CENG3420

Lab 2-1: LC-3b Simulator

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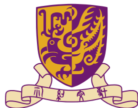

香港中文大學
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Overview

LC-3b Basis

LC-3b Assembly Examples

LC-3b Simulator

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Assembler & Simulator

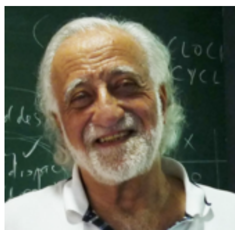
- Assembly language – symbolic (MIPS, LC-3b, ...)
- Machine language – binary

- Assembler is a program that
  - turns symbols into machine instructions.
  - EX: lc3b_asm, SPIM, ...

- Simulator is a program that
  - mimics the behavior of a processor
  - usually in high-level language
  - EX: lc3b_sim, SPIM, ...

LC-3b

- LC-3b: **Little Computer 3, b** version.
- Relatively simple instruction set
- Most used in teaching for CS & CE
- Developed by Yale Patt@UT & Sanjay J. Patel@UIUC



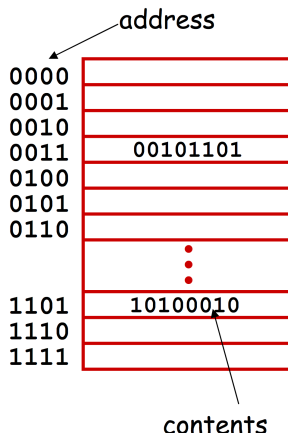
LC-3 Architecture

- RISC – only 15 instructions
- 16-bit data and address
- 8 general-purpose registers (GPR)

Plus 4 special-purpose registers:

- Program Counter (PC)
- Instruction Register (IR)
- Condition Code Register (CC)
- Process Status Register (PSR)

Memory



$2^k \times m$ array of stored bits:

Address

- unique (k-bit) identifier of location
- LC-3: $k = 16$

Contents

- m-bit value stored in location
- LC-3: $m = 16$

Basic Operations:

- READ (Load): value in a memory location $\rightarrow$ the Processor
- WRITE (Store): value in the Processor $\rightarrow$ a memory location

Interface to Memory

How does the processing unit get data to/from memory?

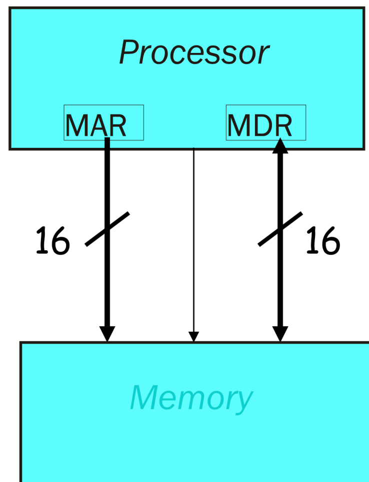
- MAR: Memory Address Register
- MDR: Memory Data Register

To LOAD from a location (A):

1. Write the address (A) into the MAR.
2. Send a “read” signal to the memory.
3. Read the data from MDR.

To STORE a value (X) into a location (A):

1. Write the data (X) to the MDR.
2. Write the address (A) into the MAR.
3. Send a “write” signal to the memory.



CPU-only Tasks

In addition to input & output a program also:

- Evaluates arithmetic & logical functions to determine values to assign to variable.
- Determines the order of execution of the statements in the program.
- In assembly this distinction is captured in the notion of arithmetic/logical, and control instructions.

Processing Unit

Functional Units:

- ALU = Arithmetic/Logic Unit
- could have many functional units.
- some of them special-purpose (floating point, multiply, square root, . . .)

Registers

- Small, temporary storage
- Operands and results of functional units
- LC-3 has eight registers (R0, . . . , R7), each 16 bits wide

Word Size

- number of bits normally processed by ALU in one instruction
- also width of registers
- LC-3 is 16 bits

Instructions

The instruction is the fundamental unit of work.

