L3 – Deeper Dive on ISAs and LC2k

EECS 370 – Introduction to Computer Organization – Fall 2022

L3_1 ISAs – Instructions and Memory

Learning Objectives

- Identify the addressing modes of memory operations used in assembly-language instructions and programs
- Understand encoding of addressing for assembly-language instructions for load, store, and branching instructions
- Usage and encoding of labels for assembly-language programs

Resources

- Many resources on 370 website
  - [EECS 370 Resources]
    - ARMv8 references
    - Binary, Hex, and 2's compliment - [YouTube channel]
- Lecture and discussion recordings
- Piazza
- Office hours

What is a Bit?

- Bit: Smallest unit of data storage
  - Values `[0, 1]`
  - Many things will be measured (for size) in bits
    - 32-bit register – a register with 32 binary digits of storage capacity
    - 32-bit instruction – machine code instruction that has 32 binary digits, i.e., an unsigned integer in the range `0` to `2^32` (`0` to `4,294,967,296`)
    - 32-bit address – memory addresses with 32 binary digits
    - 32-bit operating system - computer with 32-bit addresses
- Byte: A collection of 8 bits (contiguous)
  - On many computers, the granularity for addresses
- Word: natural group of access in a computer
  - Usually 32 bits
  - Useful because most data exceeds 1 byte of storage need

Assembly and Machine Code

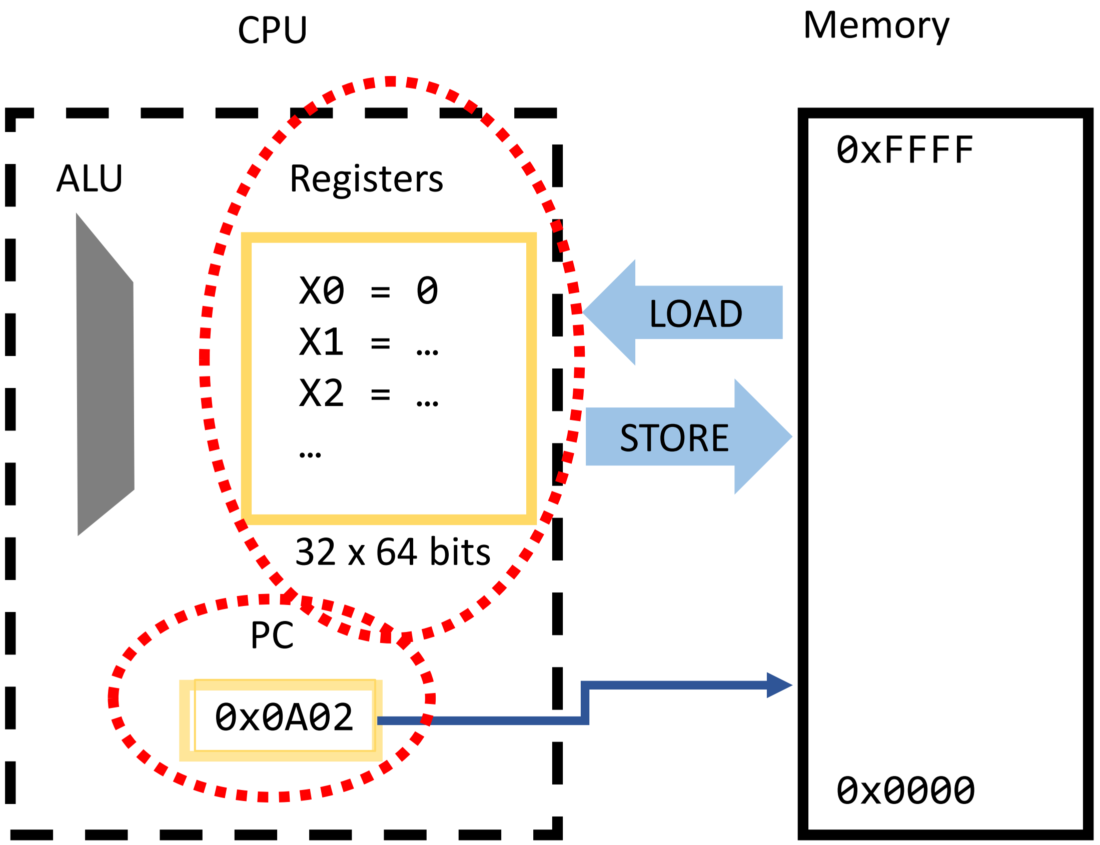
Review!
Example ISA

- von Neumann architecture: computers store data and instructions in the same memory
- Instructions *are* data, *encoded* as a **number**

	opcode	dest	src1	src2
Assembly code	ADD	X2	X3	X1
Machine code	011011	010	011	001

Registers

- Registers
  - Small array of storage locations in the processor – general purpose registers
  - Part of the processor – fast to access
  - Direct addressing only
    - That means they can not be accessed by an offset from another address
  - Special purpose registers
    - Examples: program counter (PC), instruction register (IR)



