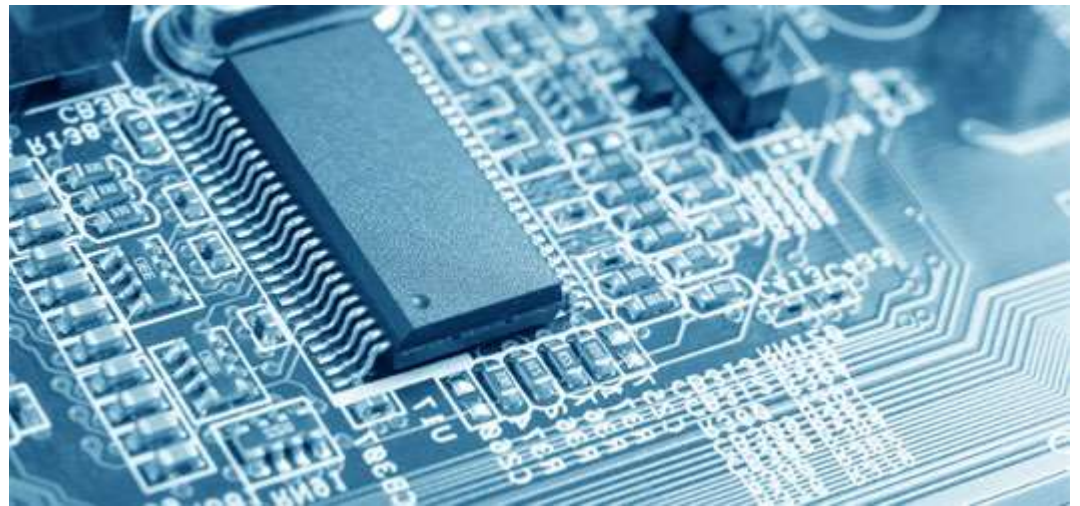




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SCHOOL OF SCIENCE AND TECHNOLOGY



ROBT206 – Microcontrollers with Lab

Lecture 24 - A Simple Computer

19 April, 2018

Topics

Today's Topics

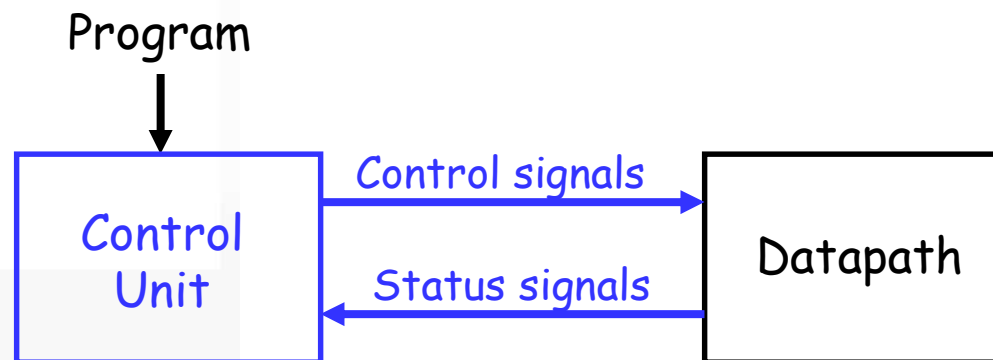
- A Simple Computer
 - Instruction Set Architecture (ISA)
 - Single-Cycle Hardwired Control
 - PC Function
 - Instruction Decoder
 - Example Instruction Execution

Control Units

- ▶ In real computers, the datapath actions are determined by the **program** that's loaded and running.
- ▶ A **control unit** is responsible for generating the correct control signals for a datapath, based on the program code.



Block Diagram of a Processor



- ▶ The **control unit** connects programs with the datapath.
 - ▶ It converts program instructions into control words for the datapath, including signals WR, DA, AA, BA, MB, FS, MV, MD.
 - ▶ It executes program instructions in the correct sequence.
 - ▶ It generates the “constant” input for the datapath.
- ▶ The datapath also sends information back to the control unit. For instance, the ALU status bits V, C, N, Z can be inspected by branch instructions to alter a program’s control flow.

Where Does the Program Go?

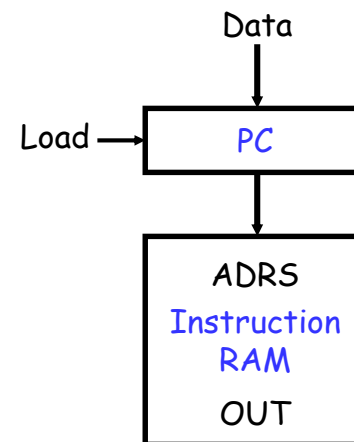
- ▶ We'll use a **Harvard architecture**, which includes two memory units.
 - ▶ An **instruction memory** holds the program.
 - ▶ A separate **data memory** is used for computations.
 - ▶ The advantage is that we can read an instruction *and* load or store data in the same clock cycle.
- ▶ For simplicity, our diagrams do not show any VVR or DATA inputs to the instruction memory.



- ▶ Caches in modern CPUs often feature a Harvard architecture like this.
- ▶ However, there is usually a single main memory that holds both program instructions and data, in a **Von Neumann architecture**.

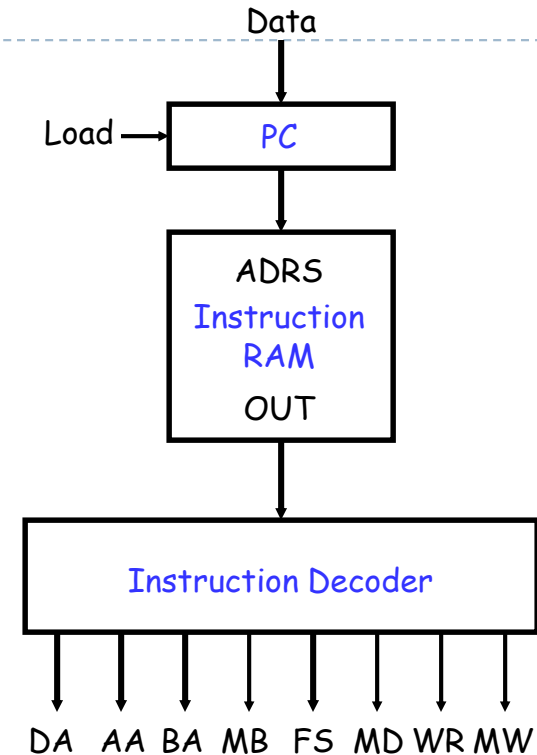
Program Counter

- ▶ A **program counter** or **PC** addresses the instruction memory, to keep track of the instruction currently being executed.
- ▶ On each clock cycle, the counter does one of two things.
 - ▶ If **Load = 0**, the PC increments, so the next instruction in memory will be executed.
 - ▶ If **Load = 1**, the PC is updated with **Data**, which represents some address specified in a jump or branch instruction.



Instruction Decoder

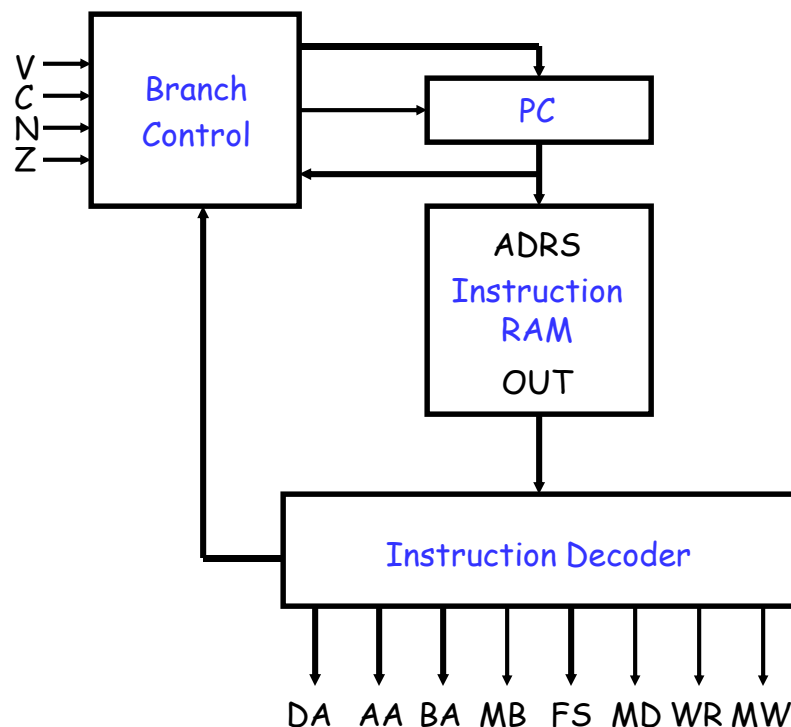
- ▶ The **instruction decoder** is a combinational circuit that takes a machine language instruction and produces the matching control signals for the datapath.
- ▶ These signals tell the datapath which registers or memory locations to access, and what ALU operations to perform.



