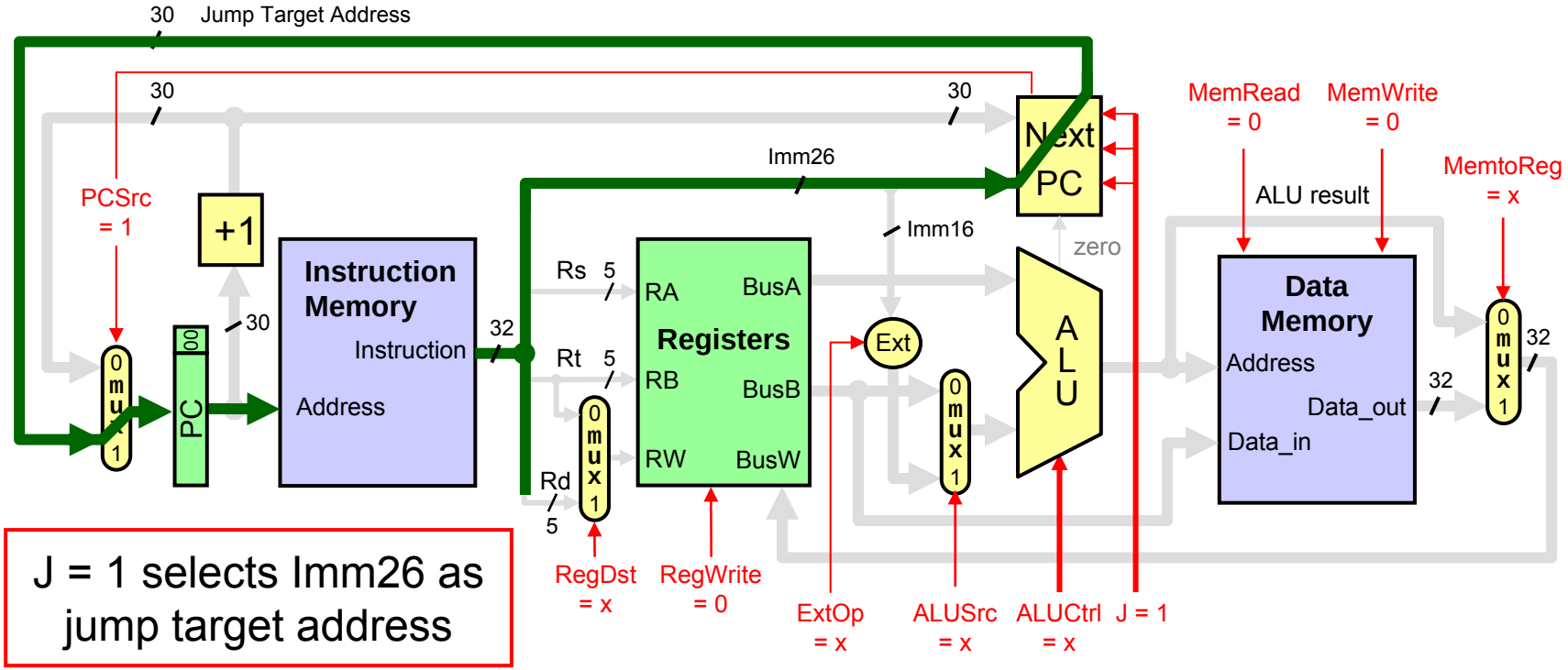


Imm16 is sign-extended to 30 bits

Jump target address: upper 4 bits of PC are concatenated with Imm26

PCSrc = J + (Beq . Zero) + (Bne . $\overline{\text{Zero}}$)