Registers

- ARMv8
  - We will use LEGv8 from Patterson & Hennessy textbook
  - 32 registers, `X0` through `X31`
  - 64-bit wide (64 bits of storage for each register)
  - Some have special uses, e.g., `X31` always contains the value `0`

- LC-2K
  - Architecture used in course projects
  - 8 registers, 32 bits wide each

LC2K is same as LC-2K
Appears both ways in documents in 370

Special Purpose Registers

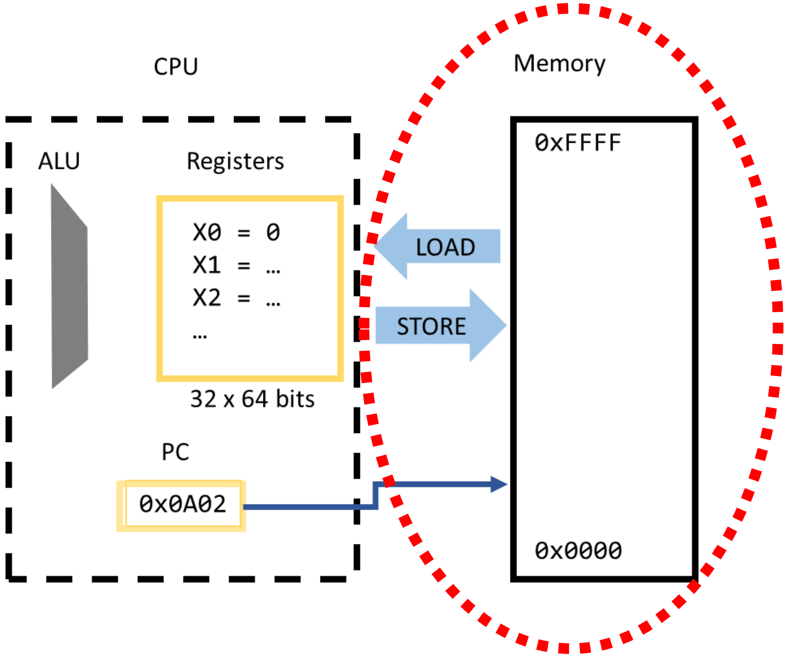
- Return address
  - Example: ARM register X30, also known as Link Register (LR)
  - Holds the return address or link address of a subroutine
- Stack pointer
  - Examples: ARM register X28 – SP, or x86 ESP
  - Holds the memory address of the stack
- Frame pointer
  - Example: ARM register X29 – FP
  - Holds the memory address of the start of the stack frame
- Program counter (usually referred to as PC)
  - Cannot be accessed directly in most architectures
    - This would be a security problem!

These registers store memory addresses

Special Purpose Registers

- 0 value register (ARM register X31 – XZR)
  - no storage, reading always returns 0
  - lots of uses – ex: mov→add
- Status register
  - Examples: ARM SPSR, or x86 EFLAGs
  - Status bits set by various instructions
    - Compare, add (overflow and carry) etc.
  - Used by other instructions like conditional branches