Specifies two things:

- opcode: operation to be performed
- Operands: data/locations to be used for operation

Three basic kinds of instructions:

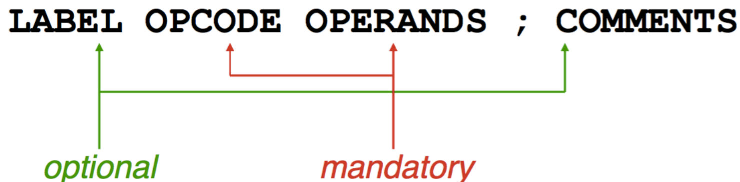
- Computational instructions
- Data-movement instructions
- Flow-control instructions

Instruction Encoding

- in LC-3, the most-significant four bits contain the instruction's OPCODE always.
- The meaning of the other bits changes according to the instruction.
- Look up the "`LC-3b-ISA.pdf`" find all 16 instruction format descriptions

LC-3b Instructions

- 16 bit instruction
- Memory address space is 16 bits $\rightarrow 2^{16}$ locations
- Each memory address containing one byte (eight bits).
- One instruction or declaration per line



LC-3 v.s. MIPS

LC-3

1. 16 bit
2. NO floating point instruction
3. 8 registers
4. NO hardwired register value
5. Only has `AND`, `NOT`, and `ADD`

MIPS

1. 32 bit
2. Floating point instruction
3. 32 registers
4. `$0` is hardwired to 0
5. Full complement of arithmetic, logical, and shift operations

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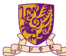

LC-3b Example 1: Do nothing

"./lc3b_asm nop.asm nop.cod"

nop.asm:

```
.ORIG x3000
NOP
NOP
.END
```

nop.cod:

```
0x3000
0x0000
0x0000
```

- NOP instruction translates into machine code 0x0000.

Assembler Directives

- Directives give information to the assembler
- Not executed by the program
- All directives start with a period '.'

`.ORIG`	Where to start in placing things in memory
`.FILL`	Declare a memory location (variable)
`.END`	Tells assembly where your program source ends

Assembler Directives: `.ORIG`

- Tells where to put code in memory (starting location)
- Only one `.ORIG` allowed per program module
- PC is set to this address at start up
- Similar to the `main()` function in C
- Example:

```
.ORIG x3000
```

Assembler Directives: `.FILL`

- Declaration and initialization of variables
- Always declaring words
- Examples:

```
flag        .FILL   x0001
counter     .FILL   x0002
letter      .FILL   x0041
letters     .FILL   x4241
```

Assembler Directives: `.END`

- Tells the assembler where your program ends
- Only one `.END` allowed in your program module
- NOT where the execution stops!

LC-3b Example 2: Count from 10 to 1

count10.asm:

```
      .ORIG x3000
      LEA R0, TEN
      LDW R1, R0, #0
START ADD R1, R1, #-1
      BRZ DONE
      BR START

DONE  TRAP x25
TEN   .FILL x000A
      .END
```

count10.cod:

```
0x3000
0xE005
0x6200
0x127F
0x0401
0x0FFD

0xF025
0x000A
```

- More explanations will be in Lab2-2.

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LC-3b Simulator: lc3b_sim

- Download from course website (`lab2-assignment.tar.gz`)
- The simulator will
  - Execute the input LC-3b program
  - One instruction at a time
  - Modify the architectural state of the LC-3b
- Two main sections: the shell and the simulation routines
- Only need to work on simulation routine part.

LC-3b Shell

```
./lc3b_sim [cod file]
```

```
LC-3b-SIM> ?

----------------LC-3b ISIM Help-----------------------
go                -  run program to completion
run n             -  execute program for n instructions
mdump low high    -  dump memory from low to high
rdump             -  dump the register & bus values
?                 -  display this help menu
quit              -  exit the program

LC-3b-SIM>
```

LC-3b Architecture State

- Please refer to LC-3b_ISA for more details
- PC
- General purpose registers (REGS): 8 registers
- Condition codes: N (negative); Z (zero); P (positive).

```
65 #define LC_3b_REGS 8
66
67 /* Data Structure for Latch */
68 typedef struct System_Latches_Struct{
69     int PC,                /* program counter */
70         N,                 /* n condition bit */
71         Z,                 /* z condition bit */
72         P;                 /* p condition bit */
73     int REGS[LC_3b_REGS]; /* register file.  */
74 } System_Latches;
75
76 System_Latches CURRENT_LATCHES, NEXT_LATCHES;
```

