Digital Design & Computer Arch.

Lecture 10a: Instruction Set Architectures II

Prof. Onur Mutlu

ETH Zürich

Spring 2022

25 March 2022

Assignment: Lecture Video (April 1)

- 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 by April 1

Extra Assignment: 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 7

- 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**

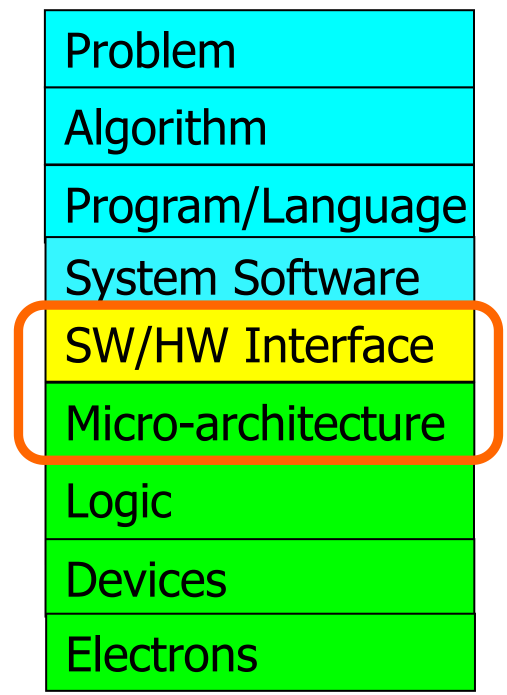
  - Guideline slides: pdf ppt
  - Video: https://www.youtube.com/watch?v=tOL6FANAJ8c

  - 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

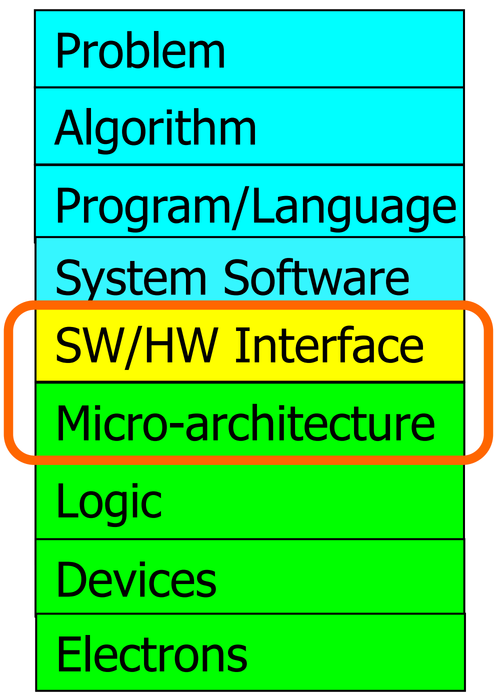
Agenda for Today & Next Few Lectures

- 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



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



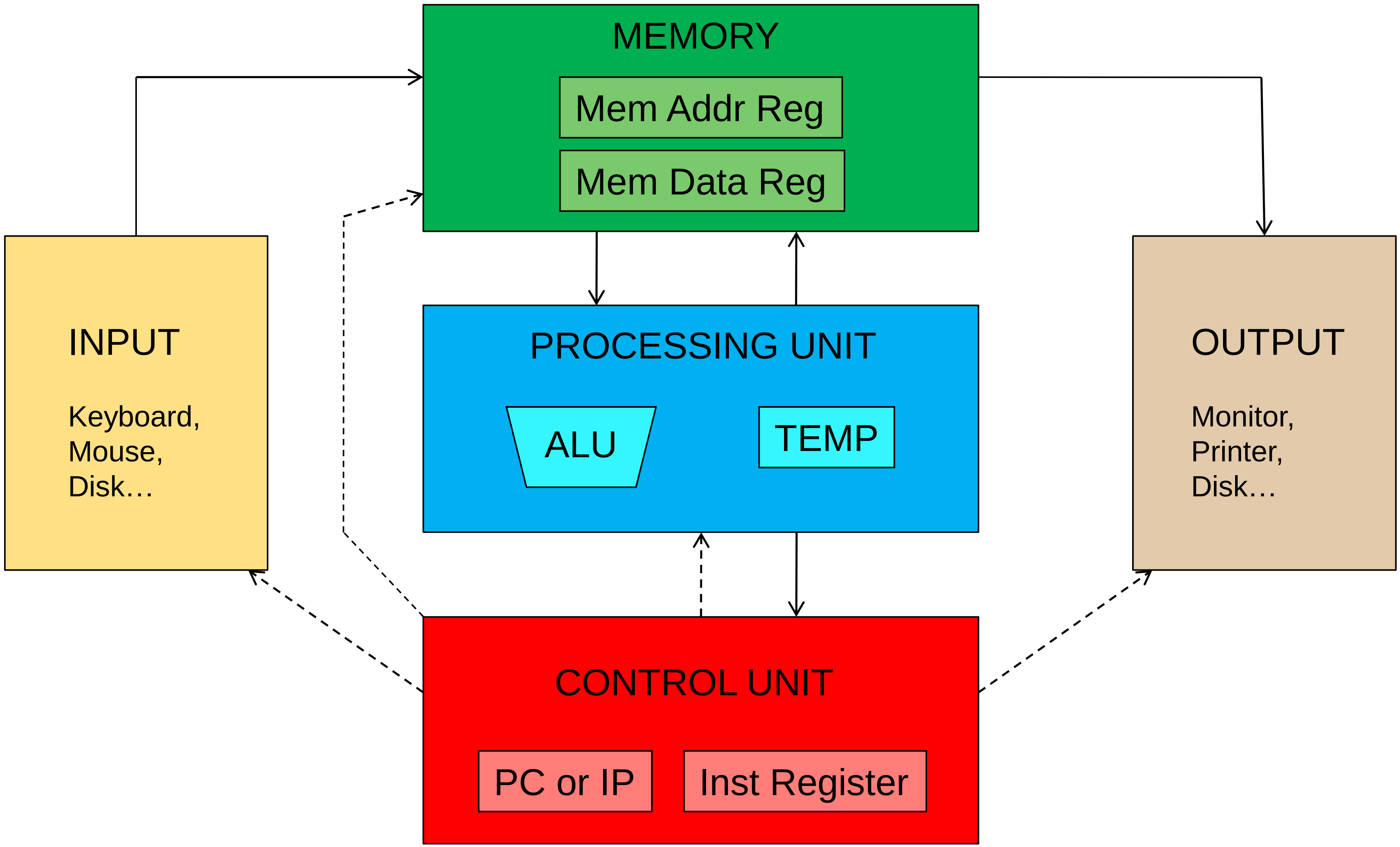
Readings

- This week
  - Von Neumann Model, ISA, LC-3, and MIPS
    - P&P, Chapters 4, 5 (we will follow these today & tomorrow)
    - 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 (we will follow this tomorrow)
  - **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

