Digital Design & Computer Arch.

Lecture 10a: Instruction Set Architectures II

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ETH Zürich

Spring 2021

26 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=kgiZlSOcGFM (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, ISA, LC-3, and MIPS
    - P&P, Chapters 4, 5
    - H&H, Chapter 6 (until 6.5)
    - 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

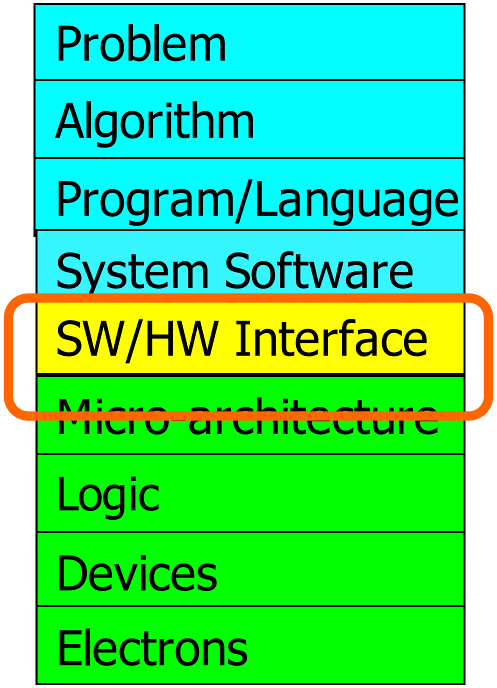
Recall: What Will We Learn Today?

- Basic elements of a computer & 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

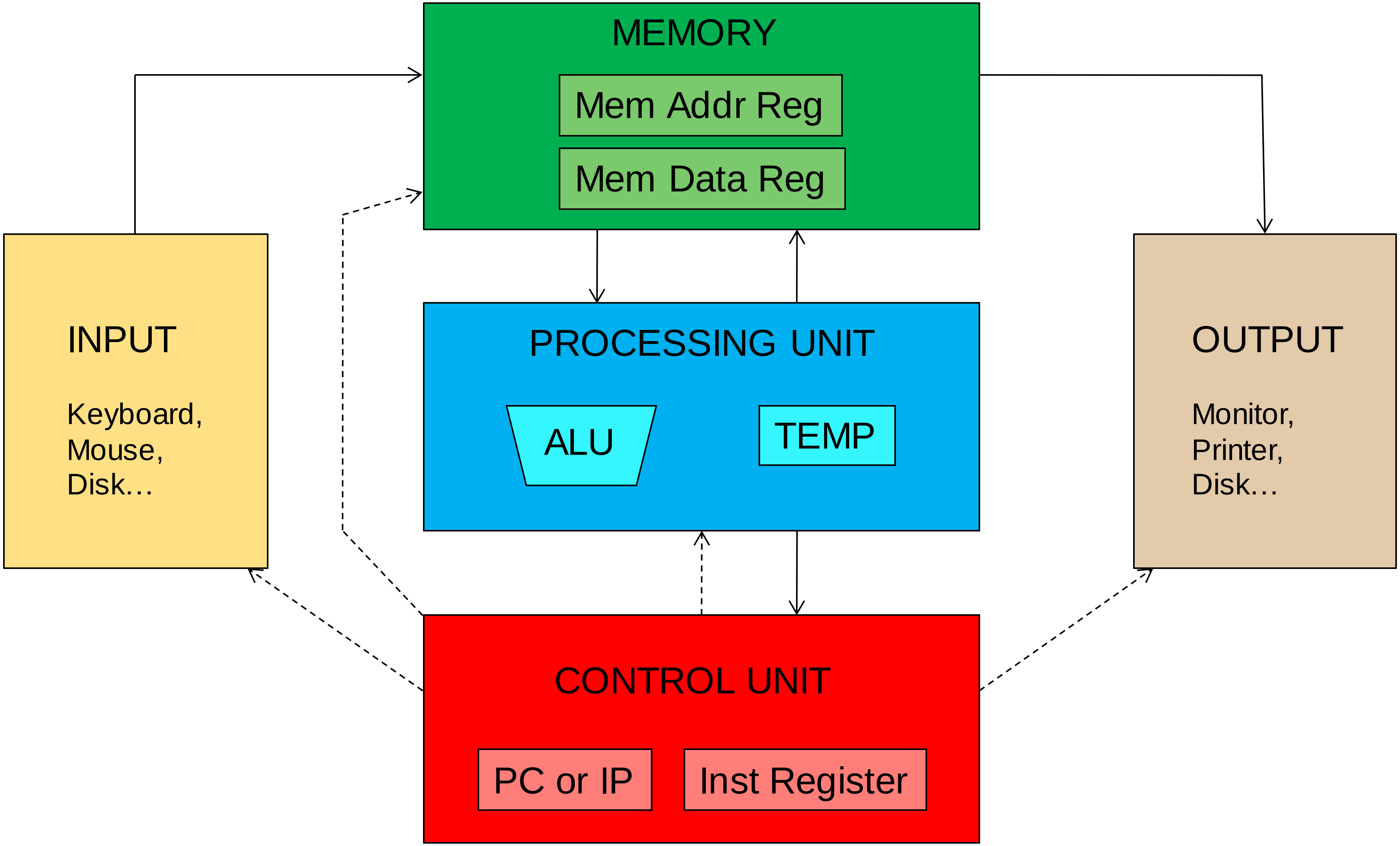
- Instruction formats

- Addressing modes



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

Recall: The von Neumann Model



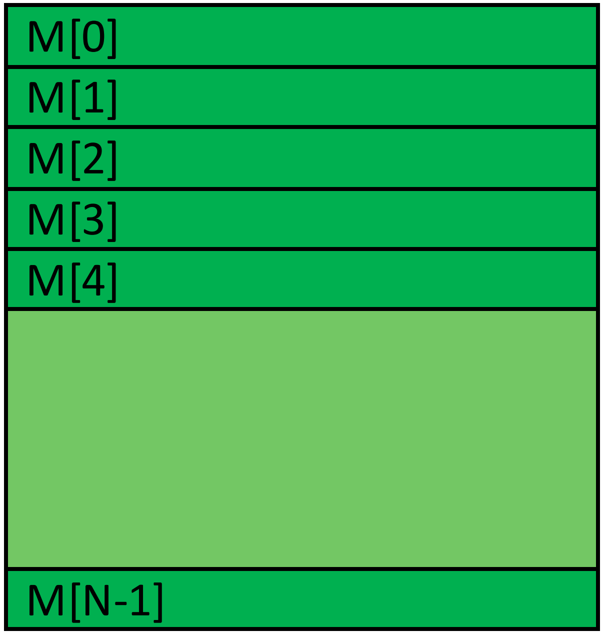
Recall: von Neumann Model: Two Key Properties

- 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

Recall: Programmer Visible (Architectural) State



Memory

array of storage locations
indexed by an address

Registers

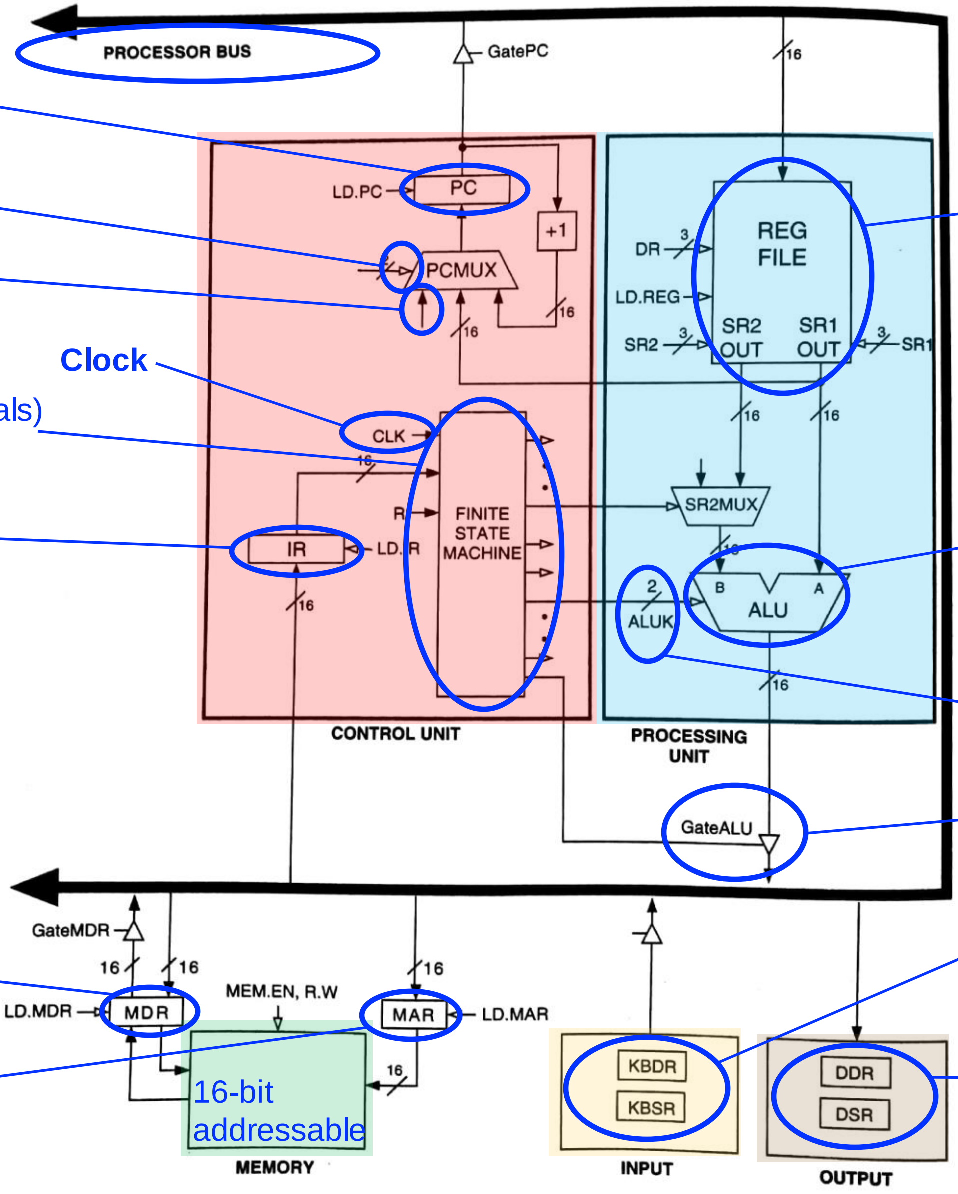
- given special names in the ISA (as opposed to addresses)
- general vs. special purpose

Program Counter

memory address
of the current (or next) instruction

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

Recall: LC-3: A von Neumann Machine



Program Counter

Control signals

Data

Finite State Machine (for Generating Control Signals)

