

Chapter 7

Assembly Language

Human-Readable Machine Language

Computers like ones and zeros...

0001110010000110

Humans like symbols...

ADD R6,R2,R6 ; *increment index reg.*

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
- additional operations for allocating storage and initializing data

An Assembly Language Program

```
;
; Program to multiply a number by the constant 6
;
        .ORIG    x3050
        LD      R1, SIX
        LD      R2, NUMBER
        AND     R3, R3, #0      ; Clear R3.  It will
                                ; contain the product.
; The inner loop
;
AGAIN   ADD     R3, R3, R2
        ADD     R1, R1, #-1    ; R1 keeps track of
        BRp    AGAIN          ; the iteration.
;
        HALT
;
NUMBER  .BLKW   1
SIX     .FILL   x0006
;
        .END
```

LC-3 Assembly Language Syntax

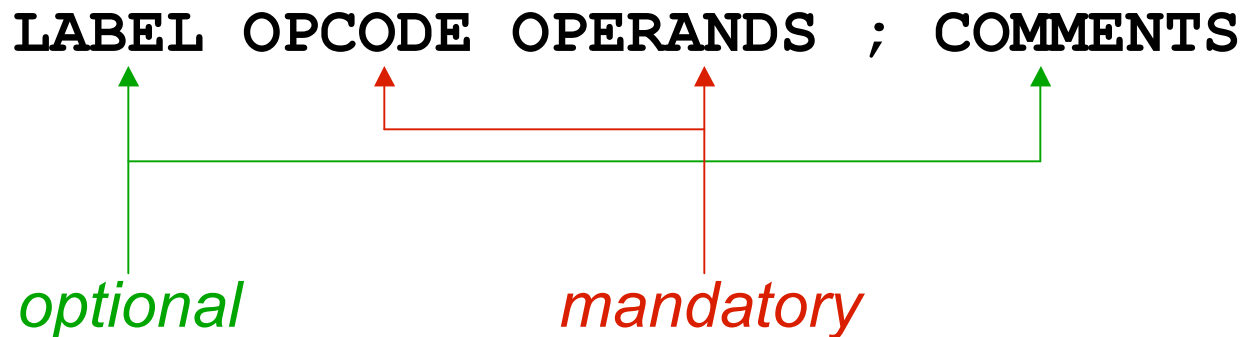
Each line of a program is one of the following:

- an instruction
- an assembler directive (or pseudo-op)
- a comment

Whitespace (between symbols) and case are ignored.

Comments (beginning with “;”) are also ignored.

An instruction has the following format:



Opcodes and Operands

Opcodes

- reserved symbols that correspond to LC-3 instructions
- listed in Appendix A
 - ex: ADD, AND, LD, LDR, ...

Operands

- registers -- specified by Rn, where n is the register number
- numbers -- indicated by # (decimal) or x (hex)
- label -- symbolic name of memory location
- separated by comma
- number, order, and type correspond to instruction format

➤ ex:

```
ADD R1 , R1 , R3
ADD R1 , R1 , #3
LD   R6 , NUMBER
BRz  LOOP
```

Labels and Comments

Label

- placed at the beginning of the line
- assigns a symbolic name to the address corresponding to line

➤ ex:

```
LOOP  ADD  R1 , R1 , #-1  
      BRp  LOOP
```

Comment

- anything after a semicolon is a comment
- 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

Assembler Directives

Pseudo-operations

- do not refer to operations executed by program
- used by assembler
- look like instruction, but “opcode” starts with dot

| <i>Opcode</i> | <i>Operand</i> | <i>Meaning</i> |
|-----------------|---------------------------|---|
| .ORIG | address | starting address of program |
| .END | | end of program |
| .BLKW | n | allocate n words of storage |
| .FILL | n | allocate one word, initialize with value n |
| .STRINGZ | n-character string | allocate n+1 locations, initialize w/characters and null terminator |

Trap Codes

LC-3 assembler provides “pseudo-instructions” for each trap code, so you don’t have to remember them.

| <i>Code</i> | <i>Equivalent</i> | <i>Description</i> |
|-------------|-------------------|---|
| HALT | TRAP x25 | Halt execution and print message to console. |
| IN | TRAP x23 | Print prompt on console, read (and echo) one character from keybd. Character stored in R0[7:0]. |
| OUT | TRAP x21 | Write one character (in R0[7:0]) to console. |
| GETC | TRAP x20 | Read one character from keyboard. Character stored in R0[7:0]. |
| PUTS | TRAP x22 | Write null-terminated string to console. Address of string is in R0. |