Quick Review of the von Neumann Model

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

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

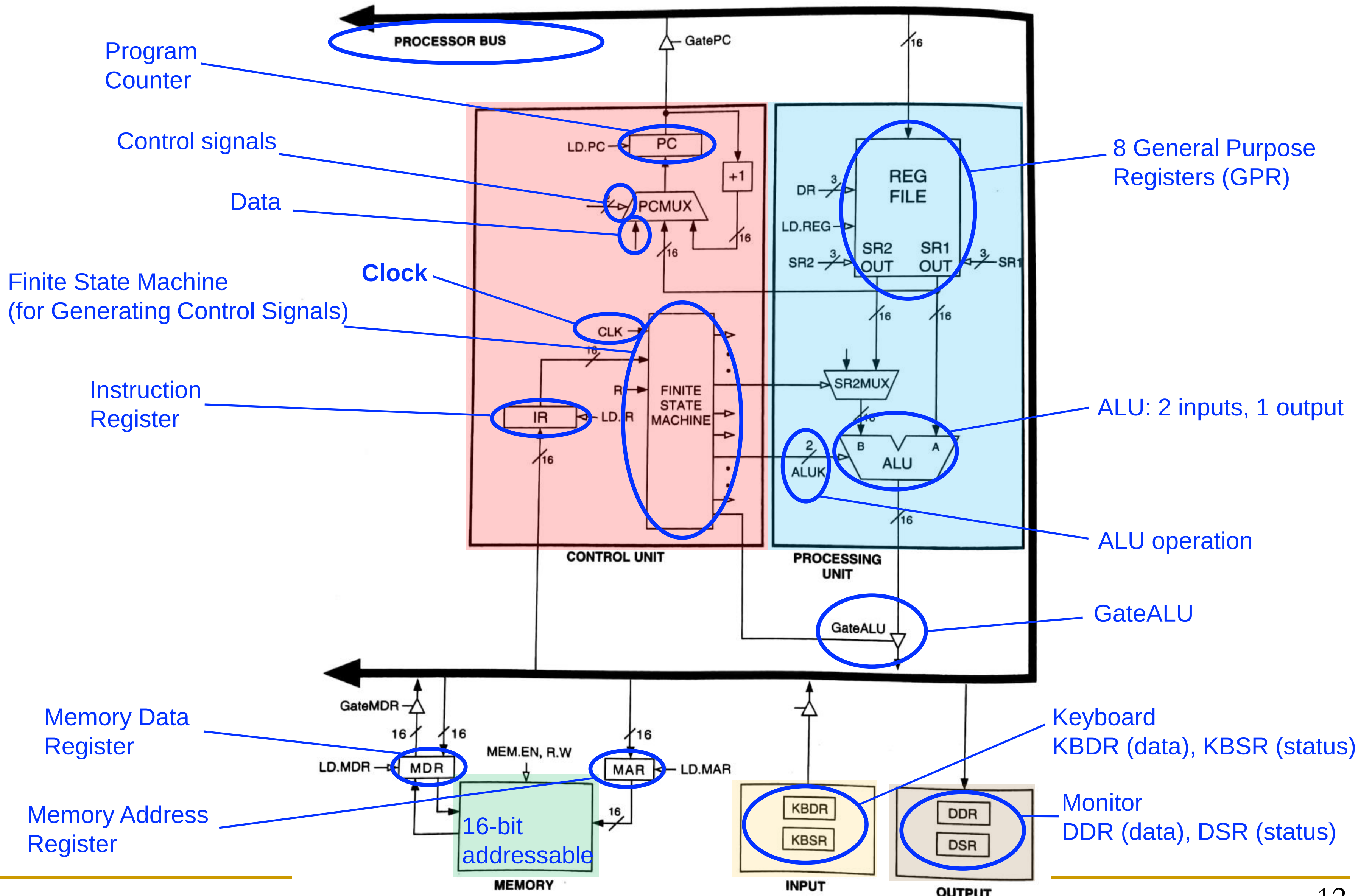


Figure 4.3 The LC-3 as an example of the von Neumann model

Recall: The Instruction (Processing) Cycle

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

Recall: Control of the Instruction Cycle

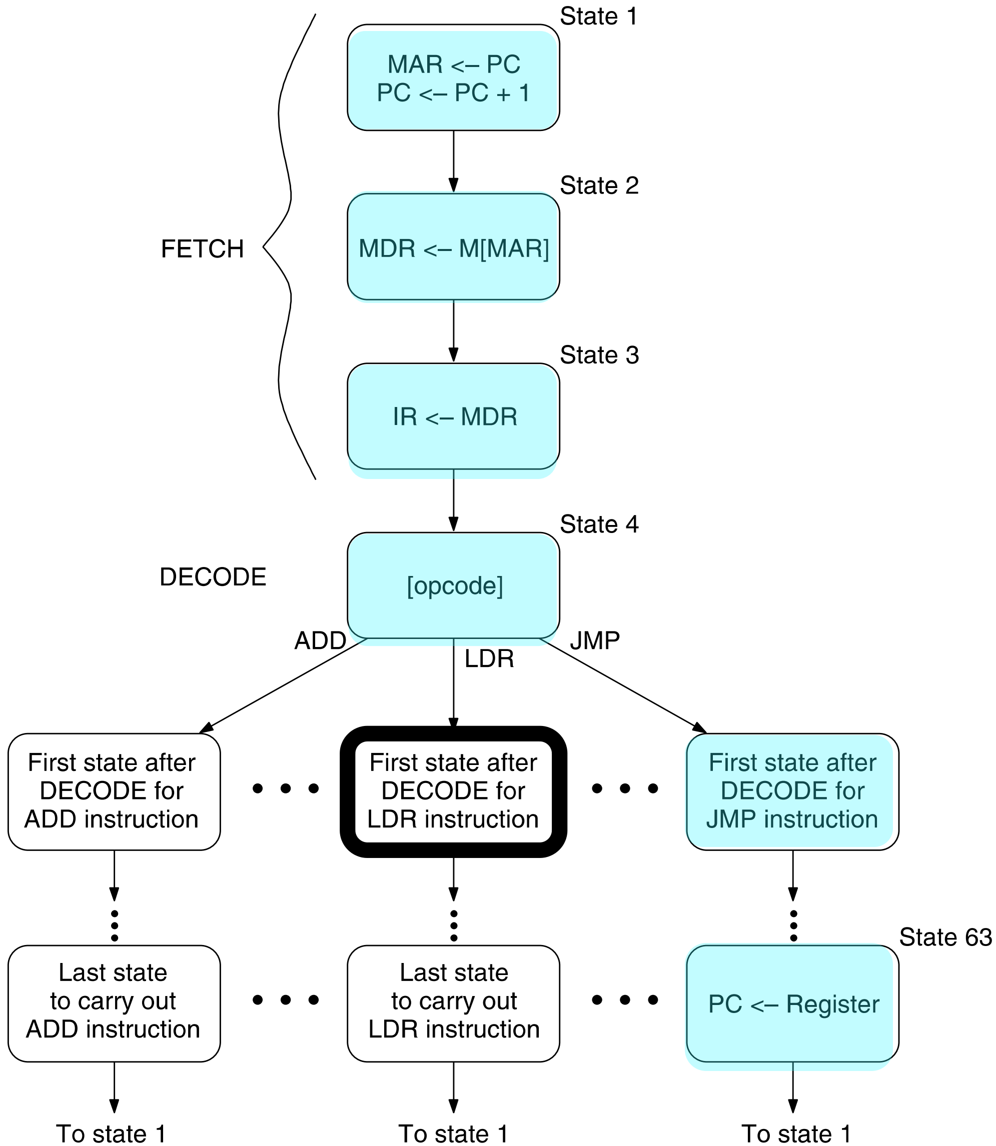


Figure 4.4 An abbreviated state diagram of the LC-3

- 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&Pattel, Appendix C

This is an FSM Controlling the LC-3 Processor

Full State Machine for LC-3b

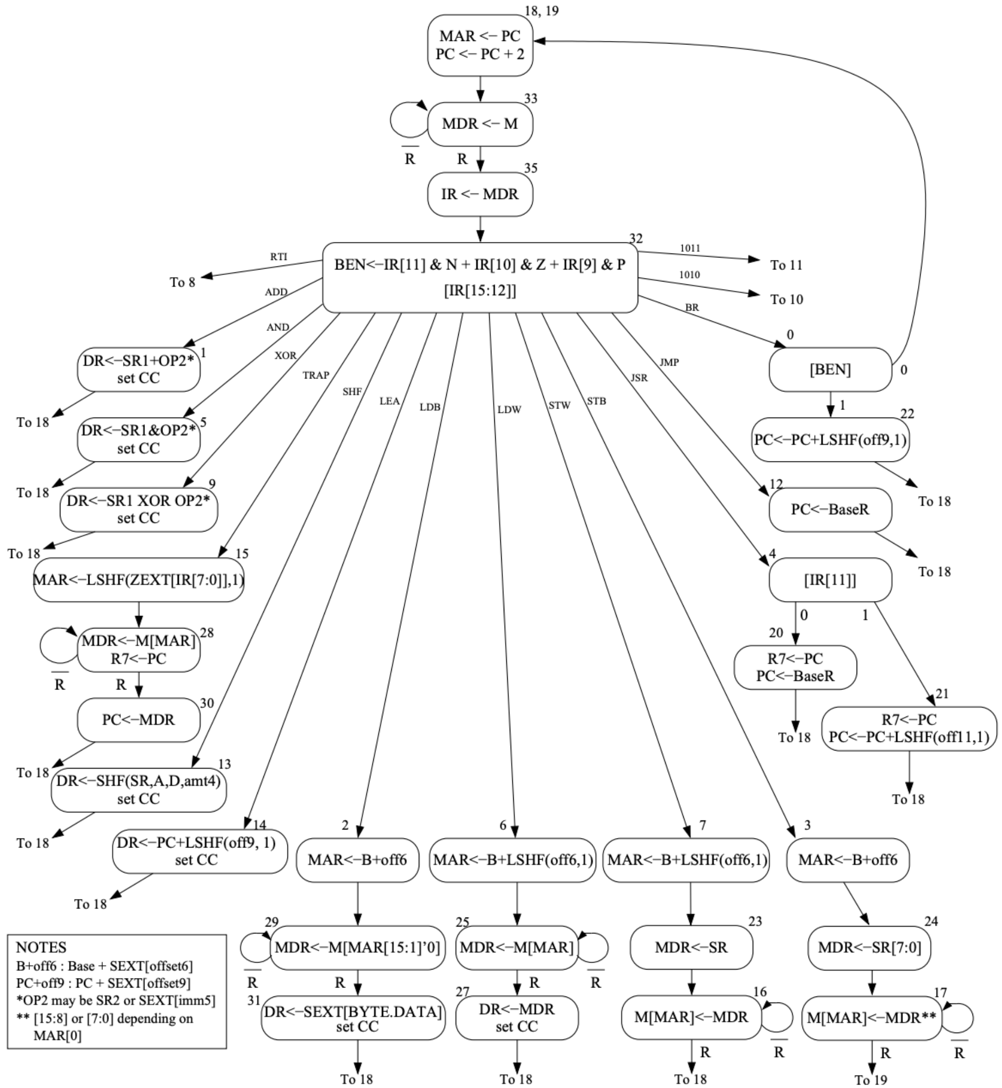


Figure C.2: A state machine for the LC-3b

https://safari.ethz.ch/digitaltechnik/spring2022/lib/exe/fetch.php?media=pp-appendixc.pdf

Recall: LC-3: A von Neumann Machine

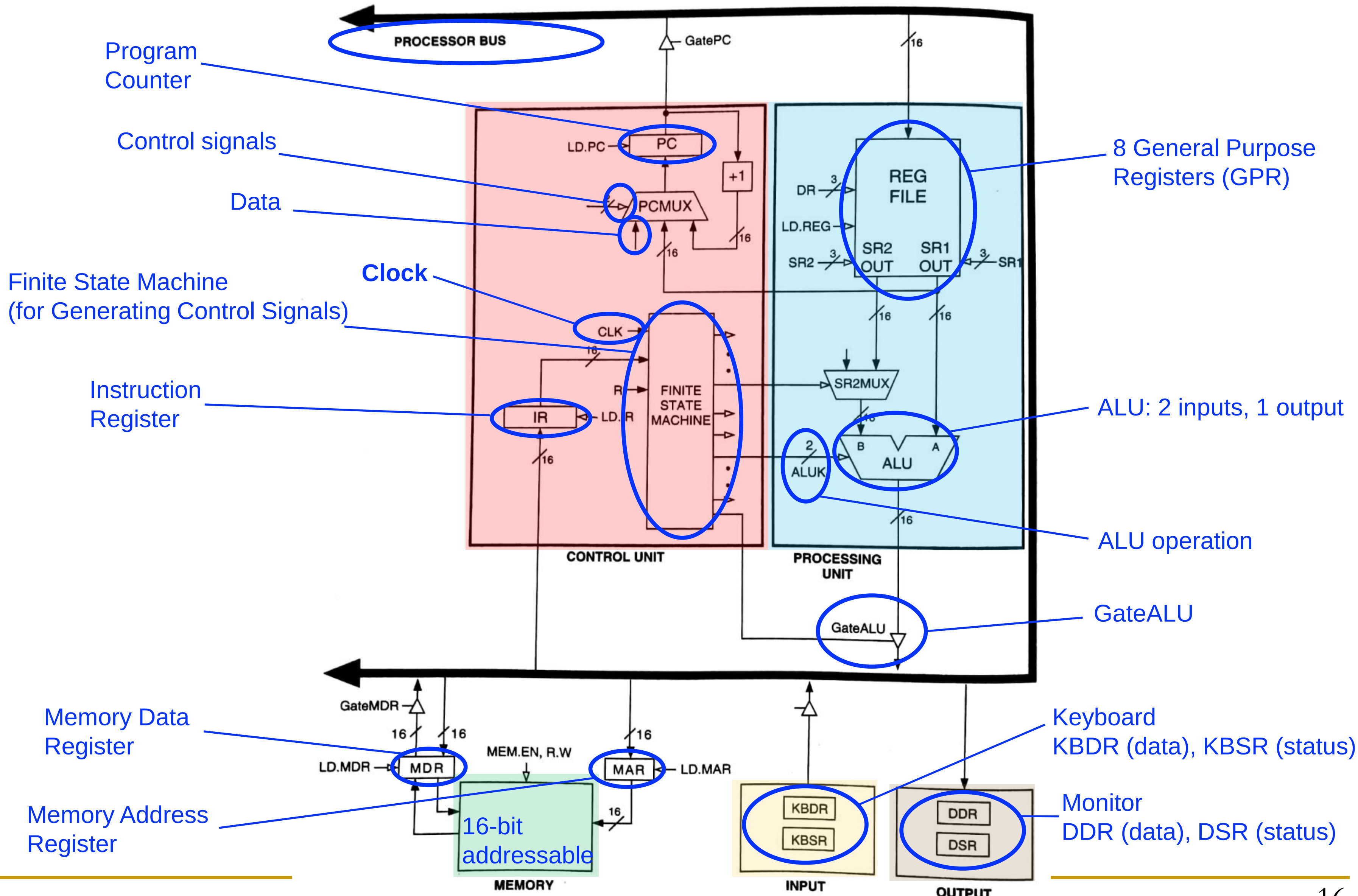
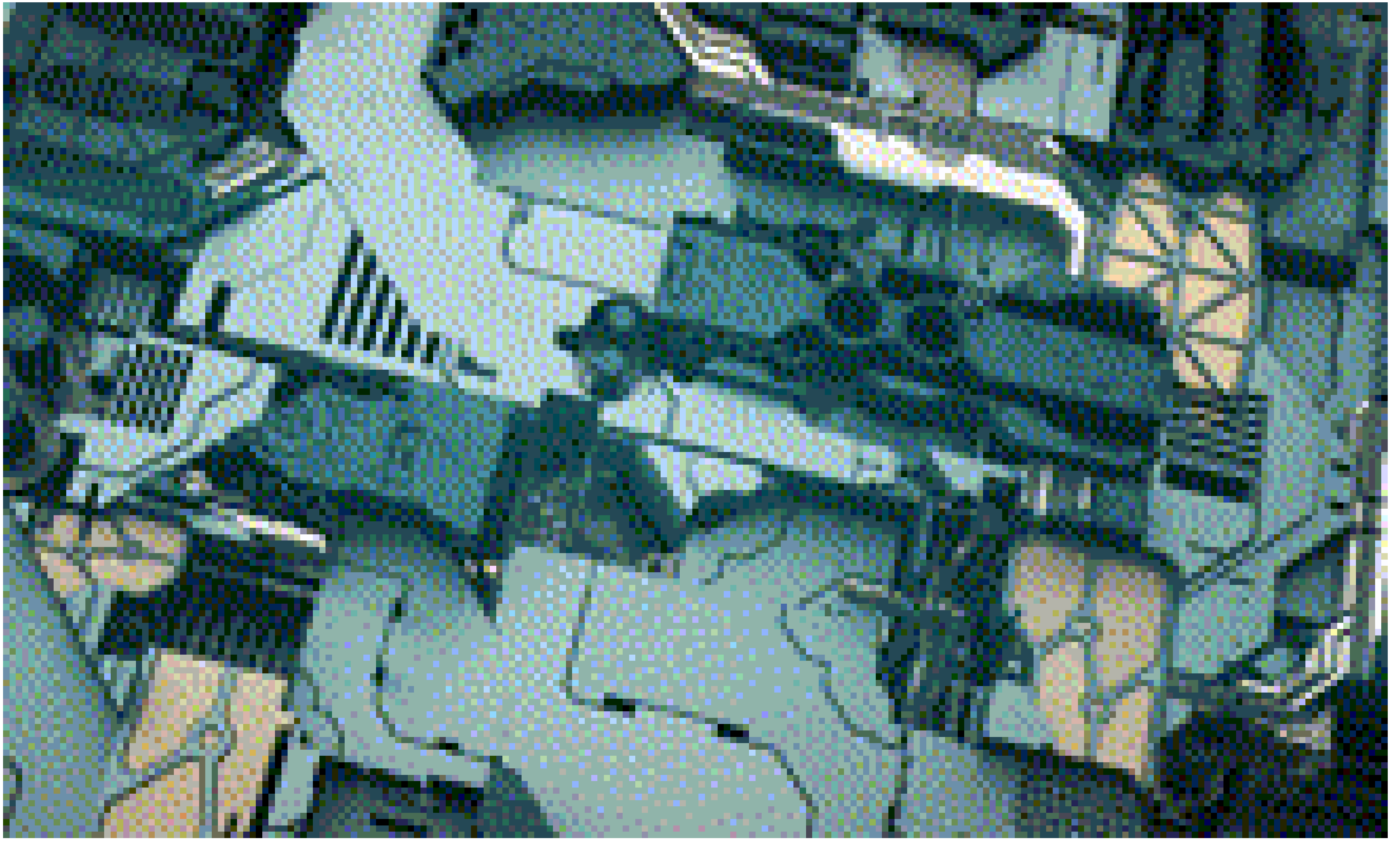
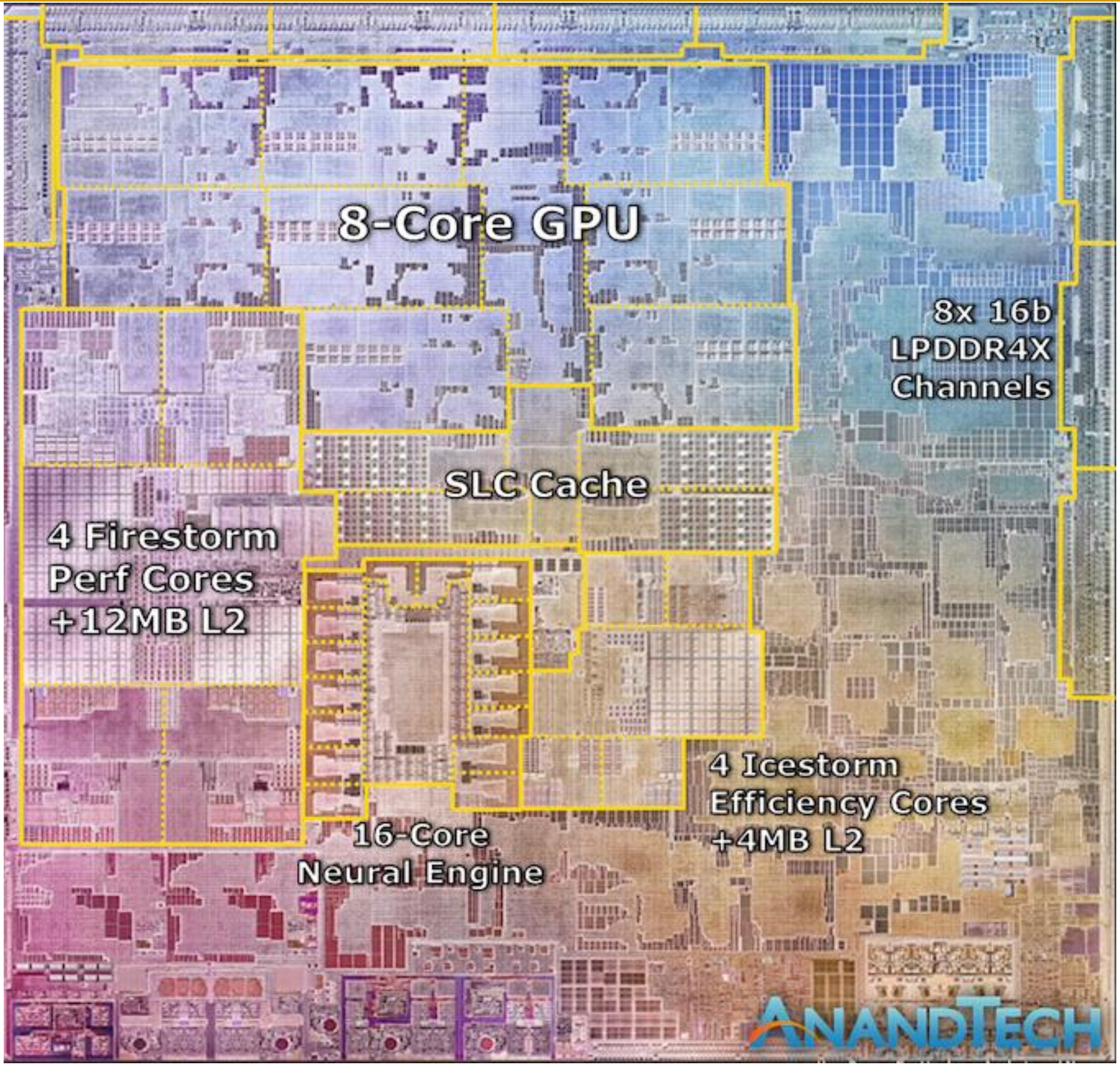