Clock

Instruction Register

8 General Purpose Registers (GPR)

ALU: 2 inputs, 1 output

ALU operation

GateALU

Memory Data Register

Memory Address Register

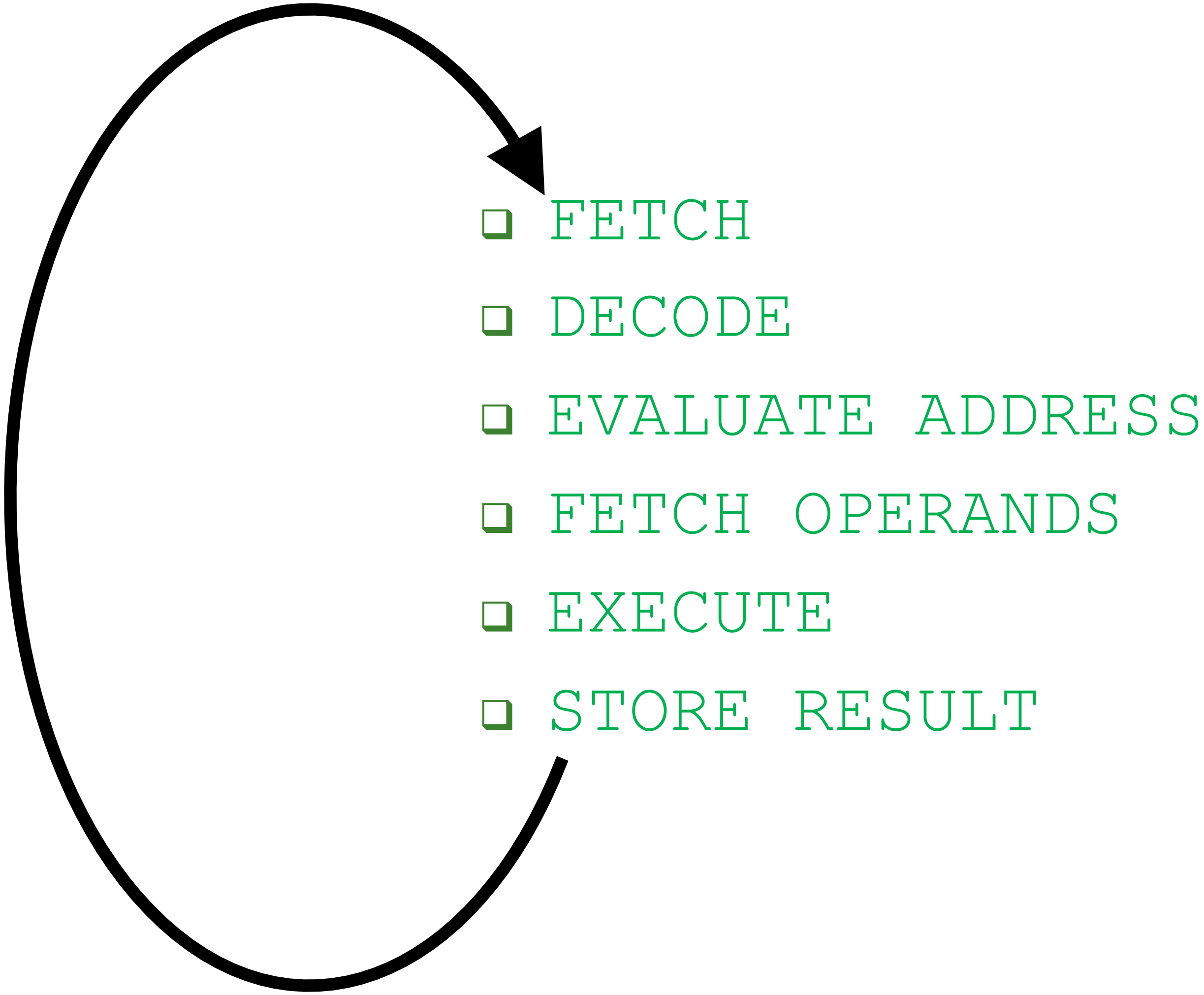
16-bit addressable

Keyboard
KBDR (data), KBSR (status)

Monitor
DDR (data), DSR (status)

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

Recall: The Instruction (Processing) Cycle



- FETCH
- DECODE
- EVALUATE ADDRESS
- FETCH OPERANDS
- EXECUTE
- STORE RESULT

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

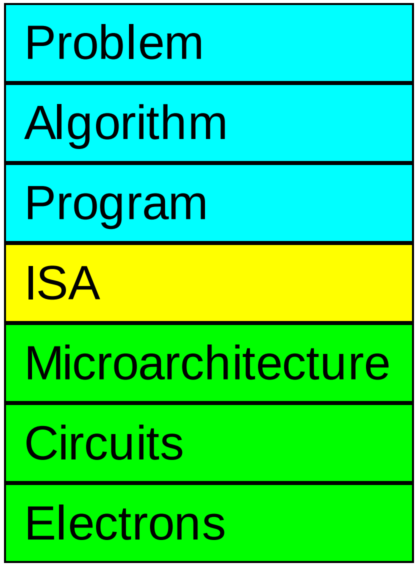
OP	DR	BaseR	offset6
6	3	0	4

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: 8 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

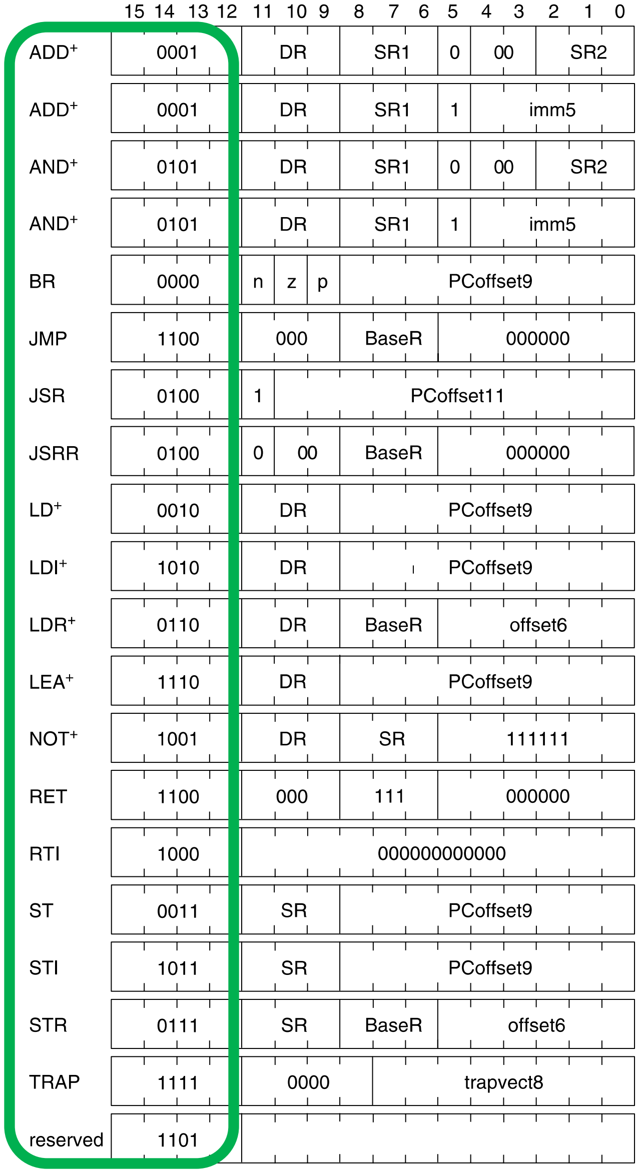
Opcodes

- A large or small set 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

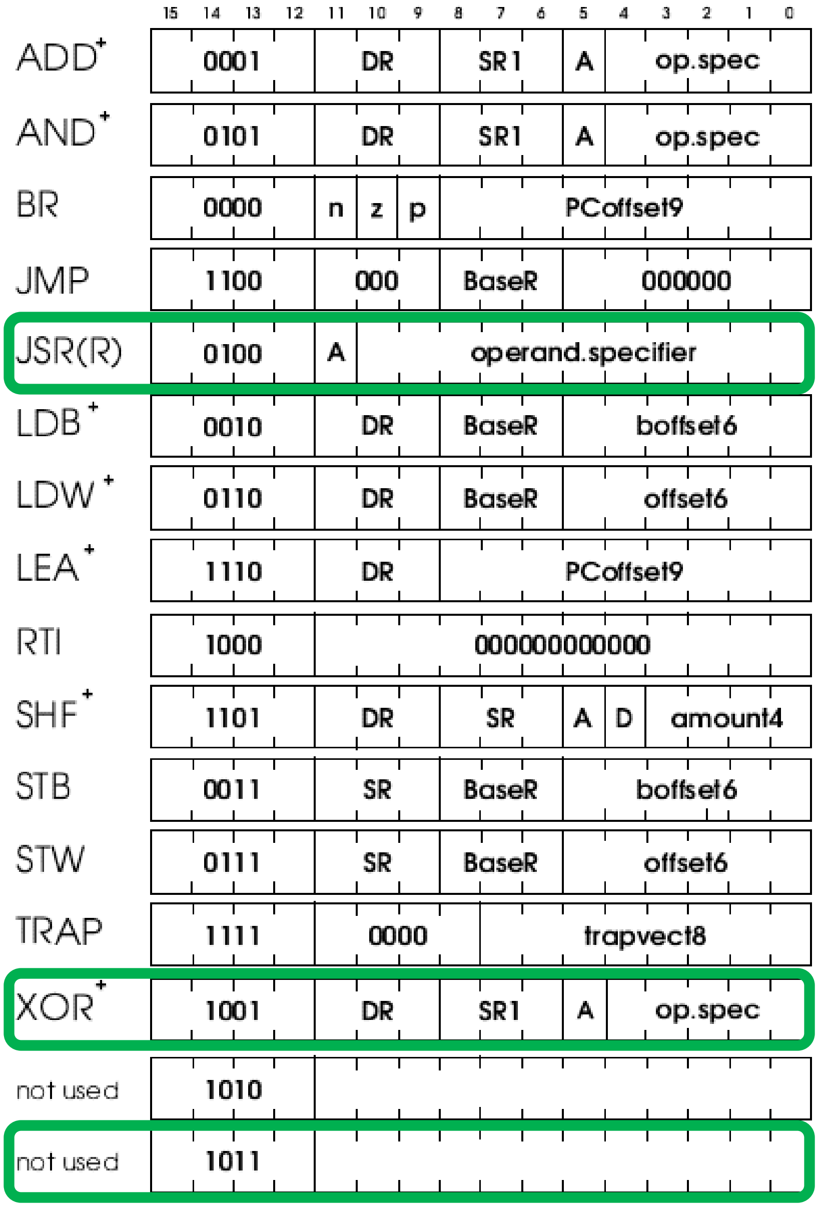
Opcodes in LC-3



	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

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															

MIPS Instruction Types

0	rs	rt	rd	shamt	funct
6-bit	5-bit	5-bit	5-bit	5-bit	6-bit

R-type

opcode	rs	rt	immediate
6-bit	5-bit	5-bit	16-bit

I-type

opcode	immediate
6-bit	26-bit

J-type

Funct in MIPS R-Type Instructions (I)