(to the datapath)

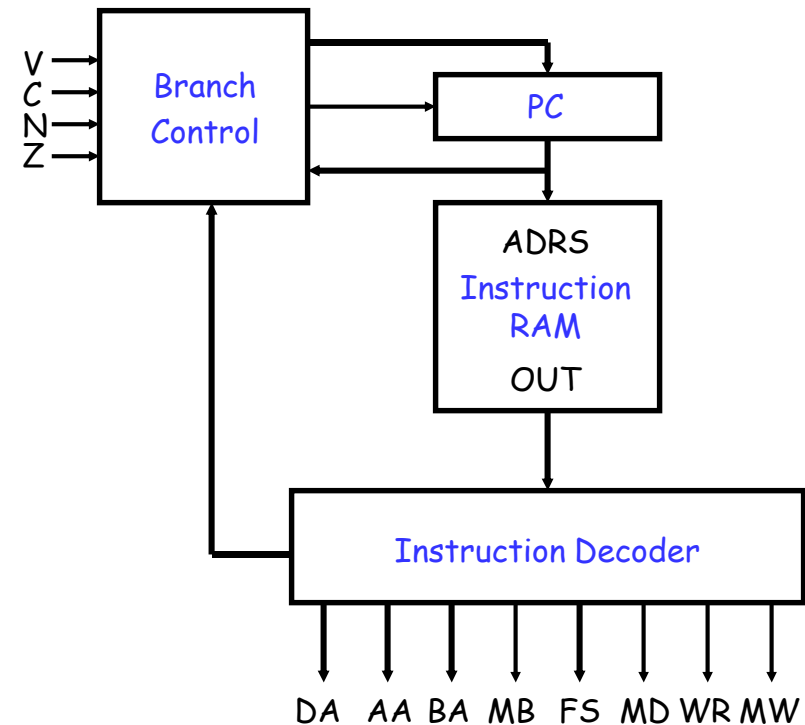
Jumps and Branches

- ▶ Finally, the **branch control unit** decides what the PC's next value should be.
 - ▶ For jumps, the PC should be loaded with the target address specified in the instruction.
 - ▶ For branch instructions, the PC should be loaded with the target address only if the corresponding status bit is true.
 - ▶ For all other instructions, the PC should just increment.

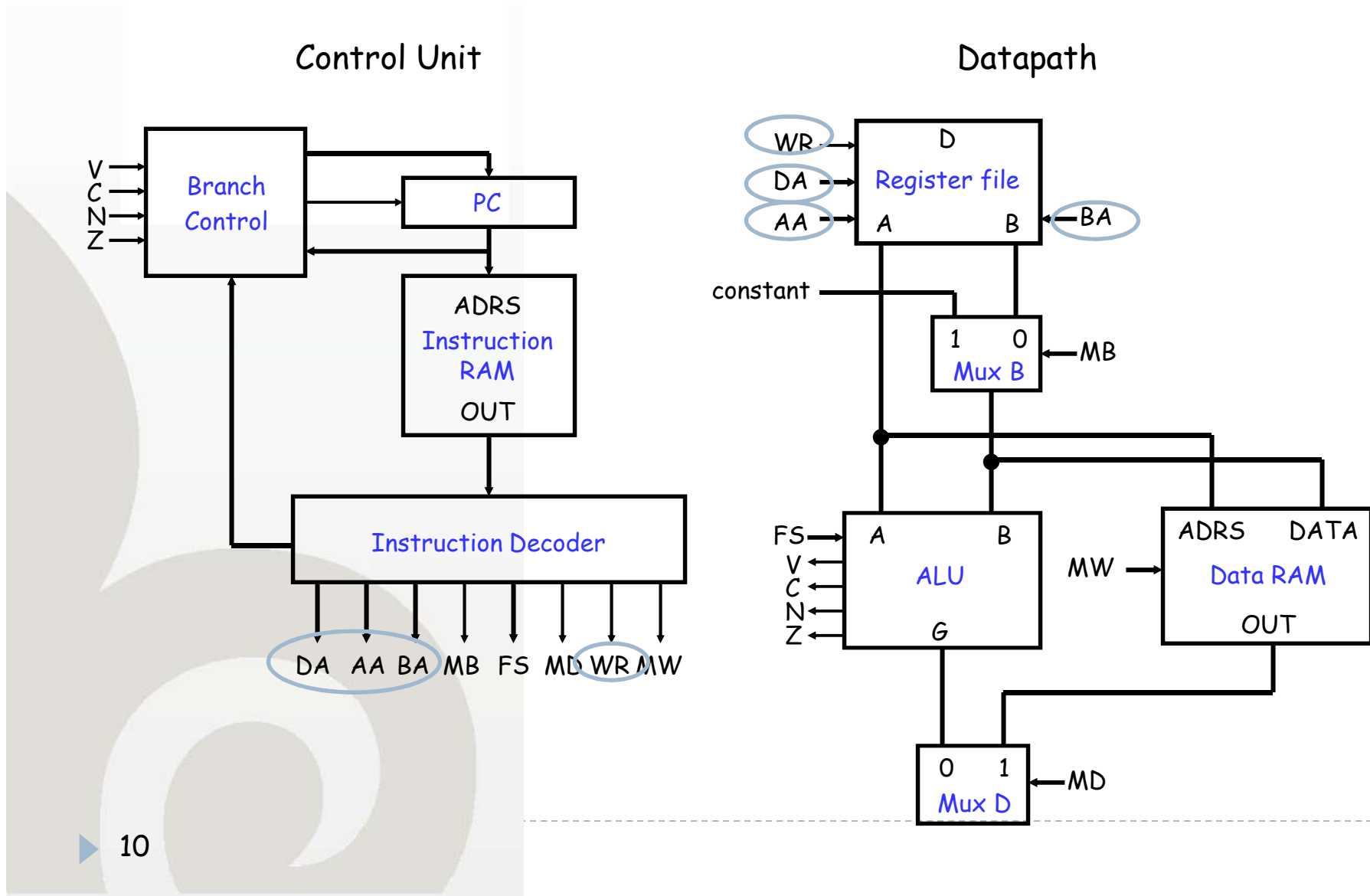


That's It!

- ▶ This is the basic control unit. On each clock cycle:
 1. An instruction is read from the instruction memory.
 2. The instruction decoder generates the matching datapath control word.
 3. Datapath registers are read and sent to the ALU or the data memory.
 4. ALU or RAM outputs are written back to the register file.
 5. The PC is incremented, or reloaded for branches and jumps.