Figure 4.3 The LC-3 as an example of the von Neumann model

LC-3: A von Neumann Machine

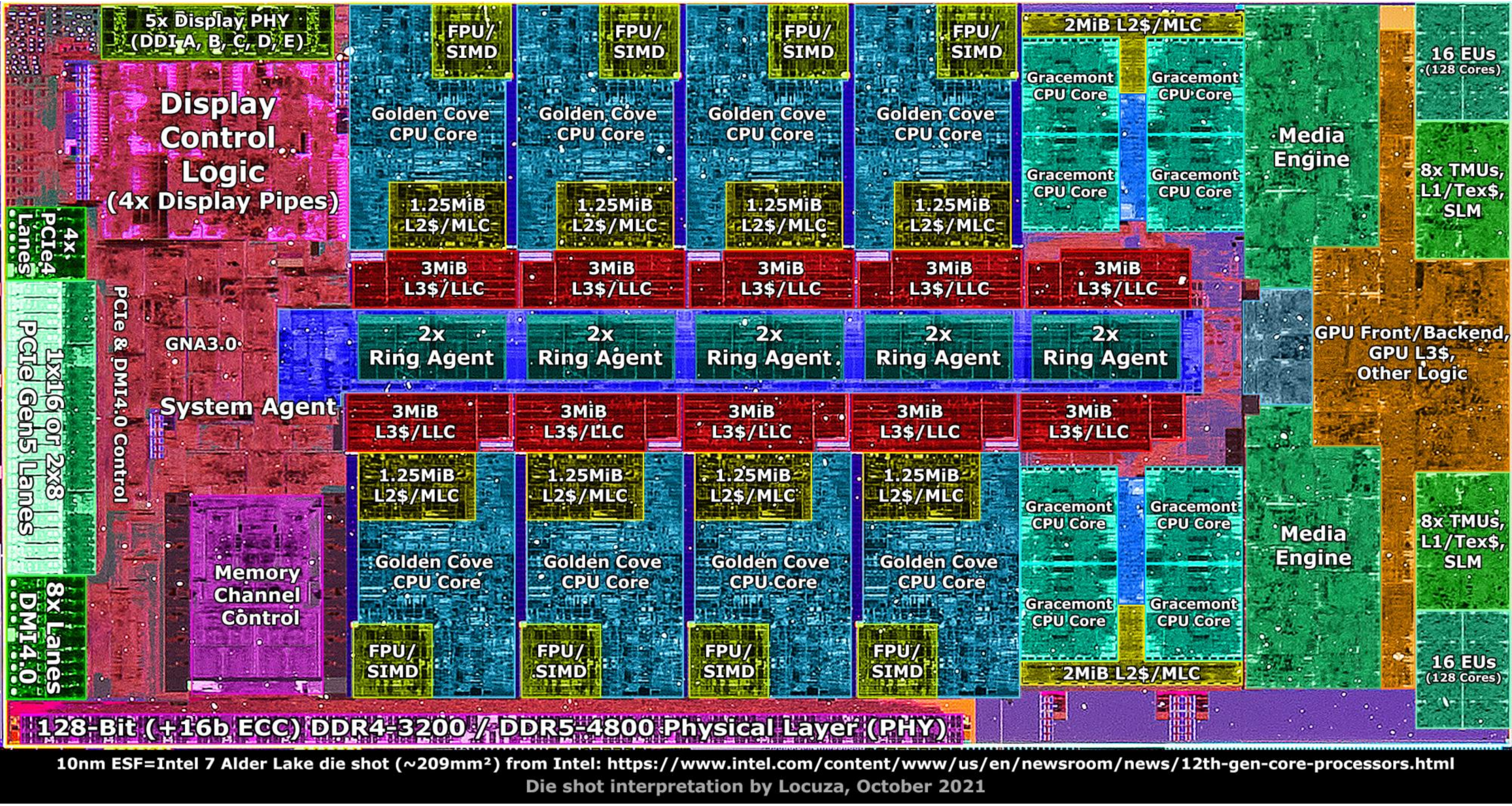


Another von Neumann Machine



Apple M1,
2021

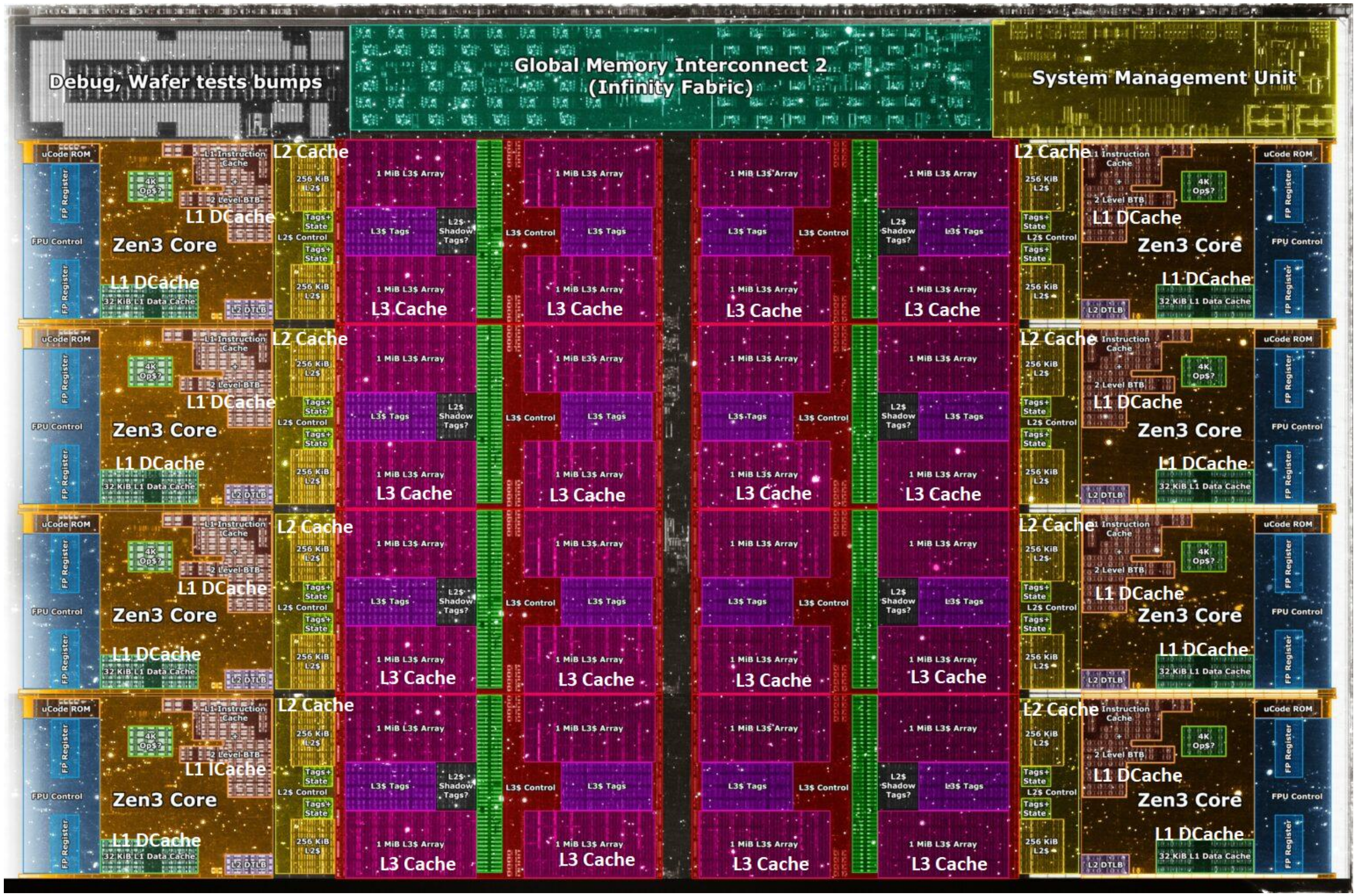
Another von Neumann Machine



Intel Alder Lake, 2021

Source: https://twitter.com/Locuza_/status/1454152714930331652

Another von Neumann Machine



AMD Ryzen 5000, 2020

Cores:
8 cores/16 threads

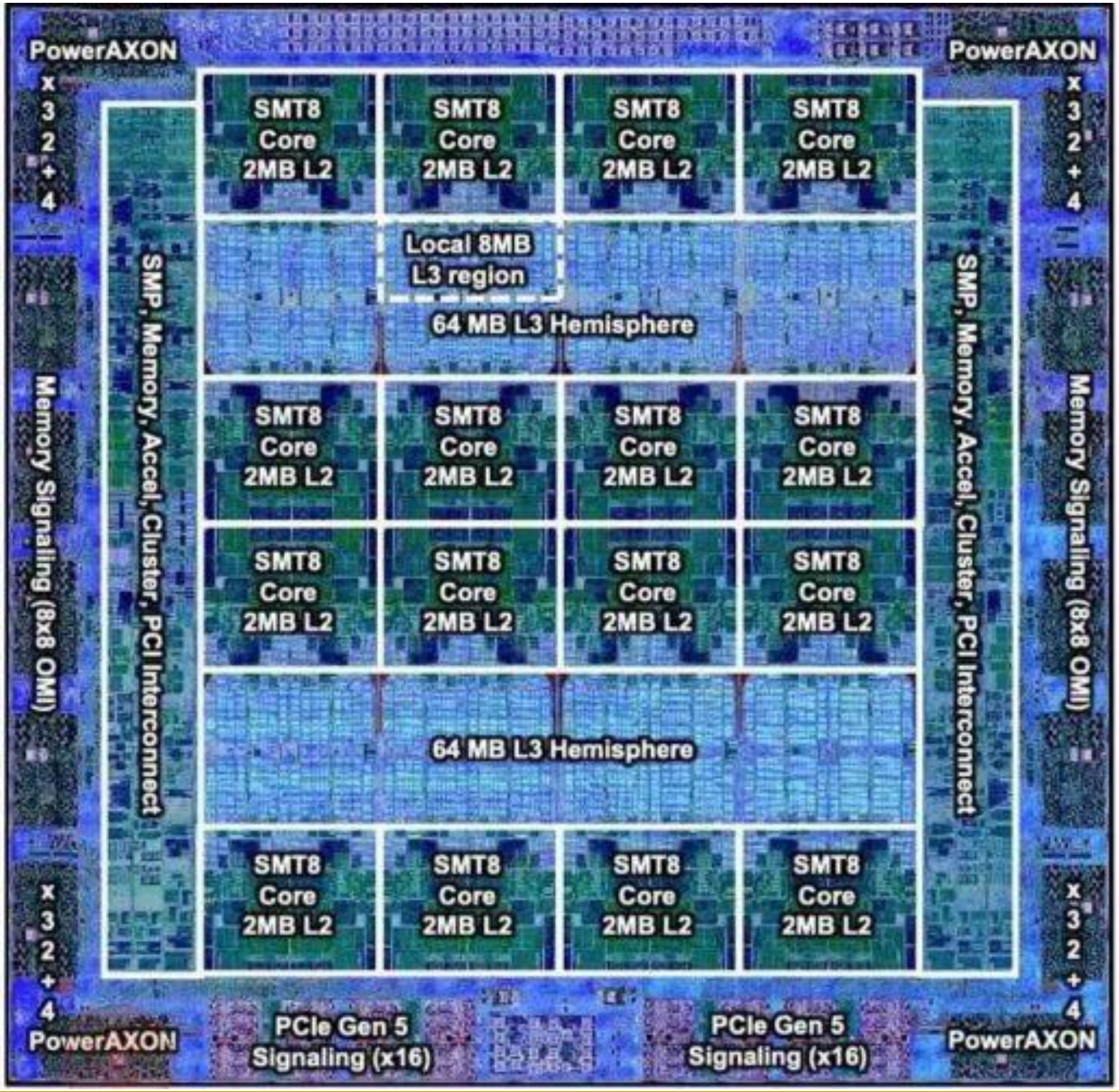
L1 Caches:
32 KB per core

L2 Caches:
512 KB per core

L3 Cache:
32 MB shared

https://wccftech.com/amd-ryzen-5000-zen-3-vermeer-undressed-high-res-die-shots-close-ups-pictured-detailed/

Another von Neumann Machine



IBM POWER10, 2020

Cores:
15-16 cores,
8 threads/core

L2 Caches:
2 MB per core

L3 Cache:
120 MB shared

https://www.it-techblog.de/ibm-power10-prozessor-mehr-speicher-mehr-tempo-mehr-sicherheit/09/2020/

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

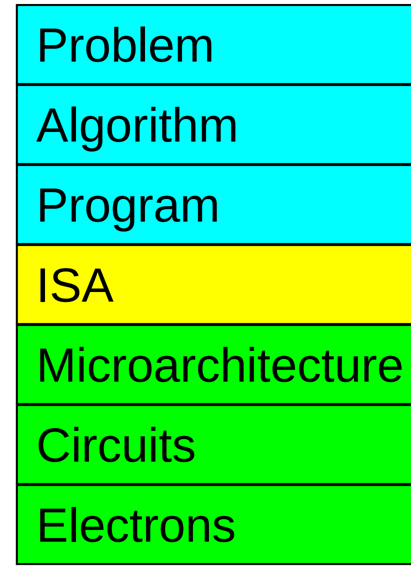
OP	DR	BaseR	offset6
6	3	0	4

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
    - 8 registers (R0 to R7) in LC-3
    - 32 registers in MIPS
  - The instruction set
    - Opcodes
    - Data types
    - Addressing modes
    - Length and format of instructions



Instructions (Opcodes)

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. Examples:
  - Hardware complexity vs. software complexity
  - Latency of simple vs. complex instructions
- In LC-3 and in MIPS there are three types of opcodes
  - Operate
  - Data movement
  - Control

Opcodes in LC-3

Instruction	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

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	R-type
6-bit	5-bit	5-bit	5-bit	5-bit	6-bit	

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

opcode	immediate	J-type
6-bit	26-bit	

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)

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

- More complete list of instructions are in H&H Appendix B

Data Types

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

- Tradeoffs are involved. Examples:
  - Hardware complexity vs. software complexity
  - Latency of operations on supported vs. unsupported data types

Why Have Different Data Types in ISA?

- An example of programmer vs. microarchitect tradeoff

- Advantage of more data types:
  - Enables better mapping of high-level programming constructs to hardware
    - Hardware can directly operate on data types present in programming languages → small number of instructions and code size