Style Guidelines

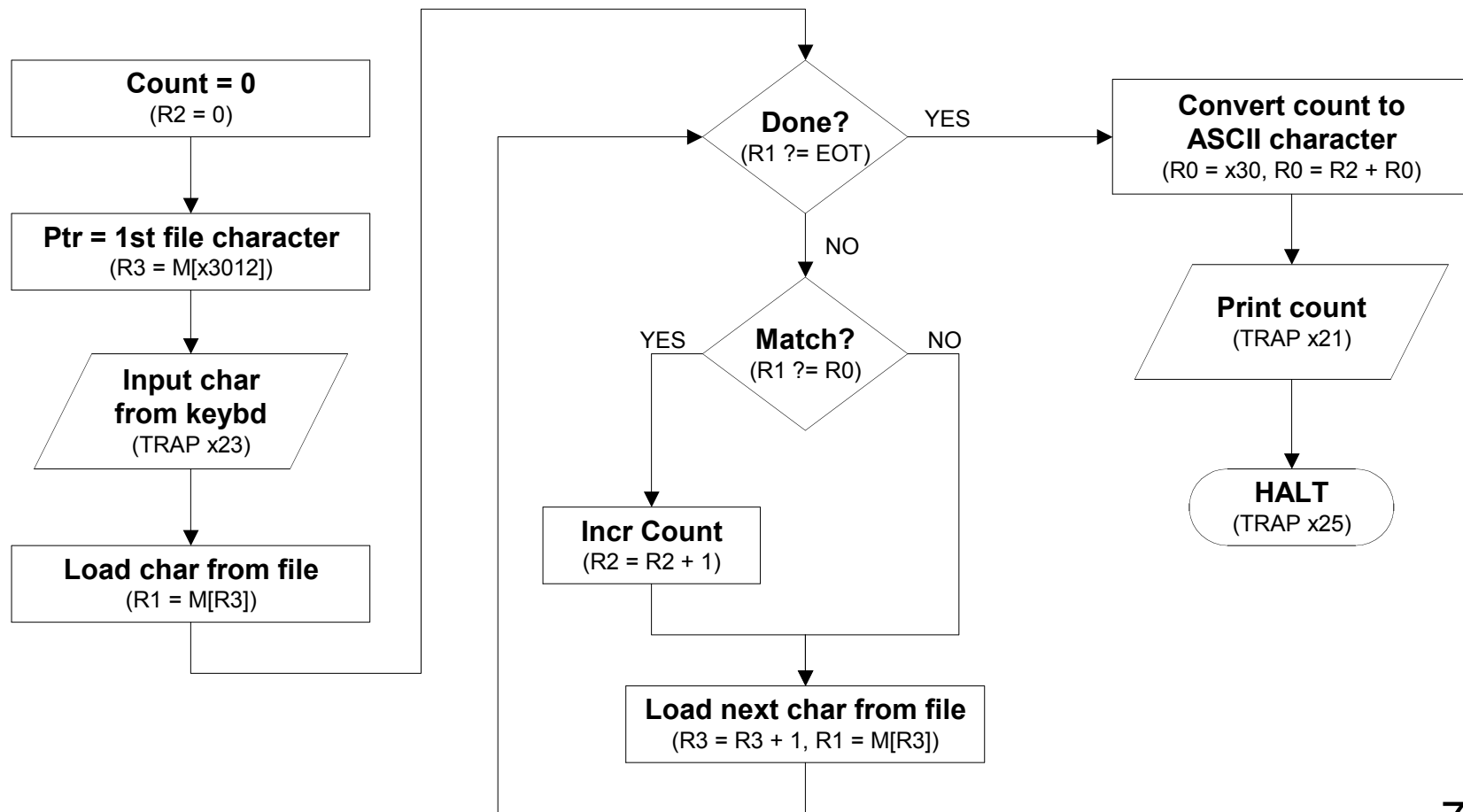
Use the following style guidelines to improve the readability and understandability of your programs:

- 1. Provide a program header, with author's name, date, etc., and purpose of program.**
- 2. Start labels, opcode, operands, and comments in same column for each line. (Unless entire line is a comment.)**
- 3. Use comments to explain what each register does.**
- 4. Give explanatory comment for most instructions.**
- 5. Use meaningful symbolic names.**
 - **Mixed upper and lower case for readability.**
 - **ASCIItoBinary, InputRoutine, SaveR1**
- 6. Provide comments between program sections.**
- 7. Each line must fit on the page -- no wraparound or truncations.**
 - **Long statements split in aesthetically pleasing manner.**

Sample Program

Count the occurrences of a character in a file.