Controlling the Execution of Jump



J = 1 selects Imm26 as jump target address

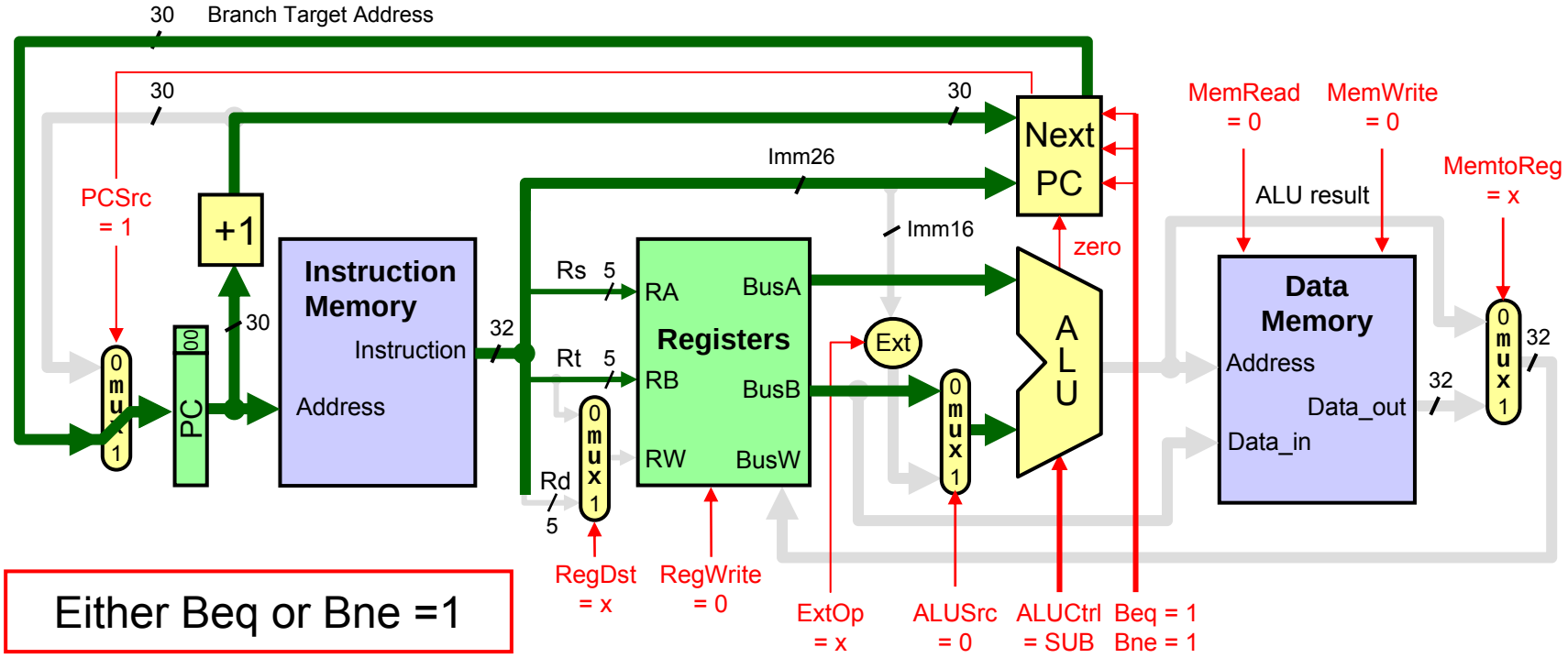
Upper 4 bits are from the incremented PC

PCSrc = 1 to select jump target address

MemRead, MemWrite & RegWrite are 0

We don't care about RegDst, ExtOp, ALUSrc, ALUCtrl, and MemtoReg

Controlling the Execution of Branch



Either Beq or Bne =1

Next PC outputs branch target address

ALUSrc = '0' (2nd ALU input is BusB)
ALUCtrl = 'SUB' produces zero flag

Next PC logic determines PCSrc according to zero flag

MemRead = MemWrite = RegWrite = 0

RegDst = ExtOp = MemtoReg = x

Next . . .