LC-3b Memory Structure

```
46 /***************************************************************/
47 /* Main memory.                                                */
48 /***************************************************************/
49 /* MEMORY[A][0] stores the least significant byte of word at word address A
50    MEMORY[A][1] stores the most significant byte of word at word address A
51 */
52
53 #define WORDS_IN_MEM    0x08000
54 int MEMORY[WORDS_IN_MEM][2];
```

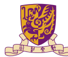
Two word-aligned locations are to store one 16-bit word.

- addresses differ only in bit 0
- Locations `x0006` and `x0007` are word-aligned

```
276 void init_memory() {
277     int i;
278
279     for (i=0; i < WORDS_IN_MEM; i++) {
280         MEMORY[i][0] = 0;
281         MEMORY[i][1] = 0;
282     }
283 }
```

How to use LC-3b Simulator?

1. Compile your C codes through `make` command.
2. Run the compiled LC-3b simulator through `./lc3b_sim2 bench/xxx.cod`. Here the parameter is a machine code file.
3. In the simulator, run “n” instructions. When n = 3, `run 3`
4. In the simulator, print out register information: `rdump`



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Lab2 Task 1

architectural state:

- In `process_instruction()`, update `NEXT_LATCHES`
- At this moment, only update (increase `PC` value)

memory:

- Given `CURRENT_LATCHES.PC`, read related word in memory
- Implement function `int memWord (int startAddr)`

Task 1 Golden Results: nop.cod

Output after `run 2`

```
process_instruction()| curInstr = 0x0000
process_instruction()| curInstr = 0x0000
```

Output after `rdump`:

```
Instruction Count : 2
PC                : 0x3004
CCs: N = 0  Z = 1  P = 0
Registers:
0: 0x0000
1: 0x0000
2: 0x0000
3: 0x0000
4: 0x0000
5: 0x0000
6: 0x0000
7: 0x0000
```

Task 1 Golden Results: count10.cod

Output after `run 7`:

```
process_instruction()| curInstr = 0xe005
process_instruction()| curInstr = 0x6200
process_instruction()| curInstr = 0x127f
process_instruction()| curInstr = 0x0401
process_instruction()| curInstr = 0x0ffd
process_instruction()| curInstr = 0xf025
Simulator halted
```

Output after `rdump`:

```
Instruction Count : 6
PC                : 0x0000
CCs: N = 0  Z = 1  P = 0
Registers:
0: 0x0000
1: 0x0000
2: 0x0000
3: 0x0000
4: 0x0000
5: 0x0000
6: 0x0000
7: 0x300c
```

Task 1 Golden Results: toupper.cod

Output after `run 18`:

```
process_instruction()| curInstr = 0xe00f
process_instruction()| curInstr = 0x6000
process_instruction()| curInstr = 0x6000
process_instruction()| curInstr = 0xe20d
process_instruction()| curInstr = 0x6240
process_instruction()| curInstr = 0x6240
process_instruction()| curInstr = 0x2400
process_instruction()| curInstr = 0x0406
process_instruction()| curInstr = 0x14b0
process_instruction()| curInstr = 0x14b0
process_instruction()| curInstr = 0x3440
process_instruction()| curInstr = 0x1021
process_instruction()| curInstr = 0x1261
process_instruction()| curInstr = 0x0ff8
process_instruction()| curInstr = 0x3440
process_instruction()| curInstr = 0xf025
Simulator halted
```

Task 1 Golden Results: toupper.cod (cont.)

Output after `rdump`:

```
Instruction Count : 16
PC                : 0x0000
CCs: N = 0  Z = 1  P = 0
Registers:
0: 0x0000
1: 0x0000
2: 0x0000
3: 0x0000
4: 0x0000
5: 0x0000
6: 0x0000
7: 0x3020
```