Memory Storage

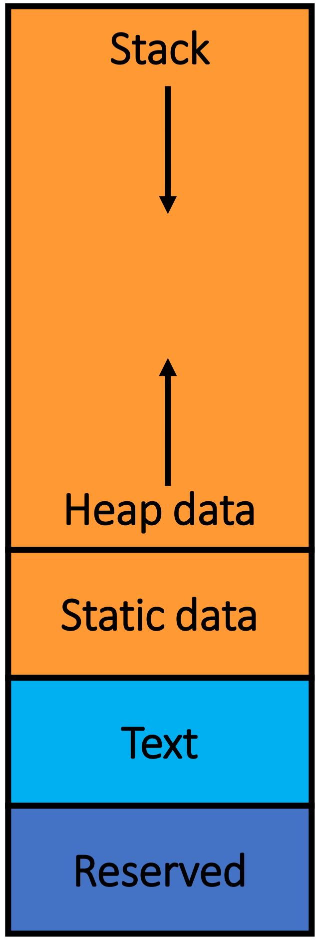


- Large array of storage accessed using memory addresses
- A machine with a 32-bit address can reference memory locations `0` to 2^{32}`-1` (or 4,294,967,295).
- A machine with a 64-bit address can reference memory locations `0` to 2^{64}`-1` (or 18,446,744,073,709,551,615—18 exa-locations)
  - In practice 64-bit machines do not have 64-bit physical addresses

Assembly instructions have multiple ways to access memory (i.e., addressing)

Memory: ARM (Linux) Memory Image

Review!



Activation records: local variables, parameters, etc.

Dynamically allocated data—`new` or `malloc()`

Global data and static local data

Machine code instructions (and some constants)

Reserved for operating system

Addressing Modes

- Addressing (accessing memory using addresses) modes for assembly instructions
  - Direct addressing – memory address is in the instruction
  - Register indirect – memory address is stored in a register
  - Base + displacement – register indirect plus an immediate value
  - PC-relative – base + displacement using the PC special-purpose register

Direct Addressing

Example ISA (Simplified)

- Specify the address as immediate (constant) in the instruction

```
load  r1, M[ 1500 ]   ; r1 <- contents of location 1500
jump #6000            ; jump to address 6000
```

Direct Addressing

Example ISA (Simplified)

- Specify the address as immediate (constant) in the instruction

```
load  r1, M[ 1500 ]   ; r1 <- contents of location 1500
jump #6000            ; jump to address 6000
```

- Not practical for something like ARMv8

```
load  r1, M[1073741823]
```
// 1073741823 is the address in memory

With 32-bit instruction encodings, a 32-bit address would fill the instruction!

Register Indirect

Example ISA (Simplified)

- Store reference address in a register

```
load r1, M[ r2 ]
add  r2, r2, #4
load r1, M[ r2 ]
```

Useful for pointers and arrays
`load r1, M[ r2 ]` is a pointer dereference in assembly

register file

R1	6666
R2	3340

memory

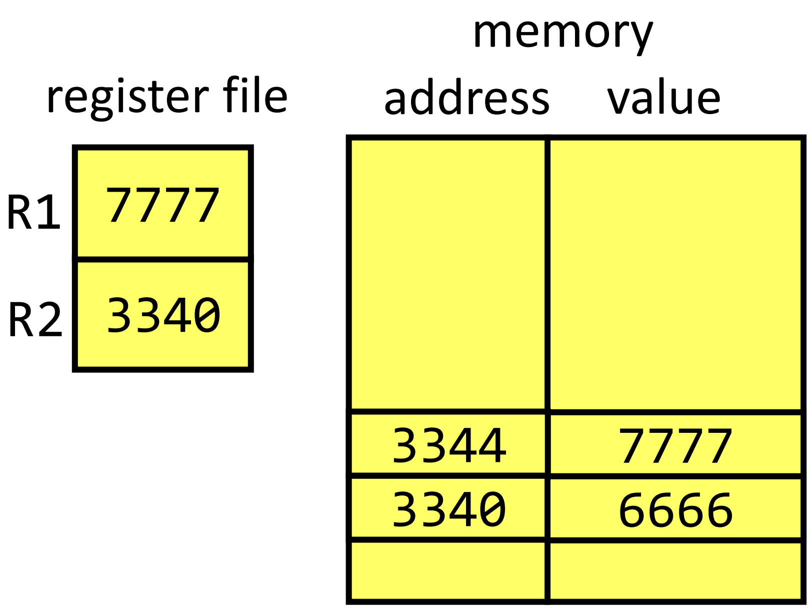
address	value
3344	7777
3340	6666

Base + Displacement

Example ISA (Simplified)

- Most common addressing mode
- Address is computed as register value + immediate

```
load r1, M[ r2 + 4 ]
```



Useful for accessing structures or class objects

C code

```
struct Distance {
  int feet;
  int inch;
} x, y;
```

```
x.feet = 11;
y.inches = 5;
```

Addressing Example 1

Example ISA (Simplified)

What are the contents of registers and memory after executing the assembly instructions?

```
load  r2, M[ r3 ]
load  r3, M[ r2 + 4 ]
store r3, M[ r2 + 8 ]
```

register file

R1	
R2	
R3	

memory

address	value
108	
104	
100	

Starting values

register file

R1	0
R2	10
R3	108

memory

address	value
108	100
104	-1
100	108

Addressing Example 1

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What are the contents of registers and memory after executing the assembly instructions?

```
load  r2, M[ r3 ]
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```
load  r2, M[ r3 ]
```

register file

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Starting values

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Addressing Example 1

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register file

R1	0
R2	100
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memory

address	value
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Starting values

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Addressing Example 1

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What are the contents of registers and memory after executing the assembly instructions?