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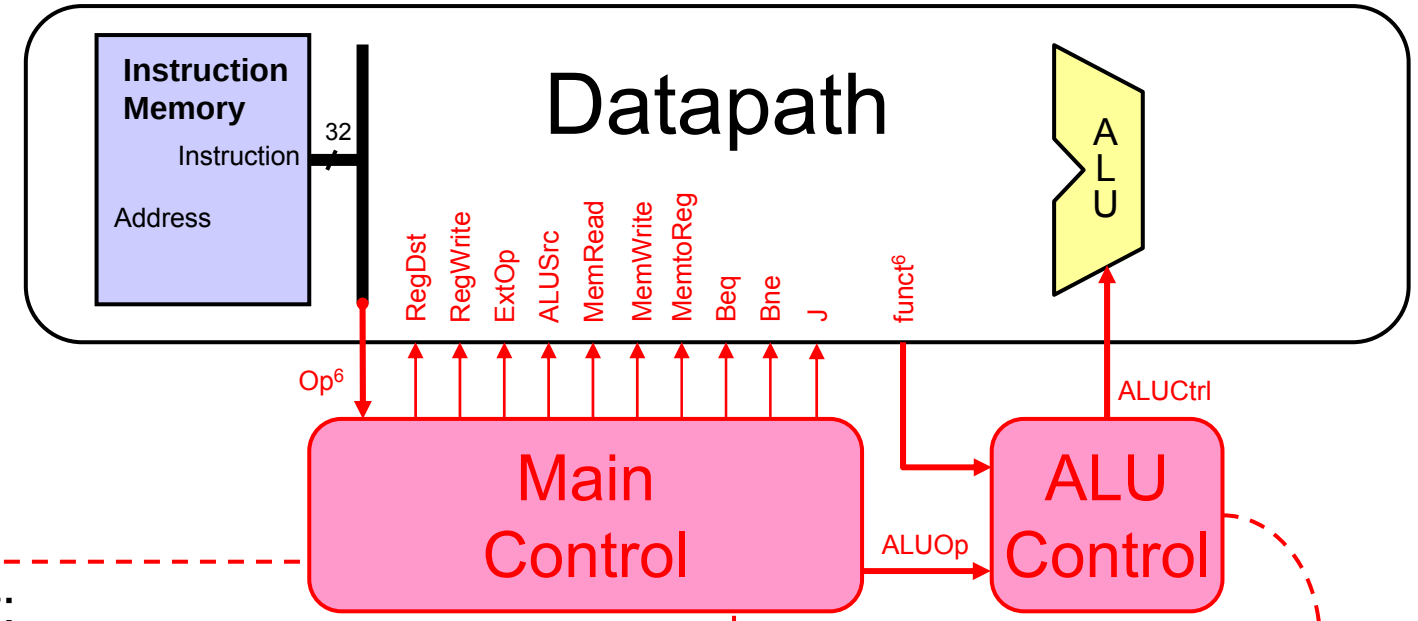
- The Main Controller and ALU Controller
- Drawback of the single-cycle processor design

Main Control and ALU Control



Input:

- 6-bit opcode field from instruction

Output:

- 10 control signals for datapath
- ALUOp for ALU Control

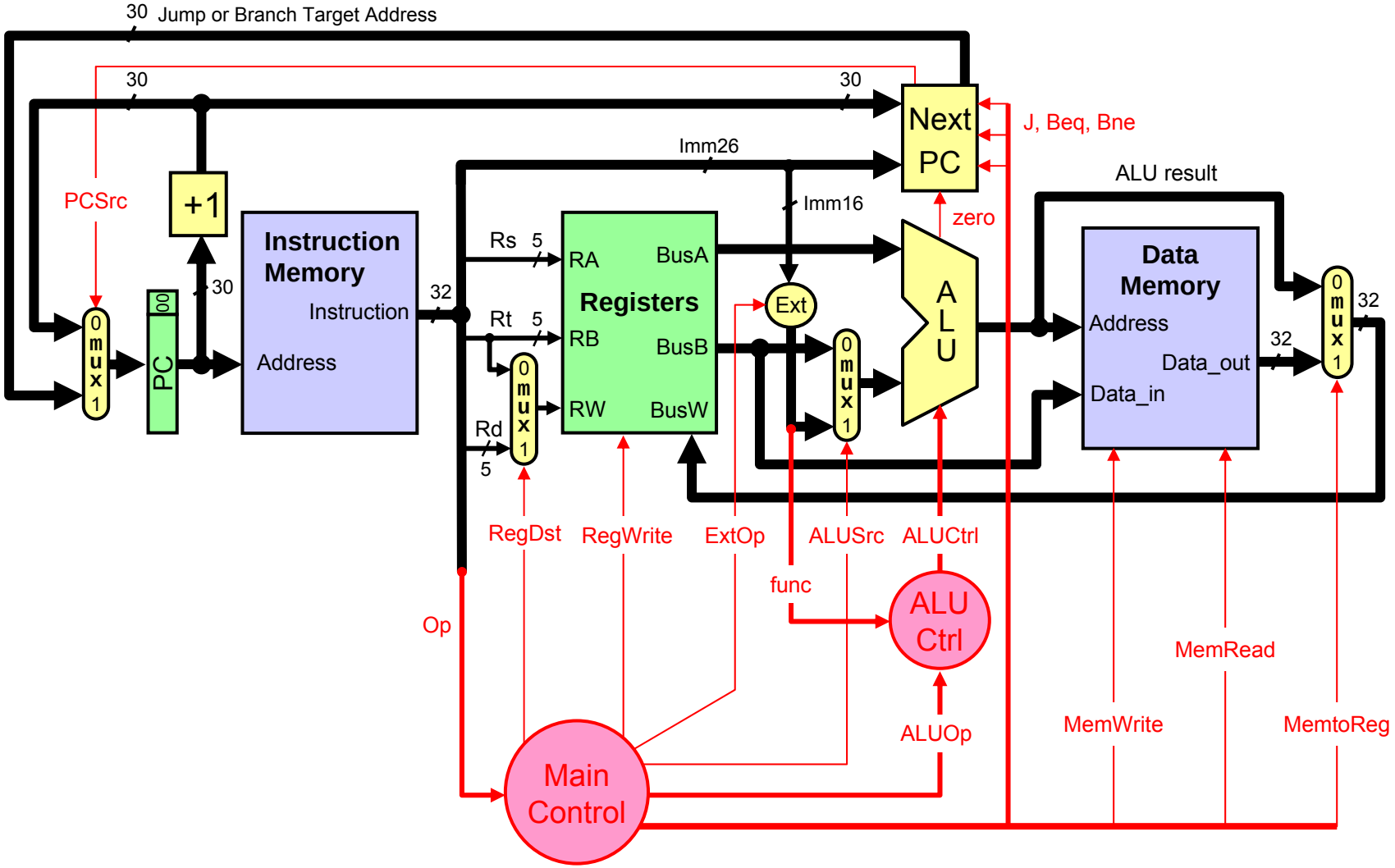
Input:

- 6-bit function field from instruction
- ALUOp from main control

Output:

- ALUCtrl signal for ALU

Single-Cycle Datapath + Control



Main Control Signals

Signal	Effect when '0'	Effect when '1'
RegDst	Destination register = Rt	Destination register = Rd
RegWrite	None	Destination register is written with the data value on BusW
ExtOp	16-bit immediate is zero-extended	16-bit immediate is sign-extended
ALUSrc	Second ALU operand comes from the second register file output (BusB)	Second ALU operand comes from the extended 16-bit immediate
MemRead	None	Data memory is read Data_out ← Memory[address]
MemWrite	None	Data memory is written Memory[address] ← Data_in
MemtoReg	BusW = ALU result	BusW = Data_out from Memory
Beq, Bne	PC ← PC + 4	PC ← Branch target address If branch is taken
J	PC ← PC + 4	PC ← Jump target address
ALUOp	This multi-bit signal specifies the ALU operation as a function of the opcode	

Main Control Signal Values

Op	Reg Dst	Reg Write	Ext Op	ALU Src	ALU Op	Beq	Bne	J	Mem Read	Mem Write	Mem toReg
R-type	1 = Rd	1	x	0=BusB	R-type	0	0	0	0	0	0
addi	0 = Rt	1	1=sign	1=Imm	ADD	0	0	0	0	0	0
slti	0 = Rt	1	1=sign	1=Imm	SLT	0	0	0	0	0	0
andi	0 = Rt	1	0=zero	1=Imm	AND	0	0	0	0	0	0
ori	0 = Rt	1	0=zero	1=Imm	OR	0	0	0	0	0	0
xori	0 = Rt	1	0=zero	1=Imm	XOR	0	0	0	0	0	0
lw	0 = Rt	1	1=sign	1=Imm	ADD	0	0	0	1	0	1
sw	x	0	1=sign	1=Imm	ADD	0	0	0	0	1	x
beq	x	0	x	0=BusB	SUB	1	0	0	0	0	x
bne	x	0	x	0=BusB	SUB	0	1	0	0	0	x
j	x	0	x	x	x	0	0	1	0	0	x

