

Digital Design & Computer Arch.

Lecture 9: Von Neumann Model & Instruction Set Architectures

Prof. Onur Mutlu

ETH Zürich

Spring 2021

25 March 2021

Assignment: Required Lecture Video

- Why study computer architecture? Why is it important?
- Future Computing Platforms: Challenges & Opportunities
- **Required Assignment**
 - **Watch one of** Prof. Mutlu's lectures and analyze either (or both)
 - <https://www.youtube.com/watch?v=kgiZISOcGFM> (May 2017)
 - <https://www.youtube.com/watch?v=mskTeNnf-i0> (Feb 2021)
- **Optional Assignment – for 1% extra credit**
 - **Write a 1-page summary** of one of the lectures and email us
 - What are your key takeaways?
 - What did you learn?
 - What did you like or dislike?
 - Submit your summary to [Moodle](#) – Deadline: April 5

Extra Assignment 2: Moore's Law (I)

- **Paper review**
- G.E. Moore. "Cramming more components onto integrated circuits," Electronics magazine, 1965

- **Optional Assignment – for 1% extra credit**
 - **Write a 1-page review**
 - Upload PDF file to Moodle – Deadline: April 5

- I strongly recommend that you **follow my guidelines for (paper) review** (see next slide)

Extra Assignment 2: Moore's Law (II)

■ Guidelines on how to review papers critically

- ❑ **Guideline slides:** [pdf](#) [ppt](#)
- ❑ **Video:** <https://www.youtube.com/watch?v=tOL6FANAj8c>
- ❑ Example reviews on “Main Memory Scaling: Challenges and Solution Directions” ([link to the paper](#))
 - [Review 1](#)
 - [Review 2](#)
- ❑ Example review on “Staged memory scheduling: Achieving high performance and scalability in heterogeneous systems” ([link to the paper](#))
 - [Review 1](#)

Agenda for Today & Next Few Lectures

- The von Neumann model
- LC-3: An example of von Neumann machine
- LC-3 and MIPS Instruction Set Architectures
- LC-3 and MIPS assembly and programming
- Introduction to microarchitecture and single-cycle microarchitecture
- Multi-cycle microarchitecture

Required Readings

■ This week

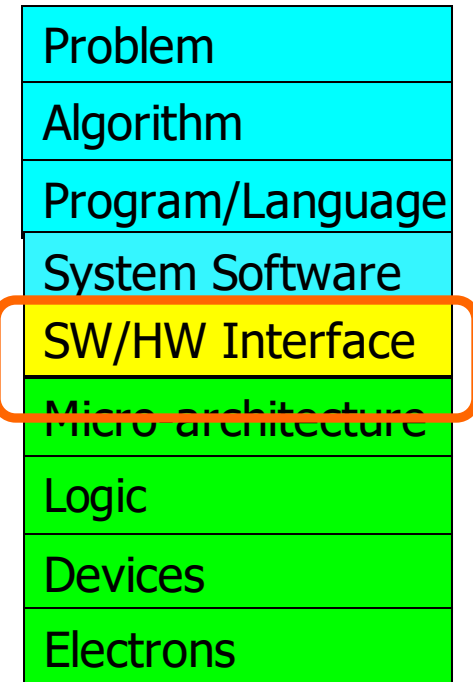
- Von Neumann Model, LC-3, and MIPS
 - P&P, Chapters 4, 5
 - H&H, Chapter 6
 - P&P, Appendices A and C (ISA and microarchitecture of LC-3)
 - H&H, Appendix B (MIPS instructions)
- Programming
 - P&P, Chapter 6
- **Recommended:** H&H Chapter 5, especially 5.1, 5.2, 5.4, 5.5

■ Next week

- Introduction to microarchitecture and single-cycle microarchitecture
 - H&H, Chapter 7.1-7.3
 - P&P, Appendices A and C
- Multi-cycle microarchitecture
 - H&H, Chapter 7.4
 - P&P, Appendices A and C

What Will We Learn Today?

- The von Neumann model
 - LC-3: An example von Neumann machine
- Instruction Set Architectures: LC-3 and MIPS
 - Operate instructions
 - Data movement instructions
 - Control instructions
- Instruction formats
- Addressing modes



The Von Neumann Model

Basic Elements of a Computer

- In past lectures we learned
 - Combinational circuits
 - Sequential circuits
- With them, we can build
 - Decision elements
 - Storage elements
- Basic elements of a computer
- To get a task done by a computer we need
 - Computer
 - Data
 - Program: A set of instructions
 - Instruction: the smallest piece of work in a computer

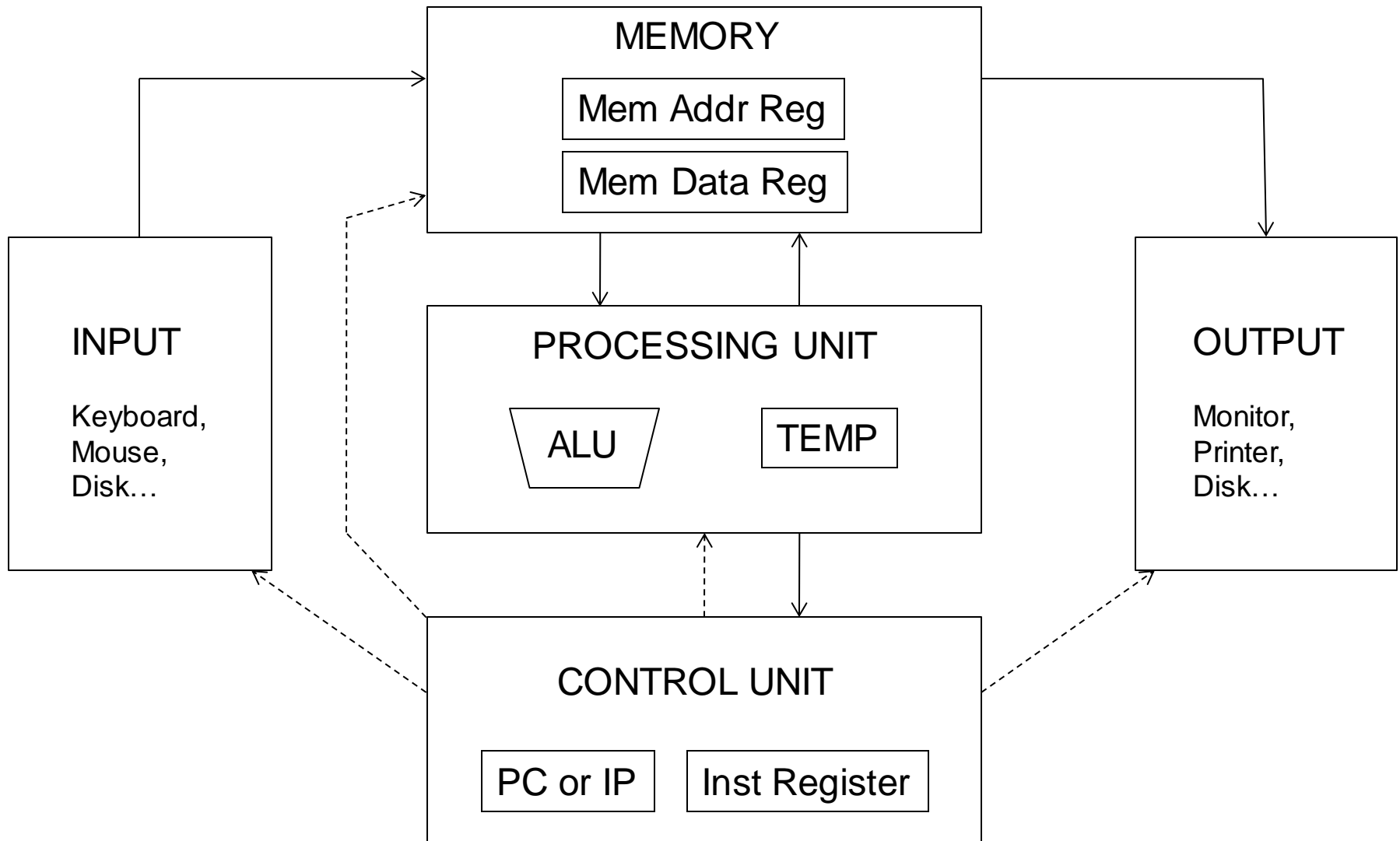
The Von Neumann Model

- Let's start **building the computer**
- In order to build a computer **we need a model**
- John von Neumann proposed **a fundamental model** in 1946
- It consists of 5 parts
 - Memory
 - Processing unit
 - Input
 - Output
 - Control unit
- Throughout this lecture, we consider two examples of the von Neumann model
 - **LC-3**
 - **MIPS**

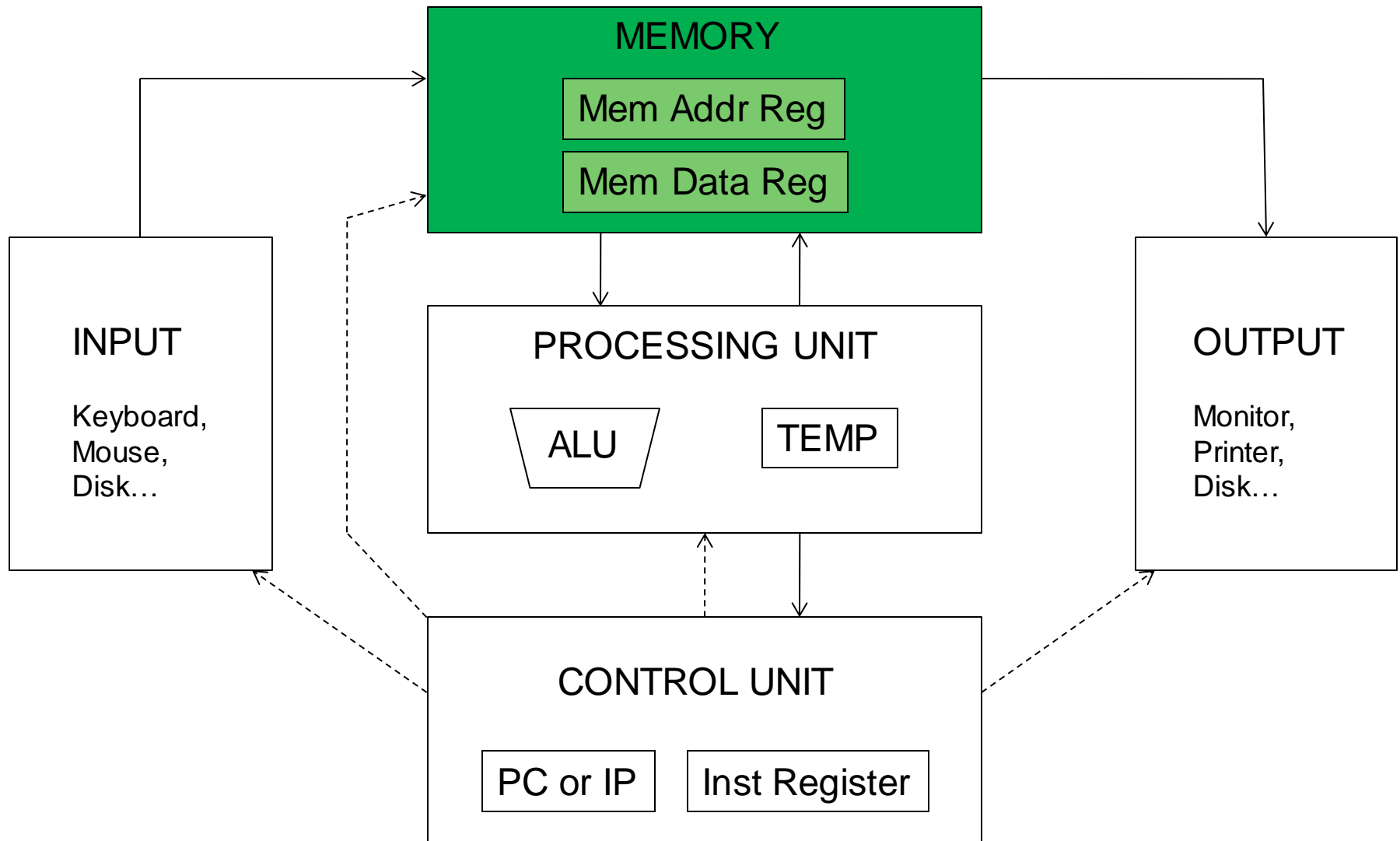


Burks, Goldstein, von Neumann,
“**Preliminary discussion of the logical design
of an electronic computing instrument**,” 1946.

The Von Neumann Model



The Von Neumann Model



Memory

- The memory stores
 - Data
 - Programs
- The memory contains bits
 - Bits are grouped into bytes (8 bits) and words (e.g., 8, 16, 32 bits)
- How the bits are accessed determines the addressability
 - E.g., word-addressable
 - E.g., 8-bit addressable (or byte-addressable)
- The total number of addresses is the address space
 - In LC-3, the address space is 2^{16}
 - 16-bit addresses
 - In MIPS, the address space is 2^{32}
 - 32-bit addresses
 - In x86-64, the address space is (up to) 2^{48}
 - 48-bit addresses

Word-Addressable Memory

- Each **data word** has a **unique address**
 - In MIPS, a unique address for each **32-bit data word**
 - In LC-3, a unique address for each **16-bit data word**

Word Address	Data	MIPS memory
·	·	·
·	·	·
·	·	·
00000003	D 1 6 1 7 A 1 C	Word 3
00000002	1 3 C 8 1 7 5 5	Word 2
00000001	F 2 F 1 F 0 F 7	Word 1
00000000	8 9 A B C D E F	Word 0

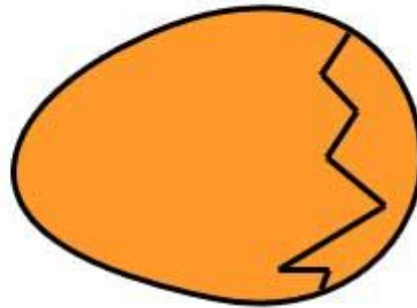
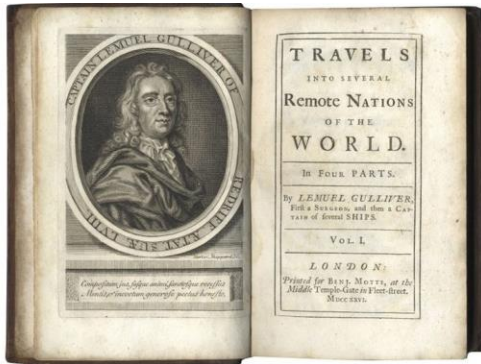
Byte-Addressable Memory

- Each **byte** has a **unique address**
 - Actually, MIPS is **byte-addressable**
 - LC-3b (updated version of LC-3) is **byte-addressable**, too

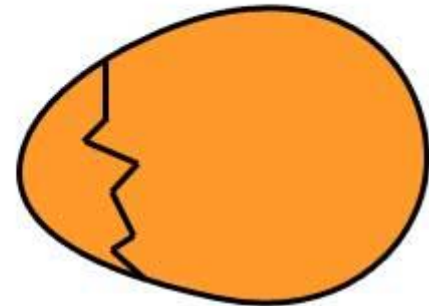
Byte Address of the Word		Data				MIPS memory	
·		·				·	
·		·				·	
·		·				·	
0000000C		D 1	6 1	7 A	1 C	Word 3	
00000008		1 3	C 8	1 7	5 5	Word 2	
00000004		F 2	F 1	F 0	F 7	Word 1	
00000000		How are these four bytes addressed?				Word 0	

Big Endian vs Little Endian

- Jonathan Swift's **Gulliver's Travels**
 - ❑ **Little Endians** broke their eggs on the little end of the egg
 - ❑ **Big Endians** broke their eggs on the big end of the egg



BIG ENDIAN - The way people always broke their eggs in the Lilliput land



LITTLE ENDIAN - The way the king then ordered the people to break their eggs

Big Endian vs Little Endian

Big Endian

Byte Address			
⋮			
C	D	E	F
8	9	A	B
4	5	6	7
0	1	2	3
MSB		LSB	

(Most Significant Byte)

(Least Significant Byte)

Little Endian

Byte Address			
⋮			
F	E	D	C
B	A	9	8
7	6	5	4
3	2	1	0
MSB		LSB	

Big Endian vs Little Endian

Big Endian

Little Endian

Does this really matter?