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load  r3, M[ r2 + 4 ]
store r3, M[ r2 + 8 ]
```

```
store r3, M[ r2 + 8 ]
```

register file

R1	0
R2	100
R3	-1

memory

address	value
108	-1
104	-1
100	108

Starting values

register file

R1	0
R2	10
R3	108

memory

address	value
108	100
104	-1
100	108

Program Counter (PC) Relative

Example ISA (Simplified)

- Useful for project - P1a
- Variation of base + displacement
- PC register is the base

Useful for branch instructions!

Relative distance from PC can be positive or negative

```
jump  [ -8 ]

jump  [ 2 ]
```

PC-Relative Addressing

LC-2K ISA

- Machine language instructions (encoded from an assembler) use numbers for pc-relative addressing'
- Assembly language instructions (written by people) use ***labels***

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LC-2K ISA

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- Assembly language instructions (written by people) use ***labels***

```
Address
      0           lw 0 1 five     load reg1 with 5 (symbolic address)
      1           lw 1 2 3        load reg2 with -1 (numeric address)
      2   start   add 1 2 1       decrement reg1
      3           beq 0 1 2       goto end of program when reg1==0
      4           beq 0 0 start   go back to the beginning of the loop
      5           noop
      6   done    halt            end of program
      7   five    .fill 5
      8   neg1    .fill -1
      9   stAddr  .fill start     will contain the address of start (2)
```

PC-Relative Addressing

LC-2K ISA

```
Address
      0          lw 0 1 five    load reg1 with 5 (symbolic address)
      1          lw 1 2 3       load reg2 with -1 (numeric address)
      2   start  add 1 2 1      decrement reg1
      3          beq 0 1 2      goto end of program when reg1==0
      4          beq 0 0 start  go back to the beginning of the loop
      5          noop
      6   done   halt           end of program
      7   five   .fill 5
      8   neg1   .fill -1
      9   stAddr .fill start    will contain the address of start (2)
```

Project P1a

- After reading specification, downloading starter files, creating project…

- Write test cases to verify your C code
  - Test cases written in LC-2K assembly
- Recommended for a start:

```
t0.ac: halt
t1.ac: noop
       halt
t2.ac: add 1 2 3
       halt
```

```
t3.ac: nor 3 1 4
       halt
```

L3_2 Two's Complement

Learning Objectives

- Represent signed and unsigned numbers in binary (base 2)
- Negate positive and negative signed values
- Complete arithmetic operations (addition and subtraction) by hand using signed and unsigned binary numbers

Binary Review

Review!

- Before starting this module, get comfortable with representing numbers in binary
- Resources (accessible from the course website)
  - Video reviews

  - Resource documents (EECS 370 website):

  EECS 370: An introduction to binary numbers and 2's complement notation

Binary Addition

Review!

- We can already represent non-negative numbers in binary