- X is a don't care (can be 0 or 1), used to minimize logic

Logic Equations for Control Signals

RegDst <= R-type

RegWrite <= $\overline{(sw + beq + bne + j)}$

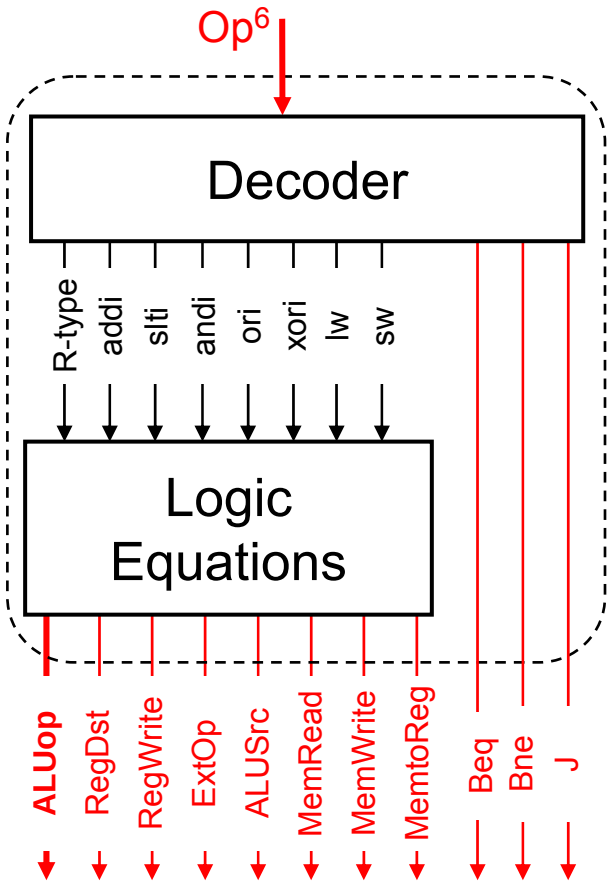
ExtOp <= $\overline{(andi + ori + xori)}$

ALUSrc <= $\overline{(R\text{-}type + beq + bne)}$

MemRead <= lw

MemWrite <= sw

MemtoReg <= lw



ALU Control Truth Table

Op^6	ALU Control			4-bit Encoding
	ALUOp	$funct^6$	ALUCtrl	
R-type	R-type	add	ADD	0000
R-type	R-type	sub	SUB	0010
R-type	R-type	and	AND	0100
R-type	R-type	or	OR	0101
R-type	R-type	xor	XOR	0110
R-type	R-type	slt	SLT	1010
addi	ADD	x	ADD	0000
slti	SLT	x	SLT	1010
andi	AND	x	AND	0100
ori	OR	x	OR	0101
xori	XOR	x	XOR	0110
lw	ADD	x	ADD	0000
sw	ADD	x	ADD	0000
beq	SUB	x	SUB	0010
bne	SUB	x	SUB	0010
j	x	x	x	x

The 4-bit encoding for ALUctrl is chosen here to be equal to the last 4 bits of the function field

Other binary encodings are also possible. The idea is to choose a binary encoding that will minimize the logic for ALU Control