Answer: No, it is a convention

Qualified answer: No, except when one big-endian system and one little-endian system have to share data

MSB

LSB

MSB

LSB

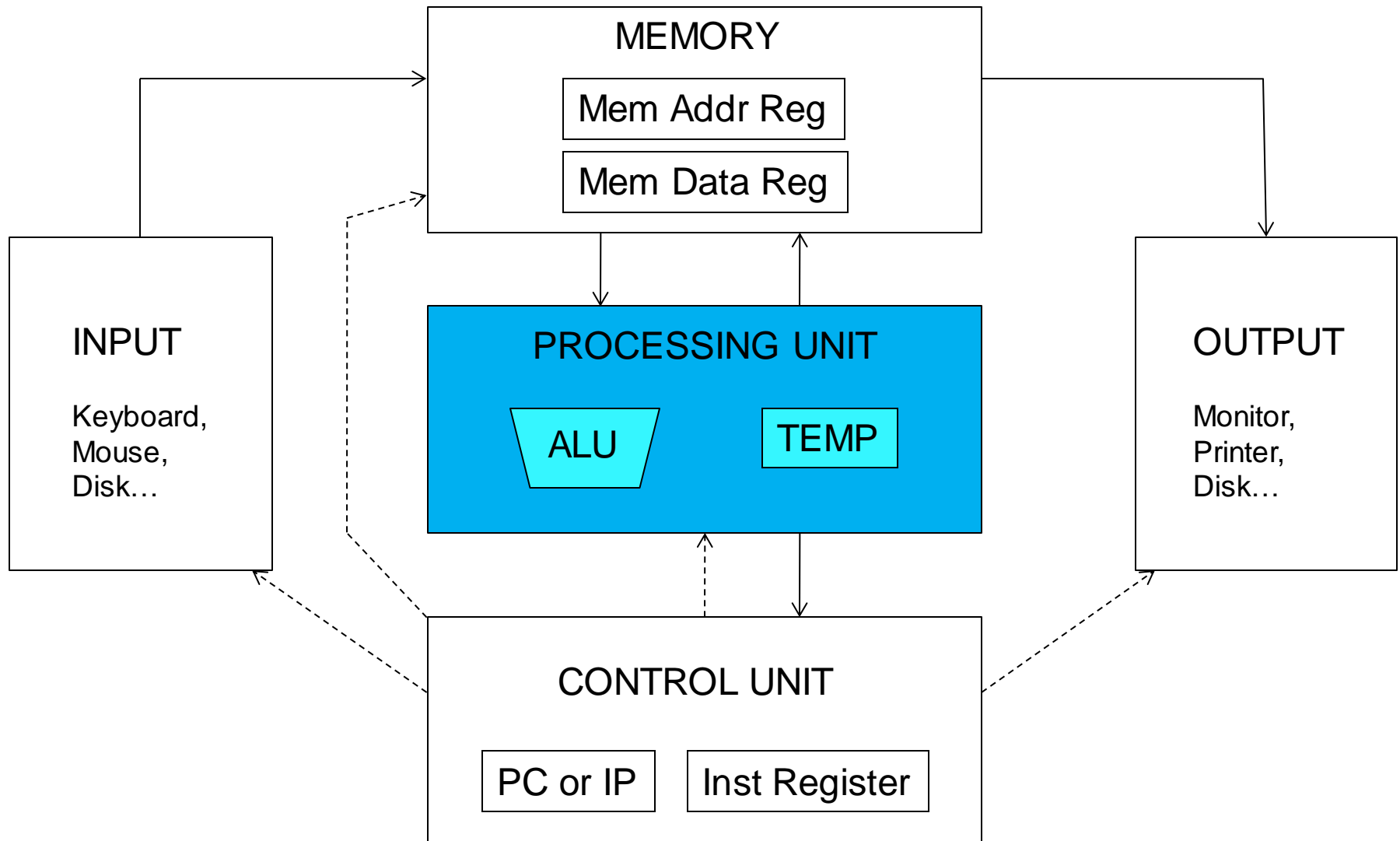
(Most Significant Byte)

(Least Significant Byte)

Accessing Memory: MAR and MDR

- There are two ways of accessing memory
 - Reading or loading
 - Writing or storing
- Two registers are necessary to access memory
 - Memory Address Register (MAR)
 - Memory Data Register (MDR)
- To read
 - Step 1: Load the MAR with the address
 - Step 2: Data is placed in MDR
- To write
 - Step 1: Load the MAR with the address and the MDR with the data
 - Step 2: Activate Write Enable signal

The Von Neumann Model



Processing Unit

- The processing unit can consist of many **functional units**
- We start with a simple **Arithmetic and Logic Unit (ALU)**, which executes computations
 - **LC-3**: ADD, AND, NOT (XOR in LC-3b)
 - **MIPS**: add, sub, mult, and, nor, sll, slr, slt...
- The ALU processes quantities that are referred to as **words**
 - **Word length** in LC-3 is 16 bits
 - In MIPS it is 32 bits
- Temporary storage: **Registers**
 - E.g., to calculate $(A+B)*C$, the intermediate result of $A+B$ is stored in a register

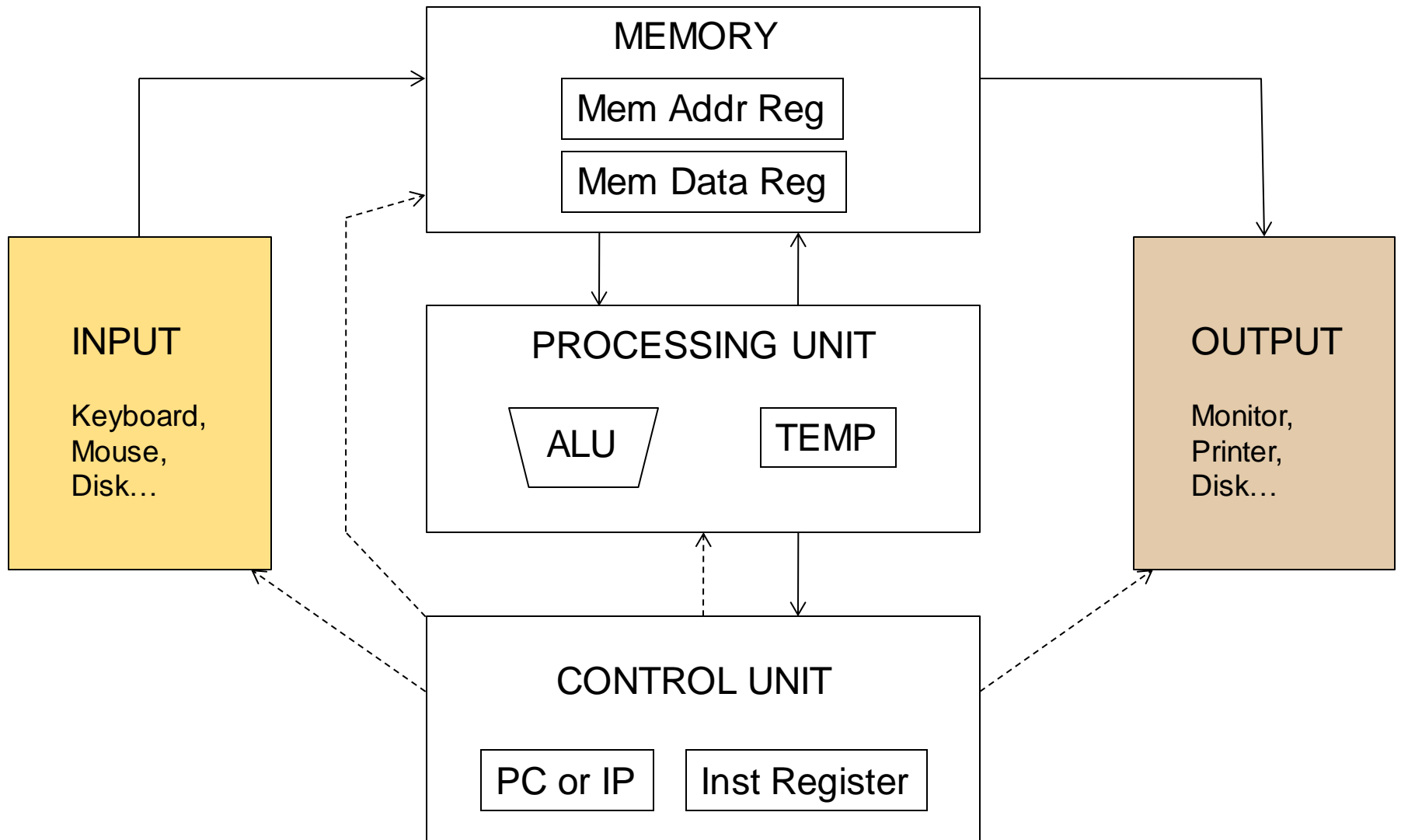
Registers

- Memory is big but slow
- Registers
 - Ensure fast access to operands
 - Typically one register contains one word
- Register set or file
 - LC-3 has 8 general purpose registers (GPR)
 - R0 to R7: 3-bit register number
 - Register size = Word length = 16 bits
 - MIPS has 32 registers
 - Register size = Word length = 32 bits

MIPS Register File

Name	Register Number	Usage
\$0	0	the constant value 0
\$at	1	assembler temporary
\$v0-\$v1	2-3	function return value
\$a0-\$a3	4-7	function arguments
\$t0-\$t7	8-15	temporary variables
\$s0-\$s7	16-23	saved variables
\$t8-\$t9	24-25	temporary variables
\$k0-\$k1	26-27	OS temporaries
\$gp	28	global pointer
\$sp	29	stack pointer
\$fp	30	frame pointer
\$ra	31	function return address

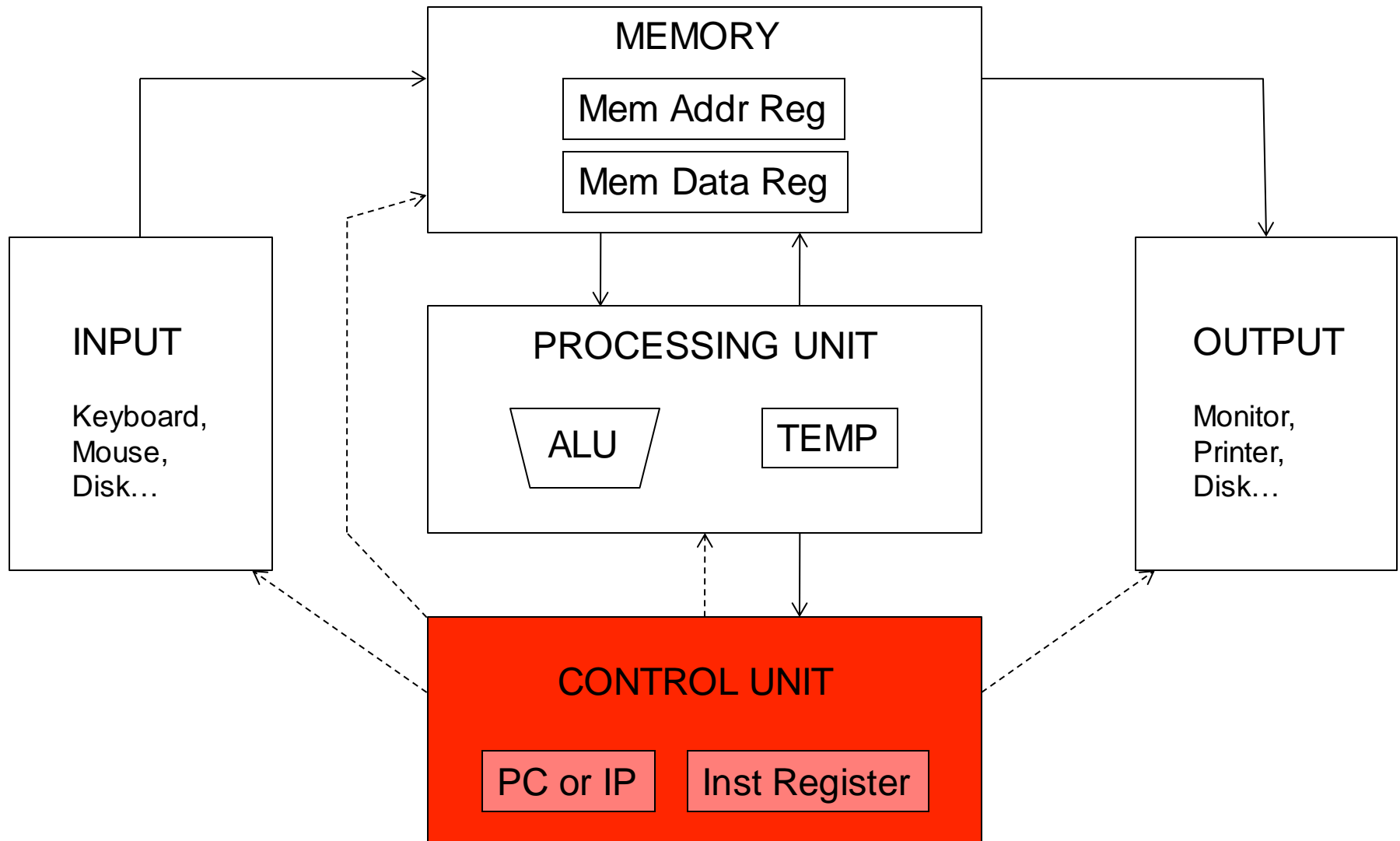
The Von Neumann Model



Input and Output

- Many devices can be used for input and output
- They are called peripherals
 - Input
 - Keyboard
 - Mouse
 - Scanner
 - Disks
 - Etc.
 - Output
 - Monitor
 - Printer
 - Disks
 - Etc.
 - In LC-3, we consider keyboard and monitor

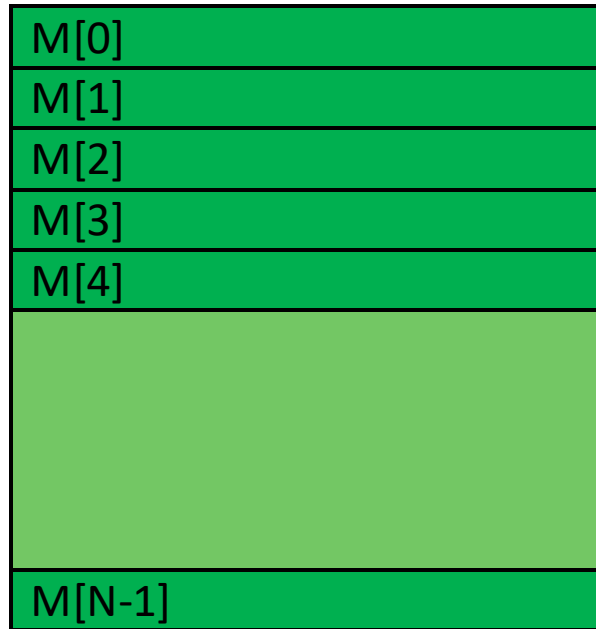
The Von Neumann Model



Control Unit

- The control unit is similar to the conductor of an orchestra
- It conducts the step-by-step process of executing (every instruction in) a program
- It keeps track of the instruction being executed with an instruction register (IR), which contains the instruction
- Another register contains the address of the next instruction to execute. It is called program counter (PC) or instruction pointer (IP)

Programmer Visible (Architectural) State



Memory
array of storage locations
indexed by an address



Registers

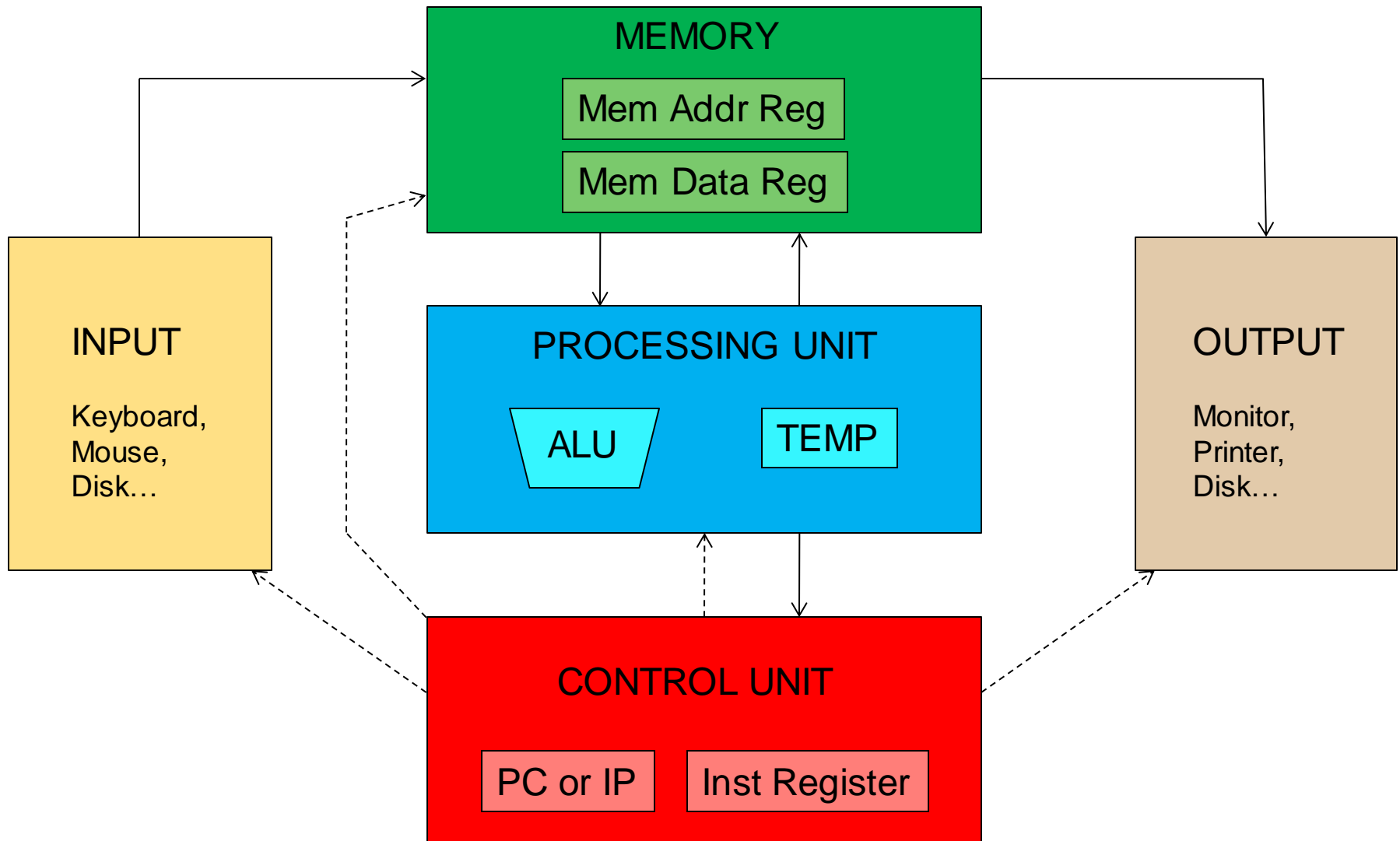
- given special names in the ISA (as opposed to addresses)
- general vs. special purpose

