12. Assembly Language, Examples (Chapter 7) October 10, 2018

- Assembly Language
  - Opcodes, operands
  - Labels, comments
  - Assembler directives
- Example: counting 1s and 0s
- Assembly process
  - First pass, symbol table
  - Second pass, machine code
- Example: counting characters in a file

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
```

"KEYWORDS"

LC-3 Assembly Language Syntax

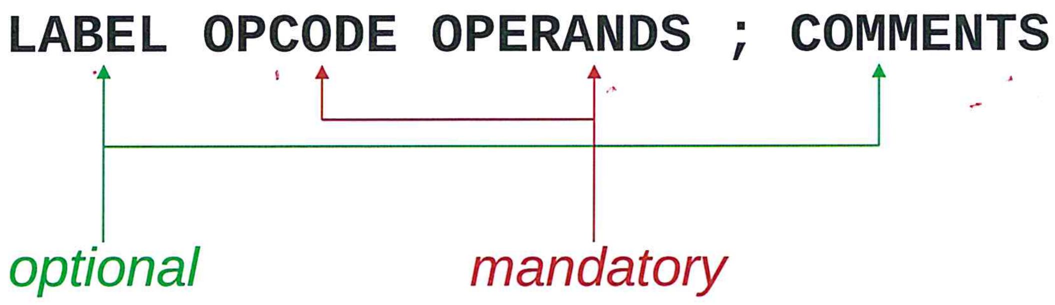
Each line of a program is one of the following:

- **an instruction**
- **an assember 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:



```
LABEL OPCODE OPERANDS ; COMMENTS
```

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) or b (binary)
- 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

Opcode	*Operand*	*Meaning*
`.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.

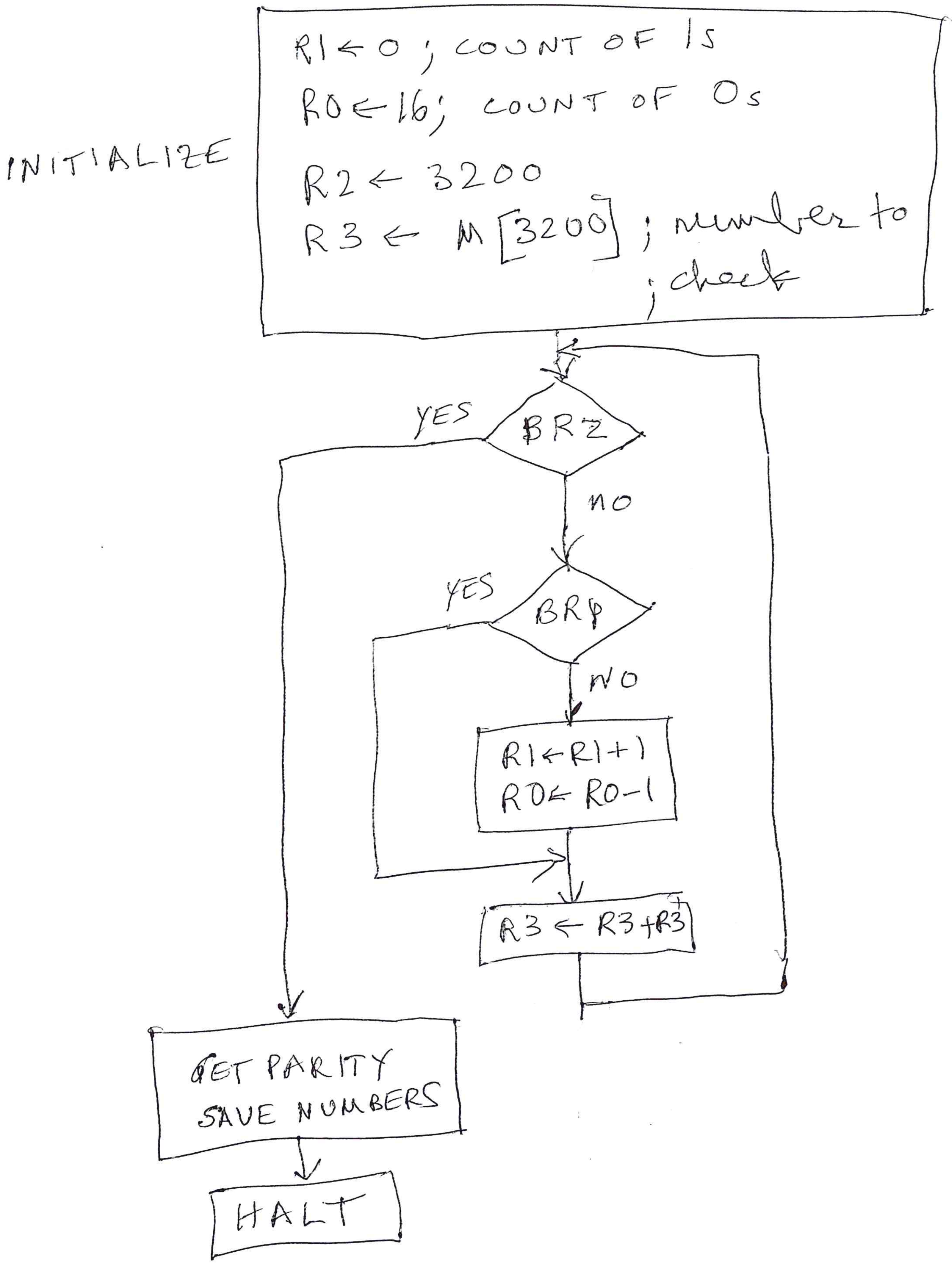
Code	*Equivalent*	*Description*
`HALT`	`TRAP x25`	Halt execution and print message to console.
`IN`	`TRAP x23`	Print prompt on console, read (and echo) one character from keybd. Character stored in R0[7:0].
`OUT`	`TRAP x21`	Write one character (in R0[7:0]) to console.
`GETC`	`TRAP x20`	Read one character 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.**

Counting the number of ones (and zeroes) in assembly language

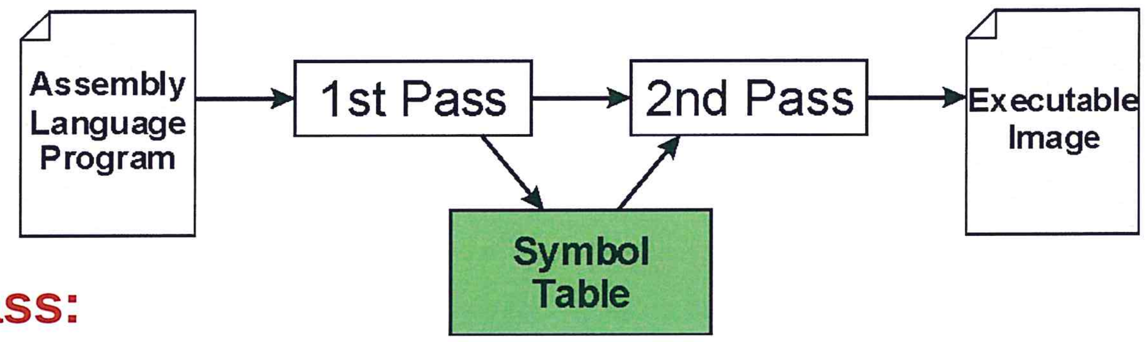


Assembly language program to count 1s, 0s and find even parity bit for a word