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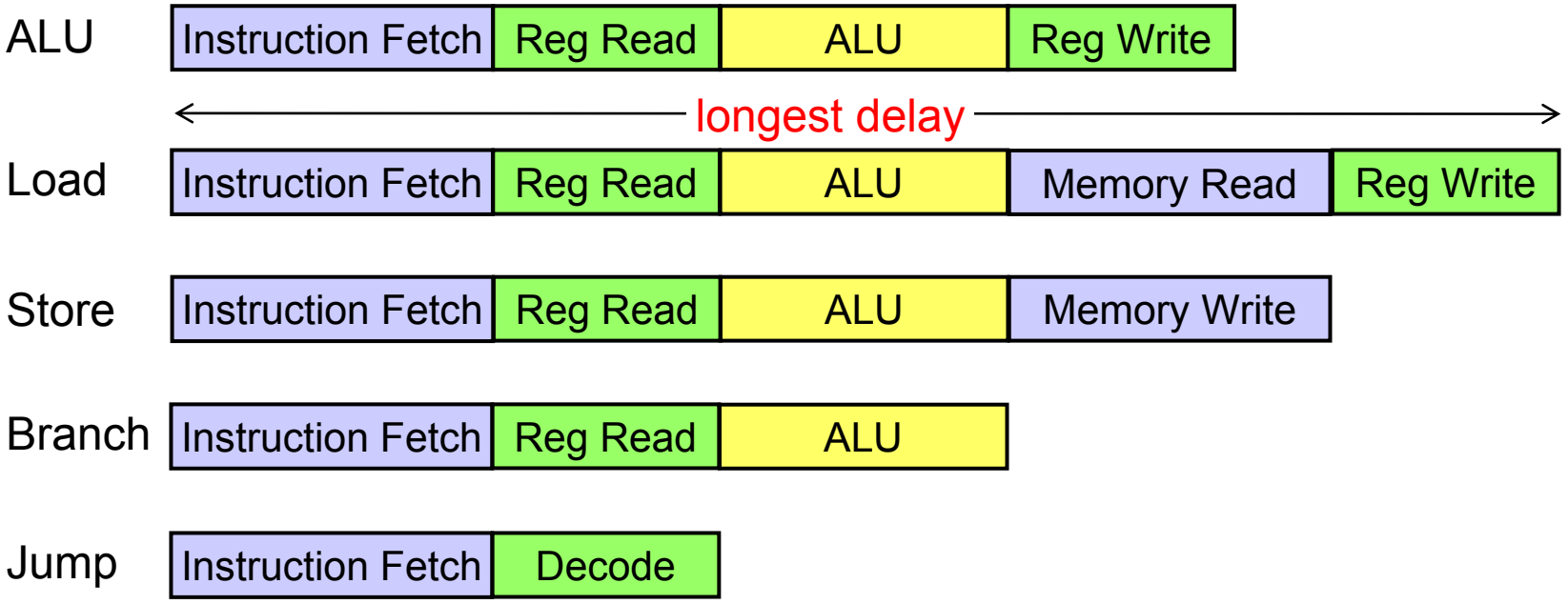
Drawbacks of Single Cycle Processor

- Long cycle time
  - All instructions take as much time as the slowest



- Alternative Solution: Multicycle implementation
  - Break down instruction execution into multiple cycles

Multicycle Implementation

- Break instruction execution into five steps
  - Instruction fetch
  - Instruction decode and register read
  - Execution, memory address calculation, or branch completion
  - Memory access or ALU instruction completion
  - Load instruction completion
- One step = One clock cycle (clock cycle is reduced)
  - First 2 steps are the same for all instructions