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

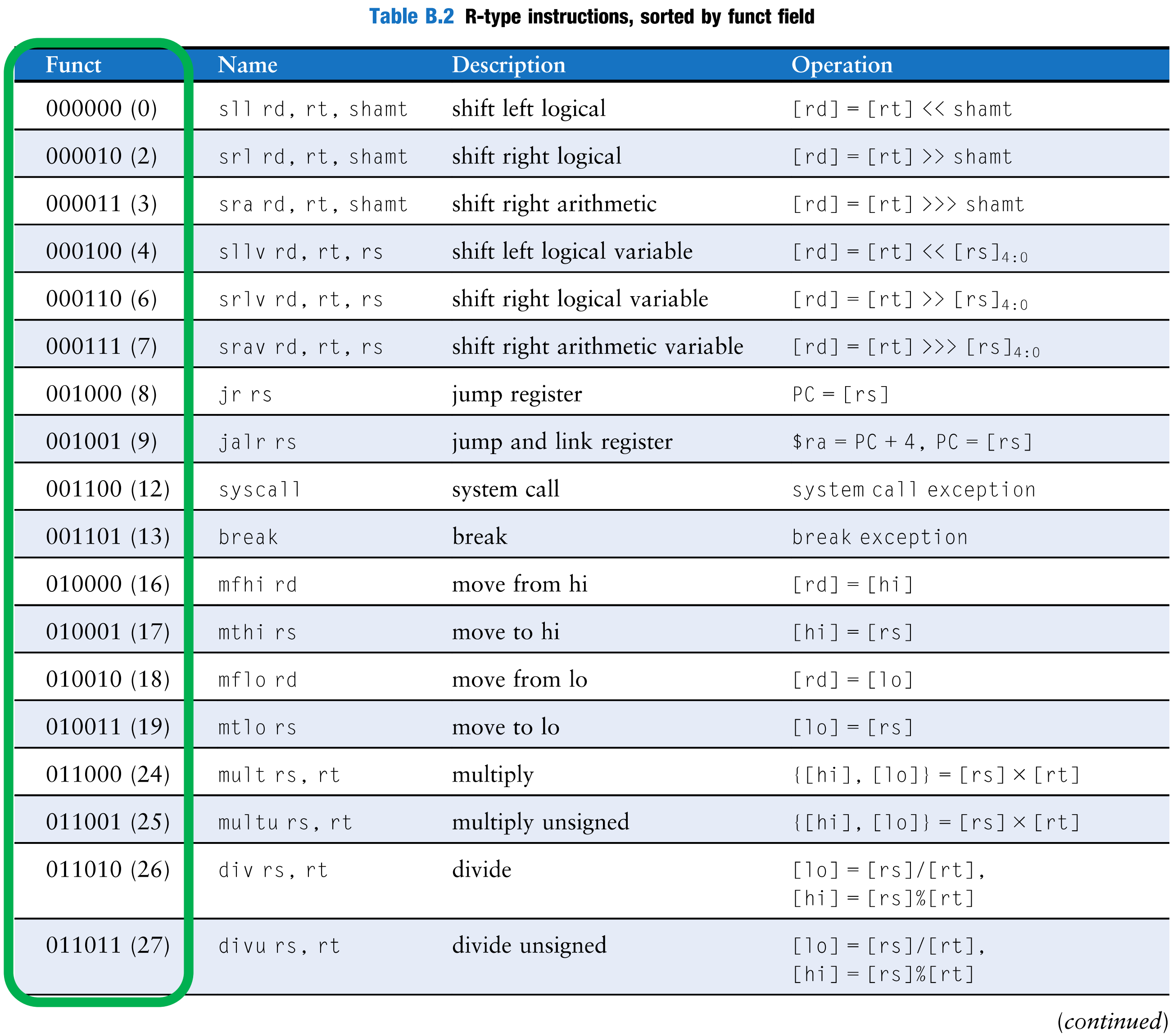


Table B.2 **R-type instructions, sorted by funct field**

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)

Harris and Harris, Appendix B: MIPS Instructions

Funct in MIPS R-Type Instructions (II)

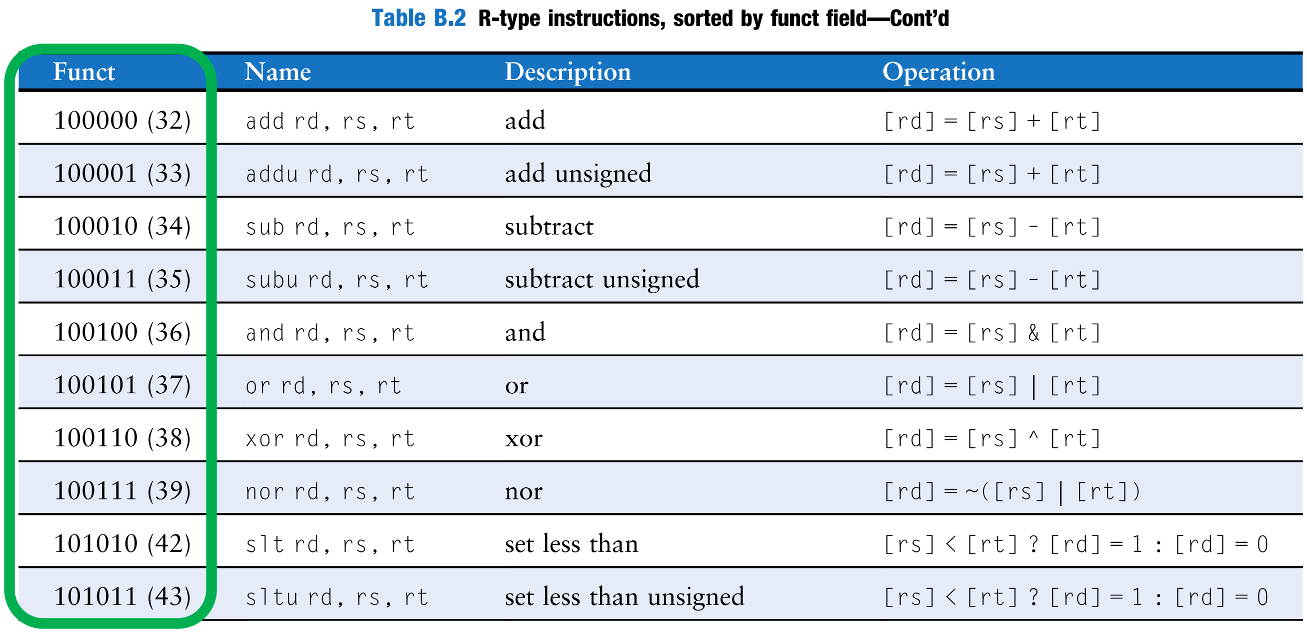


Table B.2 **R-type instructions, sorted by funct field—Cont'd**

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] | [rt]`
100110 (38)	`xor rd, rs, rt`	xor	`[rd] = [rs] ^ [rt]`
100111 (39)	`nor rd, rs, rt`	nor	`[rd] = ~([rs] | [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 H&H Appendix B

Harris and Harris, Appendix B: MIPS Instructions

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 = 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?

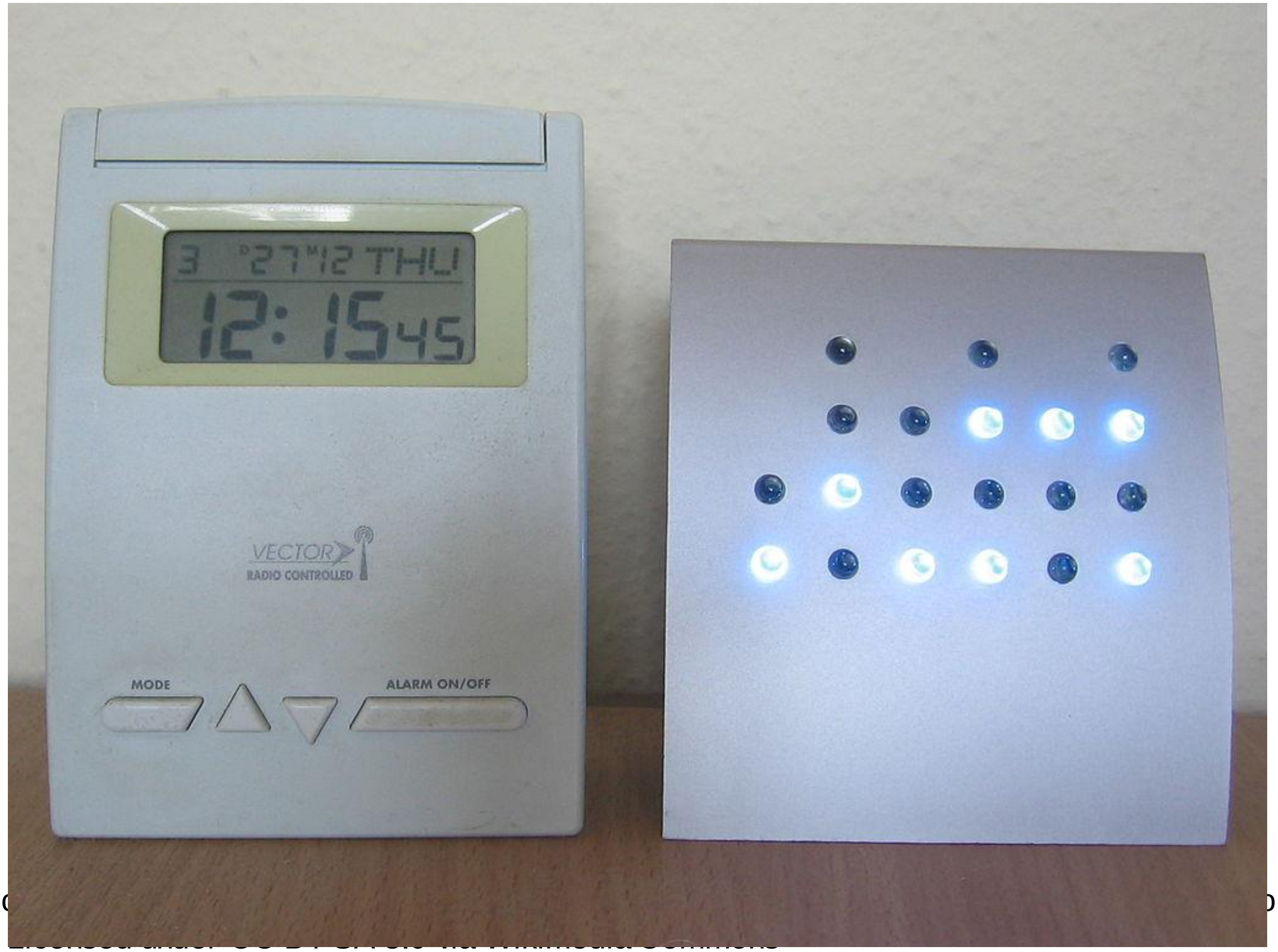
- Think compiler/programmer vs. microarchitect

- Concept of semantic gap
  - Data types coupled tightly to the semantic level, or complexity of instructions → how close are instrs. to high-level languages

- 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

Aside: An Example: **B**inary**C**oded**D**ecimal

- Each decimal digit is encoded with a fixed number of bits



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"Digital-BCD-clock" by Julo - Own work. Licensed under Public Domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Digital-BCD-clock.jpg#mediaviewer/File:Digital-BCD-clock.jpg

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 memory addressing modes
    - PC-relative
    - Indirect
    - Base+offset

- MIPS has pseudo-direct addressing (for j and jal), additionally, but does **not** have indirect addressing

Why Have Different Addressing Modes?