The Whole Processor

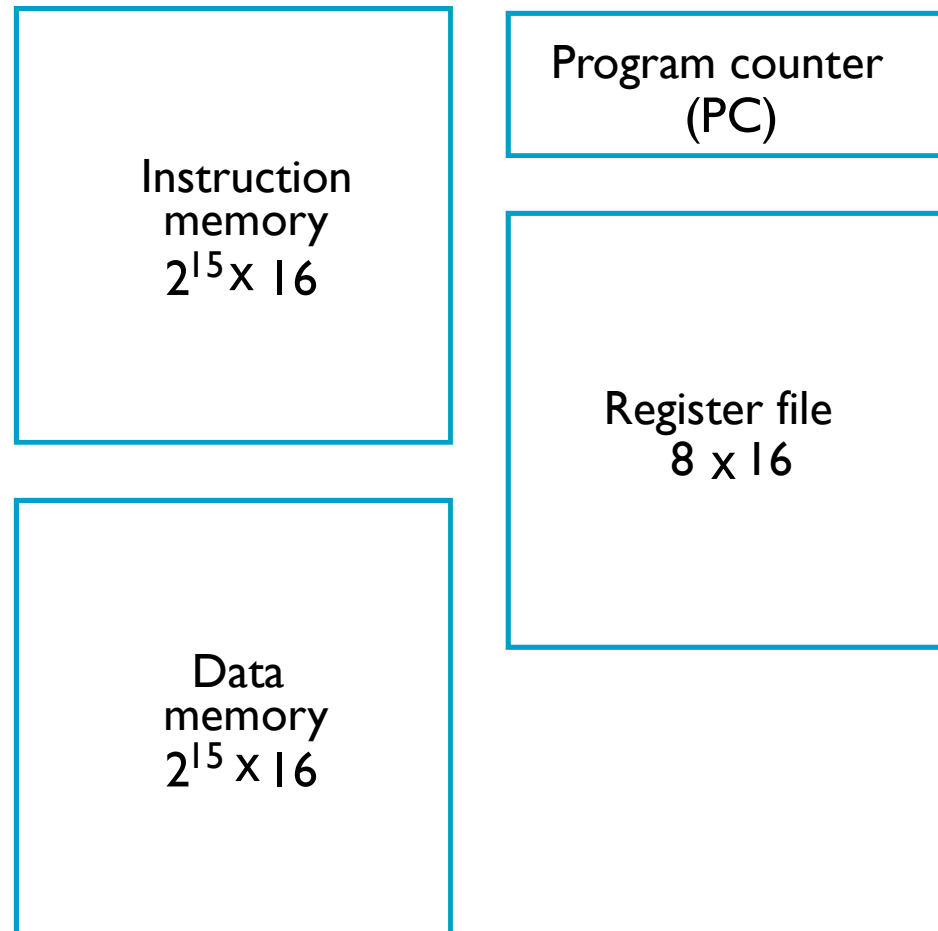


Instruction Set Architecture (ISA) for Simple Computer

- ▶ A programmable system uses a sequence of *instructions* to control its operation
- ▶ A typical instruction specifies:
 - ▶ Operation to be performed
 - ▶ Operands to use, and
 - ▶ Where to place the result, or
 - ▶ Which instruction to execute next
- ▶ Instructions are stored in RAM or ROM as a *program*
- ▶ The addresses for instructions in a computer are provided by a *program counter (PC)* that can
 - ▶ Count up
 - ▶ Load a new address based on an instruction and, optionally, status information
- ▶ Executing an instruction - activating the necessary sequence of operations specified by the instruction

ISA: Storage Resources

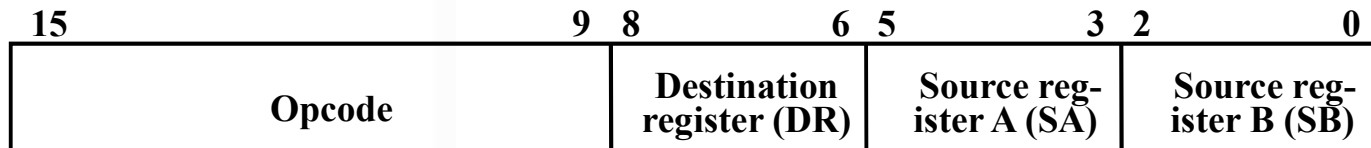
- ▶ The storage resources are "visible" to the programmer at the lowest software level (typically, machine or assembly language)
- ▶ Storage resources for the simple computer =>
- ▶ Separate instruction and data memories imply "Harvard architecture"
- ▶ Done to permit use of single clock cycle per instruction implementation
- ▶ Due to use of "cache" in modern computer architectures, is a fairly realistic model



ISA: Instruction Format

- ▶ An instruction consists of a bit vector
- ▶ The **fields** of an instruction are subvectors representing specific functions and having specific binary codes
- ▶ The *format* of an instruction defines the subvectors and their function
- ▶ An ISA usually contains multiple formats
- ▶ The simple computer (SC) ISA contains the three formats presented on the next slide

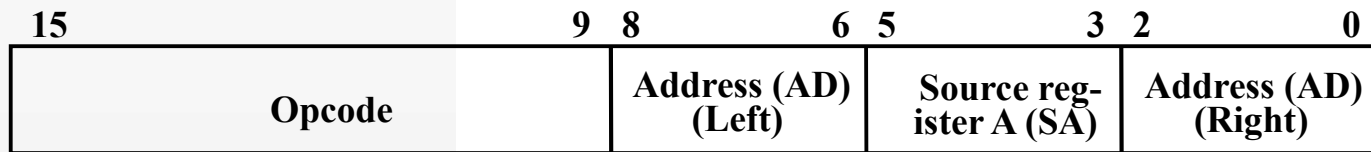
ISA: Instruction Format



(a) Register



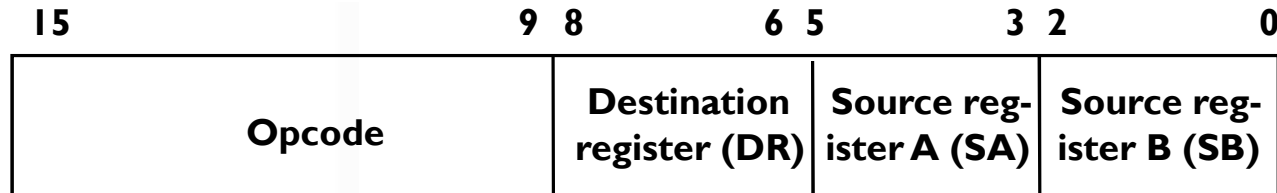
(b) Immediate



(c) Jump and Branch

- ▶ The three formats are: Register, Immediate, and Jump and Branch
- ▶ All formats contain an Opcode field in bits 9 through 15.
- ▶ The Opcode specifies the operation to be performed
- ▶ More details on each format are provided on the next three slides

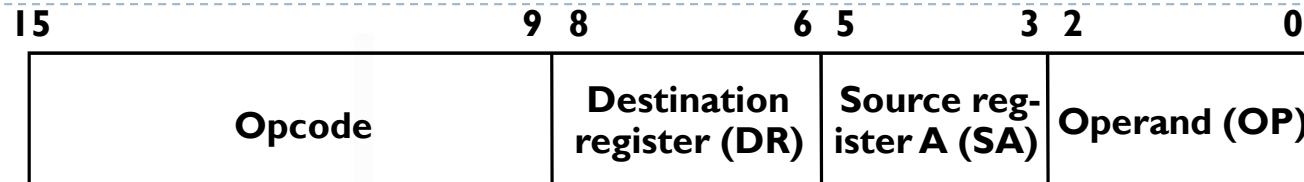
ISA: Instruction Format



(a) Register

- ▶ This format supports instructions represented by:
 - ▶ $R1 \leftarrow R2 + R3$
 - ▶ $R1 \leftarrow \text{sl } R2$
- ▶ There are three 3-bit register fields:
 - ▶ DR - specifies destination register (R1 in the examples)
 - ▶ SA - specifies the A source register (R2 in the first example)
 - ▶ SB - specifies the B source register (R3 in the first example and R2 in the second example)
- ▶ Why is R2 in the second example SB instead of SA?
 - ▶ The source for the shifter in our datapath to be used in implementation is Bus B rather than Bus A

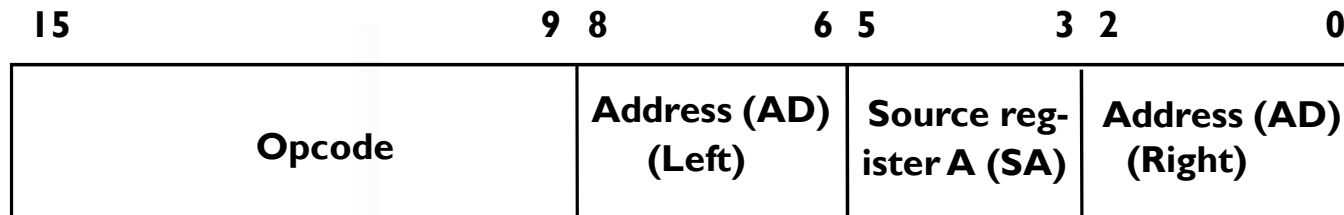
ISA: Instruction Format



(b) Immediate

- ▶ This format supports instructions described by:
 - ▶ $R1 \leftarrow R2 + 3$
- ▶ The B Source Register field is replaced by an Operand field OP which specifies a constant.
- ▶ The Operand:
 - ▶ 3-bit constant
 - ▶ Values from 0 to 7
- ▶ The constant:
 - ▶ Zero-fill (on the left of) the Operand to form 16-bit constant
 - ▶ 16-bit representation for values 0 through 7