Instruction	# cycles	Instruction	# cycles
ALU & Store	4	Branch	3
Load	5	Jump	2

Performance Example

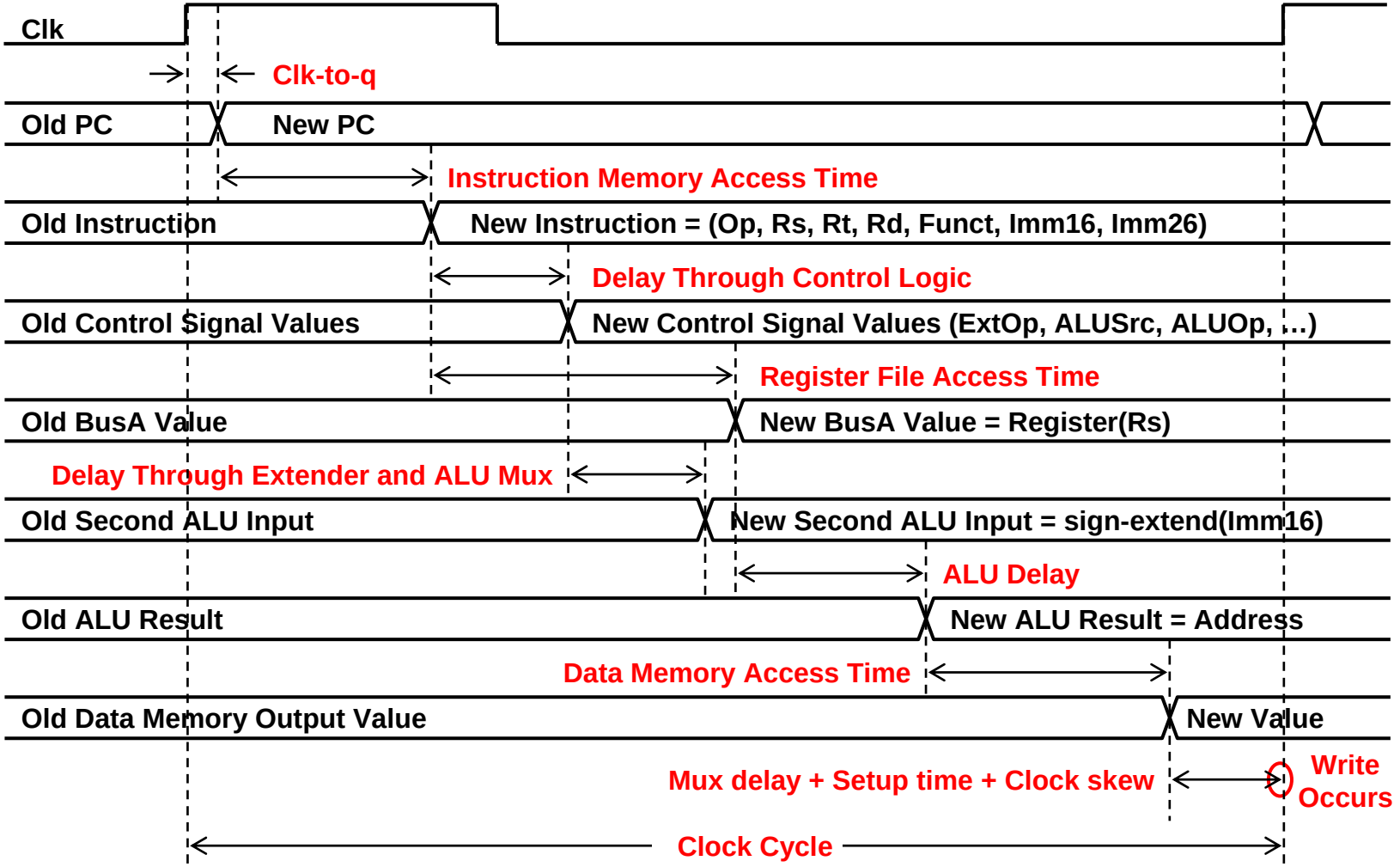
- Assume the following operation times for components:
  - Instruction and data memories: 200 ps
  - ALU and adders: 180 ps
  - Decode and Register file access (read or write): 150 ps
  - Ignore the delays in PC, mux, extender, and wires
- Which of the following would be faster and by how much?
  - Single-cycle implementation for all instructions
  - Multicycle implementation optimized for every class of instructions
- Assume the following instruction mix:
  - 40% ALU, 20% Loads, 10% stores, 20% branches, & 10% jumps

Solution

Instruction Class	Instruction Memory	Register Read	ALU Operation	Data Memory	Register Write	Total
ALU	200	150	180		150	680 ps
Load	200	150	180	200	150	880 ps
Store	200	150	180	200		730 ps
Branch	200	150	180			530 ps
Jump	200	150 ←	decode and update PC			350 ps

- For fixed single-cycle implementation:
  - Clock cycle = 880 ps determined by longest delay (load instruction)
- For multi-cycle implementation:
  - Clock cycle = max (200, 150, 180) = 200 ps (maximum delay at any step)
  - Average CPI = 0.4×4 + 0.2×5 + 0.1×4+ 0.2×3 + 0.1×2 = 3.8
- Speedup = 880 ps / (3.8 × 200 ps) = 880 / 760 = 1.16

Worst Case Timing (Load Instruction)



Worst Case Timing – Cont'd

- Long cycle time: must be long enough for Load operation

  PC's Clk-to-Q

  + Instruction Memory's Access Time

  + Maximum of (

    Register File's Access Time,

    Delay through control logic + extender + ALU mux)

  + ALU to Perform a 32-bit Add

  + Data Memory Access Time

  + Delay through MemtoReg Mux

  + Setup Time for Register File Write + Clock Skew

- Cycle time is longer than needed for other instructions
  - Therefore, single cycle processor design is not used in practice

Summary

- 5 steps to design a processor
  - Analyze instruction set => datapath requirements
  - Select datapath components & establish clocking methodology
  - Assemble datapath meeting the requirements
  - Analyze implementation of each instruction to determine control signals
  - Assemble the control logic
- MIPS makes Control easier
  - Instructions are of same size
  - Source registers always in same place
  - Immediates are of same size and same location
  - Operations are always on registers/immediates
- Single cycle datapath => CPI=1, but Long Clock Cycle