Program Counter

memory address
of the current instruction

Instructions (and programs) specify how to transform
the values of programmer visible state

The Von Neumann Model



Von Neumann Model: Two Key Properties

- Von Neumann model is also called *stored program computer* (instructions in memory). It has two key properties:
- **Stored program**
 - Instructions stored in a linear memory array
 - **Memory is unified** between instructions and data
 - The interpretation of a stored value depends on the control signals
- **Sequential instruction processing**
 - One instruction processed (fetched, executed, completed) at a time
 - **Program counter (instruction pointer)** identifies the current instruction
 - **Program counter is advanced sequentially** except for control transfer instructions

LC-3: A Von Neumann Machine

LC-3: A Von Neumann Machine

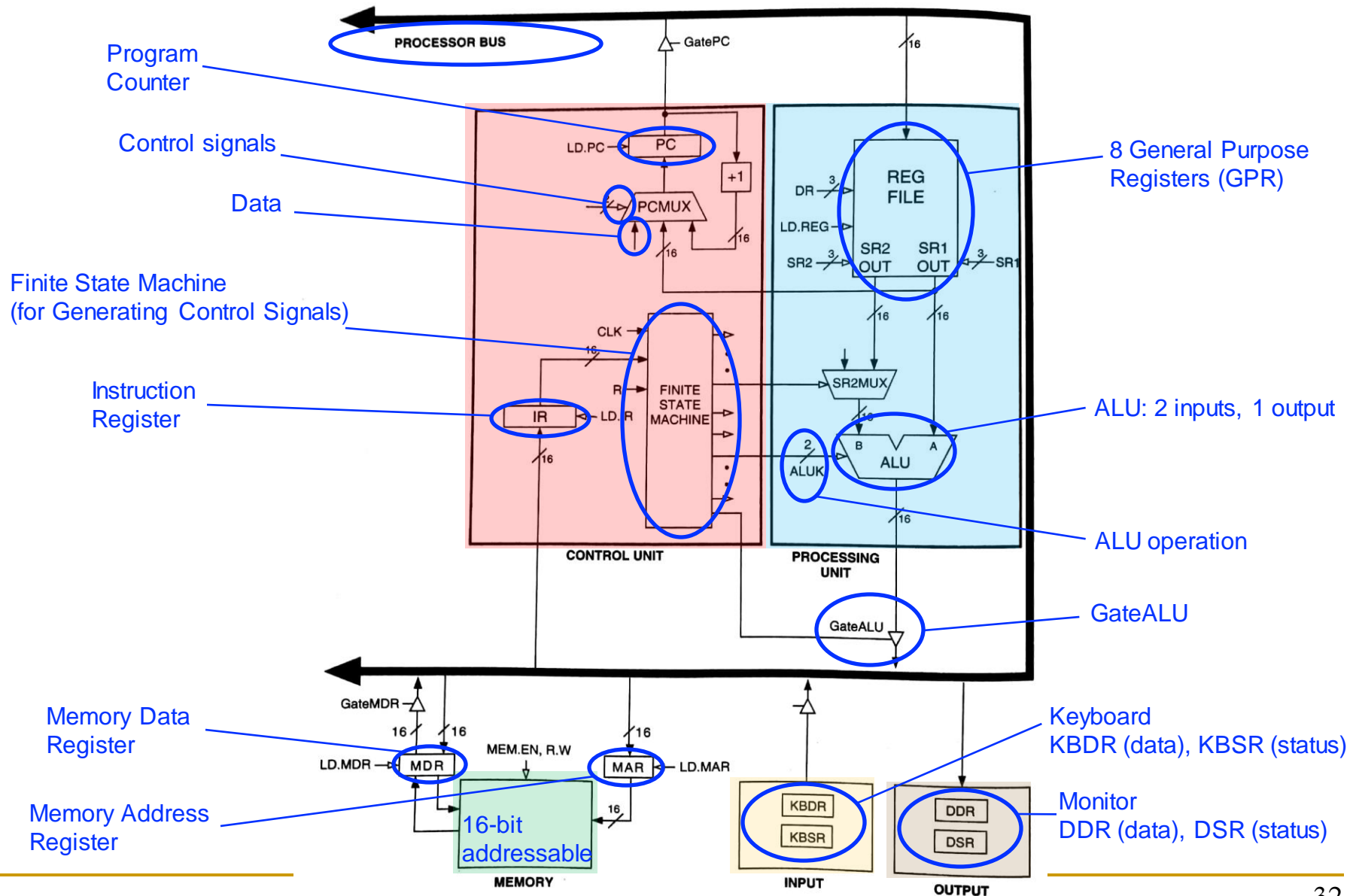


Figure 4.3 The LC-3 as an example of the von Neumann model

Stored Program & Sequential Execution

- Instructions and data are **stored in memory**
 - Typically **the instruction length is the word length**
- The processor fetches instructions from memory **sequentially**
 - Fetches one instruction
 - Decodes and executes the instruction
 - Continues with the next instruction
- The address of the current instruction is stored in the **program counter (PC)**
 - If **word-addressable** memory, the processor **increments the PC by 1** (in LC-3)
 - If **byte-addressable** memory, the processor **increments the PC by the word length** (4 in MIPS)
 - In MIPS the OS typically sets the PC to **0x00400000** (start of a program)

A Sample Program Stored in Memory

- A sample MIPS program
 - 4 instructions stored in consecutive words in memory
 - No need to understand the program now. We will get back to it

MIPS assembly

```
lw    $t2, 32($0)
add   $s0, $s1, $s2
addi  $t0, $s3, -12
sub   $t0, $t3, $t5
```

Machine code

```
0x8C0A0020
0x02328020
0x2268FFF4
0x016D4022
```

Address	Instructions	
⋮	⋮	
0040000C	0 1 6 D 4 0 2 2	
00400008	2 2 6 8 F F F 4	
00400004	0 2 3 2 8 0 2 0	
00400000	8 C 0 A 0 0 2 0	← PC
⋮	⋮	

The Instruction

- An instruction the **most basic unit of computer processing**
 - **Instructions** are words in the language of a computer
 - **Instruction Set Architecture** (ISA) is the vocabulary
- The language of the computer can be written as
 - **Machine language**: Computer-readable representation (that is, 0's and 1's)
 - **Assembly language**: Human-readable representation
- We will look at **LC-3 instructions** and **MIPS instructions**
- Let us start with some example instructions

Instruction Types

- There are **three main types of instructions**
- **Operate instructions**
 - Execute instructions in the ALU
- **Data movement instructions**
 - Read from or write to memory
- **Control flow instructions**
 - Change the sequence of execution

An Example Operate Instruction

■ Addition

High-level code

```
a = b + c;
```

Assembly

```
add a, b, c
```

- **add**: mnemonic to indicate the operation to perform
- **b, c**: source operands
- **a**: destination operand
- $a \leftarrow b + c$

Registers

- We map variables to registers

Assembly

```
add a, b, c
```

LC-3 registers

```
b = R1
```

```
c = R2
```

```
a = R0
```

MIPS registers

```
b = $s1
```

```
c = $s2
```

```
a = $s0
```

From Assembly to Machine Code in LC-3

■ Addition

LC-3 assembly

```
ADD R0, R1, R2
```

Field Values

OP	DR	SR1	SR2	
1	0	1	0	00
2				

Machine Code

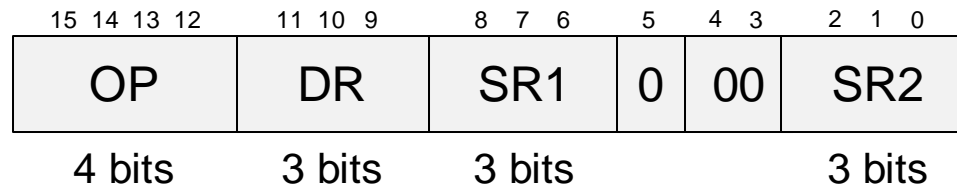
OP	DR	SR1	SR2	
0 0 0 1	0 0 0	0 0 1	0	0 0
0 1 0				
15 14 13 12	11 10 9	8 7 6	5	4 3
2 1 0				

0x1042

Machine Code, in short (hexadecimal)

Instruction Format (or Encoding)

■ LC-3



□ OP = **opcode** (what the instruction does)

■ E.g., ADD = 0001

□ **Semantics:** $DR \leftarrow SR1 + SR2$

■ E.g., AND = 0101

□ **Semantics:** $DR \leftarrow SR1 \text{ AND } SR2$

□ SR1, SR2 = source registers

□ DR = destination register

From Assembly to Machine Code in MIPS

■ Addition

MIPS assembly

```
add    $s0, $s1, $s2
```

Field Values

op	rs	rt	rd	shamt	funct
0	17	18	16	0	32

$rd \leftarrow rs + rt$

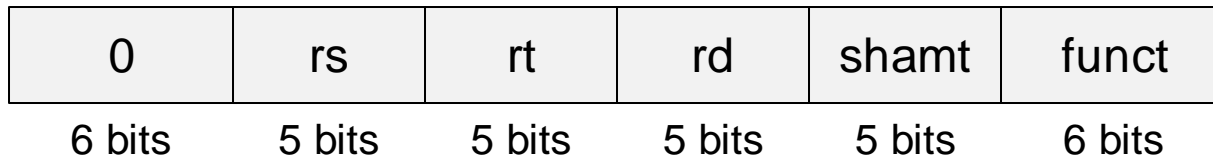
Machine Code

op		rs		rt		rd		shamt		funct	
000000		10001		10010		10000		00000		100000	
31	26	25	21	20	16	15	11	10	6	5	0

0x02328020

Instruction Formats: R-Type in MIPS

- R-type
 - 3 register operands
- MIPS



- 0 = opcode
- rs, rt = source registers
- rd = destination register
- shamt = shift amount (only shift operations)
- funct = operation in R-type instructions

Reading Operands from Memory

- With the **operate instructions**, such as addition, we tell the computer to **execute arithmetic (or logic) computations** in the ALU
- We also need instructions to **access the operands from memory**
- Next, we see how to **read (or load) from memory**
- **Writing (or storing)** is performed in a similar way, but we will talk about that later

Reading Word-Addressable Memory

■ Load word

High-level code

```
a = A[i];
```

Assembly

```
load a, A, i
```

- **load**: mnemonic to indicate the load word operation
- **A**: base address
- **i**: offset
 - E.g., **immediate or literal** (a constant)
- **a**: destination operand
- **Semantics**: $a \leftarrow \text{Memory}[A + i]$

Load Word in LC-3 and MIPS

■ LC-3 assembly

High-level code

```
a = A[2];
```

LC-3 assembly

```
LDR R3, R0, #2
```

$R3 \leftarrow \text{Memory}[R0 + 2]$

■ MIPS assembly

High-level code

```
a = A[2];
```

MIPS assembly

```
lw $s3, 2($s0)
```

$\$s3 \leftarrow \text{Memory}[\$s0 + 2]$

These instructions use a particular **addressing mode** (i.e., the way the address is calculated), called **base+offset**

Load Word in Byte-Addressable MIPS

■ MIPS assembly

High-level code

```
a = A[2];
```

MIPS assembly

```
lw    $s3, 8($s0)
```

$\$s3 \leftarrow \text{Memory}[\$s0 + 8]$

- Byte address is calculated as: $\text{word_address} * \text{bytes/word}$
 - 4 bytes/word in MIPS
 - If LC-3 were byte-addressable (i.e., LC-3b), 2 bytes/word

Instruction Format With Immediate

■ LC-3

LC-3 assembly

```
LDR R3, R0, #4
```

Field Values

OP	DR	BaseR	offset6
6	3	0	4
15	12	11	9
8	6	5	0

■ MIPS

MIPS assembly

```
lw $s3, 8($s0)
```

Field Values

op	rs	rt	imm
35	16	19	8
31	26	25	21
20	16	15	0

I-Type

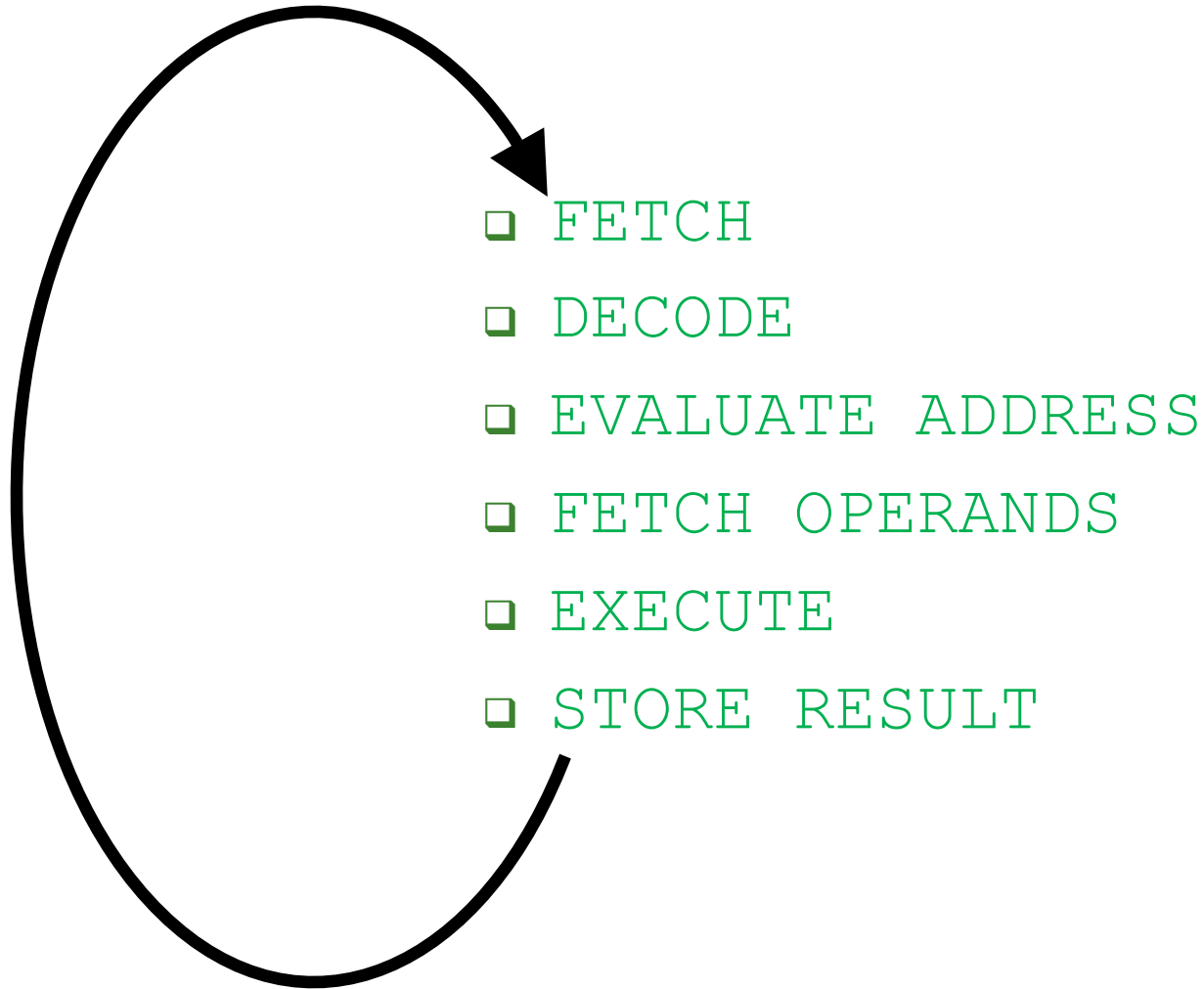
How are These Instructions Executed?