ISA: Instruction Format



(c) Jump and Branch

- ▶ This instruction supports changes in the sequence of instruction execution by adding an extended, 6-bit, signed 2s-complement *address offset* to the PC value
- ▶ The 6-bit Address (AD) field replaces the DR and SB fields
 - ▶ Example: Suppose that a jump is specified by the Opcode and the PC contains 45 (0...0101101) and Address contains – 12 (110100). Then the new PC value will be:
 $0...0101101 + (1...110100) = 0...0100001$ (45 + (– 12) = 33)
- ▶ The SA field is retained to permit jumps and branches on N or Z based on the contents of Source register A

ISA: Instruction Specifications

- ▶ The specifications provide:
 - ▶ The name of the instruction
 - ▶ The instruction's opcode
 - ▶ A shorthand name for the opcode called a ***mnemonic***
 - ▶ A specification for the instruction format
 - ▶ A register transfer description of the instruction, and
 - ▶ A listing of the status bits that are meaningful during an instruction's execution (not used in the architectures defined in this chapter)

ISA: Instruction Specifications

Instruction	Opcode	Mne- monic	Format	Description	Status Bits
Move A	0000000	MOVA	RD, RA	$R[DR] \leftarrow R[SA]^*$	N, Z
Increment	0000001	INC	RD, RA	$R[DR] \leftarrow R[SA] + 1^*$	N, Z
Add	0000010	ADD	RD, RA, RB	$R[DR] \leftarrow R[SA] + R[SB]^*$	N, Z
Subtract	0000101	SUB	RD, RA, RB	$R[DR] \leftarrow R[SA] - R[SB]^*$	N, Z
Decrement	0000110	DEC	RD, RA	$R[DR] \leftarrow R[SA] - 1^*$	N, Z
AND	0001000	AND	RD, RA, RB	$R[DR] \leftarrow R[SA] \wedge R[SB]^*$	N, Z
OR	0001001	OR	RD, RA, RB	$R[DR] \leftarrow R[SA] \vee R[SB]^*$	N, Z
Exclusive OR	0001010	XOR	RD, RA, RB	$R[DR] \leftarrow R[SA] \oplus R[SB]^*$	N, Z
NOT	0001011	NOT	RD, RA	$R[DR] \leftarrow \overline{R[SA]}^*$	N, Z
Move B	0001100	MOVB	RD, RB	$R[DR] \leftarrow R[SB]^*$	

For all of these instructions, $PC \leftarrow PC + I$ is also executed to prepare for the next cycle.

ISA: Instruction Specifications

Instruction	Opcode	Mne- monic	Format	Description	Status Bits
Shift Right	0001101	SHR	RD, RB	$R[DR] \leftarrow sr\ R[SB]^*$	
Shift Left	0001110	SHL	RD, RB	$R[DR] \leftarrow sl\ R[SB]^*$	
Load Immediate	1001100	LDI	RD, OP	$R[DR] \leftarrow zf\ OP^*$	
Add Immediate	1000010	ADI	RD, RA, OP	$R[DR] \leftarrow R[SA] + zf\ OP^*$	N, Z
Load	0010000	LD	RD, RA	$R[DR] \leftarrow M[SA]^*$	
Store	0100000	ST	RA, RB	$M[SA] \leftarrow R[SB]^*$	
Branch on Zero	1100000	BRZ	RA, AD	if ($R[SA] = 0$) $PC \leftarrow PC + se\ AD$, N, Z if ($R[SA] \neq 0$) $PC \leftarrow PC + 1$	
Branch on Negative	1100001	BRN	RA, AD	if ($R[SA] < 0$) $PC \leftarrow PC + se\ AD$, N, Z if ($R[SA] \geq 0$) $PC \leftarrow PC + 1$	
Jump	1110000	JMP	RA	$PC \leftarrow R[SA]$	

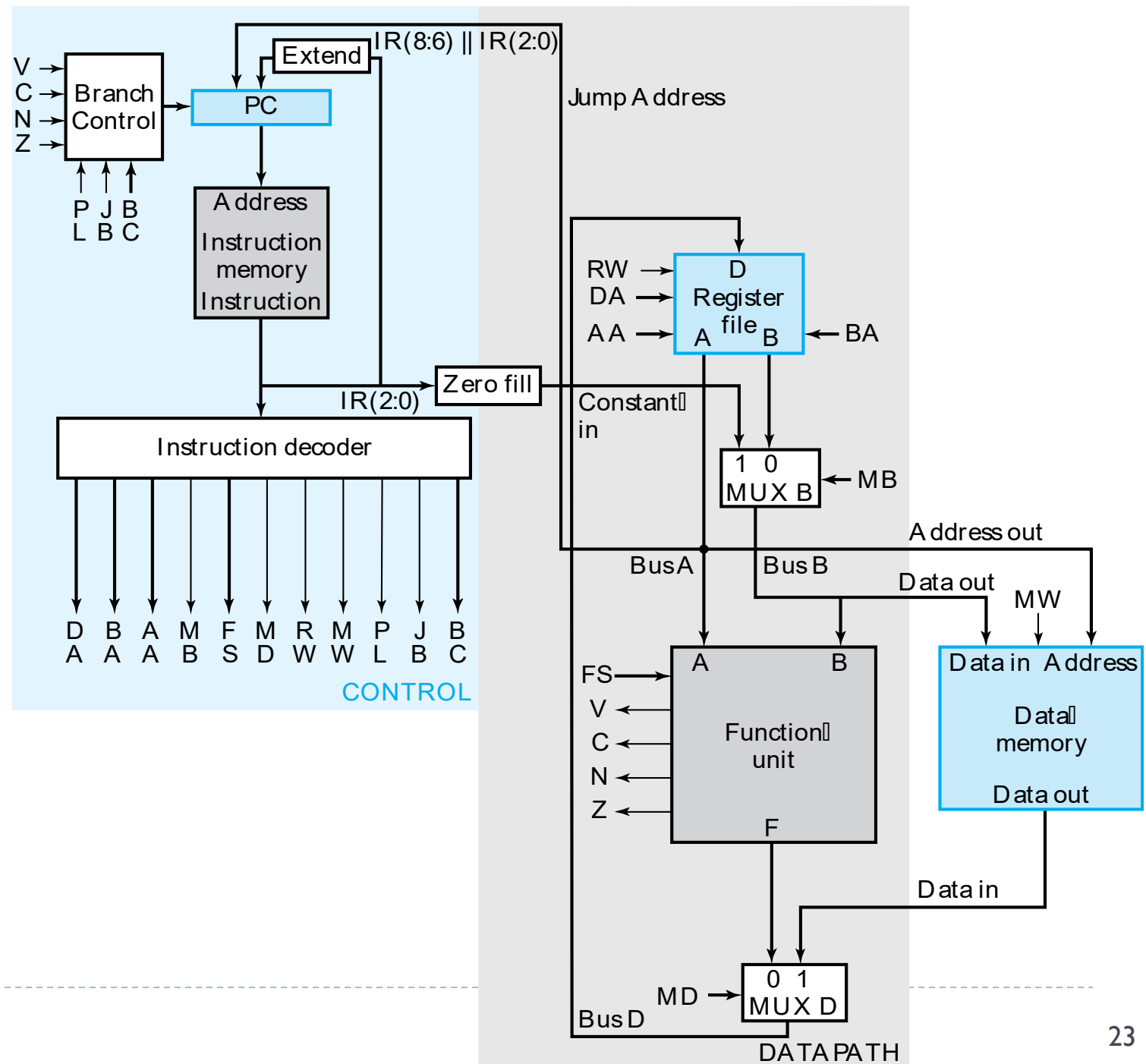
For all of these instructions, $PC \leftarrow PC + I$ is also executed to prepare for the next cycle.