      - Matrix operations vs. individual multiply/add/load/store instructions
      - Graph operations vs. individual load/store/add/… instructions

- Disadvantage:
  - More work for the microarchitect
    - who needs to implement the data types and instructions that operate on data types

Data Types and Instruction Complexity

- Data types are coupled tightly to the semantic level, or complexity of instructions

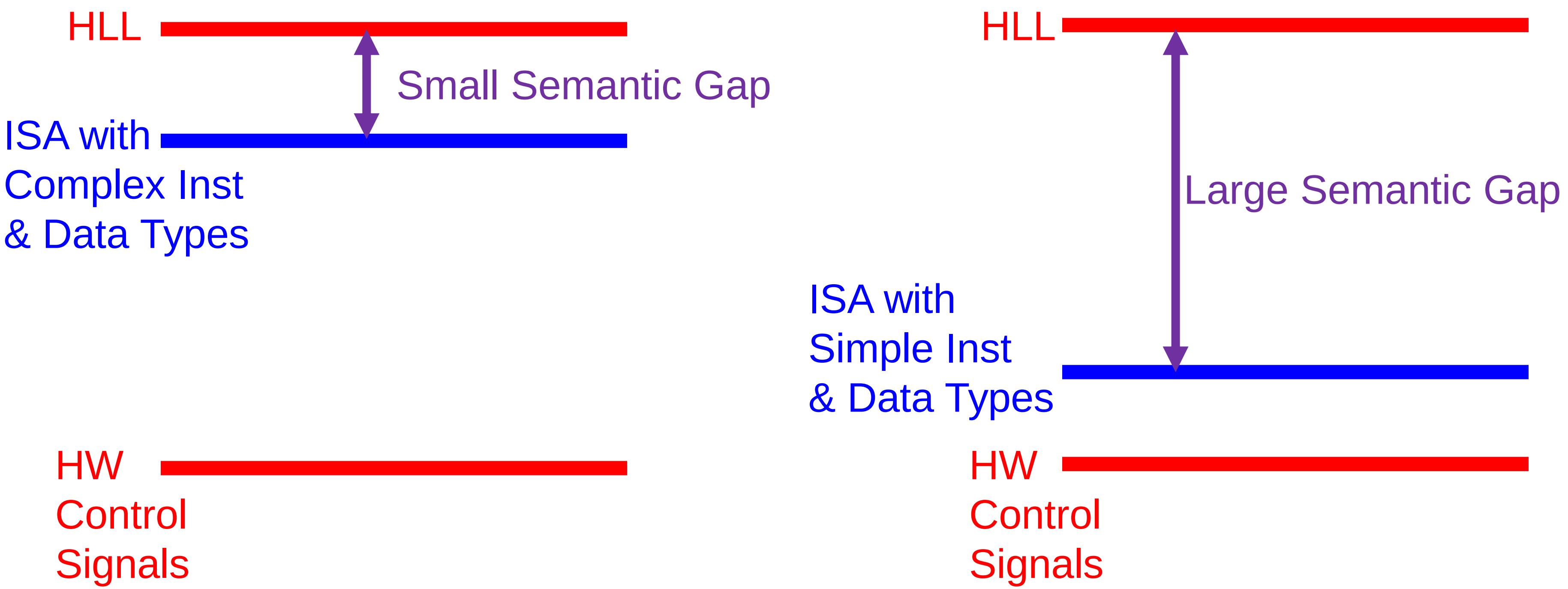
- Concept of semantic gap
  - how close instructions & data types are to high-level language

- Complex instructions + data types → small semantic gap
  - E.g., insert into a doubly linked list, multiply two matrices
  - VAX ISA: doubly-linked list, multi-dimensional arrays

- Simple instructions + data types → large semantic gap
  - E.g., primitive operations: load, store, multiply, add, nor
  - Early RISC machines: Only integer data type, simple operations

Semantic Gap

- How close instructions & data types are to high-level language (HLL)



Complex vs. Simple Instructions+Data Types

- Complex instruction: An instruction does a lot of work, e.g. many operations
  - Insert in a doubly linked list
  - Compute FFT
  - String copy
  - Matrix multiply
  - …
- Simple instruction: An instruction does little work -- it is a primitive using which complex operations can be built
  - Add
  - XOR
  - Multiply
  - …

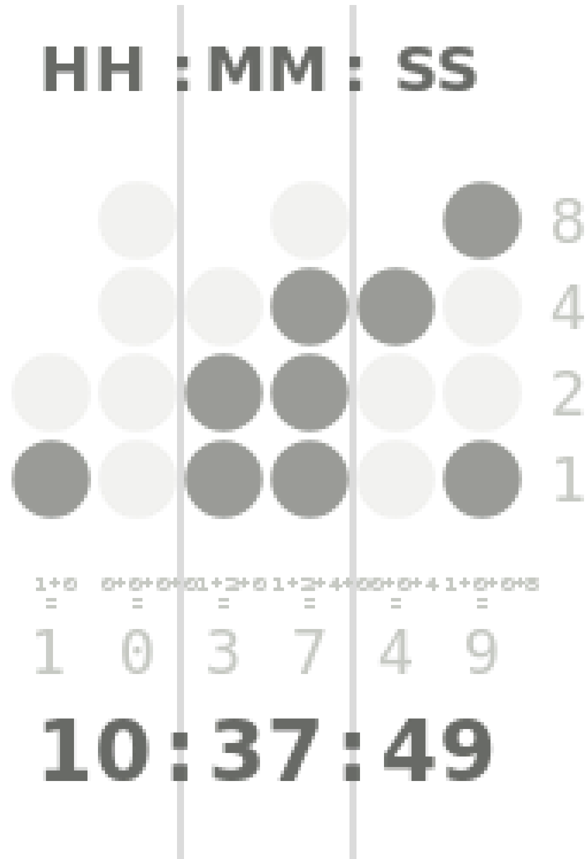
Complex vs. Simple Instructions+Data Types

- Advantages of Complex Instructions + Data Types
  - \+ 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 + Data Types
  - \- 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

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

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



"Binary clock" by Alexander Jones & Eric Pierce - Own work, based on Wapcaplet's Binary clock.png on the English Wikipedia. Licensed under CC BY-SA 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Binary_clock.svg#mediaviewer/File:Binary_clock.svg

"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

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

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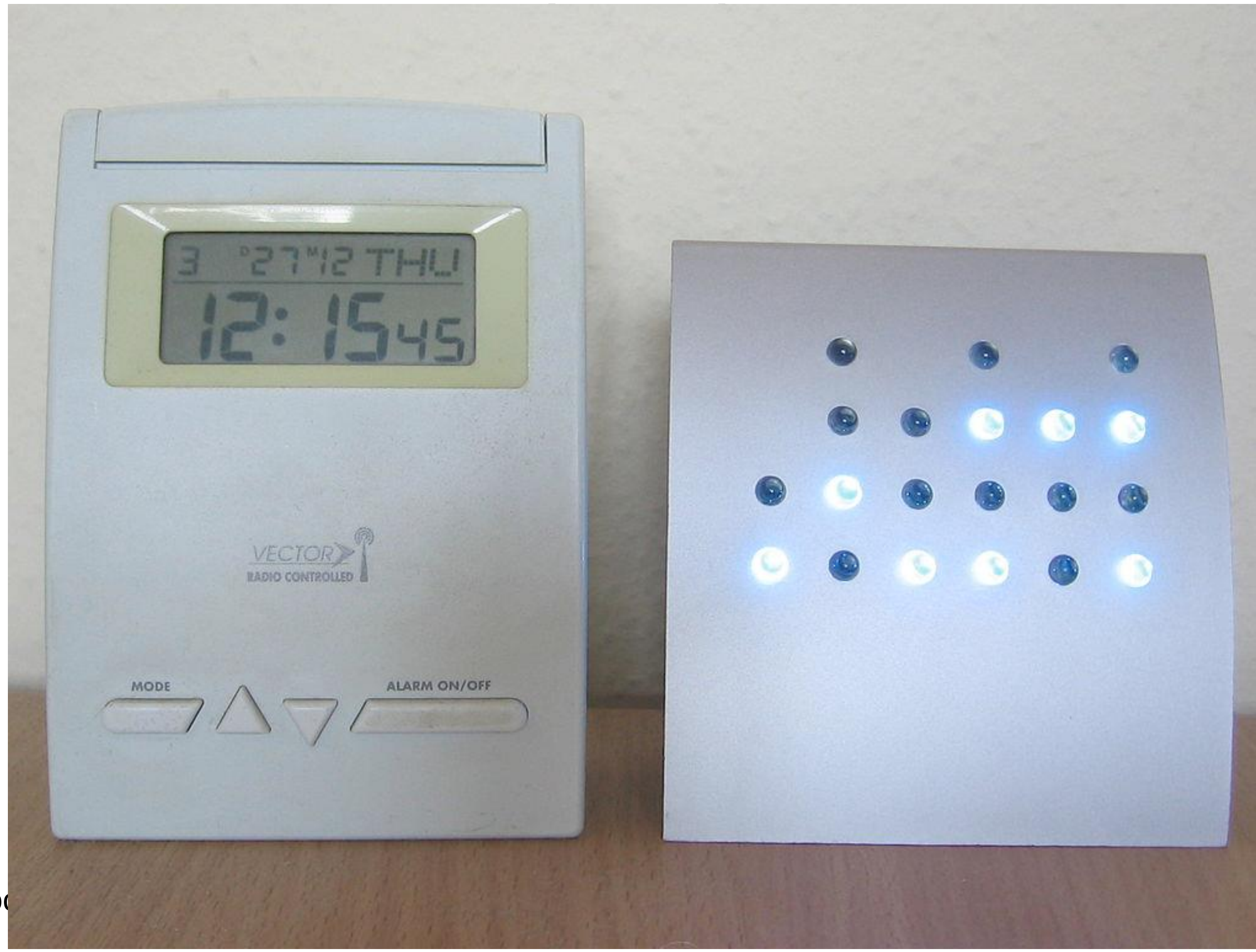


"Binary clo[...] on the English Wikipedia.
http://commons.wikimedia.org/wiki/File:Binary_clock.svg#mediaviewer/File:Binary_clock.svg

"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

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?