- By using instructions we can speak the language of the computer
- Thus, we now know how to tell the computer to
 - Execute computations in the ALU by using, for instance, an addition
 - Access operands from memory by using the load word instruction
- But, how are these instructions executed on the computer?
 - The process of executing an instruction is called is the instruction cycle

The Instruction Cycle

- The instruction cycle is a sequence of steps or **phases**, that an instruction goes through to be executed
 - FETCH
 - DECODE
 - EVALUATE ADDRESS
 - FETCH OPERANDS
 - EXECUTE
 - STORE RESULT
- **Not all instructions have the six phases**
 - LDR does not require EXECUTE
 - ADD does not require EVALUATE ADDRESS
 - Intel x86 instruction **ADD [eax], edx** is an example of instruction with six phases

After STORE RESULT, a New FETCH



FETCH

- The FETCH phase obtains the instruction from memory and loads it into the **instruction register**
- This phase is **common to every instruction type**
- **Complete description**
 - Step 1: **Load the MAR with** the contents of the **PC**, and simultaneously **increment the PC**
 - Step 2: Interrogate memory. This results the **instruction to be placed in the MDR**
 - Step 3: **Load the IR** with the contents of the **MDR**

FETCH in LC-3

Step 1: Load
MAR and
increment PC

Step 2: Access
memory

Step 3: Load IR
with the content
of MDR

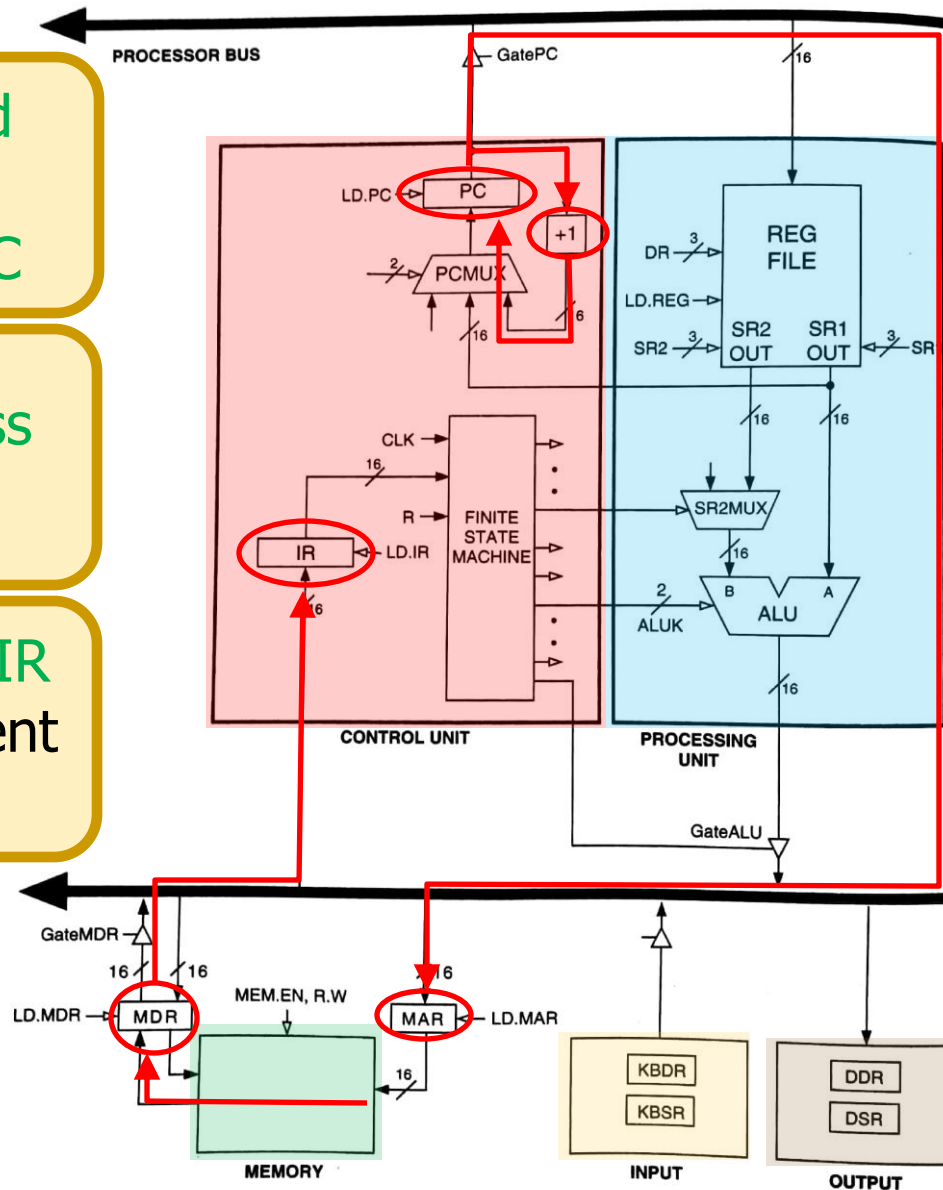


Figure 4.3 The LC-3 as an example of the von Neumann model

DECODE

- The DECODE phase identifies the instruction
- Recall the decoder (Lecture 5, Slides 47-48)
 - A 4-to-16 decoder identifies which of the 16 opcodes is going to be processed
- The input is the four bits IR[15:12]
- The remaining 12 bits identify what else is needed to process the instruction

DECODE in LC-3

DECODE
identifies the
instruction to be
processed

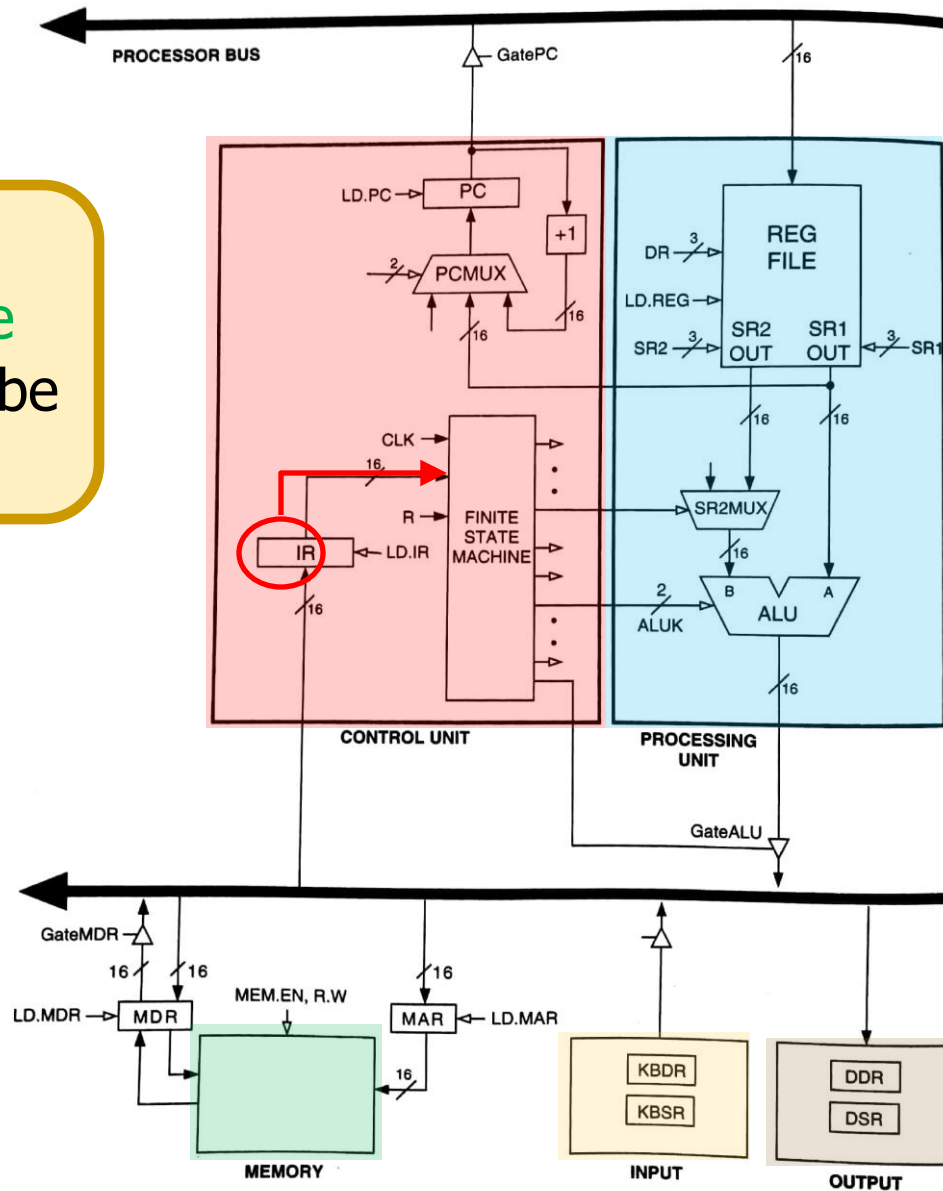


Figure 4.3 The LC-3 as an example of the von Neumann model

EVALUATE ADDRESS

- The EVALUATE ADDRESS phase computes the address of the memory location that is needed to process the instruction
- This phase is necessary in LDR
 - It computes the address of the data word that is to be read from memory
 - By adding an offset to the content of a register
- But not necessary in ADD

EVALUATE ADDRESS in LC-3

LDR calculates the address by adding a register and an immediate

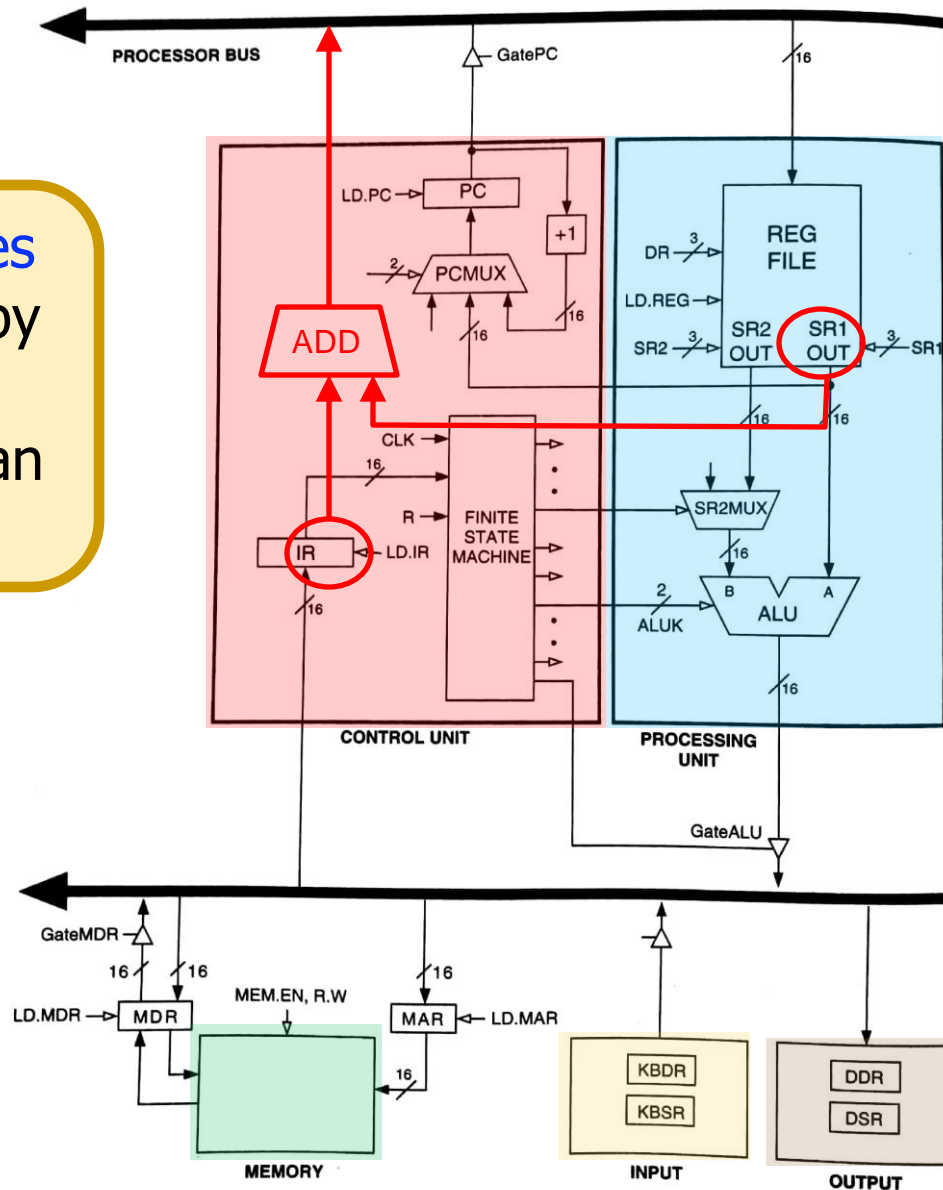


Figure 4.3 The LC-3 as an example of the von Neumann model

FETCH OPERANDS

- The FETCH OPERANDS phase obtains the source operands needed to process the instruction

- In LDR
 - Step 1: Load MAR with the address calculated in EVALUATE ADDRESS

 - Step 2: Read memory, placing source operand in MDR

- In ADD
 - Obtain the source operands from the register file

 - In most current microprocessors, this phase can be done at the same time the instruction is being decoded

FETCH OPERANDS in LC-3

LDR loads **MAR**
(step 1), and
places the
results in **MDR**
(step 2)

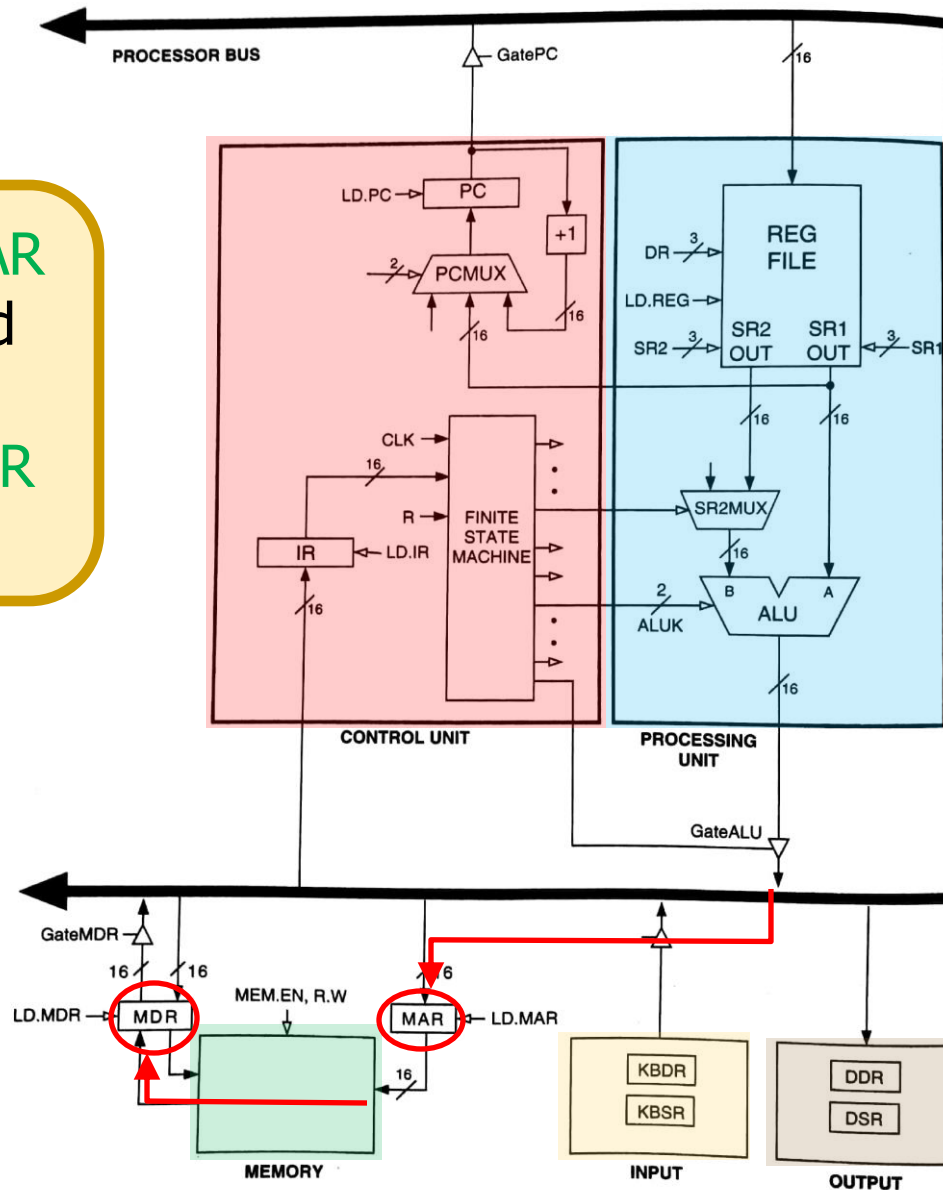


Figure 4.3 The LC-3 as an example of the von Neumann model

EXECUTE

- The EXECUTE phase **executes the instruction**
 - In ADD, it performs addition in the ALU

