LC-3 Assembly Language

Programming and tips
Textbook Chapter 7

CMPE12 – Summer 2008

Assembly and Assembler

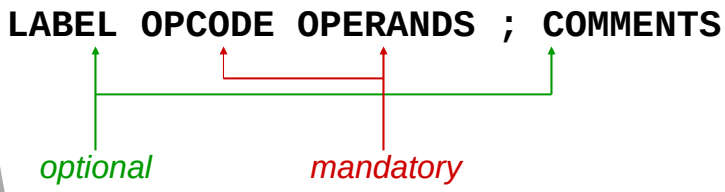
- Machine language - binary
- Assembly language - symbolic
- An assembler is a program that turns symbols into machine instruction
  - ISA-specific: close correspondence between symbols and instruction set
    - mnemonics for opcodes
    - labels for memory locations
  - `ADD  R6, R2, R6  ; increment index reg.`

Elements of Assembly Language

- Instructions (we have seen most of them)
- Comments
- Labels
- Declarations
- Assembler directives and trap codes
- Ignored
  - White space (between symbols)


Assembly Instructions

- One instruction or declaration per line




Opcodes and Operands

- Opcodes
  - Reserved symbols that correspond to LC-3 instructions
  - Listed in Appendix A (ex: `ADD`, `AND`, …)
- Operands
  - Can be registers: `Rn`, where n is the register number
  - Can be immediate numbers
    - Prefix: # (decimal), x (hex), or b (binary)
  - Can be labels
    - Symbolic names of memory locations
  - Separated by spaces, tabs, or commas
  - Number, order, and type correspond to the instruction format


Data Types

- LC-3 has two basic data types
  - Integer
  - Character
- Both are 16 bits wide (a word)
- Though a character is only 8 bits in size
- How does that work??


Comments In Code

- What is a comment?
  - Anything on a line after a semicolon is a comment
  - Comments are ignored by the assembler
  - Used by humans to document and understand programs
- Some tips for useful comments
  - Avoid restating the obvious
    - Bad: Decrement R1
  - Provide additional insight
    - Good: Accumulate the product
  - Use comments to separate pieces of program

Labels

- Placed at beginning of line
- Assign a symbolic name to their line (its address)
- Symbolic names used to identify memory locations. Two kinds:
  - Location of target of a branch or jump
  - Location of a variable for loading and storing
- Can be 1-20 characters in size

Assembler Directives

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

Directive	Description
`.ORIG`	Where to start in placing things in memory
`.FILL`	**Declare** a memory location (variable)
`.BLKW`	**Declare** a group of memory locations (array)
`.STRINGZ`	**Declare** a group of characters in memory (string)
`.END`	Tells assembly where your program source ends


Assembler Directives: `.ORIG`

- Tells simulator where to put your code in memory (starting location)
- Only one **`.orig`** allowed per program module
- PC is set to this address at start up
- Example
  - **`.orig x3000`**
  - Typical address for LC-3 is x3000


Assembler Directives: `.FILL`

- Declaration and initialization of variables
- One declaration per line
- Always declaring words
- Examples:
  - `flag  .FILL  x0001`
  - `counter  .FILL  x0002`
  - `letter  .FILL  x0041`
  - `letters  .FILL  x4241`


Assembler Directives: `.FILL`

- In C
  - `type varname;`
  - Where **`type`** is one of these
    - **`int`** (integer)
    - **`char`** (character)
    - **`float`** (floating-point)
- In LC-3
  - `varname .FILL value`
  - Where…
    - **`value`** is required
    - **`type`** is 16-bit integer


Assembler Directives: `.BLKW`

```
;set aside 3 unnamed
spaces
.BLKW 3

;set aside 1 named word
Bob   .BLKW 1

; set aside 7 labeled
words, initialize them
all to 4
Num   .BLKW 7     #4
```

Assembler Directives: `.STRINGZ`

- Declare a string of characters
- Stored contiguously in memory
- Automatically terminated with x0000
  - "Null-terminated"
- Example:
  - **`hello   .STRINGZ "Hello World!"`**

Assembler Directives: **.END**

- Tells the assembler where your program ends
- Only one **.END** allowed in your program module
- That's where the assembler stops assembling, not where the execution stops!

System Calls: **TRAP**

- A trap is an exception that interrupts normal processing to perform a system-level task
- Certain traps are pre-defined in a trap vector
- To call a trap
  - Use the **TRAP** instruction
  - Specifying the trap vector
- Very tedious and dangerous for a programmer to deal with I/O

Trap Service Routines

Trap Vector	Pseudo-Instruction	Usage & Result
x20	GETC	Read a character from console into R0, not echoed.
x21	OUT	Write the character in R0[7:0] to console.
x22	PUTS	Write string of characters to console. Start with character at address contained in R0. Stops when 0x0000 is encountered.
x23	IN	Print a prompt to console and read in a single character into R0. Character is echoed.
x24	PUTSP	Write a string of characters to console, 2 characters per address location. Start with characters at address in R0. First [7:0] and then [15:0]. Stops when 0x0000 is encountered.
x25	HALT	Halt execution and print message to console.