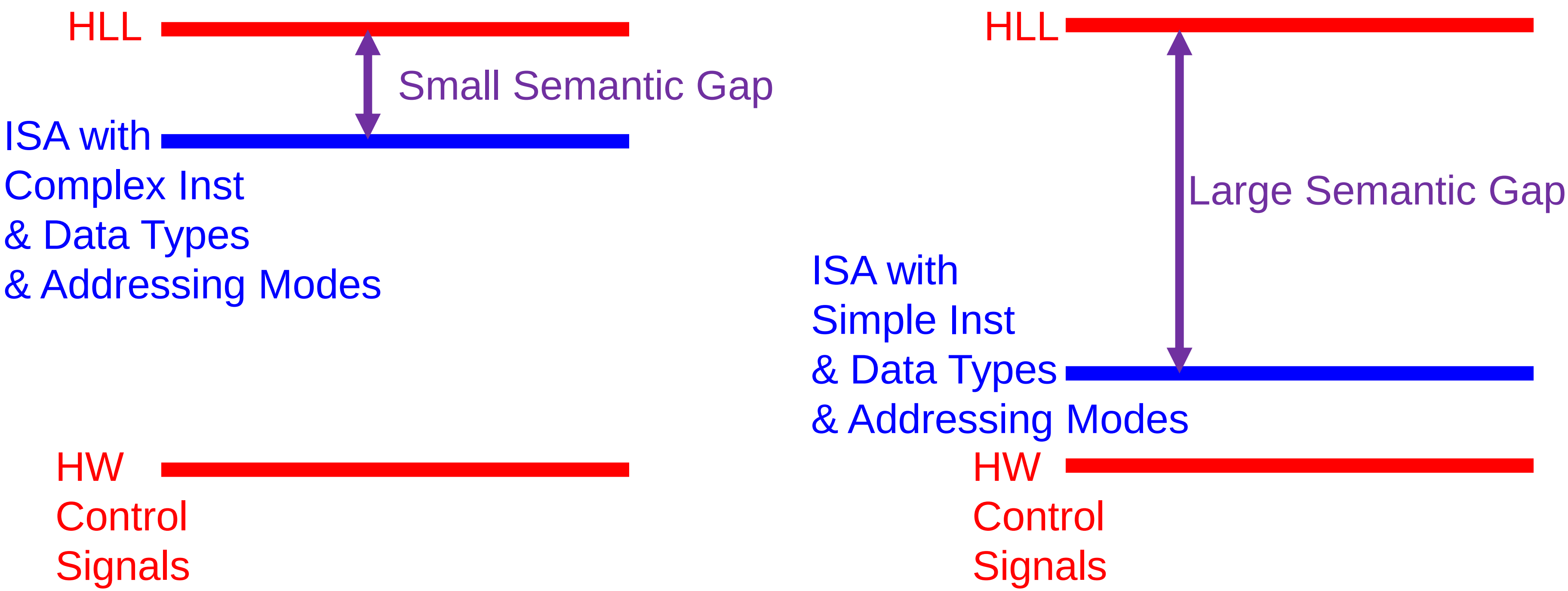
- Another example of programmer vs. microarchitect tradeoff

- 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 microarchitect
  - More options for the compiler to decide what to use

Semantic Gap Applies to Addressing Modes

- How close instructions & data types & addressing modes are to high-level language (HLL)



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
- 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

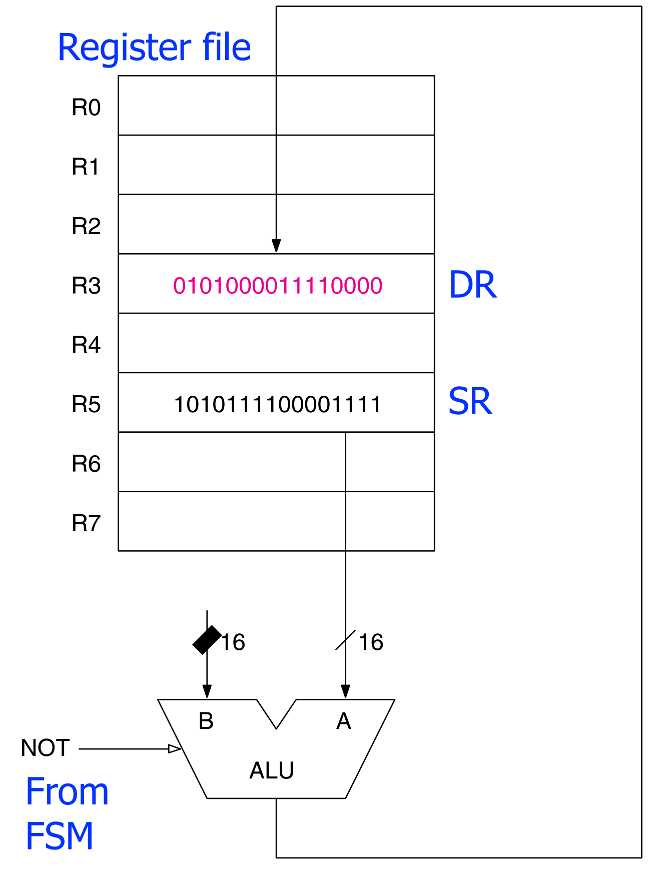
```
NOT  R3, R5
```

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

- We will use Subtraction as an example
  - How is it implemented in LC-3 and MIPS?

Recall: LC-3 Operate Instruction Format

- LC-3 Operate Instruction Format (Register OP Register)

15 14 13 12	11 10 9	8 7 6	5	4 3	2 1 0
OP	DR	SR1	0	00	SR2
4 bits	3 bits	3 bits			3 bits

  - OP = opcode (what the instruction does)
    - E.g., ADD = 0001
      - Semantics: DR ← SR1 + SR2
    - E.g., AND = 0101
      - Semantics: DR ← SR1 AND SR2
  - SR1, SR2 = source registers
  - DR = destination register

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	0	0	1	0	0	0	0	1	1	0
ADD				R6			R2						R6		

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

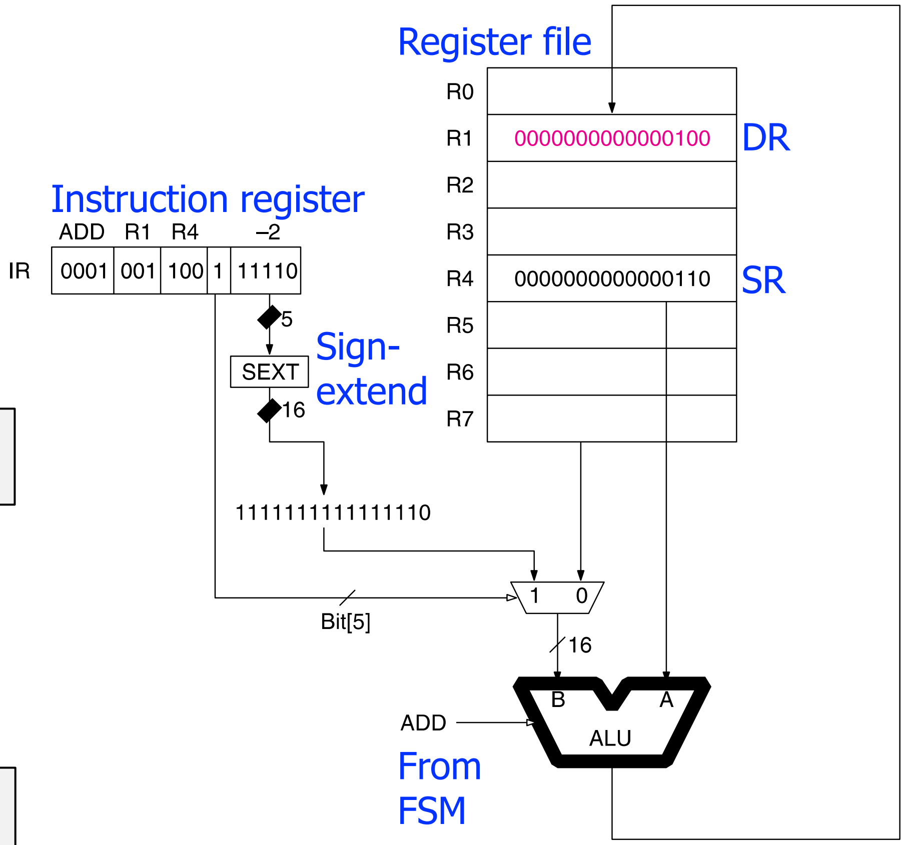
```
ADD R1, R4, #-2
```

Field Values

OP	DR	SR		imm5
1	1	4	1	-2

Machine Code

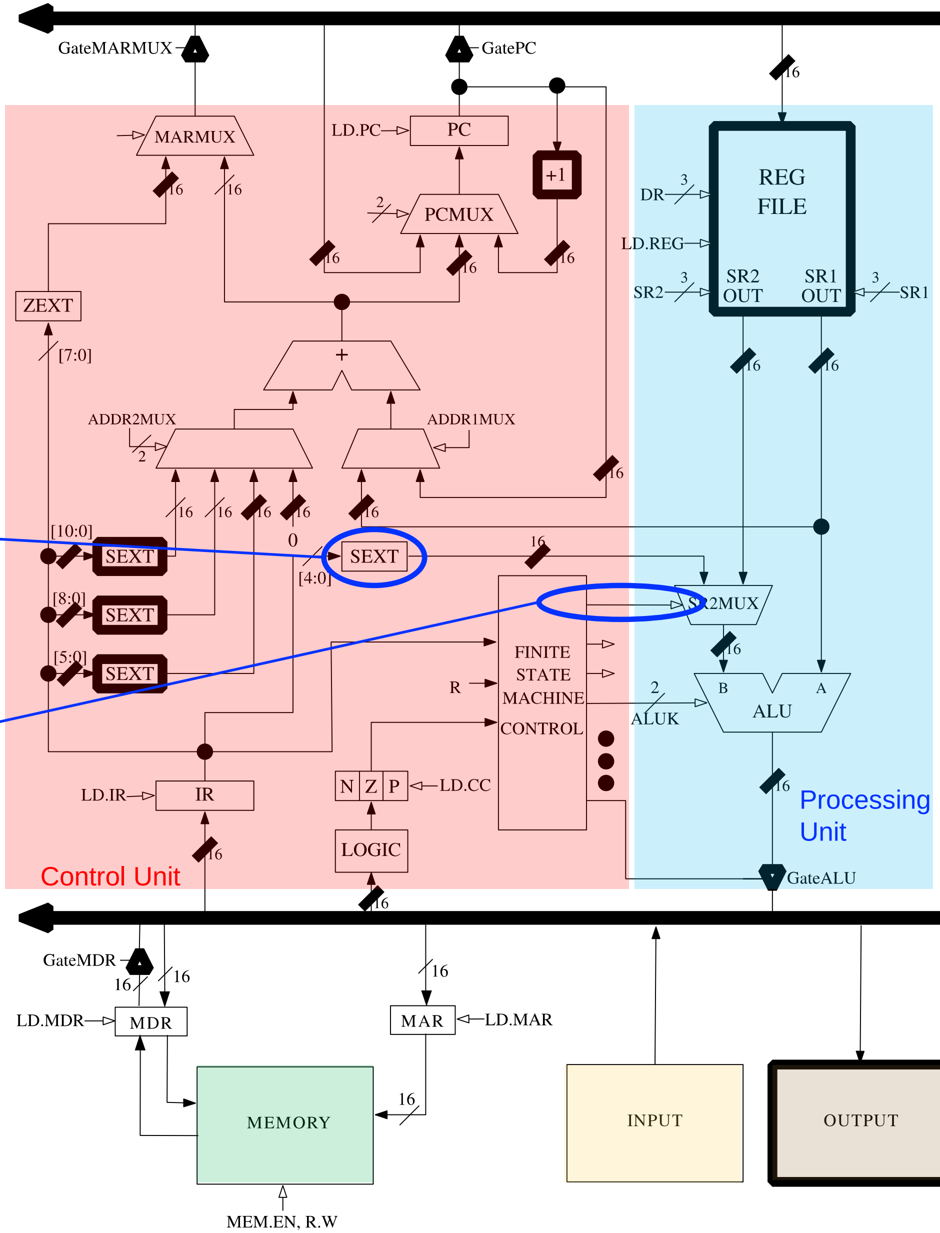
OP	DR	SR		imm5
0 0 0 1	0 0 1	1 0 0	1	1 1 1 1 0
15 12	11 9	8 6	5	4 0