EXECUTE in LC-3

ADD adds SR1
and SR2

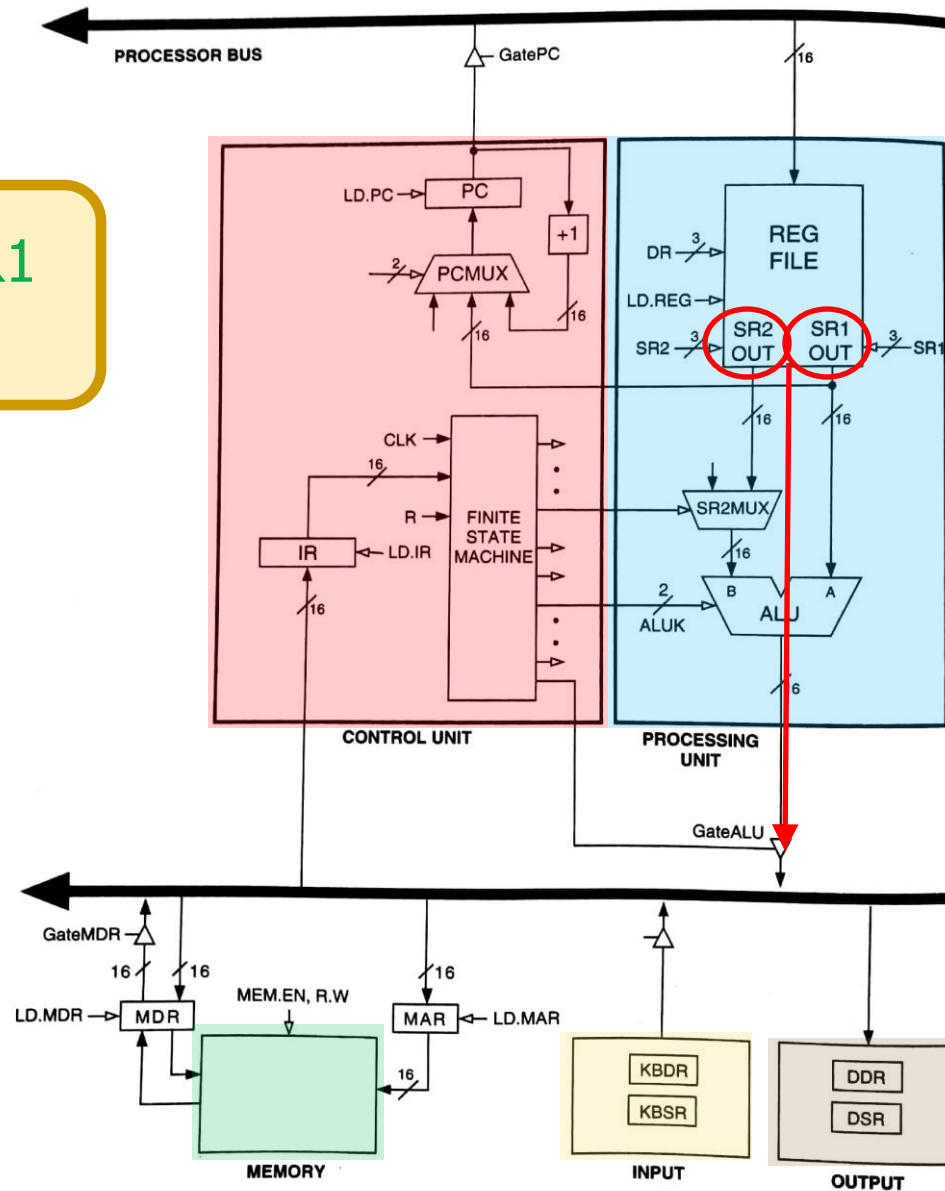
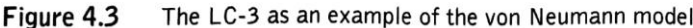


Figure 4.3 The LC-3 as an example of the von Neumann model

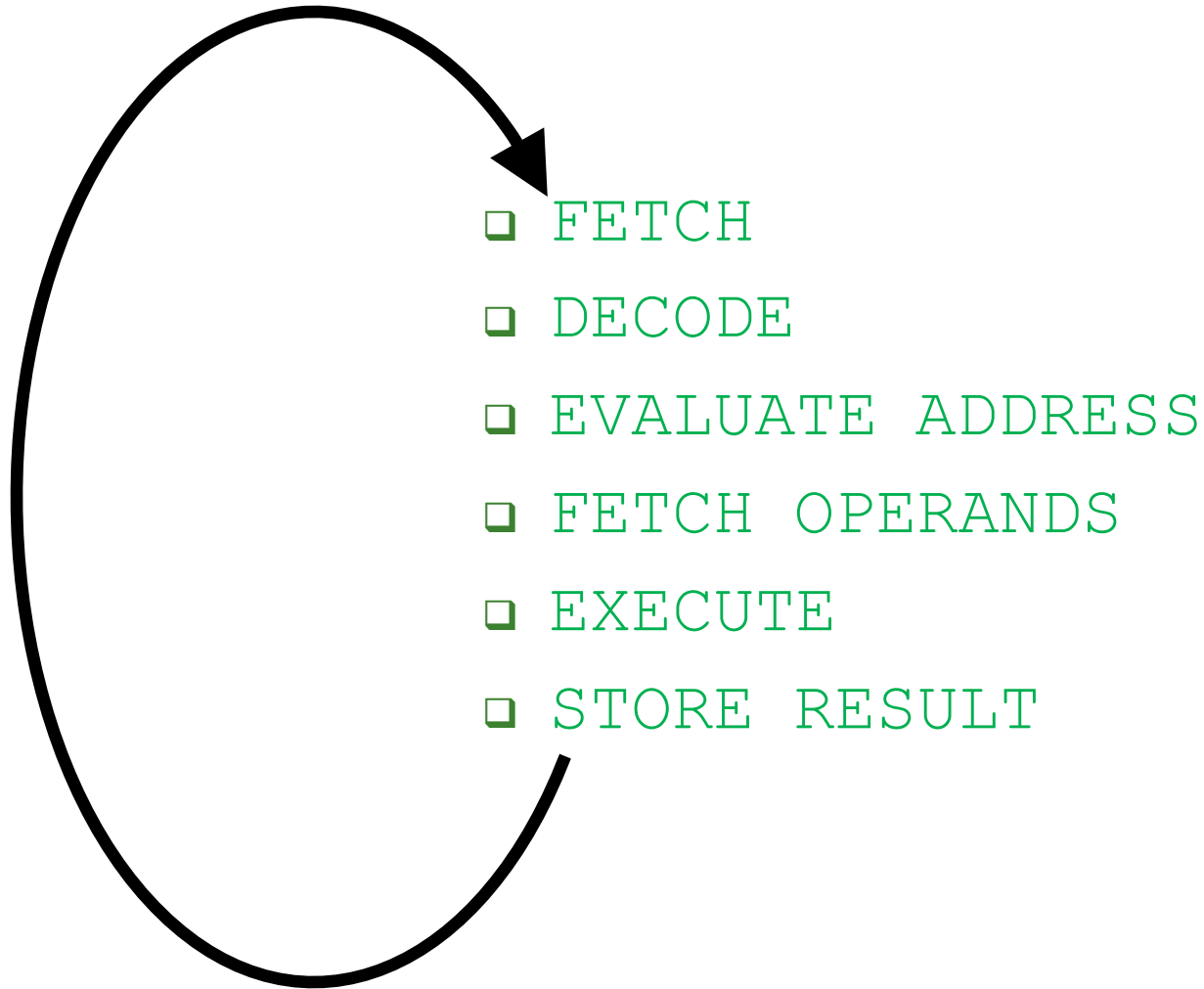
STORE RESULT

- The STORE RESULT phase writes to the designated destination
- Once STORE RESULT is completed, a new instruction cycle starts (with the FETCH phase)

LDR loads MDR
into DR



The Instruction Cycle



Changing the Sequence of Execution

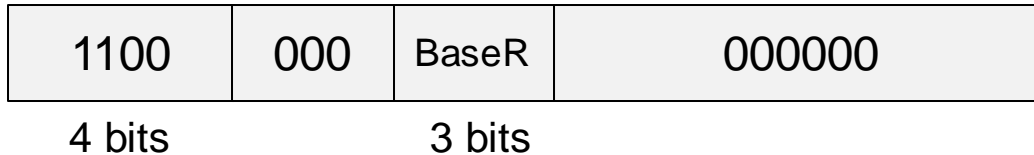
- A computer program **executes in sequence** (i.e., in program order)
 - First instruction, second instruction, third instruction and so on
- Unless we **change the sequence of execution**
- **Control instructions** allow a program to execute **out of sequence**
 - They can change the PC by loading it during the EXECUTE phase
 - That wipes out the incremented PC (loaded during the FETCH phase)

Jump in LC-3

- Unconditional branch or jump

- LC-3

JMP R2



- ❑ BaseR = Base register
- ❑ $PC \leftarrow R2$ (Register identified by BaseR)
- ❑ Variations
 - RET: special case of JMP where BaseR = R7
 - JSR, JSRR: jump to subroutine

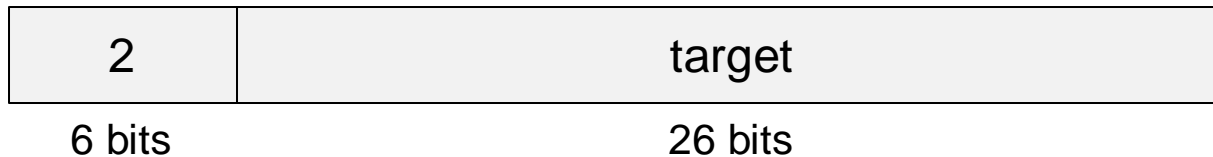
This is **register**
addressing mode

Jump in MIPS

- Unconditional branch or jump

- MIPS

j target



J-Type

- 2 = opcode
- target = target address
- $PC \leftarrow PC^+ [31:28] \mid \text{sign-extend}(\text{target}) * 4$
- Variations
 - jal: jump and link (function calls)
 - jr: jump register

jr \$s0

j uses pseudo-direct addressing mode

jr uses register addressing mode

* This is the incremented PC

LC-3 Data Path

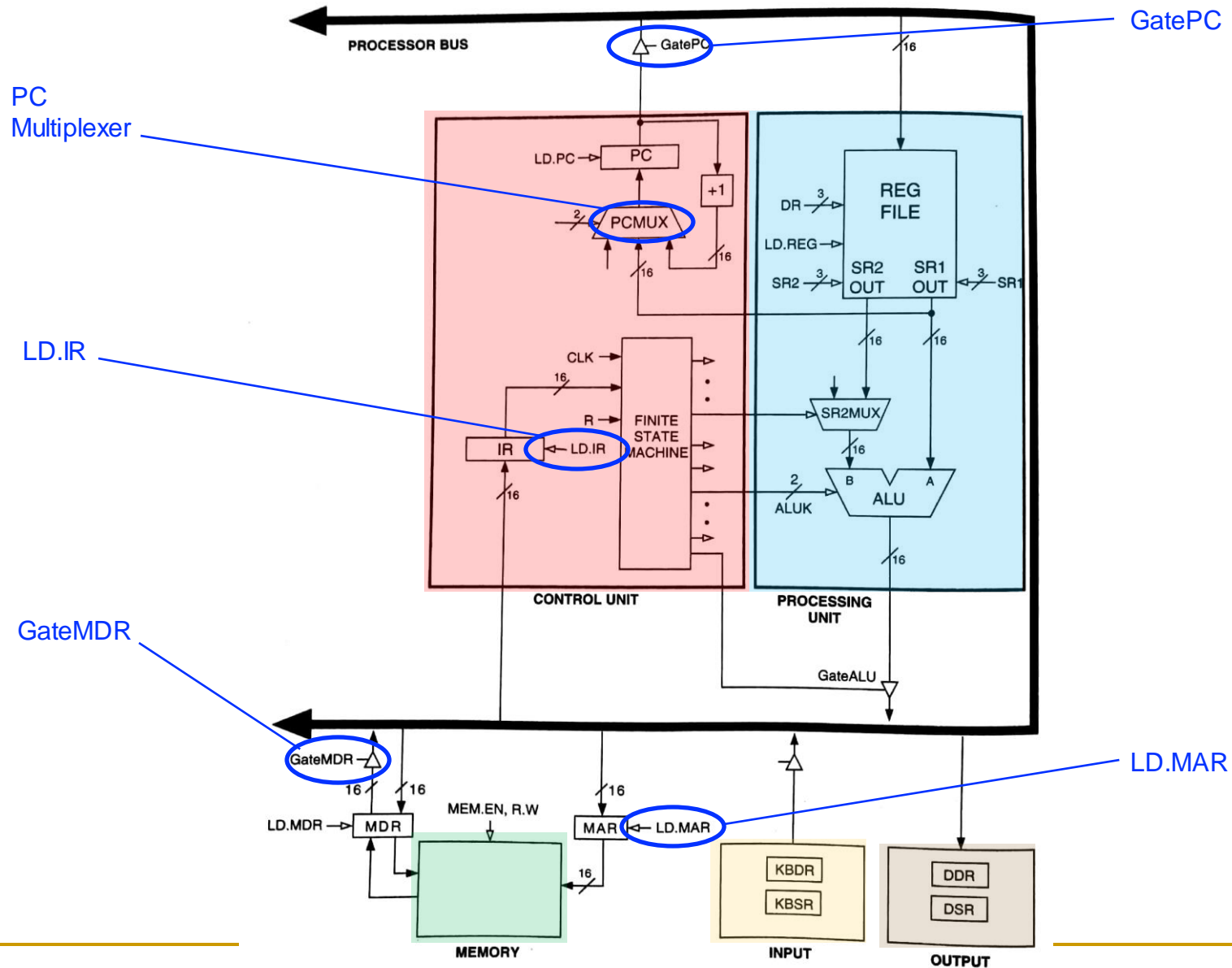


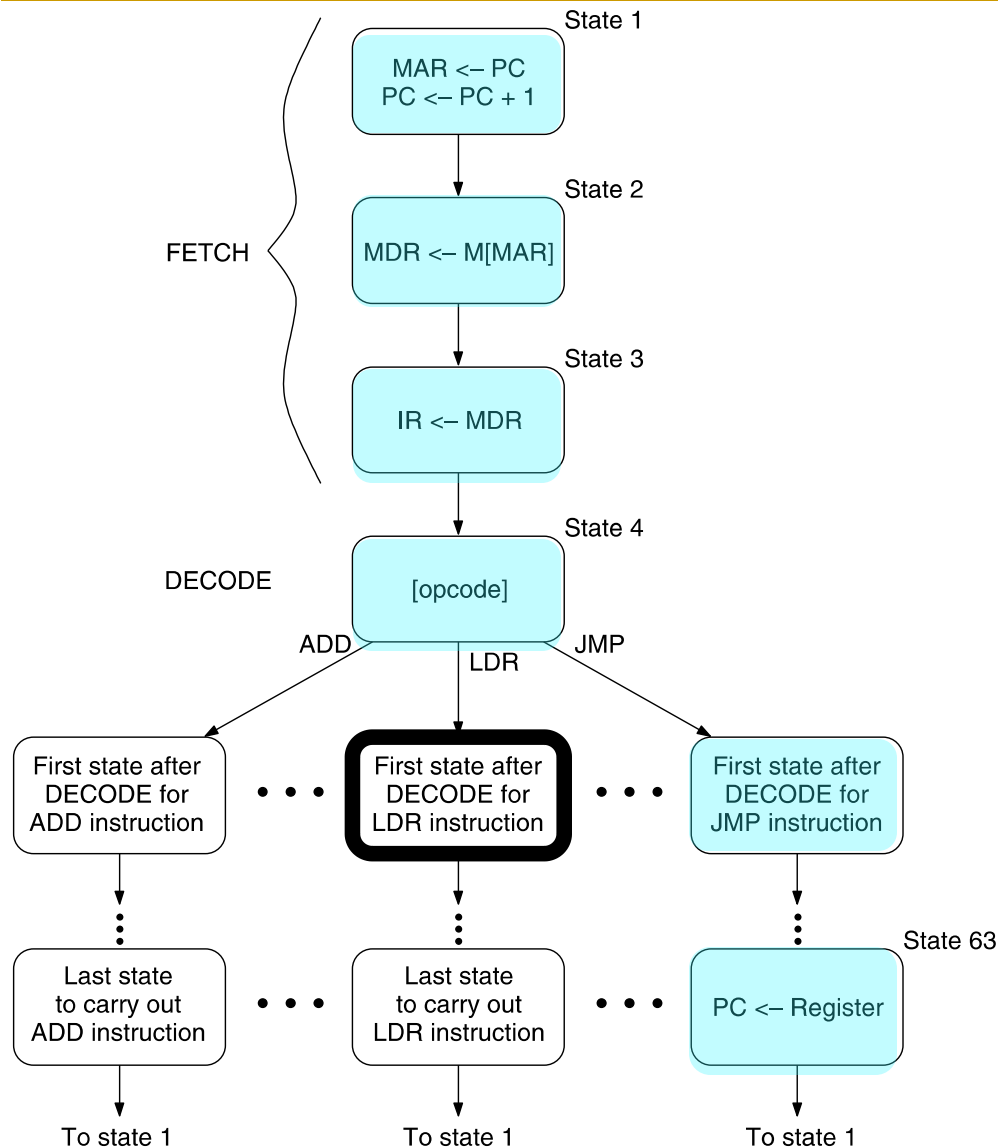
Figure 4.3 The LC-3 as an example of the von Neumann model