- Another example of programmer vs. microarchitect tradeoff

- Advantage of more addressing modes:
  - Enables better mapping of high-level programming constructs to hardware
    - some accesses are better expressed with a different mode → reduced number of instructions and code size
      - Array indexing
      - Pointer-based accesses (indirection)
      - Sparse matrix accesses

- Disadvantages:
  - More work for the compiler
  - More work for the microarchitect

Many Tradeoffs in ISA Design...

- Execution model – sequencing model and processing style
- Instruction length
- Instruction format
- Instruction types
- Instruction complexity vs. simplicity
- Data types
- Number of registers
- Addressing mode types and count
- Memory organization (address space, addressability, endianness, …)
- Memory access restrictions and permissions
- Support for multiple instructions to execute in parallel?
- …

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

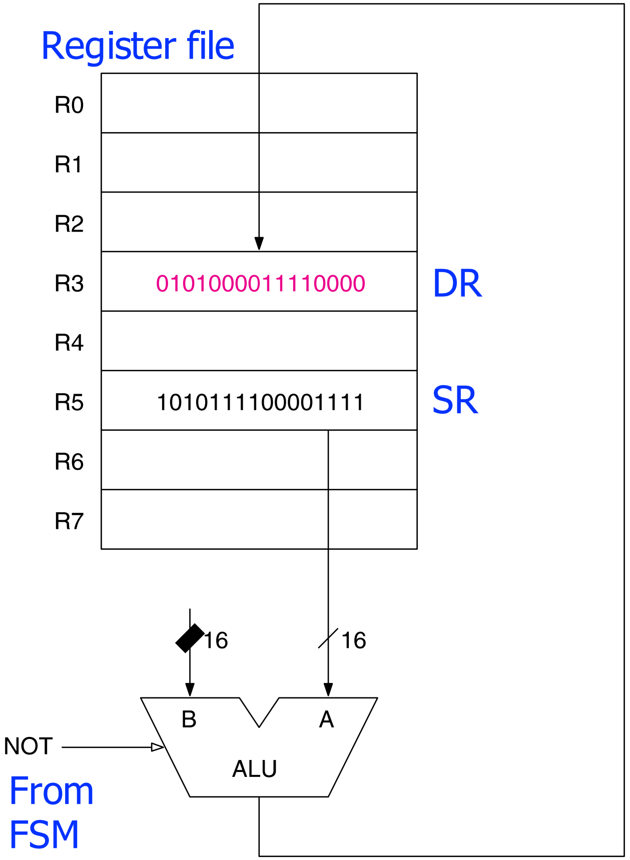
```
NOT  R3, R5
```

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	DR	SR1	1	imm5
4 bits	3 bits	3 bits		5 bits

- OP = operation
  - E.g., ADD = 0001 (same OP as the register-mode ADD)
    - DR ← SR1 + sign-extend(imm5)
  - E.g., AND = 0101 (same OP as the register-mode AND)
    - DR ← SR1 AND sign-extend(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

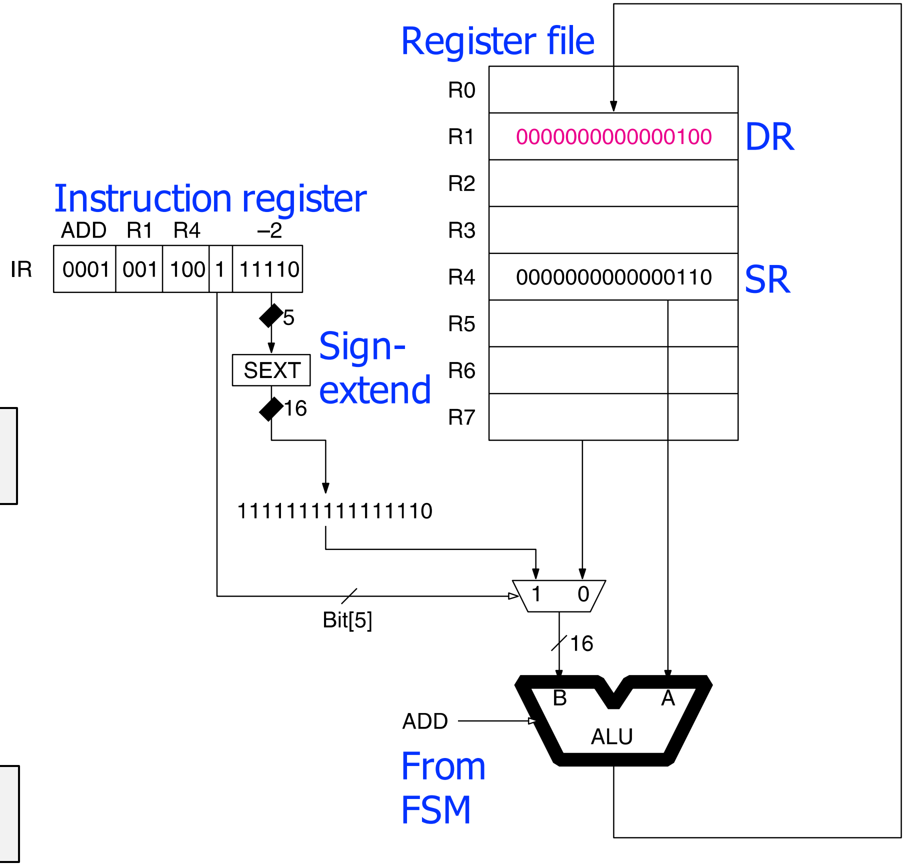
```
ADD R1, R4, #-2
```

Field Values

OP	DR	SR		imm5
1	1	4	1	-2

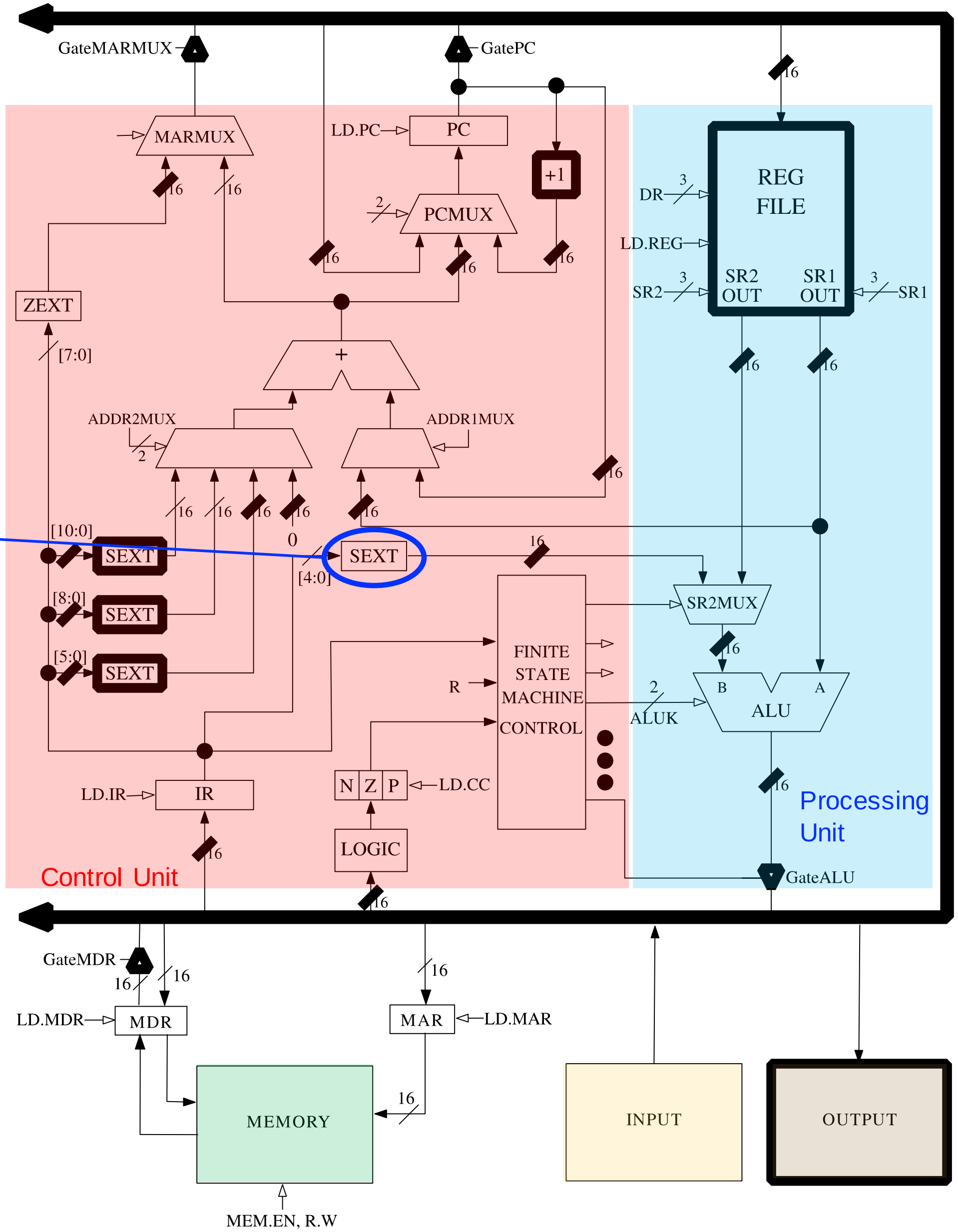
Machine Code

OP	DR	SR		imm5
0 0 0 1	0 0 1	1 0 0	1	1 1 1 1 0
15 12	11 9	8 6	5	4 0



The LC-3 Data Path

Sign extension (Operand)



Processing Unit

Control Unit

Instructions with one Literal in MIPS

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

opcode	rs	rt	imm
6 bits	5 bits	5 bits	16 bits

  - 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 ← rs + sign-extend(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)