ADD with one Literal in LC-3 Data Path

Sign extension (Operand)

Select Immediate or Register (as the 2nd input to instruction)



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
8	17	16	5

rt ← rs + sign-extend(imm)

Machine Code

op	rs	rt	imm
001000	10001	10010	0000 0000 0000 0101

0x22300005

Subtraction in MIPS vs. 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
```

(NOT R4, R3 / ADD R5, R4, #1: 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
```

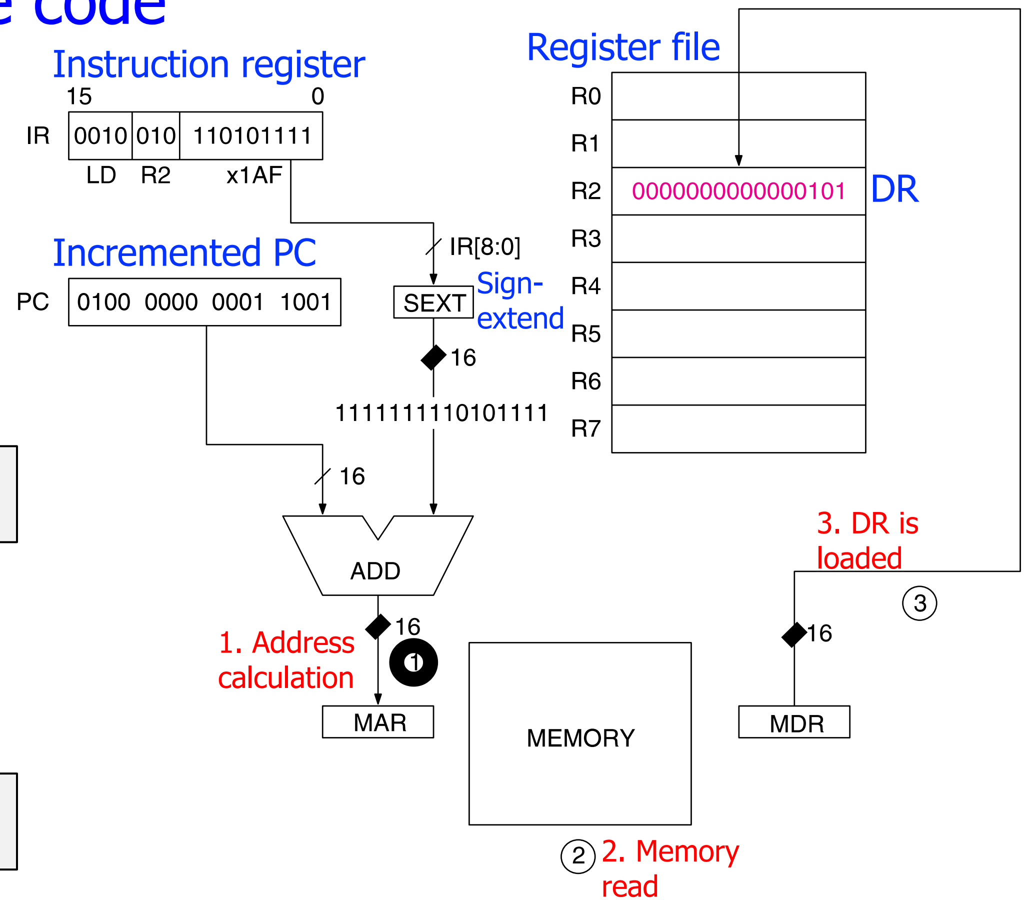
Field Values

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

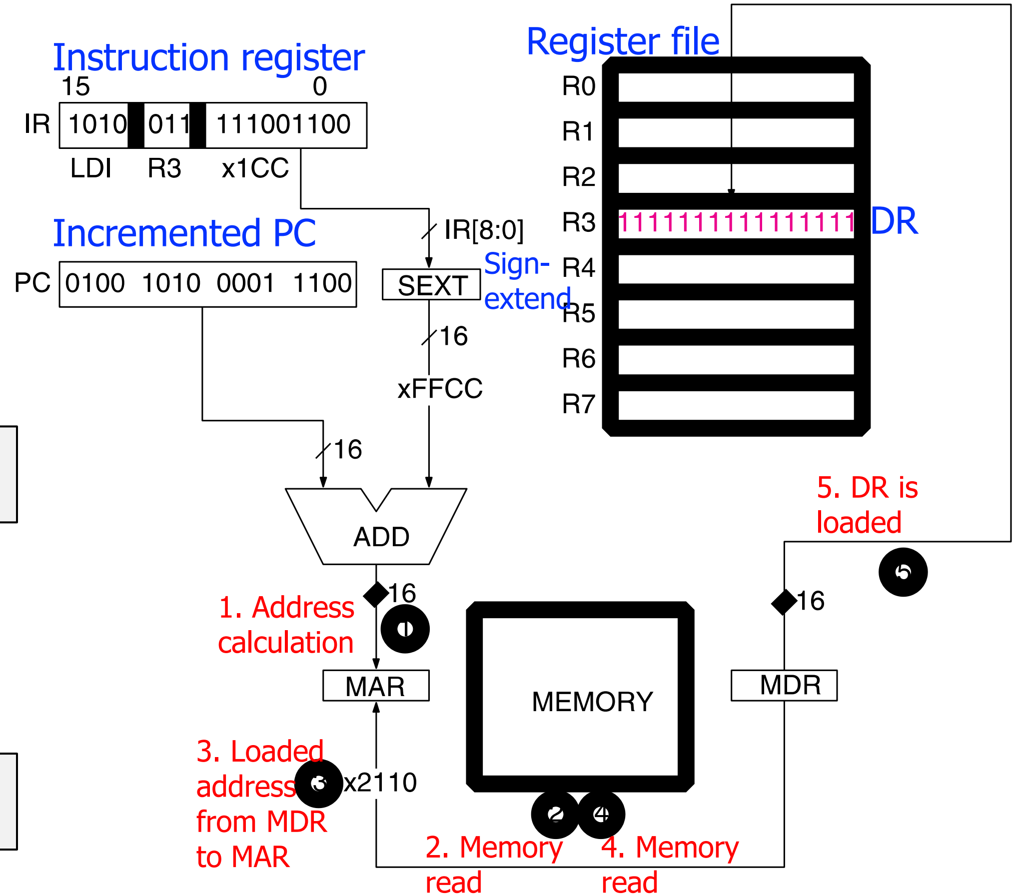
```
LDI R3, 0x1CC
```

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



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

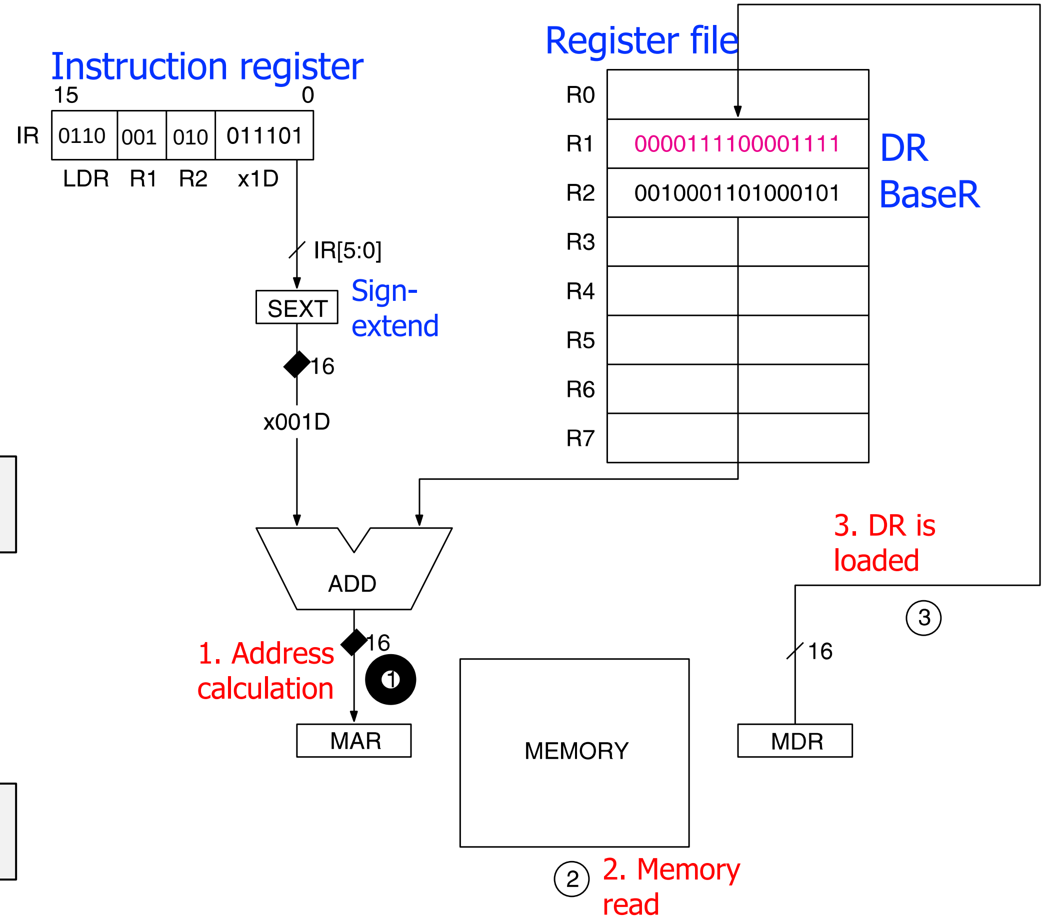
```
LDR R1, R2, 0x1D
```

Field Values

OP	DR	BaseR	offset6
6	1	2	0x1D

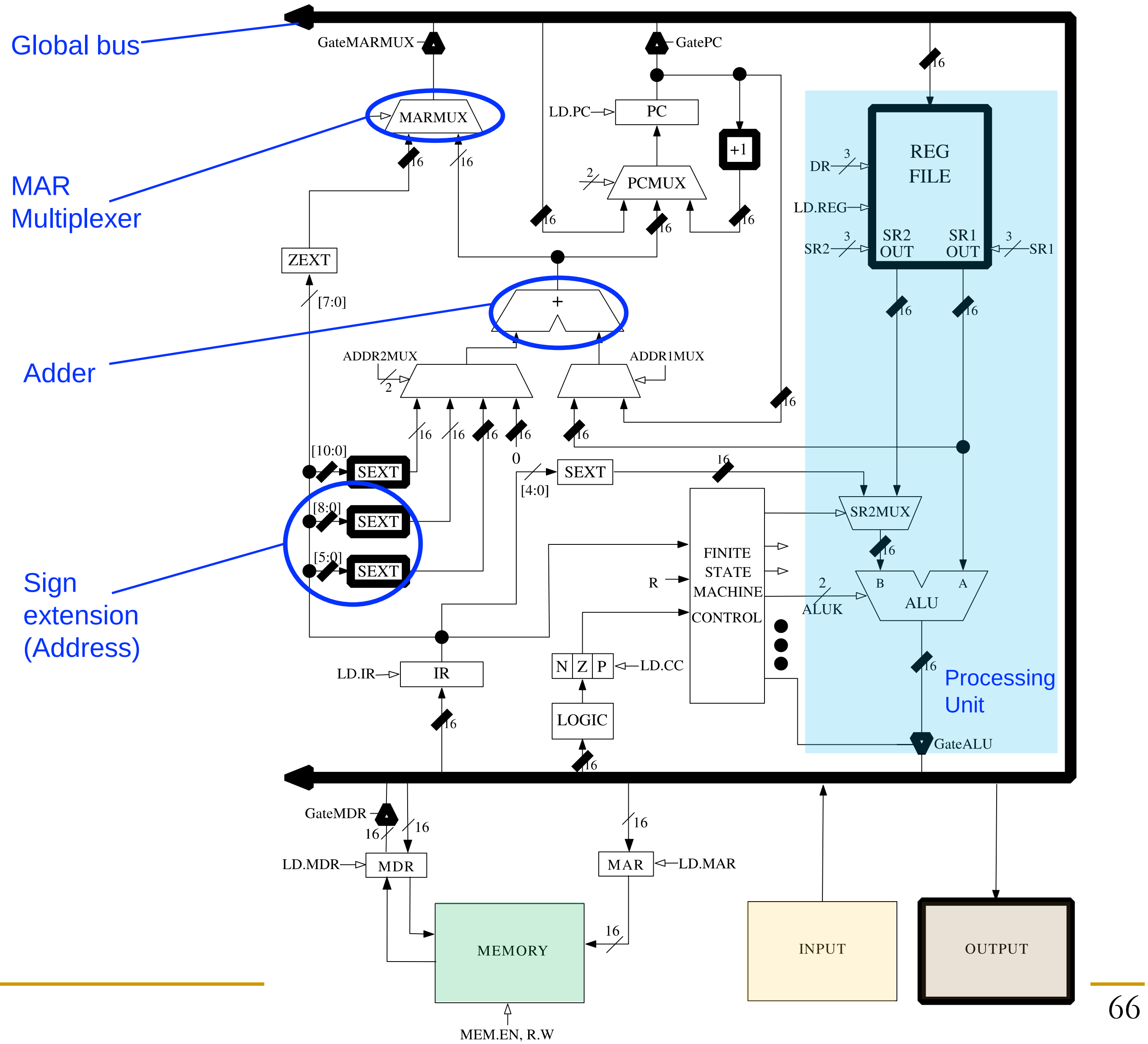
Machine Code

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

Address Calculation in LC-3 Data Path



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 (in LC-3)