ISA: Example Instructions and Data in Memory

Decimal Address	Memory Contents	Decimal Opcode	Other Fields	Operation
25	0000101 001 010 011	5 (Subtract)	DR:1, SA:2, SB:3	$R1 \leftarrow R2 - R3$
35	0100000 000 100 101	32 (Store)	SA:4, SB:5	$R4 = 70, R5 = 80$ $M[R4] \leftarrow R5$
45	1000010 010 111 011	66 (Add Immediate)	DR:2, SA:7, OP:3	$R2 \leftarrow R7 + 3$
55	1100000 101 110 100	96 (Branch on Zero)	AD: 44, SA:6	If $R6 = 0$, $PC \leftarrow PC - 20$
70	00000000011000000	Data = 192. After execution of instruction in 35, Data = 80.		

Single-Cycle Hardwired Control

- ▶ Based on the ISA defined, design a computer architecture to support the ISA
 - ▶ The architecture is to fetch and execute each instruction in a single clock cycle
 - ▶ A similar datapath to the one covered in the previous lecture will be used
 - ▶ The control unit will be defined as a part of the design
 - ▶ The block diagram is shown on the next slide
-



The Control Unit

- ▶ The Data Memory has been attached to the Address Out and Data Out and Data In lines of the Datapath.
 - ▶ The MW input to the Data Memory is the Memory Write signal from the Control Unit.
 - ▶ For convenience, the Instruction Memory, which is not usually a part of the Control Unit is shown within it.
 - ▶ The Instruction Memory address input is provided by the PC and its instruction output feeds the Instruction Decoder.
 - ▶ Zero-filled IR(2:0) becomes Constant In
 - ▶ Extended IR(8:6) || IR(2:0) and Bus A are address inputs to the PC.
 - ▶ The PC is controlled by Branch Control logic
-

PC Function

- ▶ PC function is based on instruction specifications involving jumps and branches:

Branch on Zero	BRZ	if (R[SA] = 0) $PC \leftarrow PC + seAD$
Branch on Negative	BRN	if (R[SA] < 0) $PC \leftarrow PC + seAD$
Jump	JMP	$PC \leftarrow R[SA]$

- ▶ In addition to the above register transfers, the PC must also implement: $PC \leftarrow PC + I$
- ▶ The first two transfers above require addition to the PC of:
Address Offset = Extended IR(8:6) || IR(2:0)
- ▶ The third transfer requires that the PC be loaded with: Jump
Address = Bus A = R[SA]
- ▶ The counting function of the PC requires addition to the PC of I

PC Function

- ▶ Branch Control determines the PC transfers based on five of its inputs defined as follows:
 - ▶ N,Z – negative and zero status bits
 - ▶ PL – load enable for the PC
 - ▶ JB – Jump/Branch select: If JB = 1, Jump, else Branch
 - ▶ BC – Branch Condition select: If BC = 1, branch for N = 1, else branch for Z = 1.
- ▶ The above is summarized by the following table:

PC Operation	PL	JB	BC
Count Up	0	X	X
Jump	1	1	X
Branch on Negative (else Count Up)	1	0	1
Branch on Zero (else Count Up)	1	0	0

- ▶ Sufficient information is provided here to design the PC

Instruction Decoder

- ▶ The combinational instruction decoder converts the instruction into the signals necessary to control all parts of the computer during the single cycle execution
- ▶ The input is the 16-bit Instruction
- ▶ The outputs are control signals:
 - ▶ Register file addresses DA, AA, and BA,
 - ▶ Function Unit Select FS
 - ▶ Multiplexer Select Controls MB and MD,
 - ▶ Register file and Data Memory Write Controls RW and MW, and
 - ▶ PC Controls PL, JB, and BC
- ▶ The register file outputs are simply pass-through signals:
DA = DR, AA = SA, and BA = SB
Determination of the remaining signals is more complex.

Instruction Decoder

- ▶ The remaining control signals do not depend on the addresses, so must be a function of $IR(13:9)$
- ▶ Formulation requires examining relationships between the outputs and the opcodes
- ▶ Observe that for other than branches and jumps, $FS = IR(12:9)$
- ▶ This implies that the other control signals should depend as much as possible on $IR(15:13)$ (which actually were assigned with decoding in mind!)
- ▶ To make some sense of this, we divide instructions into types as shown in the table on the next page

Instruction Decoder

□ **TABLE 9-10**
Truth Table for Instruction Decoder Logic

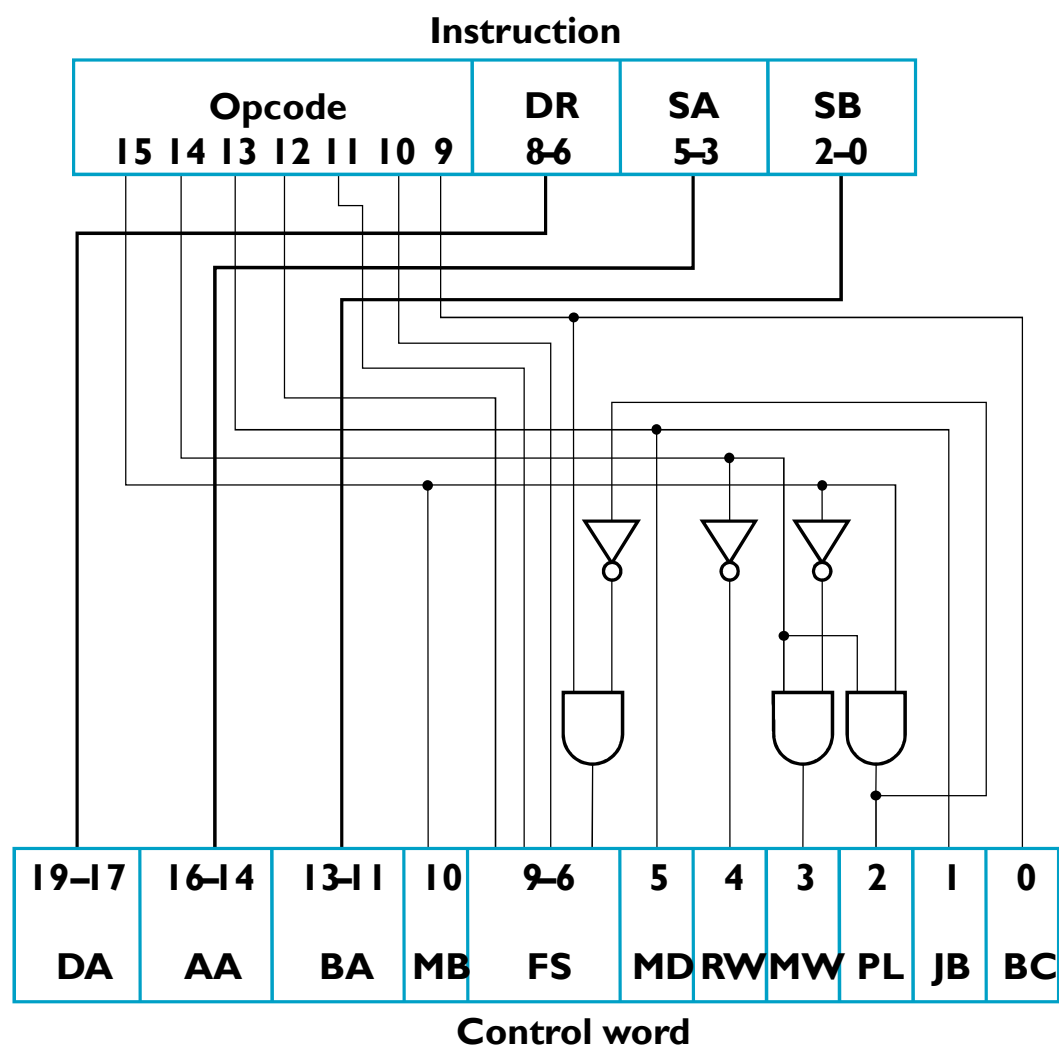
Instruction Function Type	Instruction Bits				Control Word Bits						
	15	14	13	9	MB	MD	RW	MW	PL	JB	BC
Function-unit operations using registers	0	0	0	X	0	0	1	0	0	X	X
Memory read	0	0	1	X	0	1	1	0	0	X	X
Memory write	0	1	0	X	0	X	0	1	0	X	X
Function-unit operations using register and constant	1	0	0	X	1	0	1	0	0	X	X
Conditional branch on zero (<i>Z</i>)	1	1	0	0	X	X	0	0	1	0	0
Conditional branch on negative (<i>N</i>)	1	1	0	1	X	X	0	0	1	0	1
Unconditional jump	1	1	1	X	X	X	0	0	1	1	X