15 14 13 12	11 10 9	8 7 6 5 4 3 2 1 0
OP	DR/SR	PCoffset9
4 bits	3 bits	9 bits

- OP = opcode
  - E.g., LD = 0010
  - E.g., ST = 0011

- DR = destination register in LD
- SR = source register in ST

- LD: DR ← Memory[PC[†] + sign-extend(PCoffset9)]

- ST: Memory[PC[†] + sign-extend(PCoffset9)] ← SR

[†] This is the incremented PC

LD in LC-3

- LD assembly and machine code

LC-3 assembly

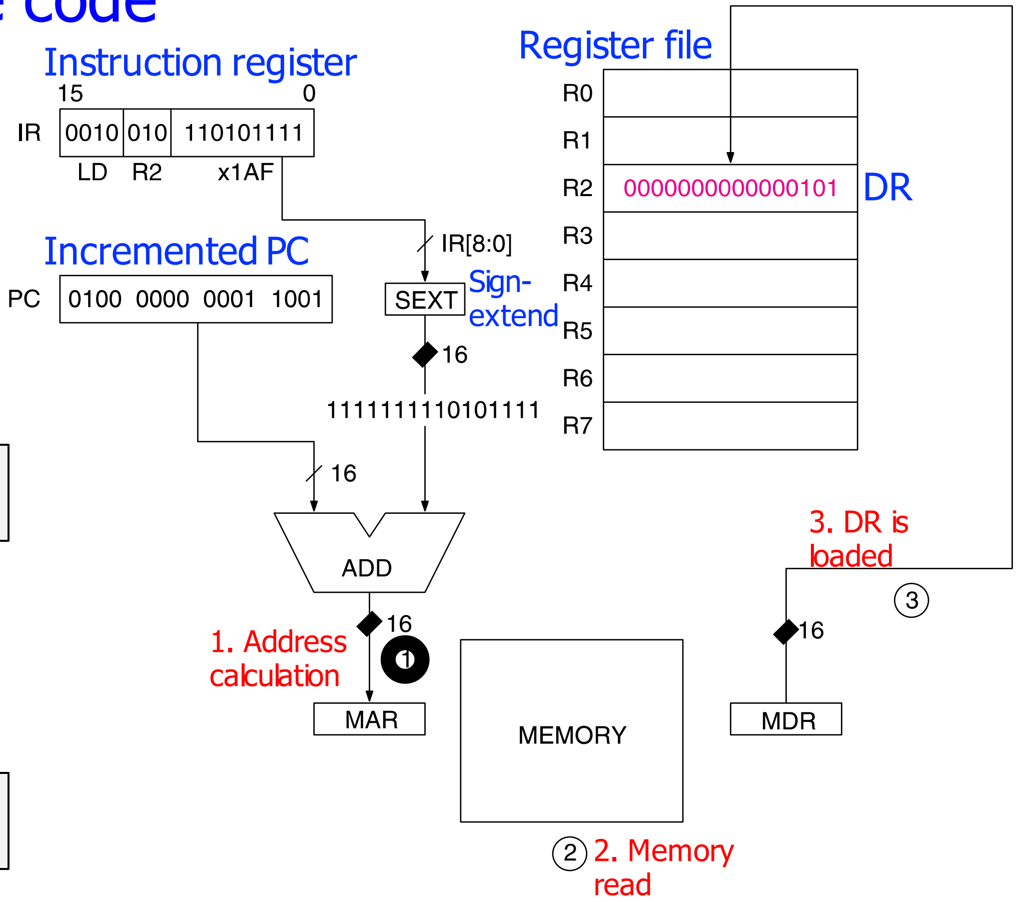
```
LD R2, 0x1AF
```

Field Values

OP	DR	PCoffset9
2	2	0x1AF

Machine Code

OP	DR	PCoffset9
0 0 1 0	0 1 0	1 1 0 1 0 1 1 1 1
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)

15 14 13 12	11 10 9	8 7 6 5 4 3 2 1 0
OP	DR/SR	PCoffset9
4 bits	3 bits	9 bits

  - OP = opcode
    - E.g., LDI = 1010
    - E.g., STI = 1011
  - DR = destination register in LDI
  - SR = source register in STI
  - LDI: DR ← Memory[Memory[PC[†] + sign-extend(PCoffset9)]]
  - STI: Memory[Memory[PC[†] + sign-extend(PCoffset9)]] ← SR

[†] This is the incremented PC

LDI in LC-3

- LDI assembly and machine code

LC-3 assembly

```
LDI R3, 0x1CC
```

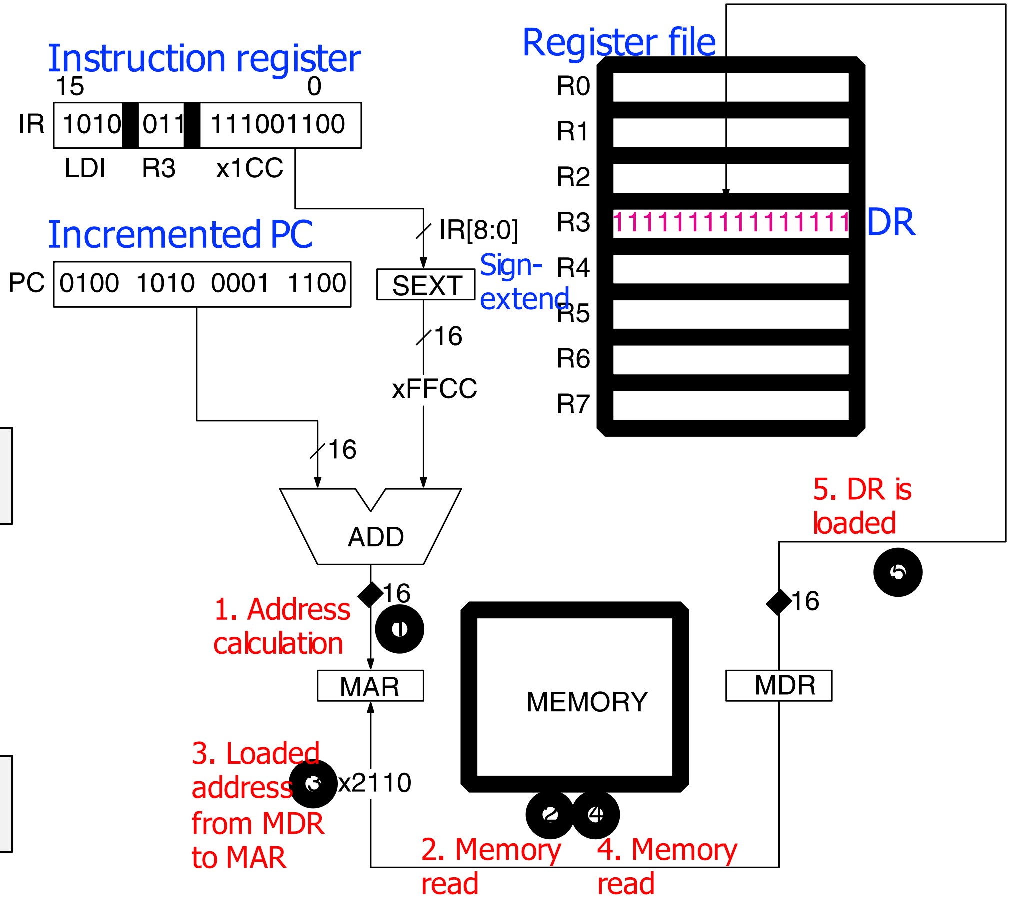
Field Values

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 0



1. Address calculation

2. Memory read

3. Loaded address from MDR to MAR

4. Memory read

5. DR is loaded

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

Base+Offset Addressing Mode

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

15 14 13 12	11 10 9	8 7 6	5 4 3 2 1 0
OP	DR/SR	BaseR	offset6
4 bits	3 bits	3 bits	6 bits

  - OP = opcode
    - E.g., LDR = 0110
    - E.g., STR = 0111

  - DR = destination register in LDR
  - SR = source register in STR

  - LDR: DR ← Memory[BaseR + sign-extend(offset6)]