- 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 load from memory, but LEA does not → Hence the name *Load Effective Address*

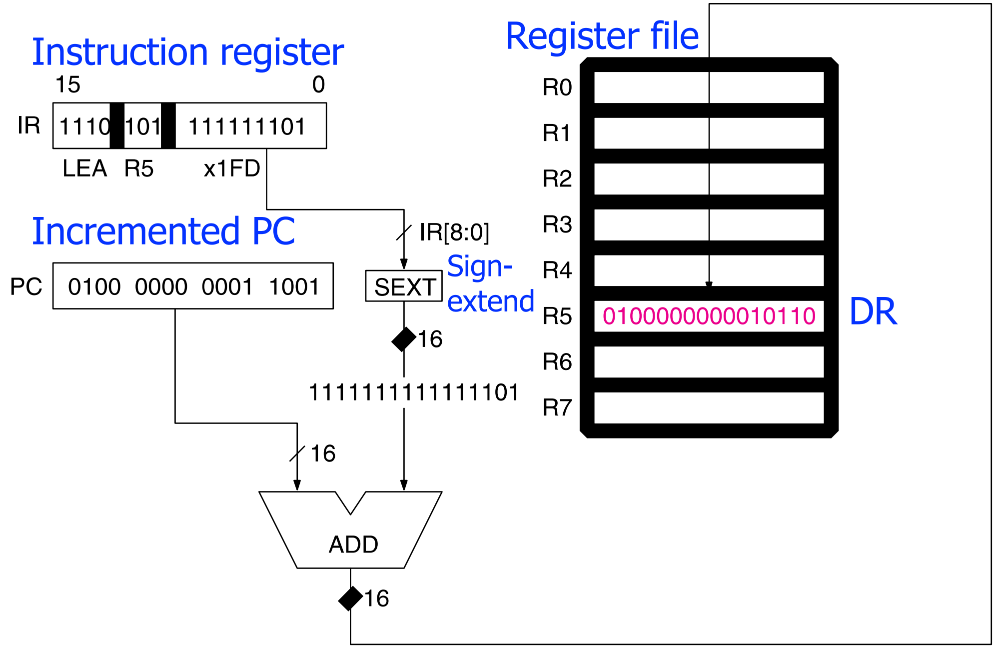
† This is the incremented PC

LEA in LC-3

- LEA assembly and machine code

LC-3 assembly

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



Field Values

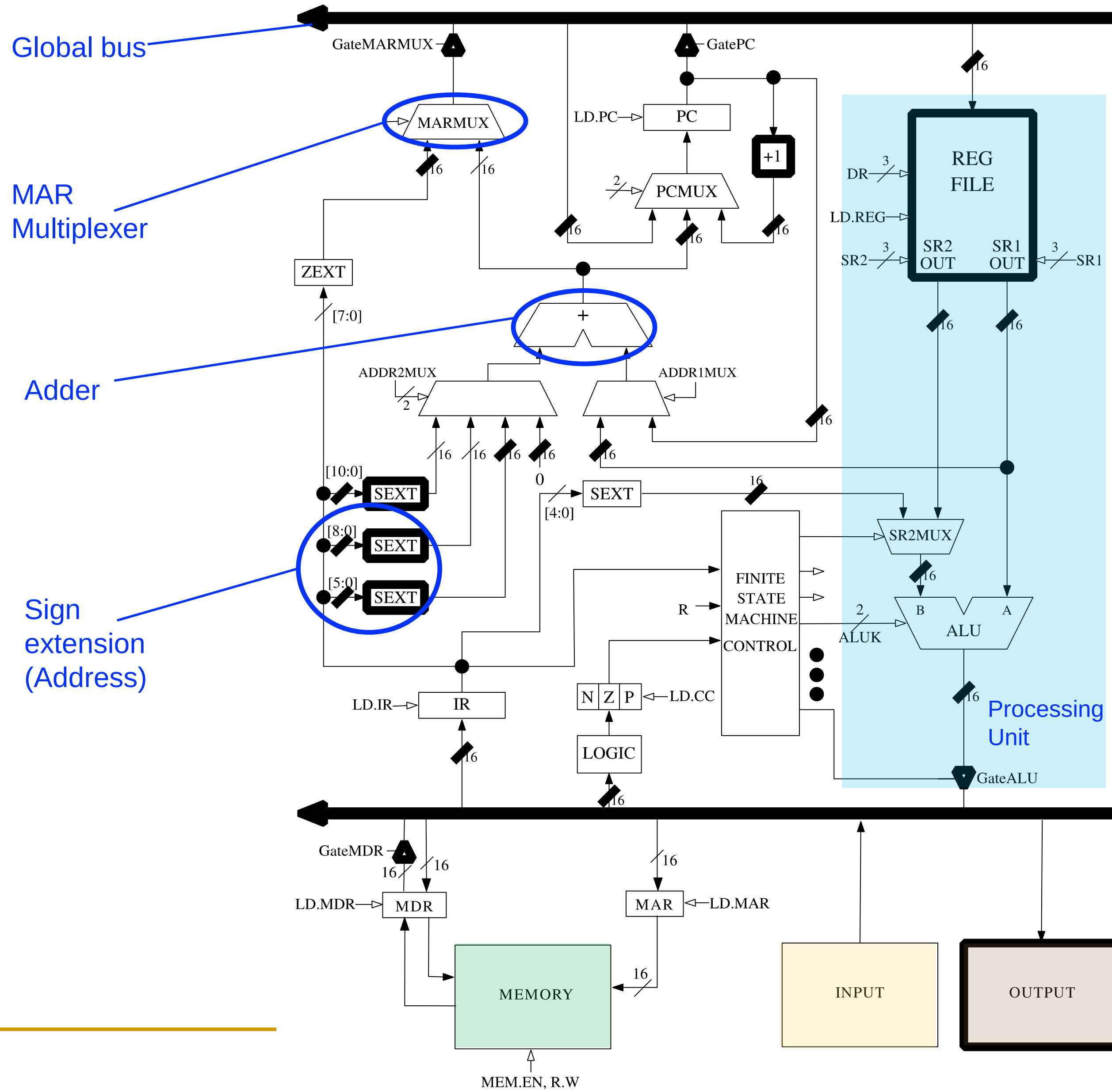
OP	DR	PCoffset9
E	5	0x1FD

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

Address Calculation in LC-3 Data Path



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
    - We have already seen these

Conditional Control Flow (Conditional Branching)

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

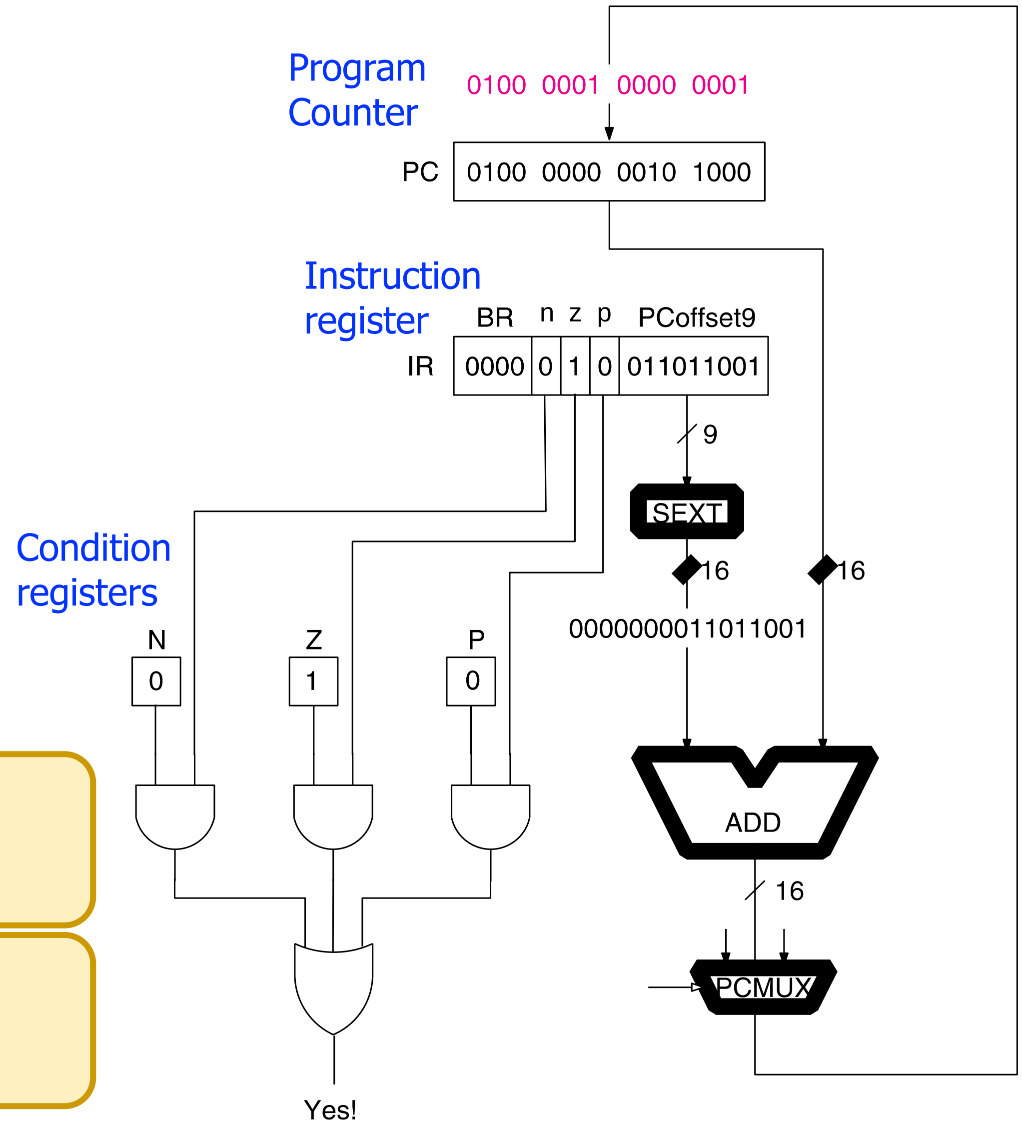
  - n, z, p = which condition code is tested (N, Z, and/or P)
    - n, z, p: instruction bits to identify the condition codes to be tested
    - N, Z, P: values of the corresponding condition codes
  - PCoffset9 = immediate or constant value
  - if ((n AND N) OR (p AND P) OR (z AND Z))
    - then PC ← 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 $\leftarrow$ 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

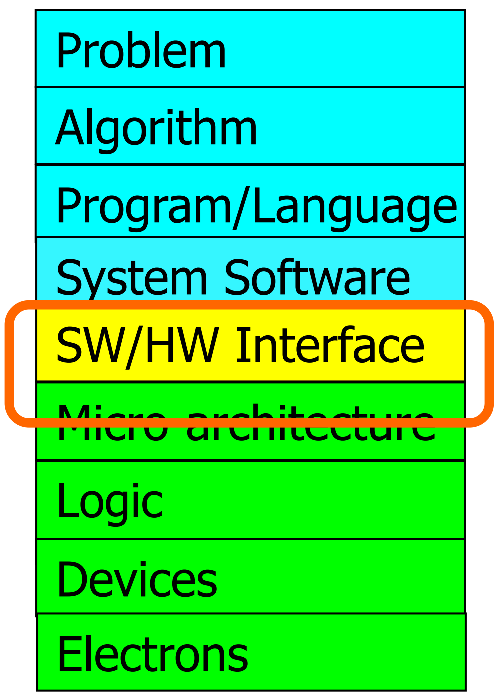
```
NOT  R2, R1
ADD  R3, R2, #1
ADD  R4, R3, R0
BRz  offset
```

Subtract (R0 - R1)