Instruction Decoder

- ▶ The types are based on the blocks controlled and the seven signals to be generated; types can be divided into two groups:
 - ▶ Datapath and Memory Control (First 4 types)
 - ▶ PC Control (Last 3 types)
 - ▶ In Datapath and Memory Control blocks controlled are considered:
 - ▶ Mux B (1st and 4th types)
 - ▶ Memory and Mux D (2nd and 3rd types)
 - ▶ By assigning codes with no or only one I for these, implementation of MB, MD, RW and MW are simplified.
 - ▶ In Control Unit more of a bit setting approach was used:
 - ▶ Bit 15 = Bit 14 = 1 were assigned to generate PL
 - ▶ Bit 13 values were assigned to generate JB.
 - ▶ Bit 9 was use as BC which contradicts FS = 0000 needed for branches. To force FS(6) to 0 for branches, Bit 9 into FS(6) is disabled by PL.
 - ▶ Also, useful bit correlations between values in the two groups were exploited in assigning the codes.
-

Instruction Decoder

- ▶ The end result by use of the types, careful assignment of codes, and use of don't cares, yields very simple logic:
- ▶ This completes the design of most of the essential parts of the single-cycle simple computer



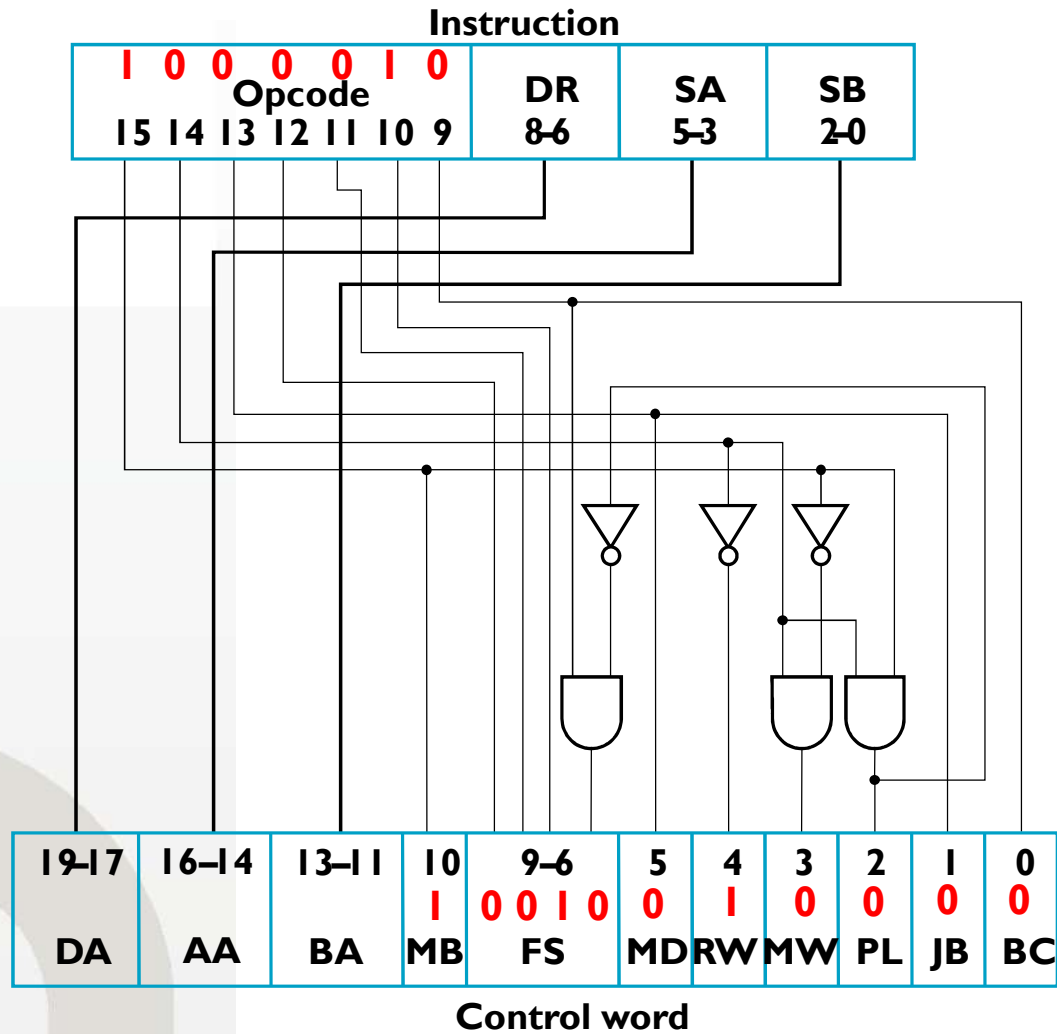
Example Instruction Execution

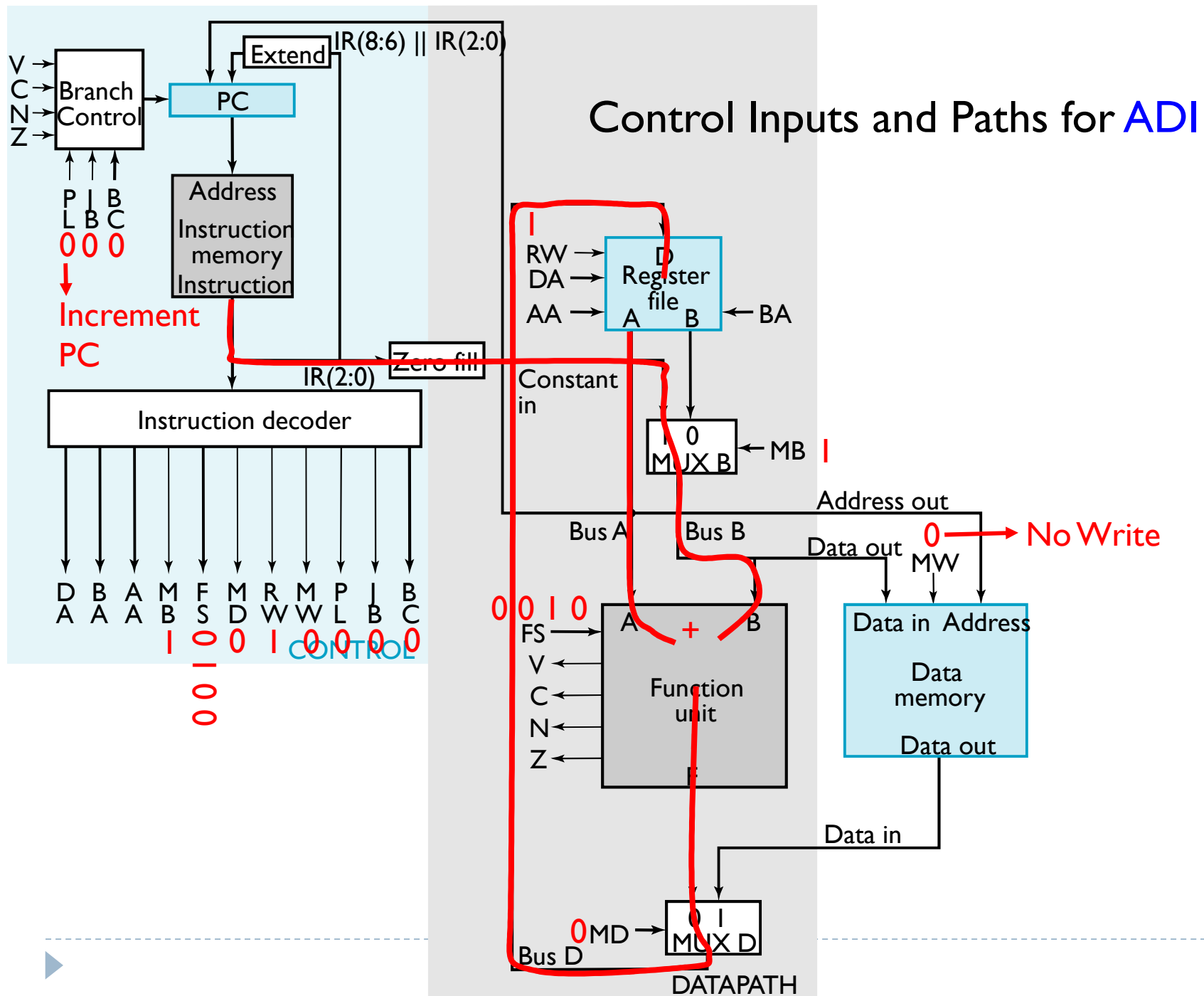
□ **TABLE 9-11**
Six Instructions for the Single-Cycle Computer