  - STR: Memory[BaseR + sign-extend(offset6)] ← SR

LDR in LC-3

- LDR assembly and machine code

LC-3 assembly

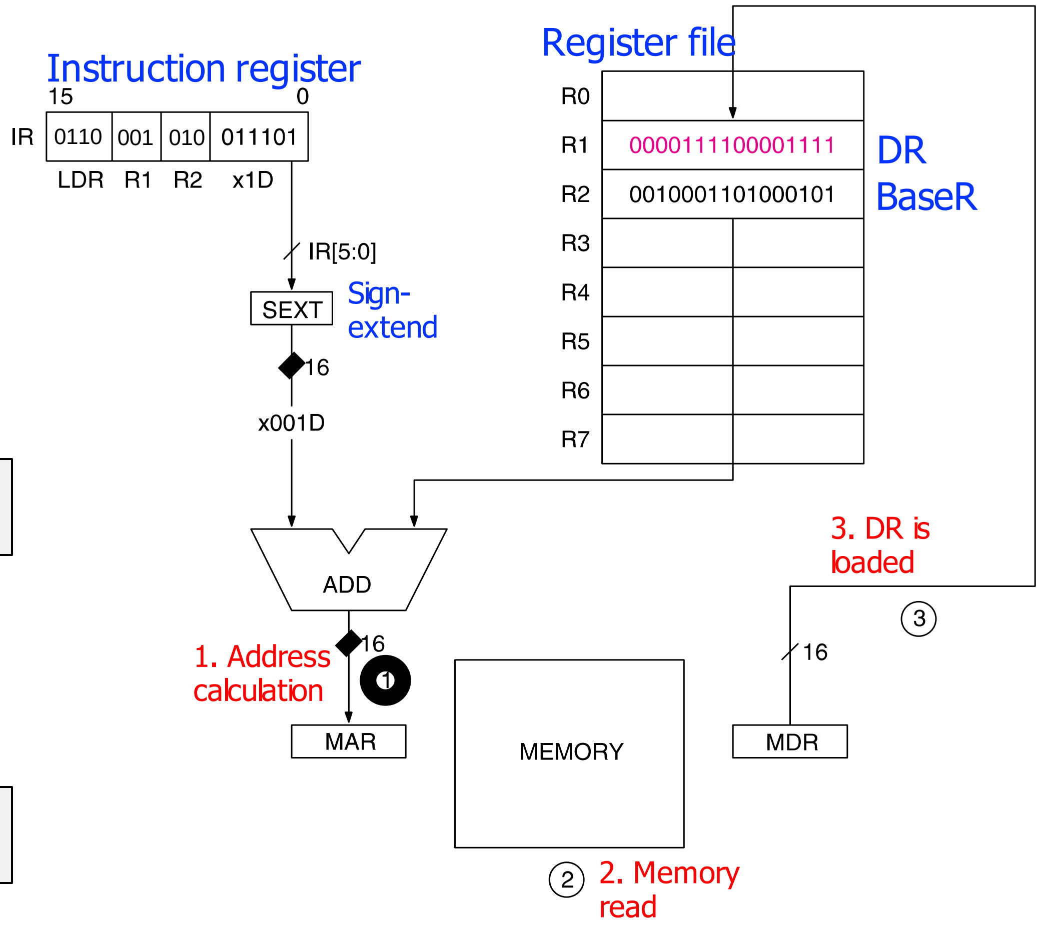
```
LDR R1, R2, 0x1D
```

Field Values

OP	DR	BaseR	offset6
6	1	2	0x1D

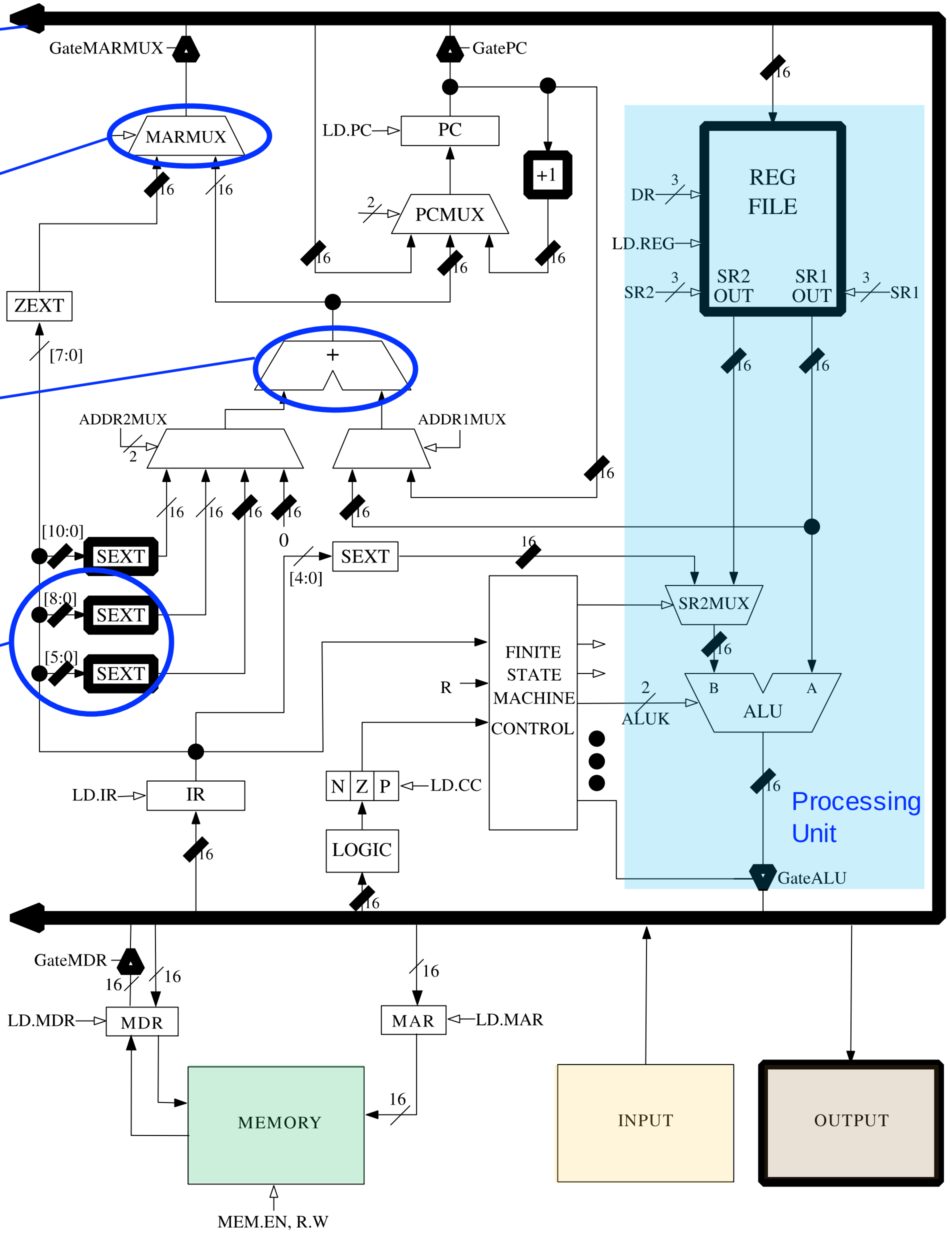
Machine Code

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

The LC-3 Data Path



Global bus

MAR Multiplexer

Adder

Sign extension (Address)

Processing Unit

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)

15 14 13 12	11 10 9	8 7 6 5 4 3 2 1 0
OP	DR	PCoffset9
4 bits	3 bits	9 bits

- OP = 1110
- DR = destination register
- LEA: DR ← PC[†] + sign-extend(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

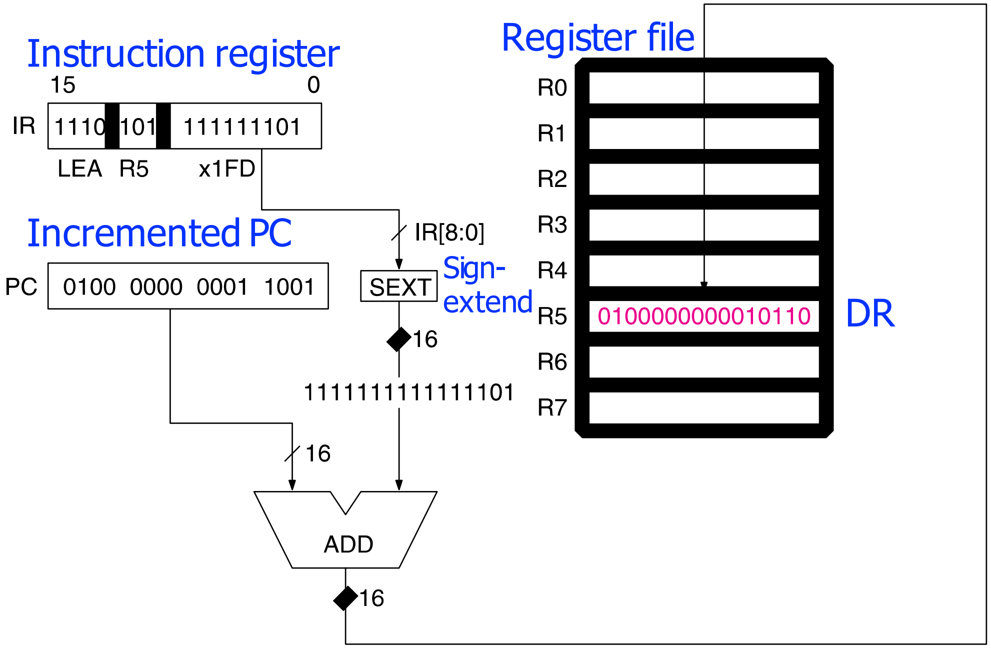
```
LEA R5, #-3
```

Field Values

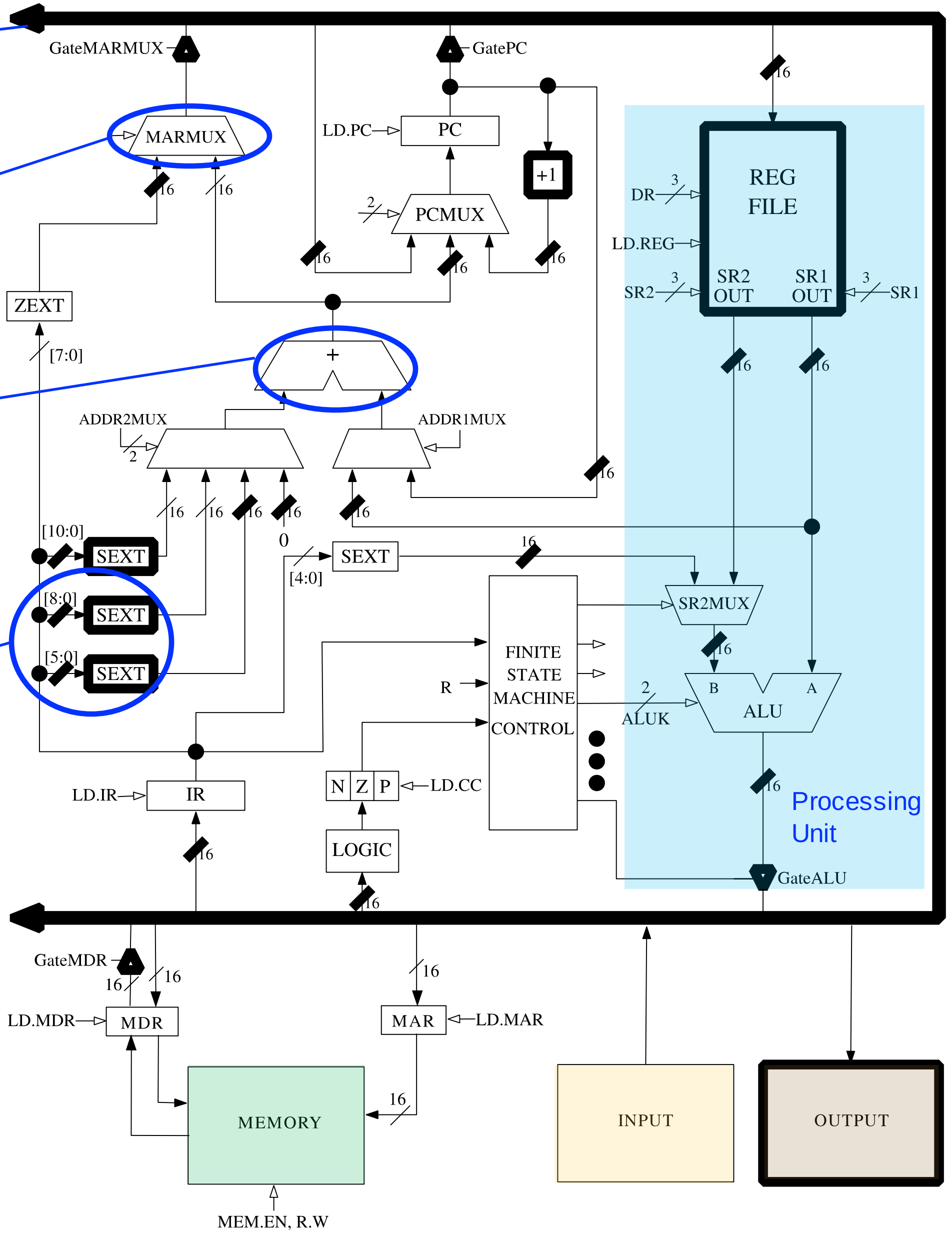
OP	DR	PCoffset9
E	5	0x1FD

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



The LC-3 Data Path



Global bus

MAR Multiplexer

Adder

Sign extension (Address)

