LC-3
Assembly Language

(Textbook Chapter 7)

Assembly and assembler

- Machine language - binary
- Assembly language - symbolic
- Assembler is a program that turns symbols into machine instructions.
  - ISA-specific: close correspondence between symbols and instruction set
    - mnemonics for opcodes
    - labels for memory locations

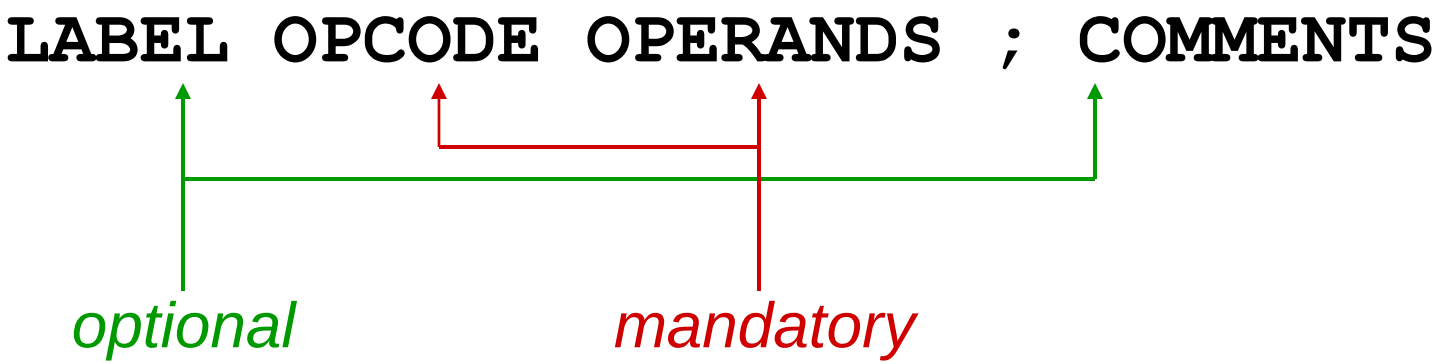
Syntax of LC-3 assembly: Language elements

- Instructions (we have seen most of them)
- Comments
- Labels
- Declarations
- Assembler directives and trap codes

Whitespaces (between symbols) and case are ignored.

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
  - **Registers**: , where is the register number
  - **Immediate numbers**: (decimal), (hex), or (binary)
  - **Labels**: symbolic names of memory locations
  - Operands are separated by spaces, tabs, or commas
  - Their number, order, and type correspond to the instruction format

Data types

LC-3 has 2 basic data types

- Integer
- Character

Both are 16 bits wide (a word), though a character is only 8 bits in size.

Comments

- Anything on a line after a semicolon is a comment
- Comments are ignored by assembler
- Used by humans to document/understand programs
- Tips for useful comments:
  - avoid restating the obvious, as "decrement R1"
  - provide additional insight, as in "accumulate product in R6"
  - 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 or psuedo-ops** 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

.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
- Similar to the **main()** function in C

- Example: the standard convention is

```
.orig  x3000
```

.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
```

.FILL

In C

```
type      varname;
```

Where `type` is

`int` (integer)

`char` (character)

`float` (floating-point)

In LC-3

```
varname  .FILL value
```

- `value` is required (initialize)
- `type` is only 16-bit integer

.BLKW

- Reserves (and initializes) a sequence of contiguous memory locations (arrays)
- Examples:

```
;set aside 3 locations
      .BLKW     3

;set aside 1 location and label it
Bob   .BLKW     1

; set aside 7 locations,
; label them, and init them all to 4
Num   .BLKW     7    #4
```

.STRINGZ

- Declare a string of characters
- Automatically terminated with x0000
- Example:

```
hello .STRINGZ "Hello World!"
```

.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!

TRAP

(System Calls)

Very tedious and dangerous for a programmer to deal with I/O.

This is why we like to have an OS.

Need an instruction to get its attention.

Use the **TRAP** instruction and a *trap vector*.

Trap Service Routines

The LC-3 assembler provides "pseudo-instructions" for each trap code, so you don't have to remember them.

Trap Vector	Assembler Name	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[7:0]
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

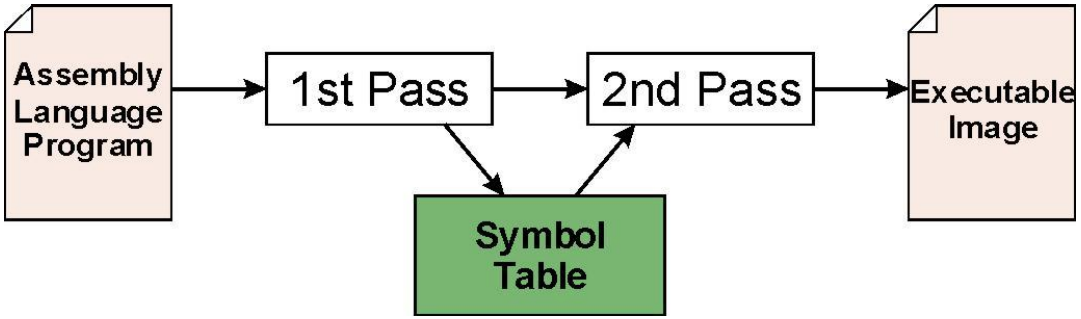
```
        .ORIG x3000
        LD    R2, Zero
        LD    R0, M0
        LD    R1, M1
Loop    BRz   Done
        ADD   R2, R2, R0
        ADD   R1, R1, -1
        BR    Loop
Done    ST    R2, Res
        HALT
Res     .FILL x0000
Zero    .FILL x0000
M0      .FILL x0007
M1      .FILL x0003
        .END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

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.