Operation Code	Symbolic Name	Format	Description	Function	MB	MD	RW	MW	PL	JB	BC
1000010	ADI	Immediate	Add immediate operand	$R[DR] \leftarrow R[SA] + zf\ I(2:0)$	1	0	1	0	0	0	0
0010000	LD	Register	Load memory content into register	$R[DR] \leftarrow M[R[SA]]$	0	1	1	0	0	1	0
0100000	ST	Register	Store register content in memory	$M[R[SA]] \leftarrow R[SB]$	0	1	0	1	0	0	0
0001110	SL	Register	Shift left	$R[DR] \leftarrow sl\ R[SB]$	0	0	1	0	0	1	0
0001011	NOT	Register	Complement register	$R[DR] \leftarrow \overline{R[SA]}$	0	0	1	0	0	0	1
1100000	BRZ	Jump/Branch	If $R[SA] = 0$, branch to $PC + se\ AD$	If $R[SA] = 0$, $PC \leftarrow PC + se\ AD$ If $R[SA] \neq 0$, $PC \leftarrow PC + 1$	1	0	0	0	1	0	0

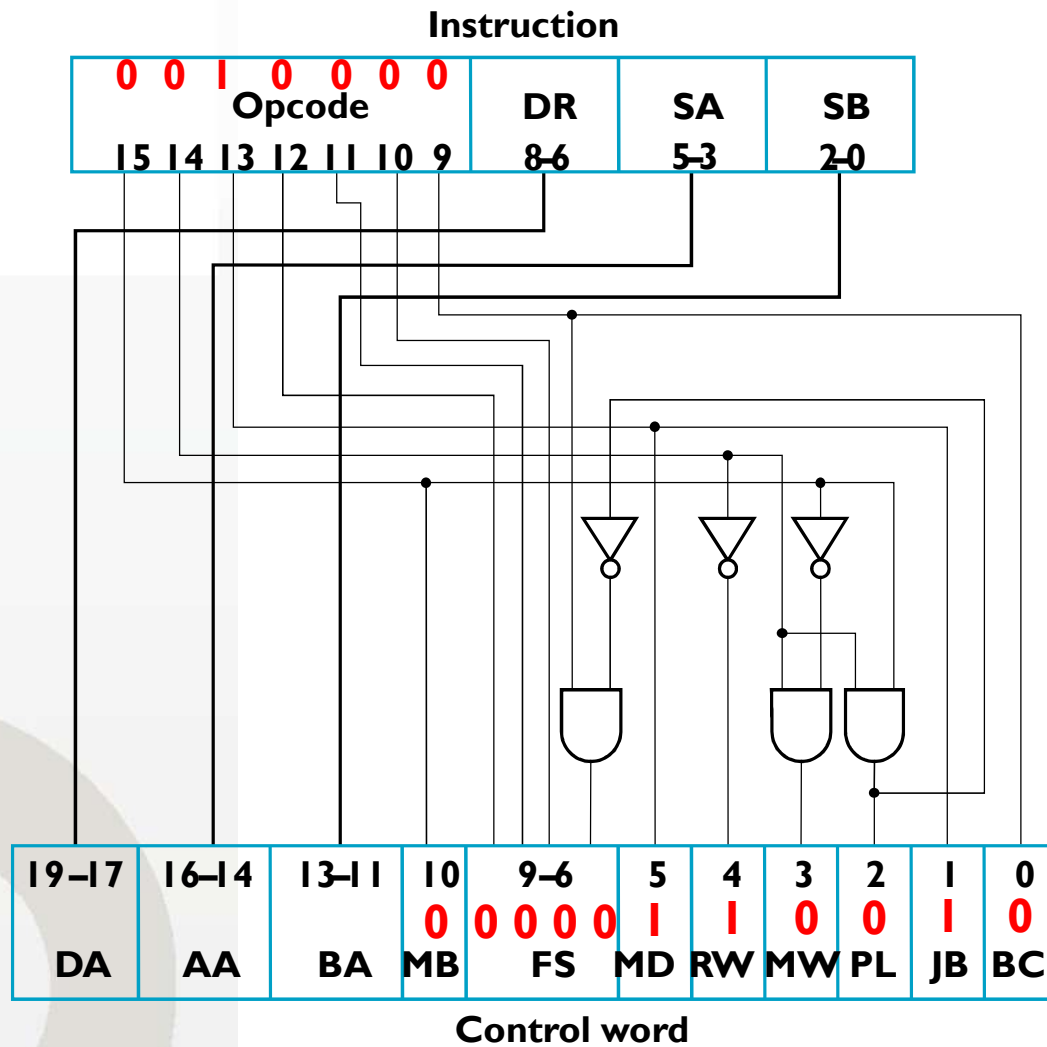
- Decoding, control inputs and paths shown for ADI, RD and BRZ on next 6 slides