Opcodes in LC-3

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ADD ⁺	0001				DR			SR1		0	00				SR2	
ADD ⁺	0001				DR			SR1		1					imm5	
AND ⁺	0101				DR			SR1		0	00				SR2	
AND ⁺	0101				DR			SR1		1					imm5	
BR	0000				n	z	p									PCOffset9
JMP	1100				000			BaseR							000000	
JSR	0100				1											PCOffset11
JSRR	0100				0		00	BaseR							000000	
LD ⁺	0010				DR											PCOffset9
LDI ⁺	1010				DR											PCOffset9
LDR ⁺	0110				DR			BaseR							offset6	
LEA ⁺	1110				DR											PCOffset9
NOT ⁺	1001				DR			SR							111111	
RET	1100				000			111							000000	
RTI	1000															000000000000
ST	0011				SR											PCOffset9
STI	1011				SR											PCOffset9
STR	0111				SR			BaseR							offset6	
TRAP	1111				0000											trapvect8
reserved	1101															

Figure 5.3 Formats of the entire LC-3 instruction set. NOTE: ⁺ indicates instructions that modify condition codes

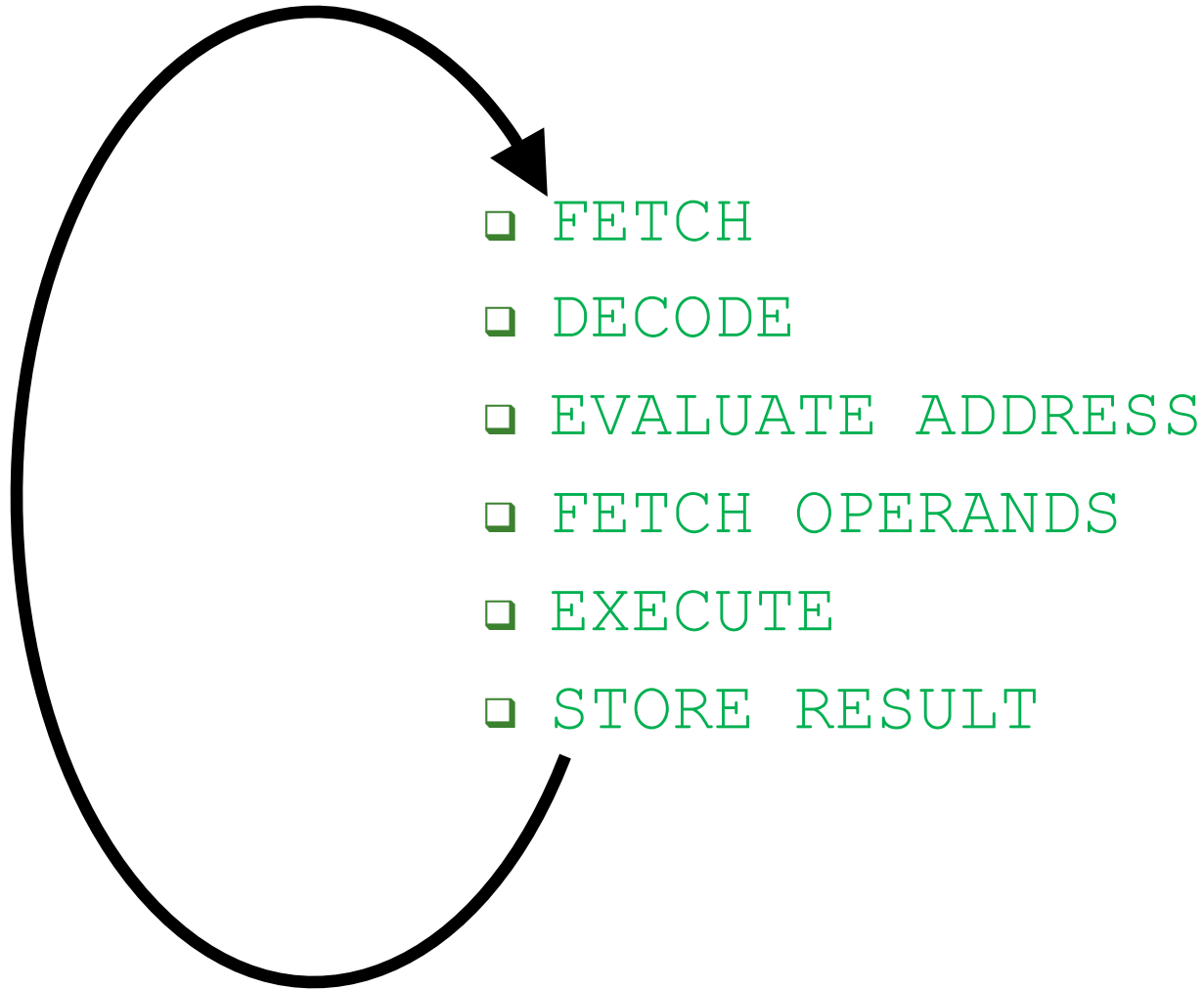
Control of the Instruction Cycle



- **State 1**
 - The FSM asserts GatePC and LD.MAR
 - It selects input (+1) in PCMUX and asserts LD.PC
- **State 2**
 - MDR is loaded with the instruction
- **State 3**
 - The FSM asserts GateMDR and LD.IR
- **State 4**
 - The FSM goes to next state depending on opcode
- **State 63**
 - JMP loads register into PC
- Full state diagram in Patt&Pattell, Appendix C

Figure 4.4 An abbreviated state diagram of the LC-3

The Instruction Cycle



LC-3 and MIPS

Instruction Set Architectures

The Instruction Set

- It defines **opcodes**, **data types**, and **addressing modes**
- ADD and LDR have been our first examples

ADD

OP	DR	SR1	SR2		
1	0	1	0	00	2

Register mode

LDR

OP	DR	BaseR	offset6
6	3	0	4

Base+offset mode

The Instruction Set Architecture

- The ISA is the **interface between** what the **software** commands and what the **hardware** carries out
- The ISA specifies
 - The **memory organization**
 - Address space (LC-3: 2^{16} , MIPS: 2^{32})
 - Addressability (LC-3: 16 bits, MIPS: 32 bits)
 - Word- or Byte-addressable
 - The **register set**
 - R0 to R7 in LC-3
 - 32 registers in MIPS
 - The **instruction set**
 - Opcodes
 - Data types
 - Addressing modes

Problem
Algorithm
Program
ISA
Microarchitecture
Circuits
Electrons

Opcodes

- Large or small **sets of opcodes** could be defined
 - E.g, HP Precision Architecture: an instruction for $A*B+C$
 - E.g, x86 ISA: multimedia extensions (MMX), later SSE and AVX
 - E.g, VAX ISA: opcode to save all information of one program prior to switching to another program
- **Tradeoffs** are involved
 - Hardware complexity vs. software complexity
- In LC-3 and in MIPS there are three **types of opcodes**
 - Operate
 - Data movement
 - Control

Opcodes in LC-3b

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ADD ⁺	0001				DR			SR1			A	op.spec				
AND ⁺	0101				DR			SR1			A	op.spec				
BR	0000				n	z	p	PCOffset9								
JMP	1100				000			BaseR			000000					
JSR(R)	0100				A	operand.specifier										
LDB ⁺	0010				DR			BaseR			boffset6					
LDW ⁺	0110				DR			BaseR			offset6					
LEA ⁺	1110				DR			PCOffset9								
RTI	1000				000000000000											
SHF ⁺	1101				DR			SR			A	D	amount4			
STB	0011				SR			BaseR			boffset6					
STW	0111				SR			BaseR			offset6					
TRAP	1111				0000			trapvect8								
XOR ⁺	1001				DR			SR1			A	op.spec				
not used	1010															
not used	1011															

Funct in MIPS R-Type Instructions (I)

Table B.2 R-type instructions, sorted by funct field

Opcode is 0
in MIPS R-
Type
instructions.
Funct defines
the operation

Funct	Name	Description	Operation
000000 (0)	sll rd, rt, shamt	shift left logical	[rd] = [rt] << shamt
000010 (2)	srl rd, rt, shamt	shift right logical	[rd] = [rt] >> shamt
000011 (3)	sra rd, rt, shamt	shift right arithmetic	[rd] = [rt] >>> shamt
000100 (4)	sllv rd, rt, rs	shift left logical variable	[rd] = [rt] << [rs] _{4:0}
000110 (6)	srlv rd, rt, rs	shift right logical variable	[rd] = [rt] >> [rs] _{4:0}
000111 (7)	srav rd, rt, rs	shift right arithmetic variable	[rd] = [rt] >>> [rs] _{4:0}
001000 (8)	jr rs	jump register	PC = [rs]
001001 (9)	jalr rs	jump and link register	\$ra = PC + 4, PC = [rs]
001100 (12)	syscall	system call	system call exception
001101 (13)	break	break	break exception
010000 (16)	mfhi rd	move from hi	[rd] = [hi]
010001 (17)	mthi rs	move to hi	[hi] = [rs]
010010 (18)	mflo rd	move from lo	[rd] = [lo]
010011 (19)	mtlo rs	move to lo	[lo] = [rs]
011000 (24)	mult rs, rt	multiply	{[hi], [lo]} = [rs] × [rt]
011001 (25)	multu rs, rt	multiply unsigned	{[hi], [lo]} = [rs] × [rt]
011010 (26)	div rs, rt	divide	[lo] = [rs]/[rt], [hi] = [rs]%[rt]
011011 (27)	divu rs, rt	divide unsigned	[lo] = [rs]/[rt], [hi] = [rs]%[rt]

(continued)

Funct in MIPS R-Type Instructions (II)

Table B.2 R-type instructions, sorted by funct field—Cont'd

Funct	Name	Description	Operation
100000 (32)	add rd, rs, rt	add	$[rd] = [rs] + [rt]$
100001 (33)	addu rd, rs, rt	add unsigned	$[rd] = [rs] + [rt]$
100010 (34)	sub rd, rs, rt	subtract	$[rd] = [rs] - [rt]$
100011 (35)	subu rd, rs, rt	subtract unsigned	$[rd] = [rs] - [rt]$
100100 (36)	and rd, rs, rt	and	$[rd] = [rs] \& [rt]$
100101 (37)	or rd, rs, rt	or	$[rd] = [rs] \mid [rt]$
100110 (38)	xor rd, rs, rt	xor	$[rd] = [rs] \wedge [rt]$
100111 (39)	nor rd, rs, rt	nor	$[rd] = \sim([rs] \mid [rt])$
101010 (42)	slt rd, rs, rt	set less than	$[rs] < [rt] ? [rd] = 1 : [rd] = 0$
101011 (43)	sltu rd, rs, rt	set less than unsigned	$[rs] < [rt] ? [rd] = 1 : [rd] = 0$

- Find the complete list of instructions in the appendix

Data Types

- An ISA supports one or several data types
- LC-3 only supports 2's complement integers
 - Negative of a 2's complement binary value $X = \text{NOT}(X) + 1$
- MIPS supports
 - 2's complement integers
 - Unsigned integers
 - Floating point
- Again, tradeoffs are involved
 - What data types should be supported and what should not be?

Data Type Tradeoffs

- What is the benefit of **having more or high-level data types** in the ISA?
- What is the disadvantage?
- Think compiler/programmer vs. microarchitect
- Concept of **semantic gap**
 - Data types coupled tightly to the semantic level, or complexity of instructions
- Example: Early RISC architectures vs. Intel 432
 - Early RISC machines: Only integer data type
 - Intel 432: Object data type, capability based machine
 - VAX: Complex types, e.g., doubly-linked list

Addressing Modes

- An addressing mode is a mechanism for specifying where an operand is located
- There are five addressing modes in LC-3
 - Immediate or literal (constant)
 - The operand is in some bits of the instruction
 - Register
 - The operand is in one of R0 to R7 registers
 - Three of them are memory addressing modes
 - PC-relative
 - Indirect
 - Base+offset
- In addition, MIPS has pseudo-direct addressing (for j and jal), but does not have indirect addressing

Operate Instructions

Operate Instructions

- In **LC-3**, there are three operate instructions
 - NOT is a **unary operation** (one source operand)
 - It executes bitwise NOT
 - ADD and AND are **binary operations** (two source operands)
 - ADD is 2's complement addition
 - AND is bitwise SR1 & SR2
- In **MIPS**, there are many more
 - Most of **R-type** instructions (they are **binary operations**)
 - E.g., add, and, nor, xor...
 - **I-type** versions (i.e., with one immediate operand) of the R-type operate instructions
 - **F-type** operations, i.e., floating-point operations

NOT in LC-3

■ NOT assembly and machine code

LC-3 assembly

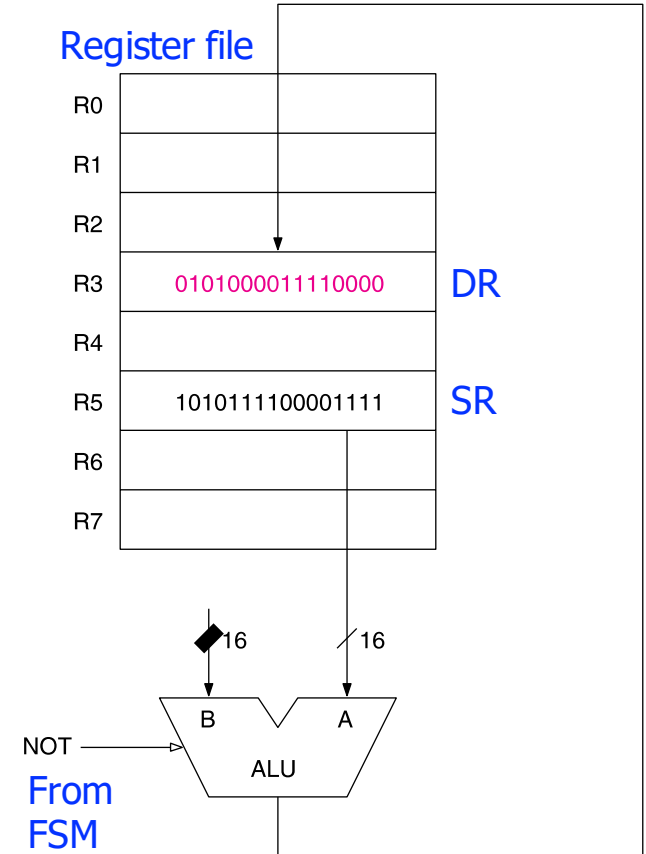
```
NOT R3, R5
```

Field Values

OP	DR	SR	
9	3	5	1 1 1 1 1 1

Machine Code

OP	DR	SR	
1 0 0 1	0 1 1	0 0 1	1 1 1 1 1 1
15	12	11 9	8 6 5 0



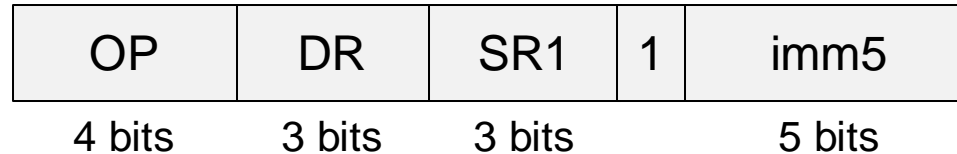
There is **no NOT in MIPS**. How is it implemented?

Operate Instructions

- We are already familiar with LC-3's ADD and AND with register mode (R-type in MIPS)
- Now let us see the versions with one literal (i.e., immediate) operand
- Subtraction is another necessary operation
 - How is it implemented in LC-3 and MIPS?