Trap Examples

To print a character

```
; the char must be in R0
TRAP   x21
   or
OUT
```

To read in a character

```
; will go into R0[7:0],
; no echo.
TRAP   x20
        or
GETC
```

To end the program

```
TRAP   x25
       or
HALT
```


Simple LC-3 program

```
        .orig x3000
        LD      R2, Zero
        LD      R0, M0
        LD      R1, M1
Loop    BRz     Done
        ADD  R2, R2, R0
        ADD  R1, R1, -1
        BR      Loop
Done    ST  R2, Res
        HALT
Res.FILL x0000
Zero.FILL x0000
M0  .FILL x0007
M1  .FILL x0003
        .END
```

- What does this program do?
- What is in **Res** at the end?

The Assembly Process

- Convert assembly language file (.asm) into an executable file (.obj) for the LC-3 simulator
- The executable file is the pure binary machine code
- LC-3 uses a two-pass assembler
  - Status messages are shown when assembling
  - E.g.,

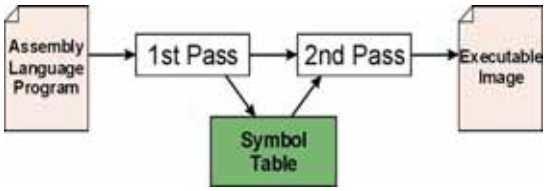
```
Starting Pass 1...
Pass 1 - 0 error(s)
Starting Pass 2...
Pass 2 - 0 error(s)
```

The Assembly Process

- The assembly process is…
  - Assembling
    - Pass 1
    - Pass 2
  - Linking
  - Loading
  - Running


The Assembly Process: Assembling

- First Pass
  - Scan program file
  - Find all labels and calculate the corresponding addresses
    - Generate the symbol table
- Second Pass
  - Convert instructions to machine language, using information from symbol table




First Pass: The Symbol Table

- Find the **`.orig`** statement
  - Tells the address of the first instruction
  - Initialize the location counter (LC), which keeps track of the current instruction
- For each non-empty line in the program
  - If a line contains a label, add label plus LC to symbol table
  - Increment LC
    - For a **`.BLKW`** or **`.STRINGZ`**, increment LC by the amount of space allocated
  - Stop when **`.END`** statement is reached
  - A line with only a comment is considered an empty line

Example: Generating a Symbol Table

Symbol	Address

```
                .ORIG   x3000
x3000   LD      R2, Zero
x3001   LD      R0, M0
x3002   LD      R1, M1
        ; begin multiply
x3003 Loop      BRz Done
x3004   ADD     R2, R2, R0
x3005   ADD     R1, R1, #-1
x3006   BR      Loop
        ; end multiply
x3007 Done      ST  R2, Result
x3008   HALT
x3009 Result    .FILL   x0000
x300A Zero      .FILL   x0000
x300B M0        .FILL   x0007
x300C M1        .FILL   x0003
        .END
```

Second Pass: Generating Machine Language

- For each executable assembly language statement, generate the corresponding machine language instruction
  - If the operand is a label, look up the address from the symbol table
- Potential problems
  - Improper number of type of arguments
    - E.g.: `NOT R1,#7`
`ADD R1,R2`
  - Immediate argument too large
    - E.g.: `ADD R1,R2,#1023`
  - Address (associated with label) more than 256 from instruction
    - Then, can't use PC-relative addressing mode

Multiple Object Files

- An object file is not necessarily a complete program
  - System-provided library routines
  - Code blocks written by multiple developers
- For LC-3, you can load multiple object files into memory, then start executing at a desired address
  - System routines, such as keyboard input, are loaded automatically
    - Loaded into "system memory," below x3000
    - User code should be loaded between x3000 and xFDFF
  - Each object file includes a starting address
  - It is possible to load overlapping object files

The Assembly Process: Linking

- Linking is the process of resolving symbols between independent object files.
  - Suppose we define a symbol in one module, and want to use it in another
  - The directive **`.EXTERNAL`** is used to tell the assembler that a symbol is defined in another module
  - The linker will search symbol tables of other modules to resolve symbols and complete code generation before loading

The Assembly Process: Loading

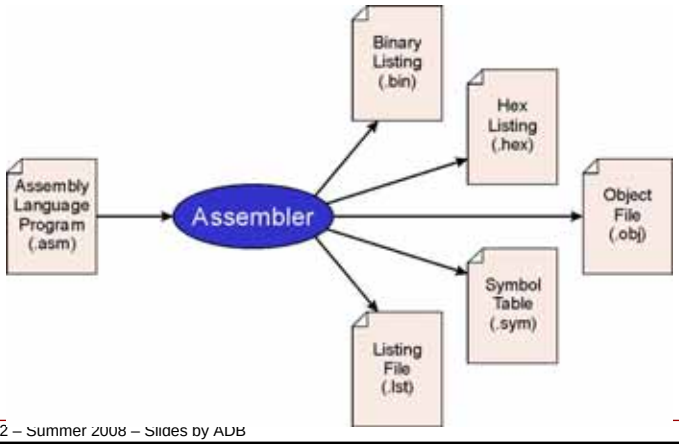
- Loading is the process of copying an executable image into memory
  - More sophisticated loaders are able to relocate images to fit into available memory
  - Must re-adjust branch targets and load/store addresses

And Finally: Running

- The loader makes the CPU jump to the first instruction
  - Specified by **`.ORIG`**
- The program executes
- When execution completes, control returns to the OS or simulator

The LC-3 Assembler

- The LC-3 assembler generates several different output files



Recommended exercises

- Ex 7.1 to 7.11
- *Especially recommended*: 7.12 to 7.16, and 7.18 to 7.25 (yes, all of them except 7.17)