Remember this?



Char Count in Assembly Language (1 of 3)

```
;
; Program to count occurrences of a character in a file.
; Character to be input from the keyboard.
; Result to be displayed on the monitor.
; Program only works if no more than 9 occurrences are found.
;
;
; Initialization
;
        .ORIG    x3000
        AND     R2, R2, #0          ; R2 is counter, initially 0
        LD      R3, PTR            ; R3 is pointer to characters
        GETC
        LDR     R1, R3, #0         ; R1 gets first character
;
; Test character for end of file
;
TEST    ADD     R4, R1, #-4        ; Test for EOT (ASCII x04)
        BRz    OUTPUT            ; If done, prepare the output
```

Char Count in Assembly Language (2 of 3)

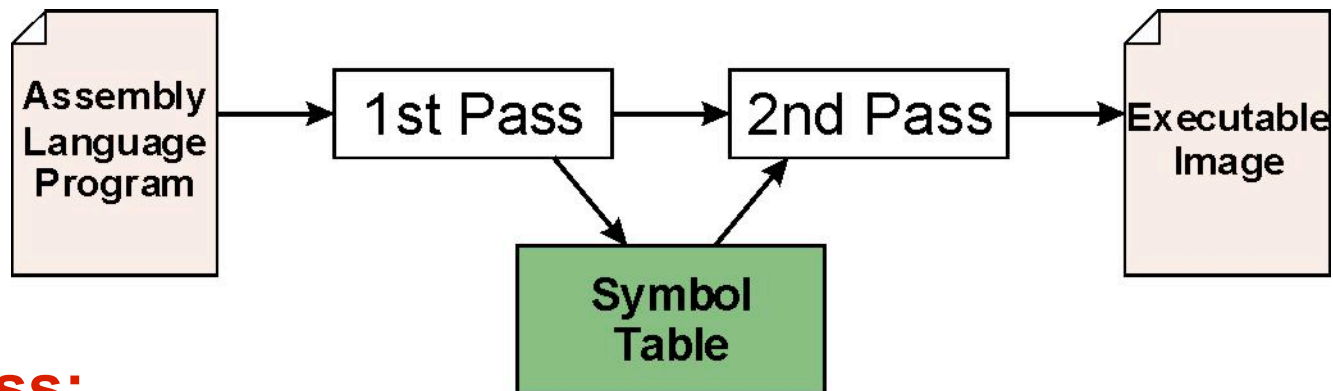
```
;
; Test character for match.  If a match, increment count.
;
        NOT      R1, R1
        ADD      R1, R1, R0 ; If match, R1 = xFFFF
        NOT      R1, R1     ; If match, R1 = x0000
        BRnp    GETCHAR    ; If no match, do not increment
        ADD      R2, R2, #1
;
; Get next character from file.
;
GETCHAR ADD      R3, R3, #1 ; Point to next character.
        LDR      R1, R3, #0 ; R1 gets next char to test
        BRnzp   TEST
;
; Output the count.
;
OUTPUT  LD        R0, ASCII ; Load the ASCII template
        ADD      R0, R0, R2 ; Covert binary count to ASCII
        OUT      ; ASCII code in R0 is displayed.
        HALT     ; Halt machine
```

Char Count in Assembly Language (3 of 3)

```
;
; Storage for pointer and ASCII template
;
ASCII    .FILL    x0030
PTR      .FILL    x4000
        .END
```

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; this is called the symbol table

Second Pass:

- convert instructions to machine language, using information from symbol table

First Pass: Constructing 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 that contains only a comment is considered an empty line.

Practice

Construct the symbol table for the program in Figure 7.1 (Slides 7-11 through 7-13).

| Symbol | Address |
|---------------|----------------|
| | |
| | |
| | |
| | |
| | |

Second 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
 - ADD R3 , R3 , NUMBER
- 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