- First Pass:
  - scan program file
  - find all labels and calculate the corresponding addresses - the *symbol table*
- Second Pass:
  - convert instructions to machine language, using information from symbol table

First Pass: The Symbol Table

1. Find the `.ORIG` statement,
   which tells us the address of the first instruction.
   - Initialize **Location Counter (LC)**, which keeps track of the current instruction.

2. For each non-empty line in the program:
   a) If line contains a label, add label and LC to **symbol table**.
   b) Increment LC.
      - NOTE: If statement is `.BLKW` or `.STRINGZ`,
        increment LC by the number of words allocated.

3. Stop when `.END` statement is reached.

NOTE: A line with only a comment is considered an empty line.

Practice: Symbol Table

Build the symbol table for the multiply program:

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
```

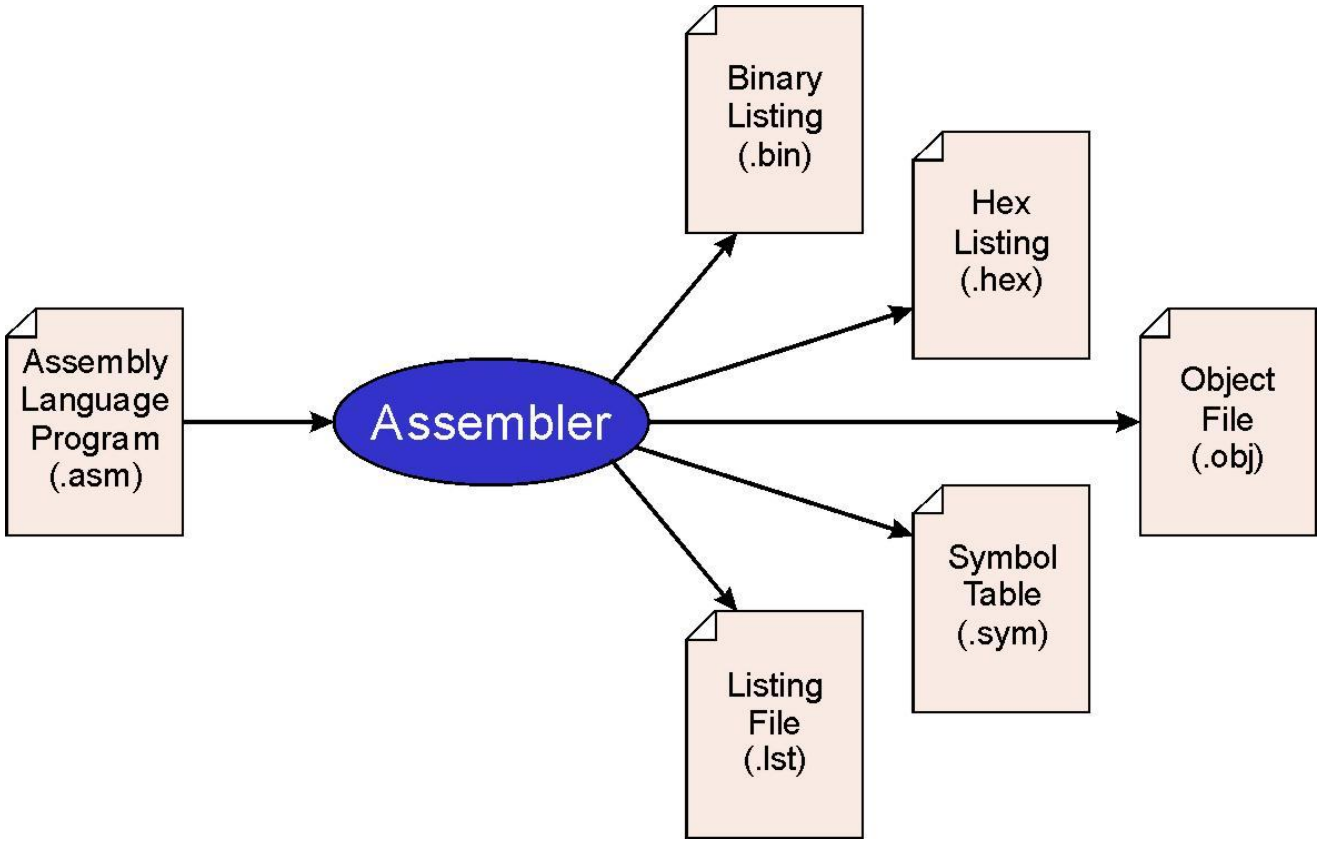
2nd Pass: Generating Machine Language

- For each executable assembly language statement, generate the corresponding machine language instruction.
  - If operand is a label, look up the address from the symbol table.

- **Potential problems:**
  - Improper number or type of arguments
    - ex:
```
NOT  R1,#7
ADD  R1,R2
```
  - Immediate argument too large
    - ex:
```
ADD  R1,R2,#1023
```
  - Address (associated with label) more than 256 from instruction
    - can't use PC-relative addressing mode

The LC-3 Assembler

- Using "assemble" (Unix) or LC3Edit (Windows), generates several different output files.



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 simulator, 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
  - be careful not to load overlapping object files

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

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 readjust branch targets, load/store addresses

Running

- The loader makes the CPU jump to the first instruction -> `.ORIG`.
- The program executes
- When execution completes, control returns to the OS or to the simulator
- Load again to run again with different data (in LC3 we must assemble again, since data is in program)

Recommended exercises:

- Ex 7.1 to7.5, 7.7 to 7.9
- *Especially recommended*: 7.13 to 7.15, and 7.18 to 7.24 (yes, all of them except 7.16 and 7.17)