```
6 (base 10) = 2² (4) + 2¹ (2) = 110 (base 2)
```

- We can do arithmetic with binary numbers

3 + 2 = 5 (base 10)	3 + 5 = 8 (base 10)

What about Negative Numbers?

- Thoughts: add another bit for sign, use one of the existing bits for sign

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1   2

1: $5 = 0101$ $\boxed{1}0101$ $-5 = \boxed{0}0101$

sign bit

2: $\boxed{0}101$

sign bit

What about Negative Numbers?

- Design space preferences:
  - Representation of positive and negative values
  - Representation of signed and unsigned values
  - Single way to represent 0
  - Equal magnitude of positive and negative values (roughly)
  - Simple (not complex) to detect sign (positive or negative)
  - Simple negation of a number
  - Simple storage for signed and unsigned
  - Simple, non-redundant hardware for operations
    - E.g., one hardware addition unit for signed and unsigned numbers

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  - Simple storage for signed and unsigned
  - Simple, non-redundant hardware for operations
    - E.g., one hardware addition unit for signed and unsigned numbers

- Thought: use existing bit of binary number for signed values

Two's Complement

Unsigned Binary Representation

- 1011 in binary is 13 in decimal

$$\begin{array}{cccc} 1 & 1 & 0 & 1 \\ 2^3 & 2^2 & 2^1 & 2^0 \end{array} = 8 + 4 + 1 = 13$$

Two's Complement Binary Representation

- 1011 in binary is 13 in decimal

$$\underset{2^3}{1} \quad \underset{2^2}{1} \quad \underset{2^1}{0} \quad \underset{2^0}{1} = 8 + 4 + 1 = 13$$

- Two's complement numbers are very similar to unsigned binary

EXCEPT the first (most significant) digit is negative in two's complement

$$\underset{-(2^3)}{1} \quad \underset{2^2}{1} \quad \underset{2^1}{0} \quad \underset{2^0}{1} = -8 + 4 + 1 = -3$$

Two's Complement – Exercise 1

What is 1010 (binary)

4 BITS

1. Decimal unsigned value?
2. Decimal signed (two's complement) value?

unsigned

1 0 1 0

2^3 2^2 2^1 2^0

Signed – 2's complement

1 0 1 0

$-(2^3)$ 2^2 2^1 2^0

Two's Complement – Exercise 1

What is 1010 (binary)

1. Decimal unsigned value?
2. Decimal signed (two's complement) value?

unsigned

1 0 1 0

2^3 2^2 2^1 2^0

8 + 2 = 10

Signed – 2's complement

1 0 1 0

$-(2^3)$ 2^2 2^1 2^0

-8 + 2 = -6

Two's Complement Range

- What is the range of representation of a 4-bit 2's complement number?
  - [-8, 7]
- What is the range of representation of an n-bit 2's complement number?
  - $[\ -2^{(n-1)}\ ,\ 2^{(n-1)}\ -1\ ]$

Negating Two's Complement

- Useful trick: You can negate a 2's complement number by inverting all the bits and adding 1.

5 (decimal) in binary is		0	1	0	1
Negate (invert) all bits		1	0	1	0
Add 1		1	0	1	0
	+	0	0	0	1
		1	0	1	1
		$-(2^3)$	2^2	2^1	2^0

$-8 + 0 + 2 + 1 = -5$

Two's Complement – Exercise 2

How would you represent -3 (decimal) in 2's complement binary using 4 bits?

Two's Complement – Exercise 2

How would you represent -3 (decimal) in 2's complement binary using 4 bits?

1. Convert 3 (decimal) to binary
2. Negate binary
    1. Invert all bits
    2. Add one

Two's Complement – Exercise 2

How would you represent -3 (decimal) in 2's complement binary using 4 bits?

1. Convert 3 (decimal) to binary
2. Negate binary
   1. Invert all bits
   2. Add one

1. Convert 3 to binary
   1. 3 -> 0011
2. Convert to 2's complement
   1. 0011 -> 1100
   2. 1100 + 1 = 1101

Signed – 2's complement

1	1	0	1
-2^3	2^2	2^1	2^0

$-8 + 4 + 0 + 1 = -3$

Sign Extension

- With two's compliment, it matters how many bits are used!

```
5 (decimal) in binary (4 bits) is   0101
5 (decimal) in binary (8 bits) is   0000 0101

-5 (decimal) in binary (4 bits) is  1011
-5 (decimal) in binary (8 bits) is  1111 1011
                                    NOT 0000 1011
```

need to **extend the most significant (sign) bit**

LC-2K: programmer (you) need to do this!

Two’s Complement Arithmetic

Decimal	2’s Complement Binary	Decimal	2’s Complement Binary
0	0000	-1	1111
1	0001	-2	1110
2	0010	-3	1101
3	0011	-4	1100
4	0100	-5	1011
5	0101	-6	1010
6	0110	-7	1001
7	0111	-8	1000

7 – 6 = 7 + (-6) = 1

6 – 7 = 6 + (-7) = -1

L3_3 LC-2K ISA

Learning Objectives

- Recognize the set of instructions for LC-2K Architecture (ISA) and be able to describe the operations and operands for each instruction
- Ability to create simple LC-2K assembly programs, e.g., using addition and branching.
- Understand and be able to replicate the encoding (translation from assembly to machine code) of instructions for any LC-2K assembly program

LC-2K Processor

LC-2K ISA

- 32-bit processor
  - Instructions are 32 bits
  - Integer registers are 32 bits
- 8 registers
- supports 65536 words of memory (addressable space)
- 8 instructions in the following common categories:
  - Arithmetic: `add`
  - Logical: `nor`
  - Data transfer: `lw, sw`
  - Conditional branch: `beq`
  - Unconditional branch (jump) and link: `jalr`
  - Other: `halt, noop`

LC-2K ISA

Instruction Encoding

- The Instruction Set Architecture (aka Architecture) defines the mapping of assembly instructions to machine code