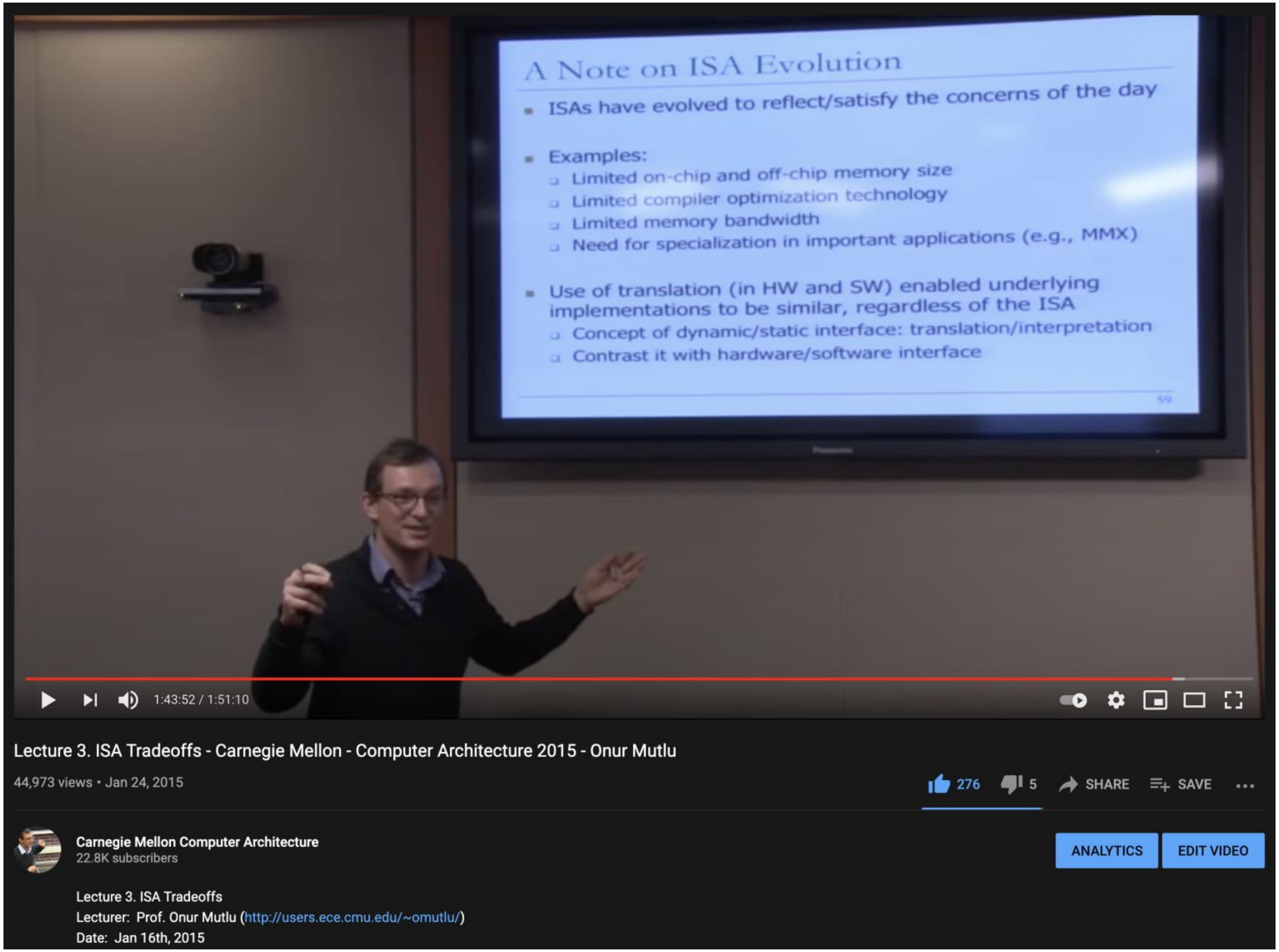
- This is an example of tradeoff in the instruction set
  - The same functionality requires more instructions in LC-3
  - But, the control logic requires more complexity in MIPS

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



There Is A Lot More to Cover on ISAs



https://www.youtube.com/onurmutlulectures

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 instructions, data types, addr. modes

Complex vs. Simple Instructions+Data Types

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

- 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+Data Types

- Advantages of Complex Instructions + Data Types

  + 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

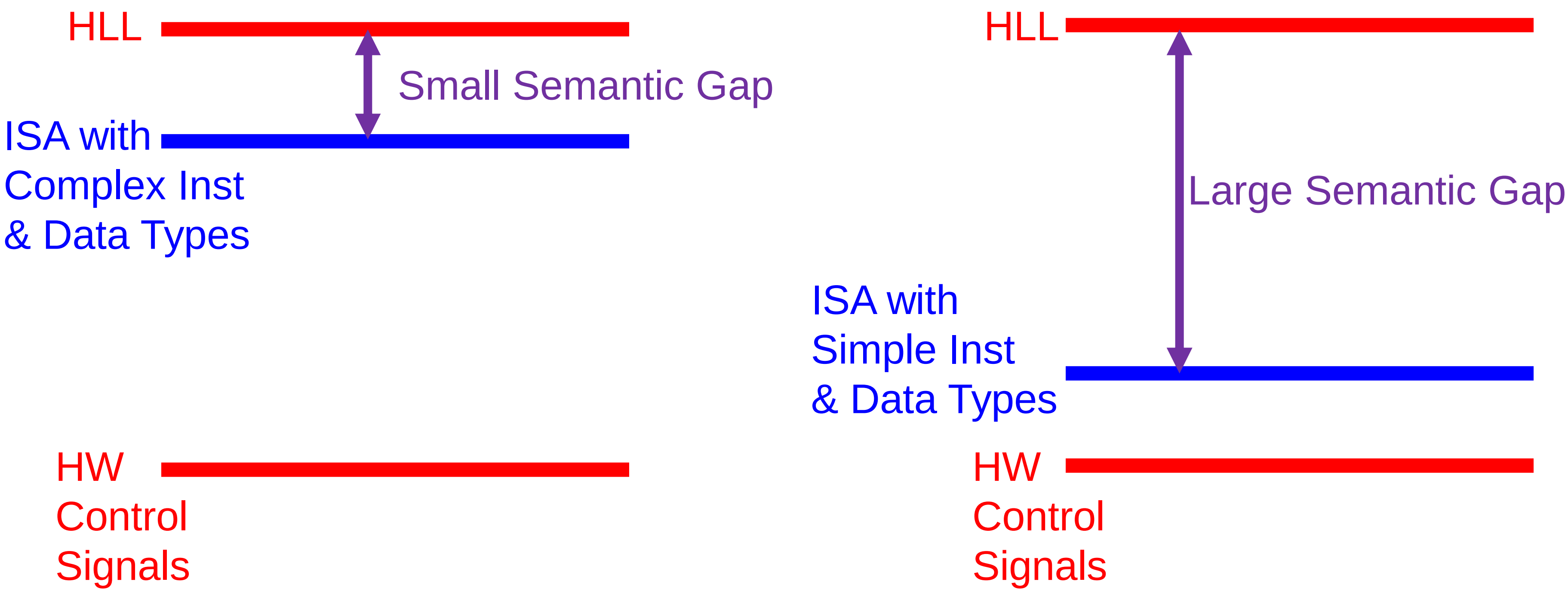
- Disadvantages of Complex Instructions + Data Types

  - 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

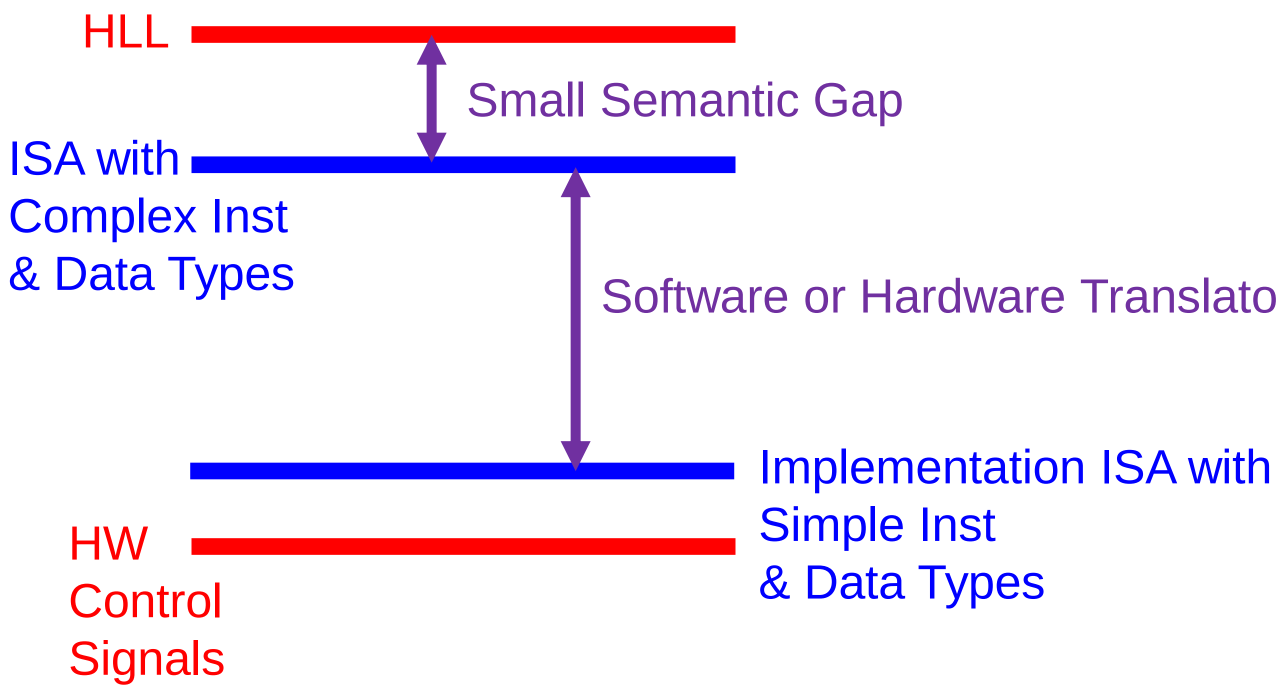
Semantic Gap

- How close instructions & data types are to high-level language (HLL)



How to Change the Semantic Gap Tradeoffs

- Translate into a different intermediate ISA



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

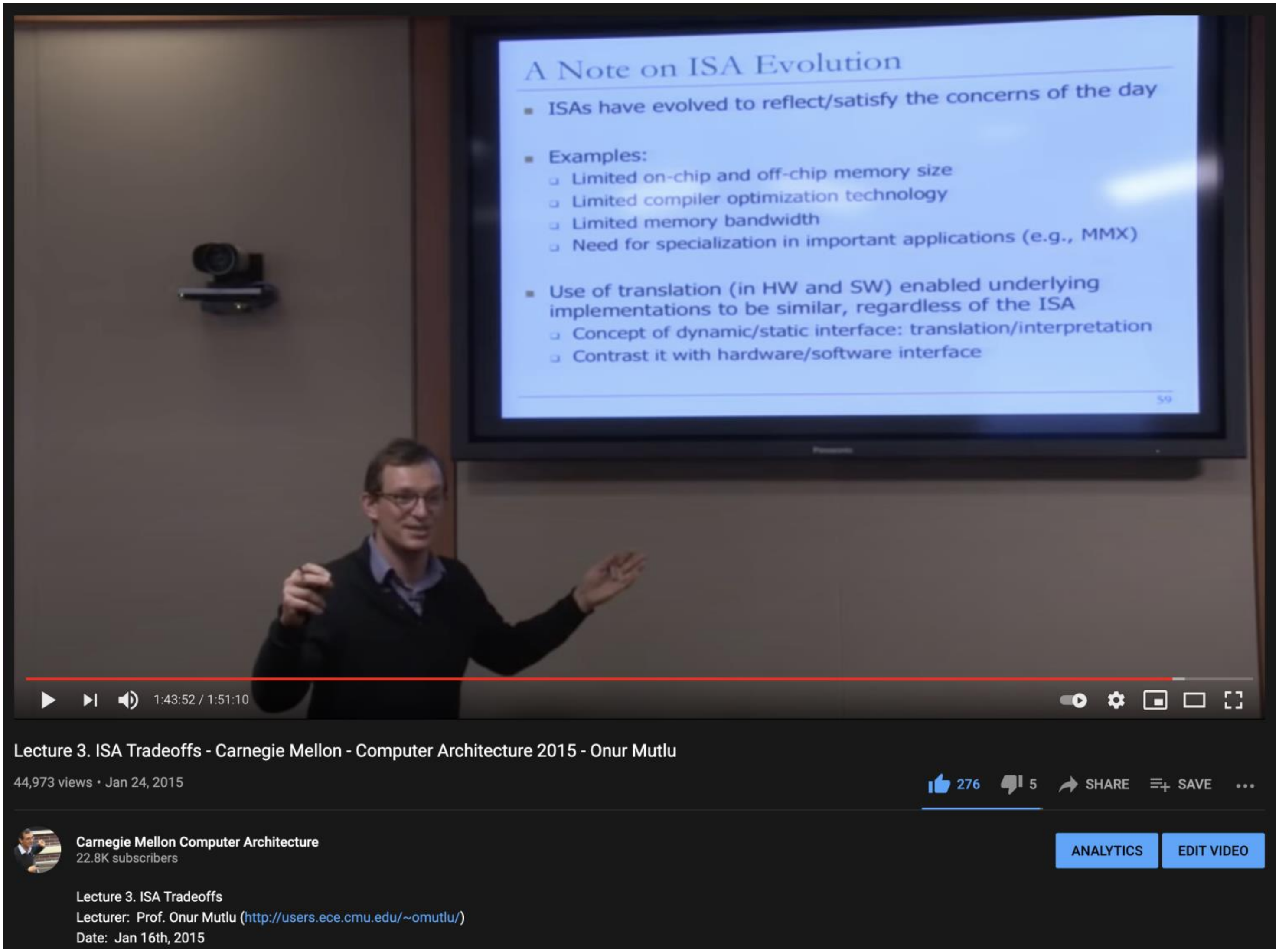
- Large number of registers:

  + 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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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 2022

25 March 2022