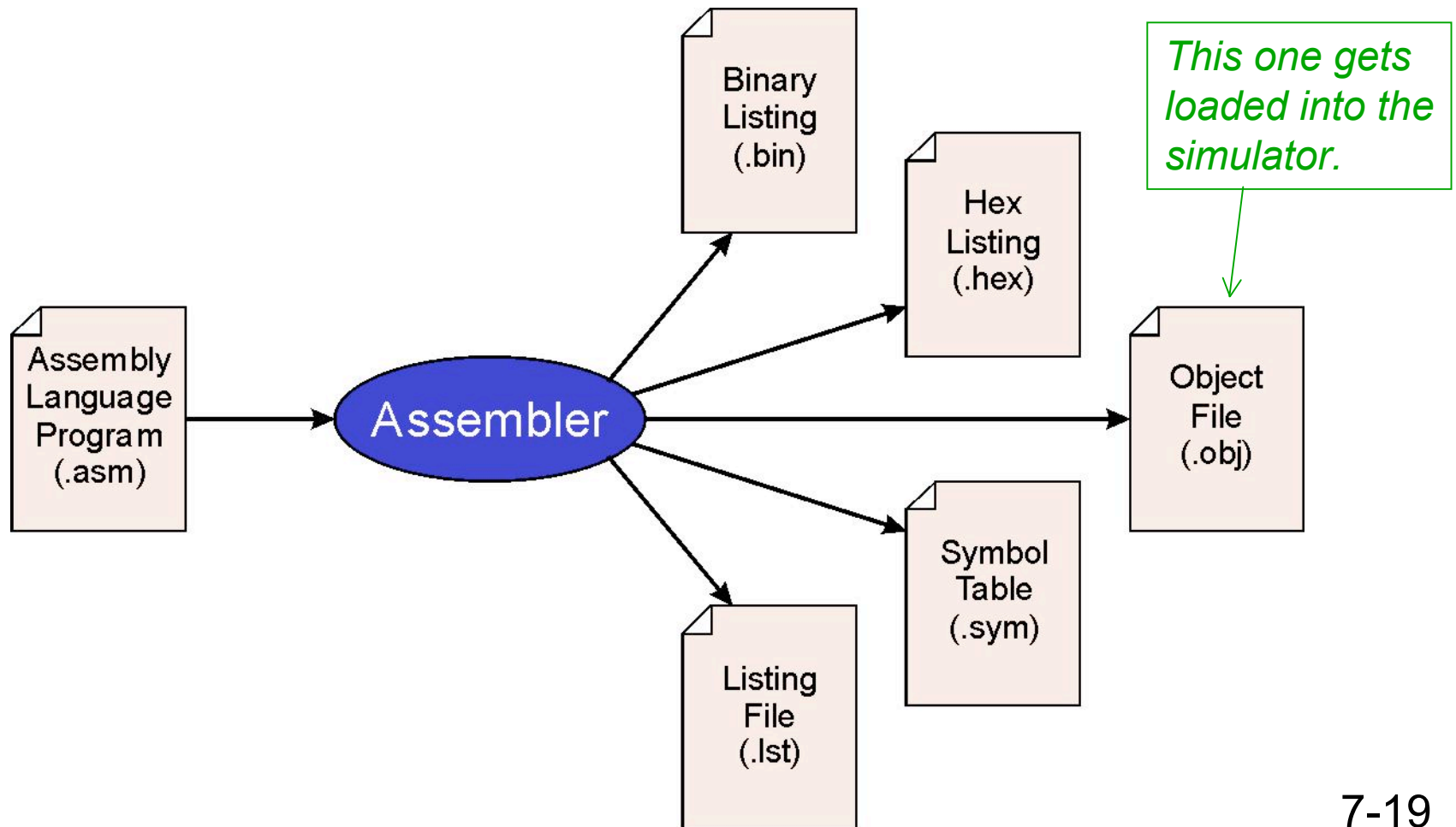
Practice

Using the symbol table constructed earlier, translate these statements into LC-3 machine language.

| Statement | Machine Language |
|-------------------|-------------------------|
| LD R3 , PTR | |
| ADD R4 , R1 , #-4 | |
| LDR R1 , R3 , #0 | |
| BRnp GETCHAR | |

LC-3 Assembler

Using “assemble” (Unix) or LC3Edit (Windows), generates several different output files.



Object File Format

LC-3 object file contains

- Starting address (location where program must be loaded), followed by...
- Machine instructions

Example

- Beginning of “count character” object file looks like this:

| | | |
|------------------|---|----------------|
| 0011000000000000 | ← | .ORIG x3000 |
| 0101010010100000 | ← | AND R2, R2, #0 |
| 0010011000010001 | ← | LD R3, PTR |
| 1111000000100011 | ← | TRAP x23 |
| | | . |
| | | . |
| | | . |

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 xFDFE**
- **each object file includes a starting address**
- **be careful not to load overlapping object files**

Linking and 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

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
- some notation, such as `.EXTERNAL`, is used to tell assembler that a symbol is defined in another module
- linker will search symbol tables of other modules to resolve symbols and complete code generation before loading