```
add  1  2  3    // r3 = r1 + r2
```

31-25	24-22	21-19	18-16	15-3	2-0
unused	**opcode**	**regA**	**regB**	*unused*	**destR**

Instruction Formats – R-type, I-type

- Tells you which bit fields correspond to which part of an assembly instruction
- R-type (register) – `add` (opcode `000`), `nor` (opcode `001`)

31-25	24-22	21-19	18-16	15-3	2-0
unused	**opcode**	**regA**	**regB**	*unused*	**destR**

- I-type (immediate) - `lw` (opcode `010`), `sw` (opcode `011`), `beq` (opcode `100`)

31-25	24-22	21-19	18-16	15-0
unused	**opcode**	**regA**	**regB**	**offset**

Instruction Formats – J-type, O-type

- J-type (jump) – `jalr` (opcode `101`)

31-25	24-22	21-19	18-16	15-0
unused	**opcode**	**regA**	**regB**	*unused*

- O-type (???) - `halt` (opcode `110`), `noop` (opcode `111`)

31-25	24-22	21-0
unused	**opcode**	*unused*

Instruction Formats

- The Instruction Set Architecture (aka Architecture) defines the mapping of assembly instructions to machine code

<table>
<tr><th>Instruction Type</th><th>Instruction</th><th>Bits 31-25</th><th>Bits 24-22</th><th>Bits 21-19</th><th>Bits 18-16</th><th>Bits 15-3</th><th>Bits 2-0</th></tr>
<tr><td rowspan="2">R-type</td><td>add</td><td rowspan="8">unused</td><td rowspan="8">opcode</td><td rowspan="6">reg A</td><td rowspan="6">reg B</td><td rowspan="2">unused</td><td rowspan="2">destReg</td></tr>
<tr><td>nor</td></tr>
<tr><td rowspan="3">I-type</td><td>lw</td><td colspan="2" rowspan="3">offsetField
16-bit, 2’s complement number
range:[-32768, 32767]</td></tr>
<tr><td>sw</td></tr>
<tr><td>beq</td></tr>
<tr><td>J-type</td><td>jalr</td><td colspan="2">unused</td></tr>
<tr><td rowspan="2">O-type</td><td>halt</td><td colspan="4" rowspan="2">unused</td></tr>
<tr><td>noop</td></tr>
</table>

Unused: all unused bits should always be 0

Bit Encodings

- Opcode binary encodings:
  - `add (000), nor (001), lw (010), sw (011), beq (100), jalr (101), halt (110), noop (111)`
- Register operands
  - Binary encoding of register number, e.g., `r2 = 2 = 010`
- Immediate values
  - Binary encoding *using 2's complement values*
  - Give all available bits a value – *do not forget sign extension!*

Encoding Example #1 - **nor**

`nor 3 4 7` (r7 = r3 nor r4)

31-25	24-22	21-19	18-16	15-3	2-0
unused	**opcode**	**regA**	**regB**	*unused*	**destR**

Encoding Example #1 - **nor**

`nor   3     4     7          (r7 = r3 nor r4)`

31-25	24-22	21-19	18-16	15-3	2-0
unused	**opcode**	**regA**	**regB**	*unused*	**destR**
0000000	001	011	100	0000000000000	111

`0000 0000 0101 1100 0000 0000 0000 0111`

Convert to Hex ⍰ 0x005C0007

Convert to Dec ⍰ 6029319

Encoding Example #2 - `lw`

`lw 5 2 -8` `(r2 = M[r5 + -8])`

31-25	24-22	21-19	18-16	15-0
unused	**opcode**	**regA**	**regB**	**offset**

Encoding Example #2 - `lw`