Processing Unit

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	0	1
x30F7	0	0	0	1	0	1	0	0	0	1	1	0	1	1	1	0
x30F8	0	0	1	1	0	1	0	1	1	1	1	1	1	0	1	1
x30F9	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0
x30FA	0	0	0	1	0	1	0	0	1	0	1	0	0	1	0	1
x30FB	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1	0
x30FC	1	0	1	0	0	1	1	1	1	1	1	1	0	1	1	1

LEA -3 R1 = PC – 3 = 0x30F7 – 3 = 0x30F4

ADD 14 R2 = R1 + 14 = 0x30F4 + 14 = 0x3102

ST -5 M[PC - 5] = M[0x030F4] = 0x3102

AND 0 R2 = 0

ADD 5 R2 = R2 + 5 = 5

STR M[R1 + 14] = M[0x30F4 + 14] = M[0x3102] = 5

LDI -9 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 unconditional 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)

```
BRz  PCoffset9
```

0000	n	z	p	PCoffset9
4 bits				9 bits

- 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 AND N) OR (p AND P) OR (z AND Z))
  - then PC ← PC[†] + sign-extend(PCoffset9)

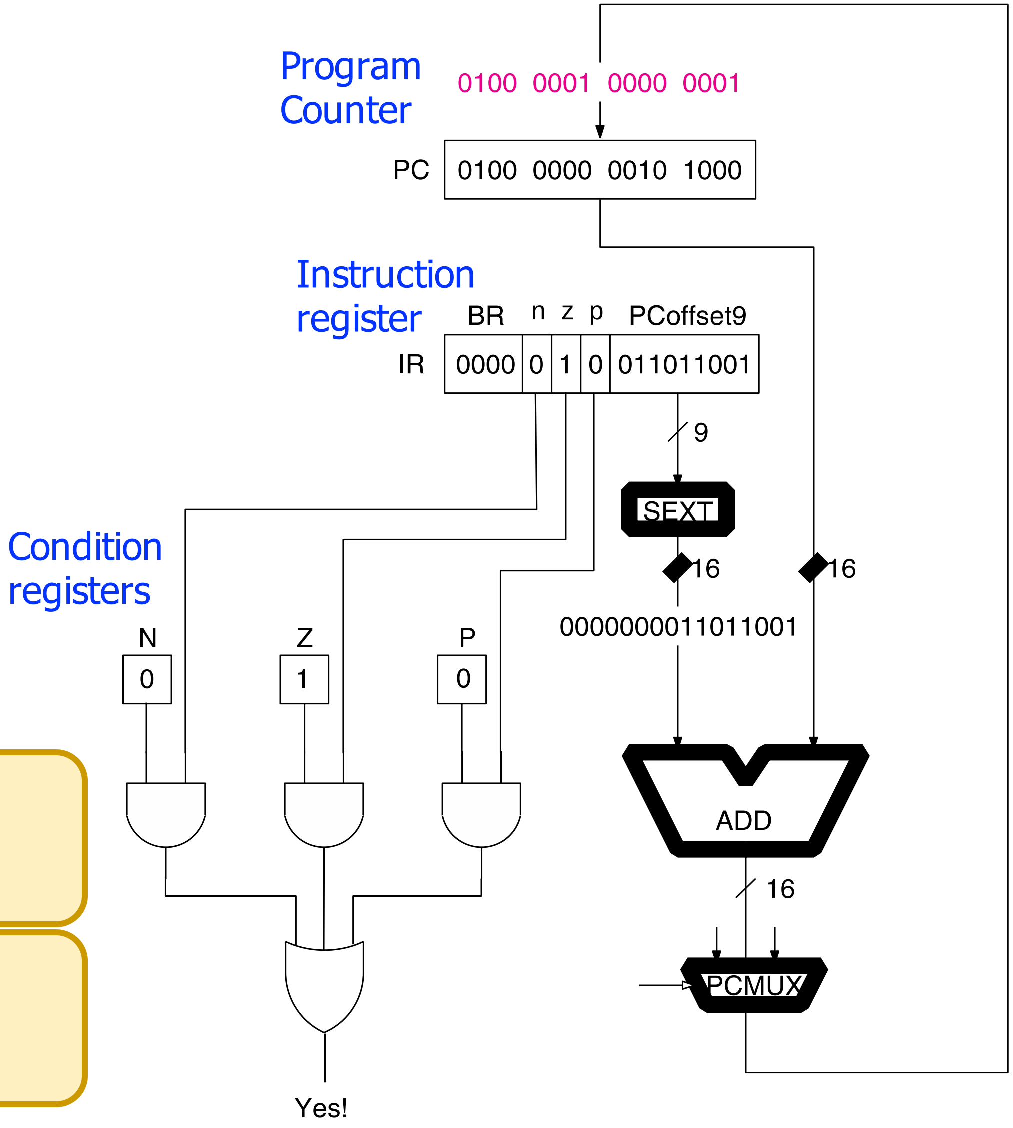
- Variations: BRn, BRz, BRp, BRzp, BRnp, BRnz, BRnzp

[†] 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	rs	rt	offset
6 bits	5 bits	5 bits	16 bits

  - 4 = opcode
  - rs, rt = source registers
  - offset = immediate or constant value
  - if rs == rt
    - then PC ← PC[†] + sign-extend(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

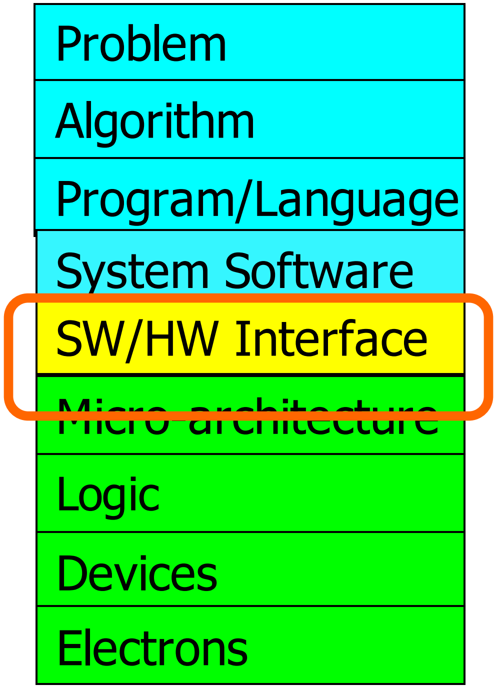
What We Learned

- Basic elements of a computer & 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

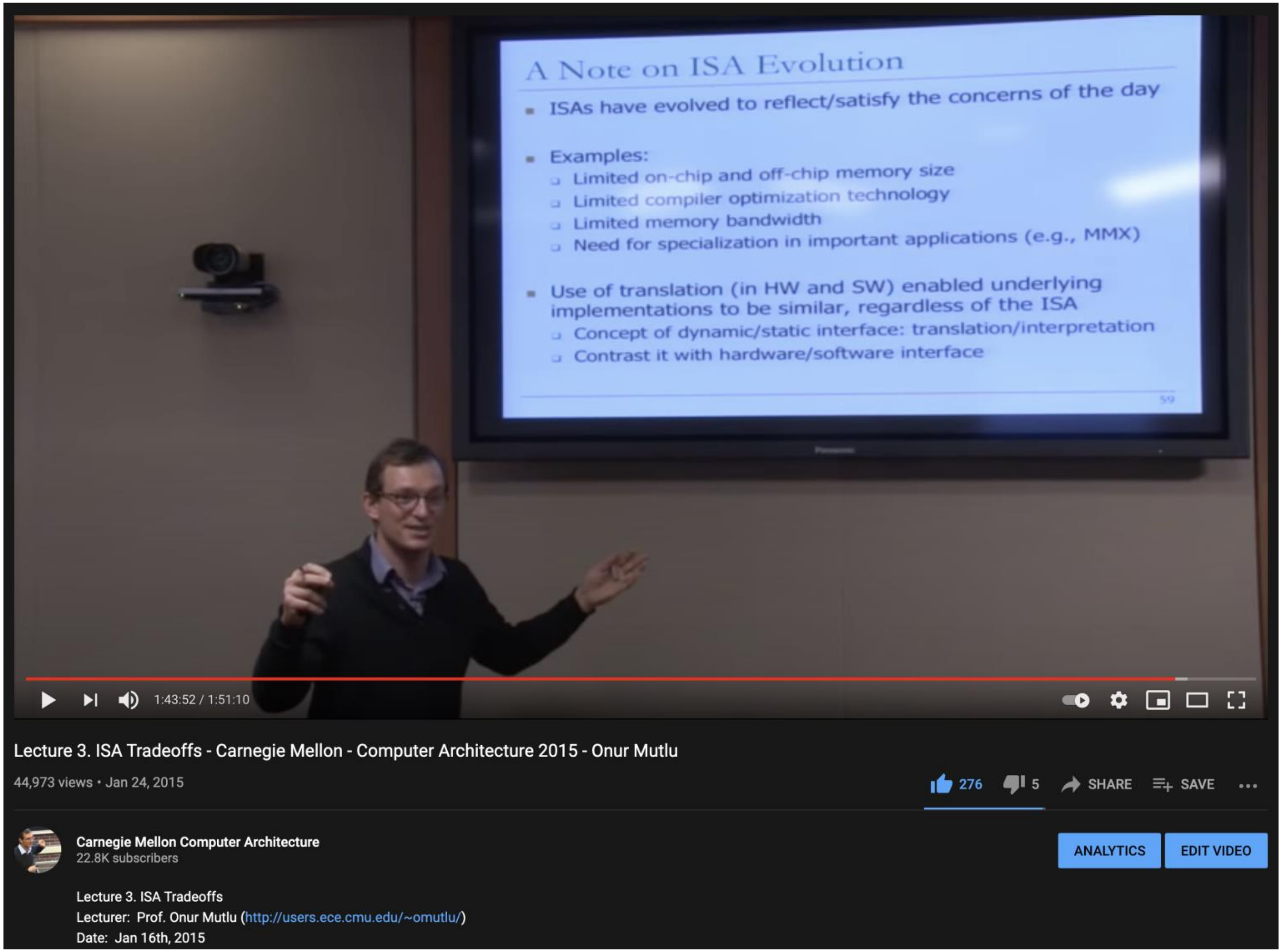
- Instruction formats

- Addressing modes



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

There Is A Lot More to Cover on ISAs



A Note on ISA Evolution

- ISAs have evolved to reflect/satisfy the concerns of the day
- Examples:
  - Limited on-chip and off-chip memory size
  - Limited compiler optimization technology
  - Limited memory bandwidth
  - Need for specialization in important applications (e.g., MMX)
- Use of translation (in HW and SW) enabled underlying implementations to be similar, regardless of the ISA
  - Concept of dynamic/static interface: translation/interpretation
  - Contrast it with hardware/software interface

59

1:43:52 / 1:51:10

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Lecturer: Prof. Onur Mutlu (http://users.ece.cmu.edu/~omutlu/)

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Many Different ISAs Over Decades