```
        .ORIG   x3000
        AND     R1, R1, #0     ; count of 1s (start with 0)
        LD      R0, SIXTEEN    ; start with a count of 16 for 0s
        LD      R2, NUMBER     ; address of number to test
        LDR     R3, R2, #0     ; get number to be tested
LOOP    Brz     DONE           ; zero, we are done counting
        BRp     NO             ; positive, no 1 in bit 15
        ADD     R1, R1, #1     ; negative, increment count of 1s
        ADD     R0, R0, #-1    ;           decrement count of 0s
NO      ADD     R3, R3, R3     ; shifting number left
        BRnzp   LOOP
DONE    STR     R1, R2, #1     ; save count of 1s in x3201
        STR     R0, R2, #2     ; save count of 0s in x3202
        AND     R1, R1, #1     ; parity is the LSB of the count
        STR     R1, R2, #3     ; save parity in x3203
        HALT
SIXTEEN .FILL   x10
NUMBER  .FILL   x3200
        .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 to multiply a number by 6

Symbol	Address
(.ORIG) (=LC)	X 3050
AGAIN	X.3053
NUMBER	X 3057
SIX	X3058

Second Pass: Generating Machine Language

For each executable assembly language statement, generate the corresponding machine language instruction.

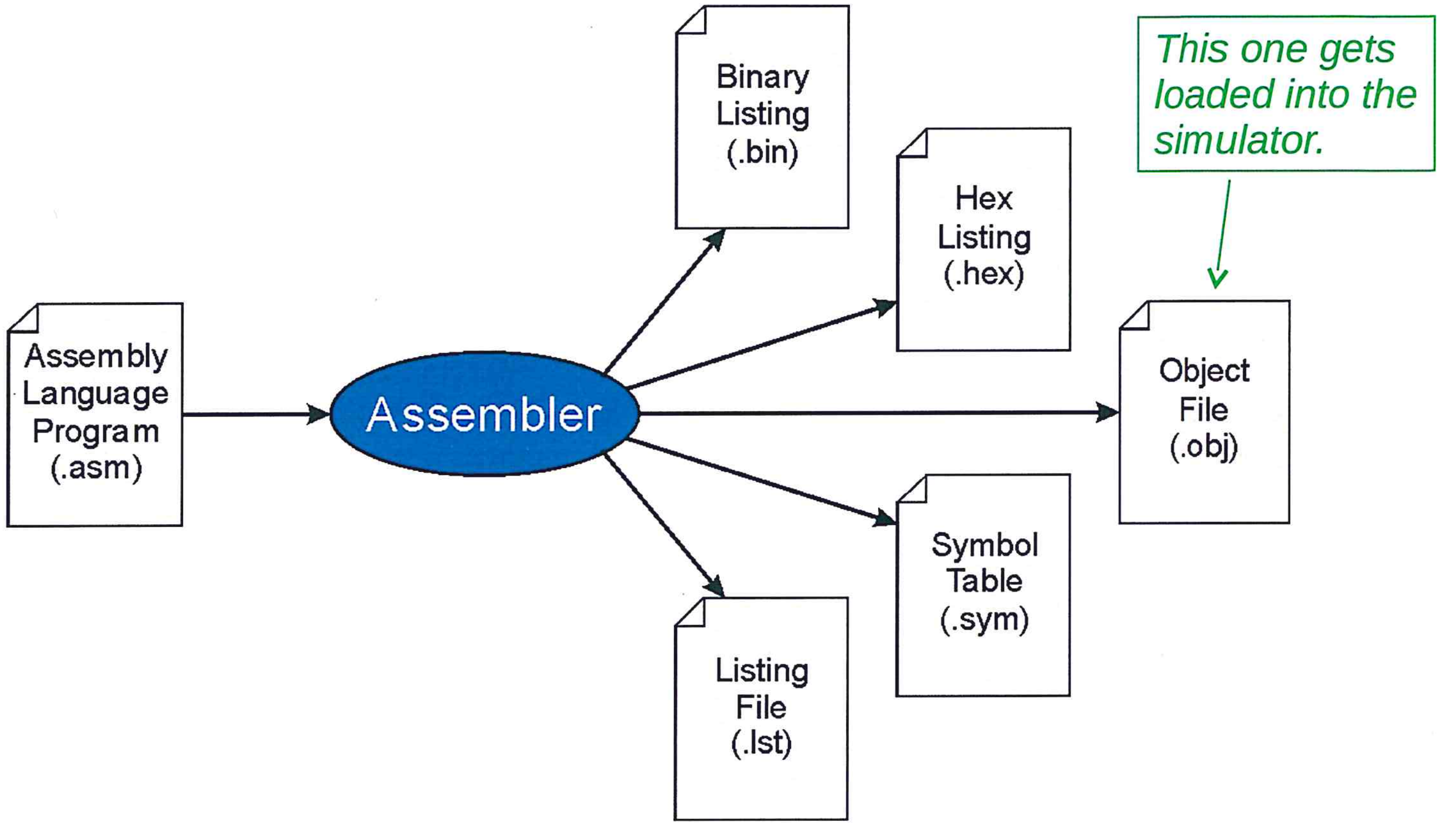
- If operand is a label,
  look up the address from the symbol table.

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

LC-3 Assembler

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



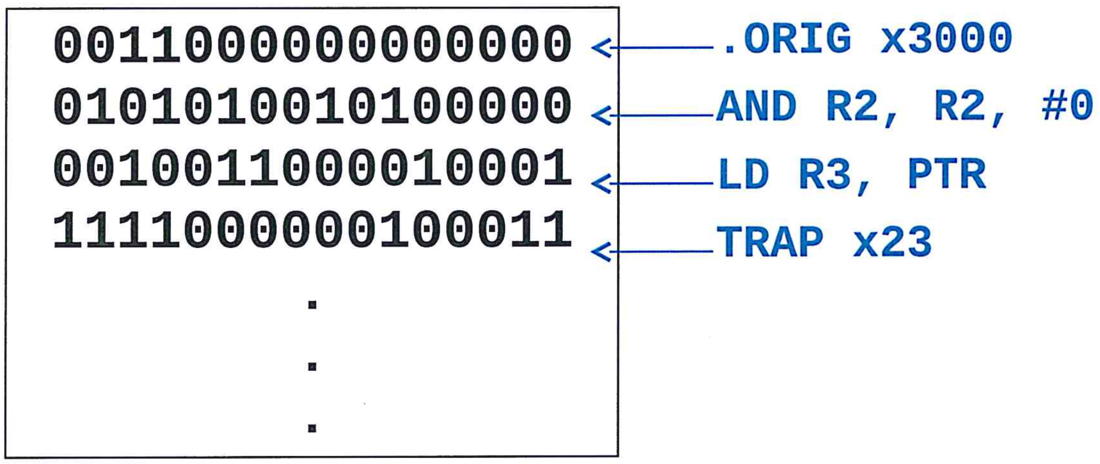
Object File Format

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 xFDFF
- 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**

Another Example

Count the occurrences of a character in a file

- **Program begins at location x3000**
- **Read character from keyboard**
- **Load each character from a "file"**
  - ➢ File is a sequence of memory locations
  - ➢ Starting address of file is stored in the memory location immediately after the program
- **If file character equals input character, increment counter**
- **End of file is indicated by a special ASCII value:** EOT (x04)
- **At the end, print the number of characters and halt**
  (assume there will be less than 10 occurrences of the character)

A special character used to indicate the end of a sequence is often called a sentinel**.**

- Useful when you don't know ahead of time how many times to execute a loop.