Operate Instr. with one Literal in LC-3

■ ADD and AND



- OP = operation
 - E.g., **ADD** = 0001 (same OP as the register-mode ADD)
 - $DR \leftarrow SR1 + \text{sign-extend}(\text{imm5})$
 - E.g., **AND** = 0101 (same OP as the register-mode AND)
 - $DR \leftarrow SR1 \text{ AND } \text{sign-extend}(\text{imm5})$
- SR1 = source register
- DR = destination register
- **imm5** = Literal or immediate (sign-extend to 16 bits)

ADD with one Literal in LC-3

■ ADD assembly and machine code

LC-3 assembly

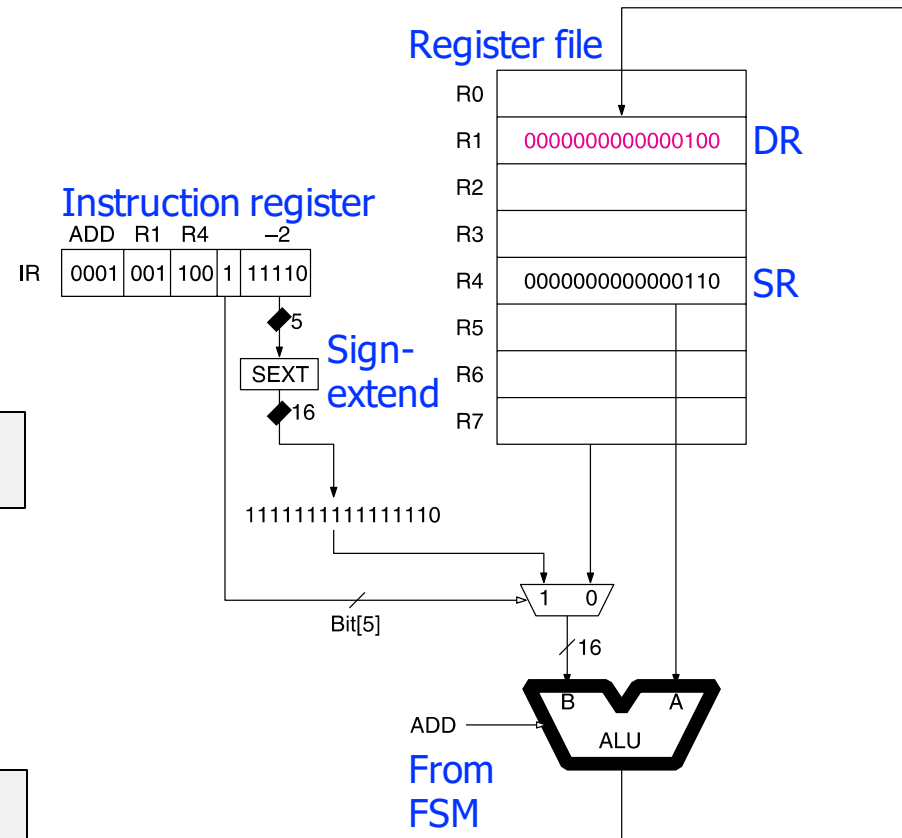
```
ADD R1, R4, #-2
```

Field Values

OP	DR	SR		imm5
1	1	4	1	-2

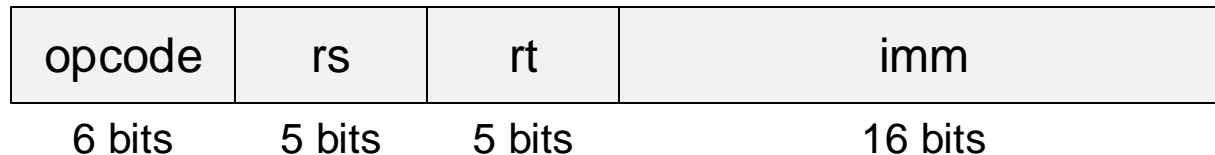
Machine Code

OP				DR		SR		imm5			
0001				001		100		1	11110		
15		12		11	9	8	6	5	4		0



Instructions with one Literal in MIPS

- I-type
 - 2 register operands and immediate
- Some operate and data movement instructions



- opcode = operation
- rs = source register
- rt =
 - destination register in some instructions (e.g., `addi`, `lw`)
 - source register in others (e.g., `sw`)
- imm = Literal or immediate

Add with one Literal in MIPS

■ Add immediate

MIPS assembly

```
addi $s0, $s1, 5
```

Field Values

op	rs	rt	imm
0	17	16	5

$rt \leftarrow rs + \text{sign-extend}(\text{imm})$

Machine Code

op	rs	rt	imm
001000	10001	10010	0000 0000 0000 0101

0x22300005

Subtract in LC-3

■ MIPS assembly

High-level code

```
a = b + c - d;
```

MIPS assembly

```
add    $t0, $s0, $s1  
sub     $s3, $t0, $s2
```

■ LC-3 assembly

High-level code

```
a = b + c - d;
```

LC-3 assembly

```
ADD    R2, R0, R1
```

```
NOT    R4, R3
```

```
ADD    R5, R4, #1
```

```
ADD    R6, R2, R5
```

2's
complement
of R3

■ Tradeoff in LC-3

- ❑ More instructions
- ❑ But, simpler control logic

Subtract Immediate

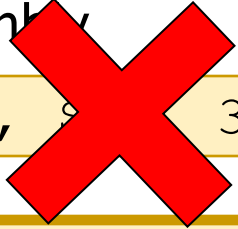
■ MIPS assembly

High-level code

```
a = b - 3;
```

MIPS assembly

```
subi $s1, $s0, 3
```



Is **subi** necessary in MIPS?

MIPS assembly

```
addi $s1, $s0, -3
```

■ LC-3

High-level code

```
a = b - 3;
```

LC-3 assembly

```
ADD R1, R0, #-3
```

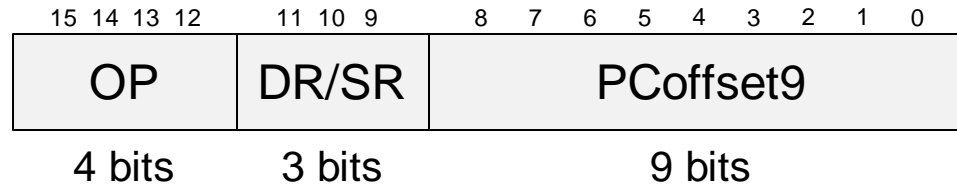
Data Movement Instructions and Addressing Modes

Data Movement Instructions

- In **LC-3**, there are seven data movement instructions
 - LD, LDR, LDI, LEA, ST, STR, STI
- Format of load and store instructions
 - Opcode (bits [15:12])
 - DR or SR (bits [11:9])
 - Address generation bits (bits [8:0])
 - Four ways to interpret bits, called **addressing modes**
 - PC-Relative Mode
 - Indirect Mode
 - Base+offset Mode
 - Immediate Mode
- In **MIPS**, there are only **Base+offset** and **immediate modes** for load and store instructions

PC-Relative Addressing Mode

■ LD (Load) and ST (Store)



- OP = opcode
 - E.g., LD = 0010
 - E.g., ST = 0011
- DR = destination register in LD
- SR = source register in ST
- LD: $DR \leftarrow \text{Memory}[PC^{\dagger} + \text{sign-extend}(\text{PCOffset9})]$
- ST: $\text{Memory}[PC^{\dagger} + \text{sign-extend}(\text{PCOffset9})] \leftarrow SR$

[†] This is the incremented PC

LD in LC-3

LD assembly and machine code

LC-3 assembly

```
LD R2, 0x1AF
```

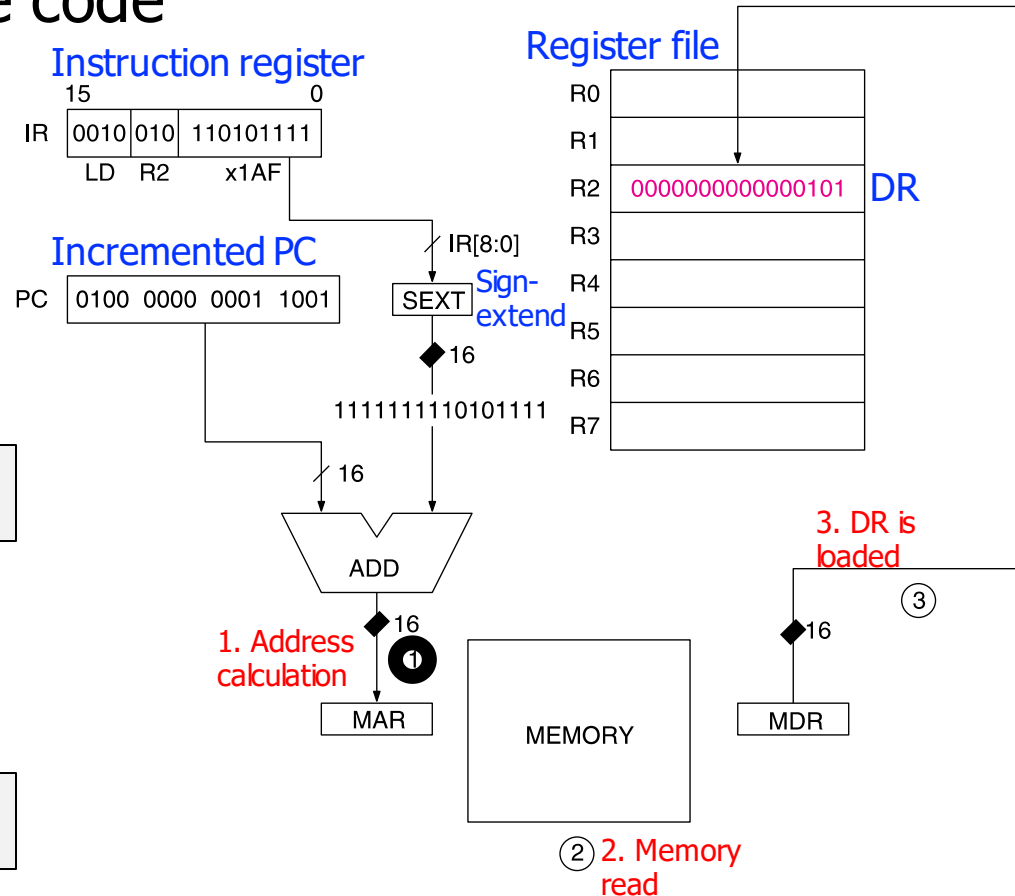
Field Values

OP	DR	PCOffset9
2	2	0x1AF

Machine Code

OP	DR	PCOffset9
0010	010	110101111

15 12 11 9 8 0

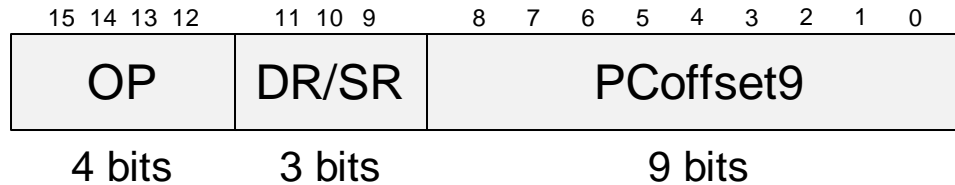


The memory address is **only +255 to -256** locations away of the **LD or ST instruction**

Limitation: The **PC-relative addressing mode** cannot address far away from the instruction

Indirect Addressing Mode

- LDI (Load Indirect) and STI (Store Indirect)



- OP = opcode
 - E.g., LDI = 1010
 - E.g., STI = 1011
- DR = destination register in LDI
- SR = source register in STI
- LDI: $DR \leftarrow \text{Memory}[\text{Memory}[PC^{\dagger} + \text{sign-extend}(\text{PCoffset9})]]$
- STI: $\text{Memory}[\text{Memory}[PC^{\dagger} + \text{sign-extend}(\text{PCoffset9})]] \leftarrow SR$

[†] This is the incremented PC

LDI in LC-3

LDI assembly and machine code

LC-3 assembly

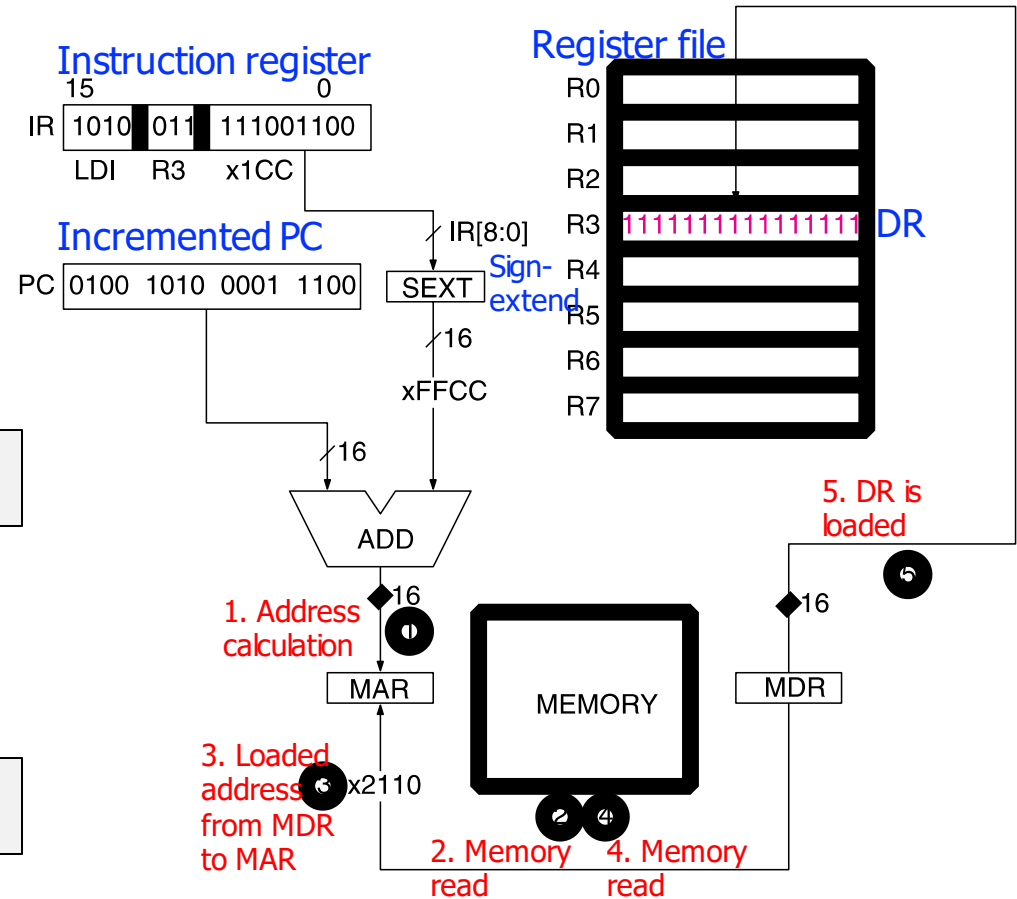
```
LDI R3, 0x1CC
```

Field Values

OP	DR	PCOffset9
A	3	0x1CC

Machine Code

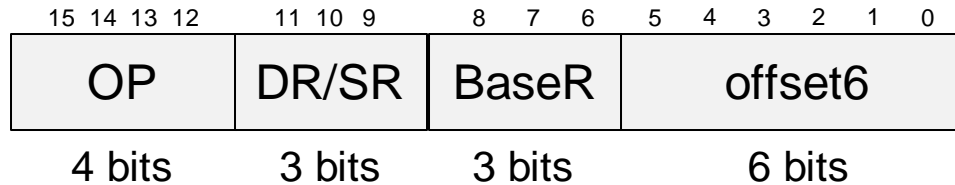
OP	DR	PCOffset9
1 0 1 0	0 1 1	1 1 1 0 0 1 1 0 0
15	12	11 9 8 7 6 5 4 3 2 1 0



Now the address of the operand can be anywhere in the memory

Base+Offset Addressing Mode

- LDR (Load Register) and STR (Store Register)



- OP = opcode
 - E.g., LDR = 0110
 - E.g., STR = 0111
- DR = destination register in LDR
- SR = source register in STR
- LDR: $DR \leftarrow \text{Memory}[\text{BaseR} + \text{sign-extend}(\text{offset6})]$
- STR: $\text{Memory}[\text{BaseR} + \text{sign-extend}(\text{offset6})] \leftarrow SR$