- x86
- PDP-x: Programmed Data Processor (PDP-11)
- VAX
- IBM 360
- CDC 6600
- SIMD ISAs: CRAY-1, Connection Machine
- VLIW ISAs: Multiflow, Cydrome, IA-64 (EPIC)
- PowerPC, POWER
- RISC ISAs: Alpha, MIPS, SPARC, ARM, RISC-V, …

- What are the fundamental differences?
  - E.g., how instructions are specified and what they do
  - E.g., how complex are the instructions

Complex vs. Simple Instructions

- Complex instruction: An instruction does a lot of work, e.g. many operations
  - Insert in a doubly linked list
  - Compute FFT
  - String copy
  - …

- Simple instruction: An instruction does little work -- it is a primitive using which complex operations can be built
  - Add
  - XOR
  - Multiply
  - …

Complex vs. Simple Instructions

- Advantages of Complex instructions

  + Denser encoding → smaller code size → better memory utilization, saves off-chip bandwidth, better cache hit rate (better packing of instructions)

  + Simpler compiler: no need to optimize small instructions as much

- Disadvantages of Complex Instructions

  - Larger chunks of work → compiler has less opportunity to optimize (limited in fine-grained optimizations it can do)

  - More complex hardware → translation from a high level to control signals and optimization needs to be done by hardware

ISA-level Tradeoffs: Number of Registers

- Affects:
  - Number of bits used for encoding register address
  - Number of values kept in fast storage (register file)
  - (uarch) Size, access time, power consumption of register file

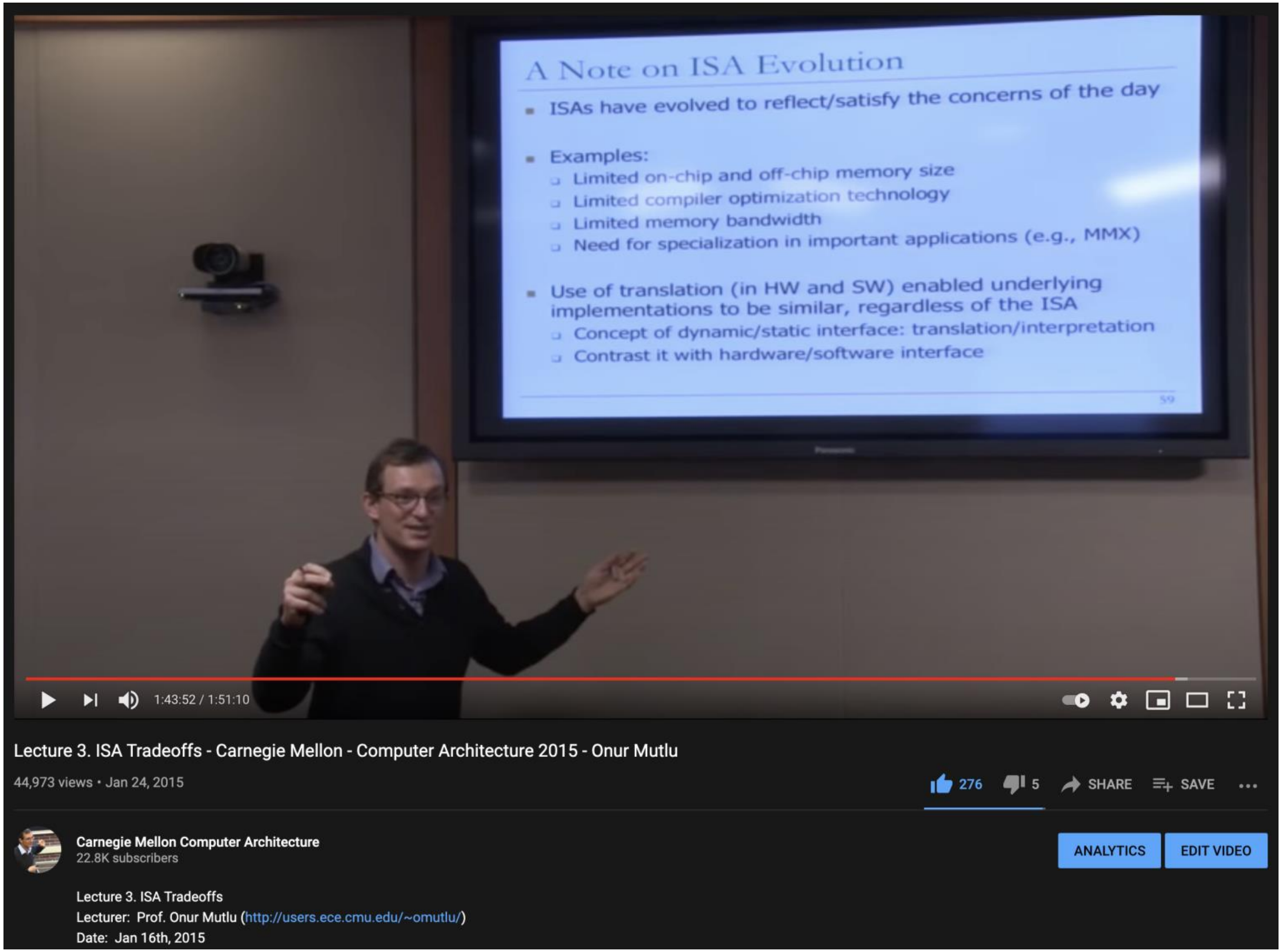
- Large number of registers:

  + Enables better register allocation (and optimizations) by compiler → fewer saves/restores

  -- Larger instruction size

  -- Larger register file size

There Is A Lot More to Cover on ISAs



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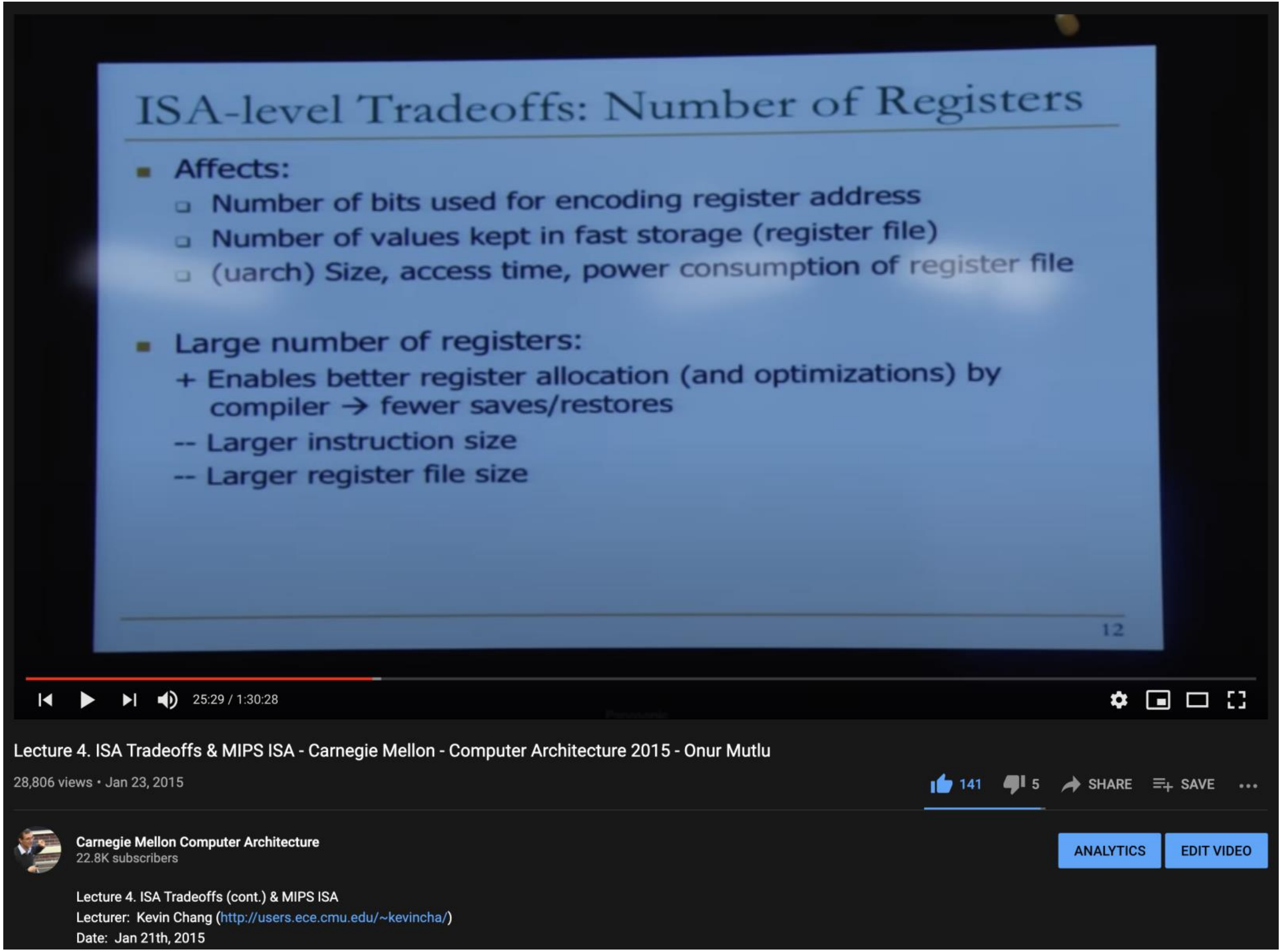
There Is A Lot More to Cover on ISAs



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  - -- Larger register file size

12

Lecture 4. ISA Tradeoffs & MIPS ISA - Carnegie Mellon - Computer Architecture 2015 - Onur Mutlu

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Lecture 4. ISA Tradeoffs (cont.) & MIPS ISA
Lecturer: Kevin Chang (http://users.ece.cmu.edu/~kevincha/)
Date: Jan 21th, 2015

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Detailed Lectures on ISAs & ISA Tradeoffs

- Computer Architecture, Spring 2015, Lecture 3
  - ISA Tradeoffs (CMU, Spring 2015)
  - https://www.youtube.com/watch?v=QKdiZSfwg-g&list=PL5PHm2jkkXmi5CxxI7b3JCL1TWybTDtKq&index=3

- Computer Architecture, Spring 2015, Lecture 4
  - ISA Tradeoffs & MIPS ISA (CMU, Spring 2015)
  - https://www.youtube.com/watch?v=RBgeCCW5Hjs&list=PL5PHm2jkkXmi5CxxI7b3JCL1TWybTDtKq&index=4

- Computer Architecture, Spring 2015, Lecture 2
  - Fundamental Concepts and ISA (CMU, Spring 2015)
  - https://www.youtube.com/watch?v=NpC39uS4K4o&list=PL5PHm2jkkXmi5CxxI7b3JCL1TWybTDtKq&index=2

Digital Design & Computer Arch.

Lecture 10a: Instruction Set Architectures II

Prof. Onur Mutlu

ETH Zürich
Spring 2021
26 March 2021