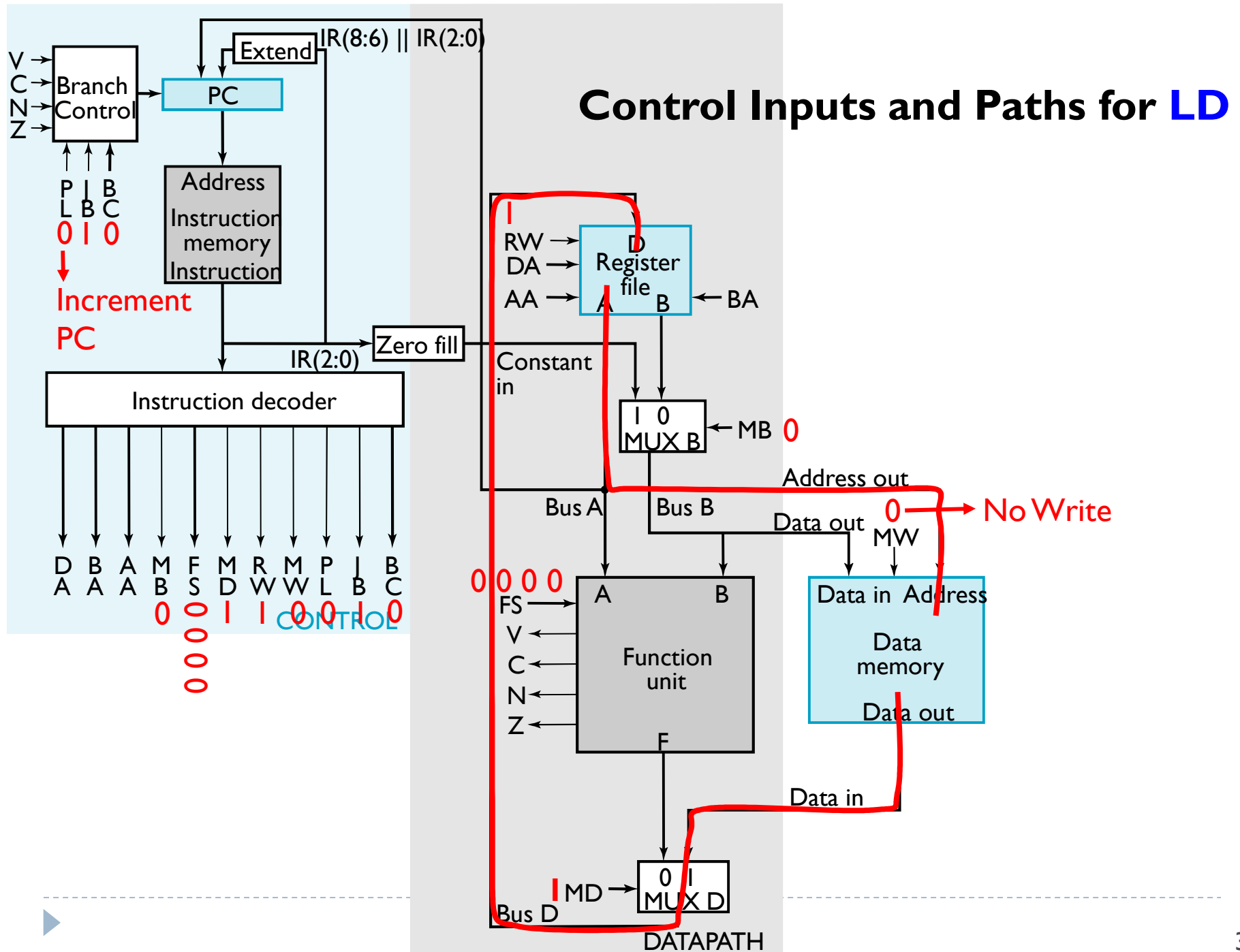
Decoding for ADI



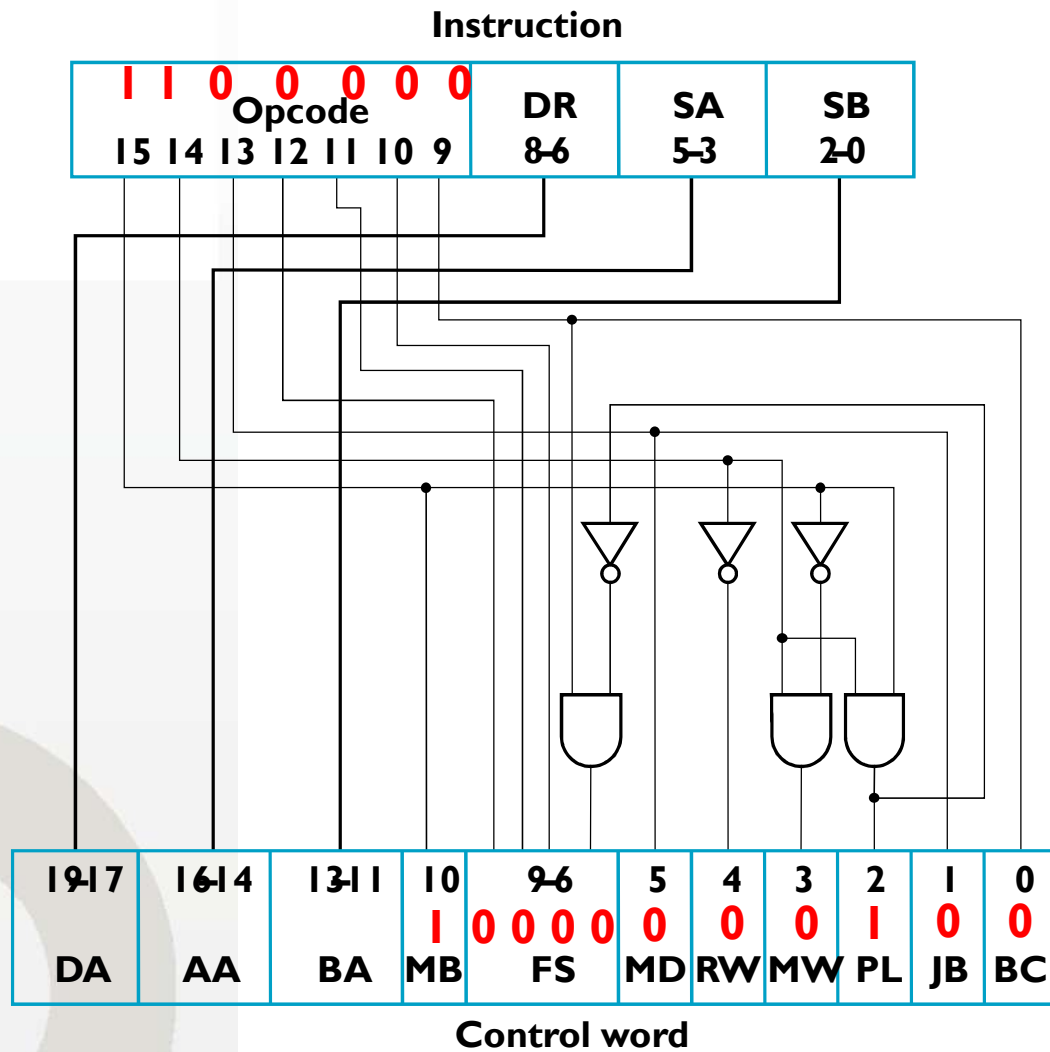


Decoding for LD

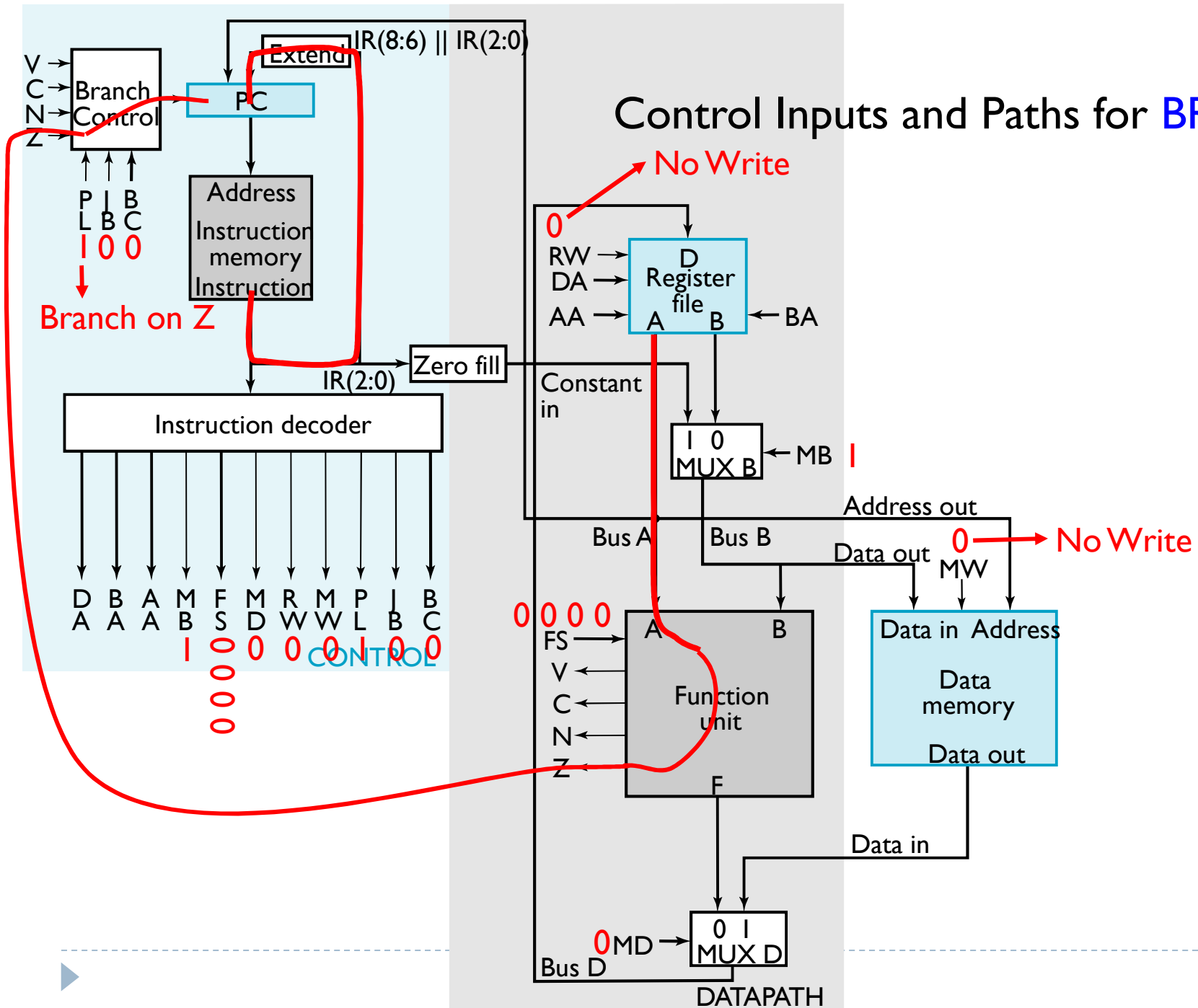




Decoding for BRZ



Control Inputs and Paths for BRZ



Any Questions?