LDR in LC-3

■ LDR assembly and machine code

LC-3 assembly

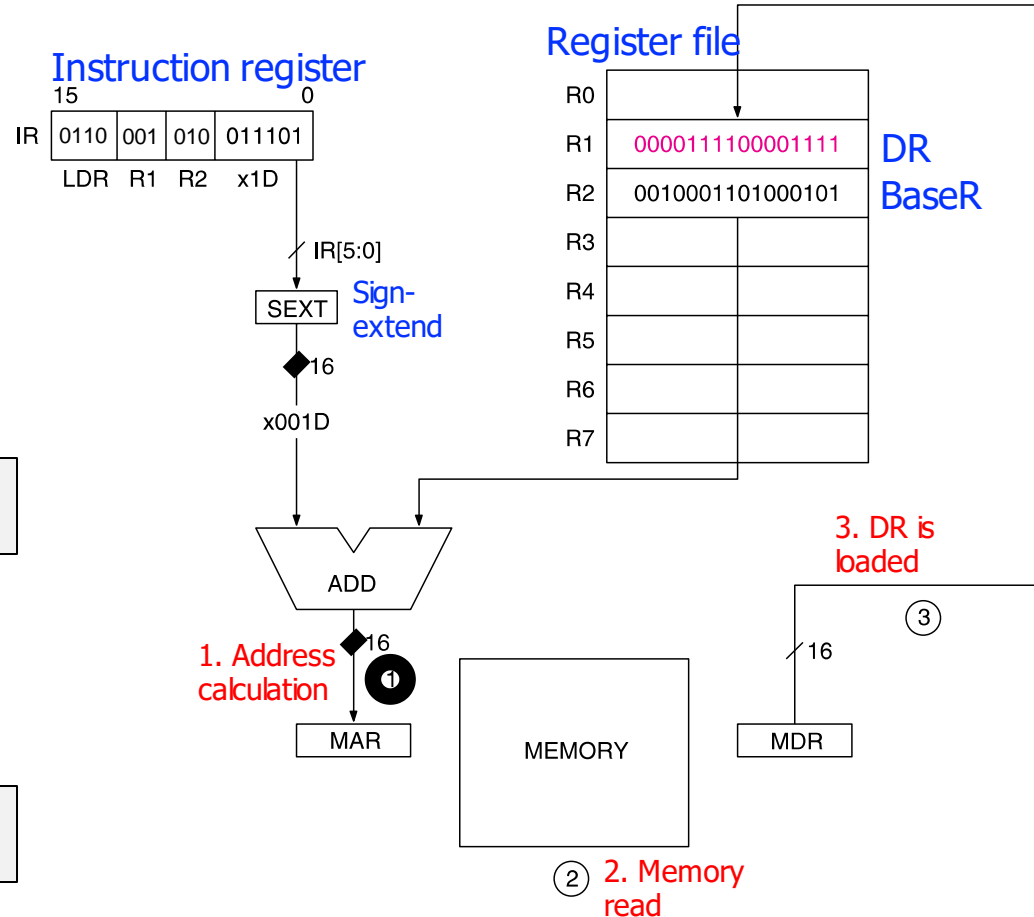
```
LDR R1, R2, 0x1D
```

Field Values

OP	DR	BaseR	offset6
6	1	2	0x1D

Machine Code

OP				DR		BaseR		offset6							
0 1 1 0				0 0 1		0 1 0		0 1 1 1 0 1							
15		12		11		9		8		6		5		0	



Again, the address of the operand can be **anywhere in the memory**

Base+Offset Addressing Mode in MIPS

- In MIPS, **lw** and **sw** use base+offset mode (or **base addressing mode**)

High-level code

```
A[2] = a;
```

MIPS assembly

```
sw    $s3, 8($s0)
```

Memory[\$s0 + 8] ← \$s3

Field Values

op	rs	rt	imm
43	16	19	8

- imm** is the 16-bit offset, which is **sign-extended to 32 bits**

An Example Program in MIPS and LC-3

High-level code

```
a      = A[0];  
c      = a + b - 5;  
B[0]   = c;
```

MIPS registers

```
A = $s0  
b = $s2  
B = $s1
```

LC-3 registers

```
A = R0  
b = R2  
B = R1
```

MIPS assembly

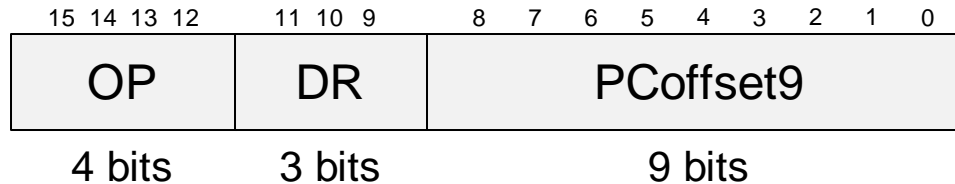
```
lw      $t0, 0($s0)  
add     $t1, $t0, $s2  
addi    $t2, $t1, -5  
sw      $t2, 0($s1)
```

LC-3 assembly

```
LDR     R5, R0, #0  
ADD     R6, R5, R2  
ADD     R7, R6, #-5  
STR     R7, R1, #0
```

Immediate Addressing Mode

■ LEA (Load Effective Address)



- OP = 1110
- DR = destination register
- LEA: $DR \leftarrow PC^{\dagger} + \text{sign-extend}(\text{PCoffset9})$

What is the **difference from PC-Relative** addressing mode?

Answer: Instructions with **PC-Relative** mode **access memory**, but **LEA does not** → Hence the name *Load Effective Address*

[†] This is the incremented PC

LEA in LC-3

LEA assembly and machine code

LC-3 assembly

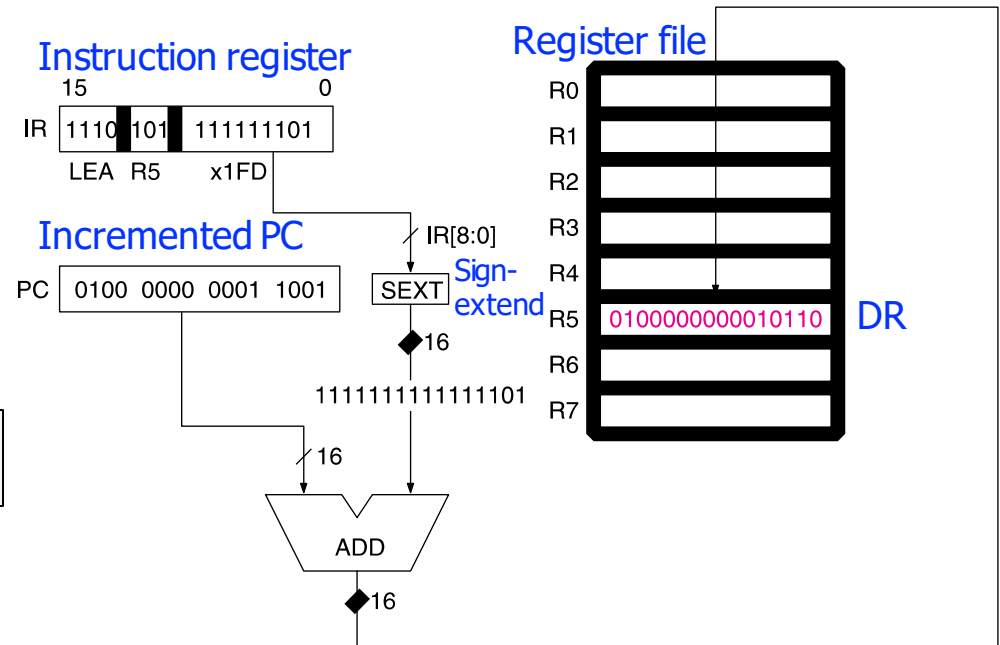
```
LEA R5, #-3
```

Field Values

OP	DR	PCOffset9
E	5	0x1FD

Machine Code

OP	DR	PCOffset9
1 1 1 0	1 0 1	1 1 1 1 1 1 1 0 1
15	12	11 9 8 0



Immediate Addressing Mode in MIPS

- In MIPS, **lui** (load upper immediate) loads a 16-bit immediate into the upper half of a register and sets the lower half to 0
- It is used to assign 32-bit constants to a register

High-level code

```
a = 0x6d5e4f3c;
```

MIPS assembly

```
# $s0 = a  
lui    $s0, 0x6d5e  
ori    $s0, 0x4f3c
```

Addressing Example in LC-3

- What is the final value of R3?

P&P, Chapter 5.3.5

Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x30F6	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0	1	R1 ← PC - 3
x30F7	0	0	0	1	0	1	0	0	0	1	1	0	1	1	1	0	R2 ← R1 + 14
x30F8	0	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1	M[x30F4] ← R2
x30F9	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 ← 0
x30FA	0	0	0	1	0	1	0	0	1	0	1	0	0	1	0	1	R2 ← R2 + 5
x30FB	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1	0	M[R1 + 14] ← R2
x30FC	1	0	1	0	0	1	1	1	1	1	1	1	0	1	1	1	R3 ← M[M[x30F4]]

Addressing Example in LC-3

- What is the final value of R3?

P&P, Chapter 5.3.5

Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x30F6	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	R1 = PC - 3 = 0x30F7 - 3 = 0x30F4
x30F7	0	0	0	1	0	1	0	0	0	1	1	0	1	0	1	1	R2 = R1 + 14 = 0x30F4 + 14 = 0x3102
x30F8	0	1	1	1	0	1	0	1	1	1	1	1	1	0	1	1	M[PC - 5] = M[0x030F4] = 0x3102
x30F9	1	0	1	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 = 0
x30FA	0	0	1	1	0	1	0	0	1	0	1	1	0	1	0	1	R2 = R2 + 5 = 5
x30FB	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	M[R1 + 14] = M[0x30F4 + 14] = M[0x3102] = 5
x30FC	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	R3 = M[M[PC - 9]] = M[M[0x30FD - 9]] = M[M[0x30F4]] = M[0x3102] = 5

- The final value of **R3 is 5**

Control Flow Instructions

Control Flow Instructions

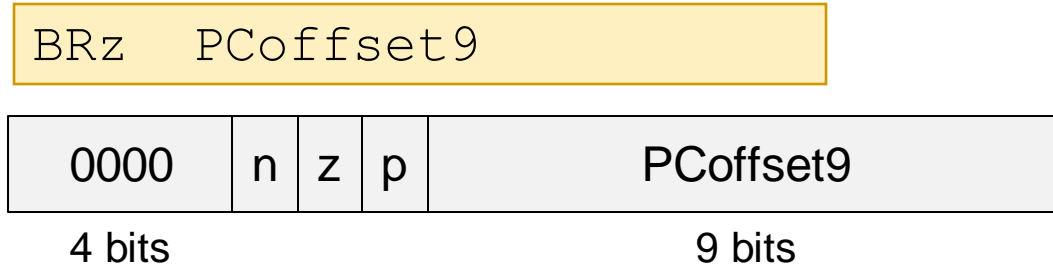
- Allow a program to execute **out of sequence**
- Conditional branches and jumps
 - **Conditional branches** are used to **make decisions**
 - E.g., if-else statement
 - In LC-3, three **condition codes** are used
 - **Jumps** are used to implement
 - **Loops**
 - **Function calls**
 - **JMP** in LC-3 and **j** in MIPS

Condition Codes in LC-3

- Each time one GPR (R0-R7) is written, **three single-bit registers** are updated
- Each of these **condition codes** are either set (set to 1) or cleared (set to 0)
 - If the written value is **negative**
 - **N** is set, Z and P are cleared
 - If the written value is **zero**
 - **Z** is set, N and P are cleared
 - If the written value is **positive**
 - **P** is set, N and Z are cleared
- x86 and SPARC are examples of ISAs that use condition codes

Conditional Branches in LC-3

■ BRz (Branch if Zero)



- n, z, p = **which condition code is tested** (N, Z, and/or P)
 - n, z, p : instruction bits to identify the condition codes to be tested
 - N, Z, P : values of the corresponding condition codes
- $PCoffset9$ = immediate or constant value
- if $((n \text{ AND } N) \text{ OR } (p \text{ AND } P) \text{ OR } (z \text{ AND } Z))$
 - then $PC \leftarrow PC^{\dagger} + \text{sign-extend}(PCoffset9)$
- Variations: BRn, BRz, BRp, BRzp, BRnp, BRnz, BRnzp

[†] This is the incremented PC

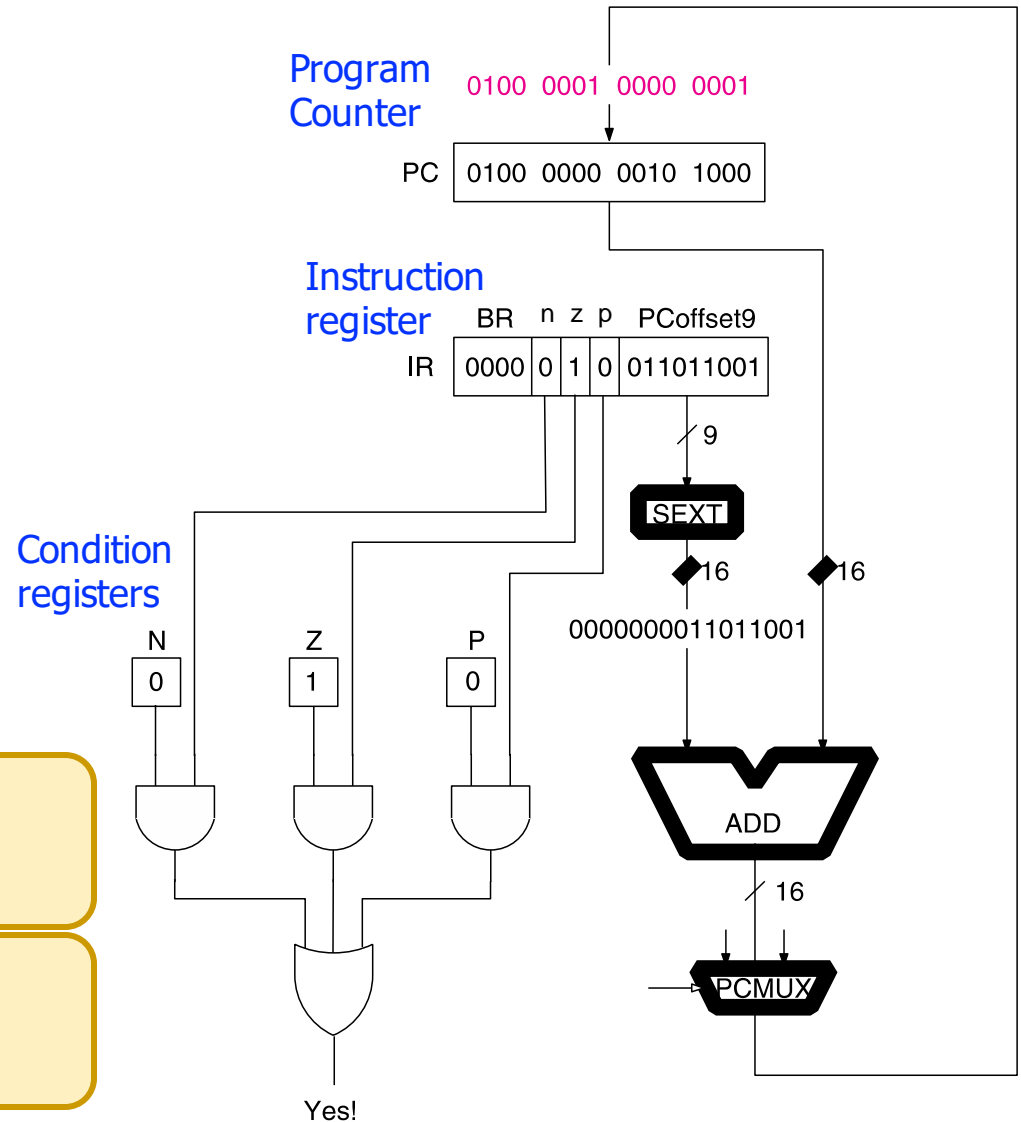
Conditional Branches in LC-3

■ BRz

BRz 0x0D9

What if $n = z = p = 1$?*
(i.e., BRnzp)

And what if $n = z = p = 0$?

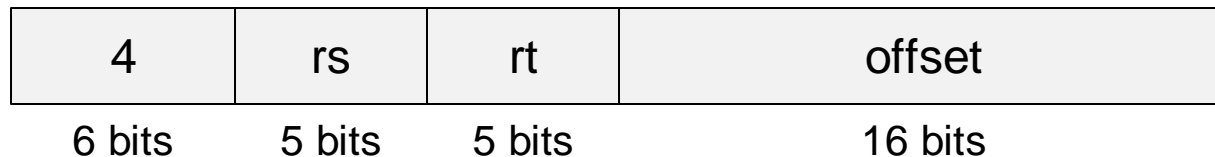


*n, z, p are the instruction bits to identify the condition codes to be tested

Conditional Branches in MIPS

■ beq (Branch if Equal)

```
beq  $s0, $s1, offset
```



- 4 = opcode
- rs, rt = source registers
- offset = immediate or constant value
- if $rs == rt$
 - then $PC \leftarrow PC^{\dagger} + \text{sign-extend}(\text{offset}) * 4$
- Variations: beq, bne, blez, bgtz

[†] This is the incremented PC

Branch If Equal in MIPS and LC-3

MIPS assembly

```
beq  $s0, $s1, offset
```

LC-3 assembly

```
NOT  R2, R1
```

```
ADD  R3, R2, #1
```

```
ADD  R4, R3, R0
```

```
BRz  offset
```

**Subtract
(R0 - R1)**

- This is an example of **tradeoff** in the instruction set
 - The same functionality requires **more instructions in LC-3**
 - But, the **control logic** requires **more complexity in MIPS**

What We Learned

- The von Neumann model
 - LC-3: An example von Neumann machine
- Instruction Set Architectures: LC-3 and MIPS
 - Operate instructions
 - Data movement instructions
 - Control instructions
- Instruction formats
- Addressing modes

Problem
Algorithm
Program/Language
System Software
SW/HW Interface
Micro-architecture
Logic
Devices
Electrons

Digital Design & Computer Arch.

Lecture 9: Von Neumann Model & Instruction Set Architectures

Prof. Onur Mutlu

ETH Zürich

Spring 2021

25 March 2021