```
lw   5     2     -8       (r2 = M[r5 + -8])
```

31-25	24-22	21-19	18-16	15-0
unused	**opcode**	**regA**	**regB**	**offset**
0000000	010	101	010	1111111111111000

```
0000 0000 1010 1010 1111 1111 1111 1000
```

Convert to Hex ⍰ 0x00AAFFF8

Convert to Dec ⍰ 11206648

Encoding Example #3 - `add`

- Compute the encoding in Hex for:

```
add  3   7   3    (r3 = r3 + r7)    (add = 000)
```

Encoding Example #3 - **add**

- Compute the encoding in Hex for:

```
add  3   7   3     (r3 = r3 + r7)     (add = 000)
```

31-25	24-22	21-19	18-16	15-3	2-0
unused	**opcode**	**regA**	**regB**	*unused*	**destR**
0000000	000	011	111	000…000	011

Convert to Hex 0x001F000003
Convert to Dec 2031619

Encoding Example #4 - `sw`

- Compute the encoding in Hex for:

```
sw  1   5  67      (M[r1+67] = r5)   (sw = 011)
```

31-25	24-22	21-19	18-16	15-0
unused	**opcode**	**regA**	**regB**	**offset**

Encoding Example #4 - `sw`

- Compute the encoding in Hex for:

```
sw  1   5  67      (M[r1+67] = r5)    (sw = 011)
```

31-25	24-22	21-19	18-16	15-0
unused	**opcode**	**regA**	**regB**	**offset**
0000000	011	001	101	0000000001000011

Convert to Hex 0x00CD0043
Convert to Dec 13434947

Assembler, aka, P1a

- Each line of assembly code corresponds to a number
  - “add 0 0 0” is just 0.
  - “lw 5 2 -8” is 11206648
- Assembly code is how people write instructions for an ISA
  - We only use assembly because it’s easier to read.
- Assembly code must be assembled (instructions encoded) to machine code for execution

Assembler Directive - `.fill`

- You might want a number to be, well, a number.
  - Data for `lw`, `sw` instructions will be added to LC-2K assembly code file

- `.fill` tells the assembler to put a number instead of an instruction

- The syntax (to have a value of 7) is just `.fill 7`

- Question:
  - What do `.fill 7` and `add 0 0 7` have in common?

Assembler Directive - `.fill`

- You might want a number to be, well, a number.
  - Data for `lw`, `sw` instructions will be added to LC-2K assembly code file
- `.fill` tells the assembler to put a number instead of an instruction
- The syntax (to have a value of 7) is just `.fill 7`
- Question:
  - What do `.fill 7` and `add 0 0 7` have in common?

They have the same value in machine code: 7 (decimal) 111 (binary)
really `0000 0000 0000 0000 0000 0000 0000 0111`

Labels in LC-2K

- Labels are used in lw/sw instructions or beq instruction
- For `lw` or `sw` instructions, the assembler should compute `offsetField` to be equal to the address of the label
  - i.e. `offsetField` = address of the label
- For `beq` instructions, the assembler should translate the label into the numeric `offsetField` needed to branch to that label
  - i.e. `PC+1+ offsetField` = address of the label

Labels in LC-2K – Example #1

- Labels are a way of referring to a line in an assembly-language program

```
loop   beq   3   4   end
       noop
       beq   1   3   loop
end    halt
```

Labels in LC-2K – Example #1

- Labels are a way of referring to a line in an assembly-language program

```
loop   beq   3   4   end
       noop
       beq   1   3   loop
end    halt
```

```
loop  is address 0
end is address 3
```

Replacing use of labels with values

Addresses	instructions				
0	loop	beq	3	4	2
1		noop			
2		beq	1	3	-3
3	end	halt			

Program in LC-2K – Example

1. Encode program instructions 2. What does this program do?

```
loop  lw   0  1  one
      add  1  1  1
      sw   0  1  one
      halt
one   .fill 1
```

Program in LC-2K – Example

1. Encode program instructions 2. What does this program do?

```
loop   lw    0   1   one
       add   1   1   1
       sw    0   1   one
       halt
one    .fill 1
```

Program in LC-2K – Example

1. Encode program instructions 2. What does this program do?

test.as	test.mc
`loop  lw    0   1   one`	8454148
`      add   1   1   1`	589825
`      sw    0   1   one`	12648452
`      halt`	25165824
`one   .fill 1`	1

Logistics

- There are two worksheets for lecture 3
    1. Addressing and 2’s complement
    2. LC-2K program encoding