Assembly Language

Human-Readable Machine Language

- Computers like ones and zeros…

```
0001110010000110
```

- Humans like symbols…

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

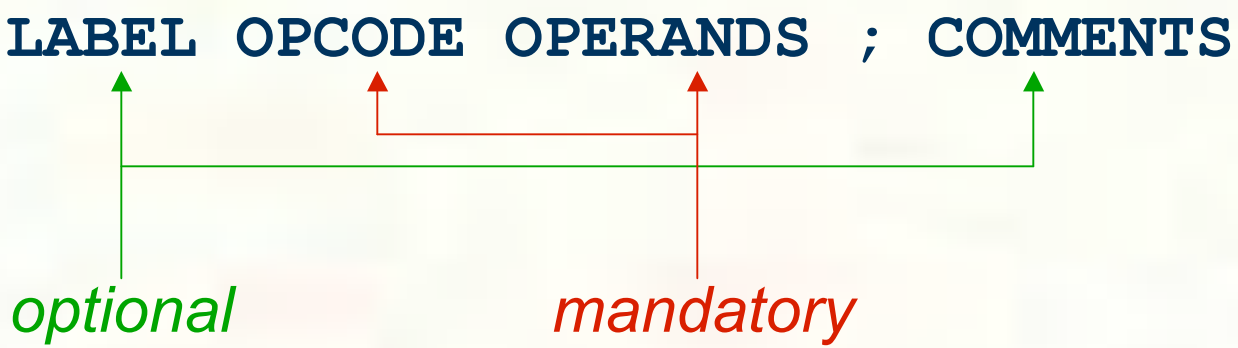
- Assembler is a program that turns symbols into machine instructions.
  - ISA-specific:
    close correspondence between symbols and instruction set
    - mnemonics for opcodes
    - labels for memory locations
  - additional operations for allocating storage and initializing data

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 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:



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

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

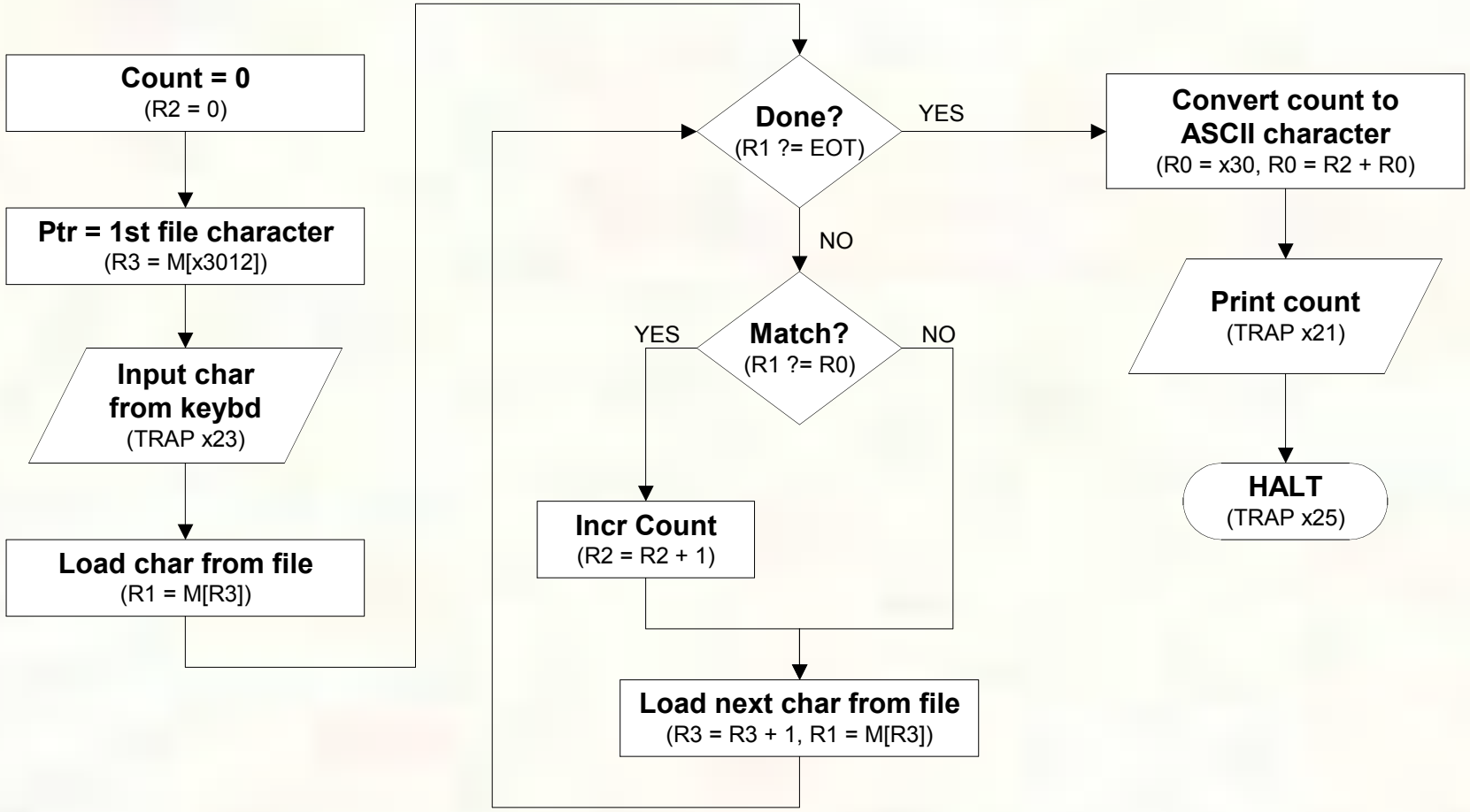
- Use the following style guidelines to improve the readability and understandability of your programs:

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.

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            ; R0 gets character input
   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)

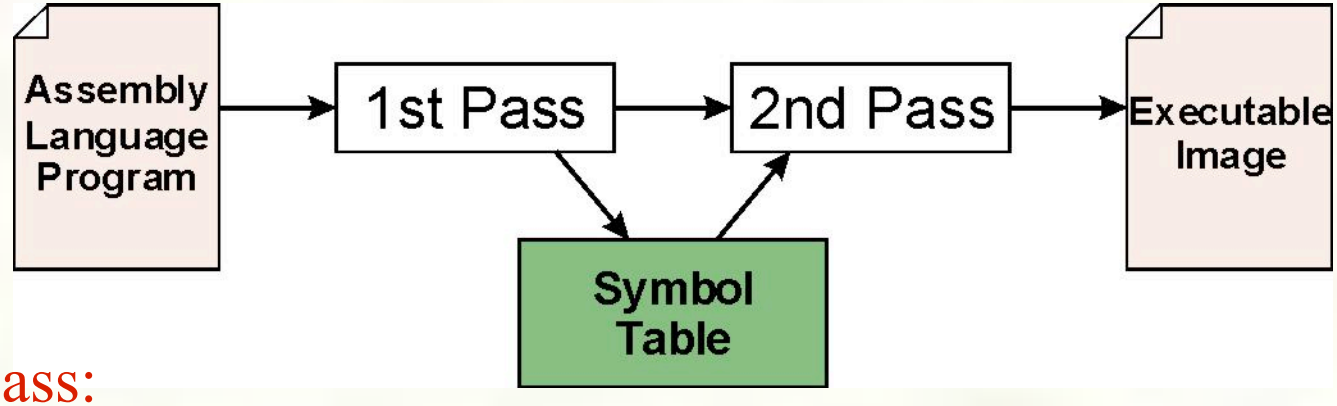
```
;
; Test character for match.  If a match, increment count.
;
   NOT    R1, R1
   ADD    R1, R1, R0            ; If match, R1 = xFFFF
   NOT    R1, R1   ; If match, R1 = x0000
   BRnp   GETCHAR  ; If no match, do not increment
   ADD    R2, R2, #1
;
; Get next character from file.
;
GETCHAR   ADD      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

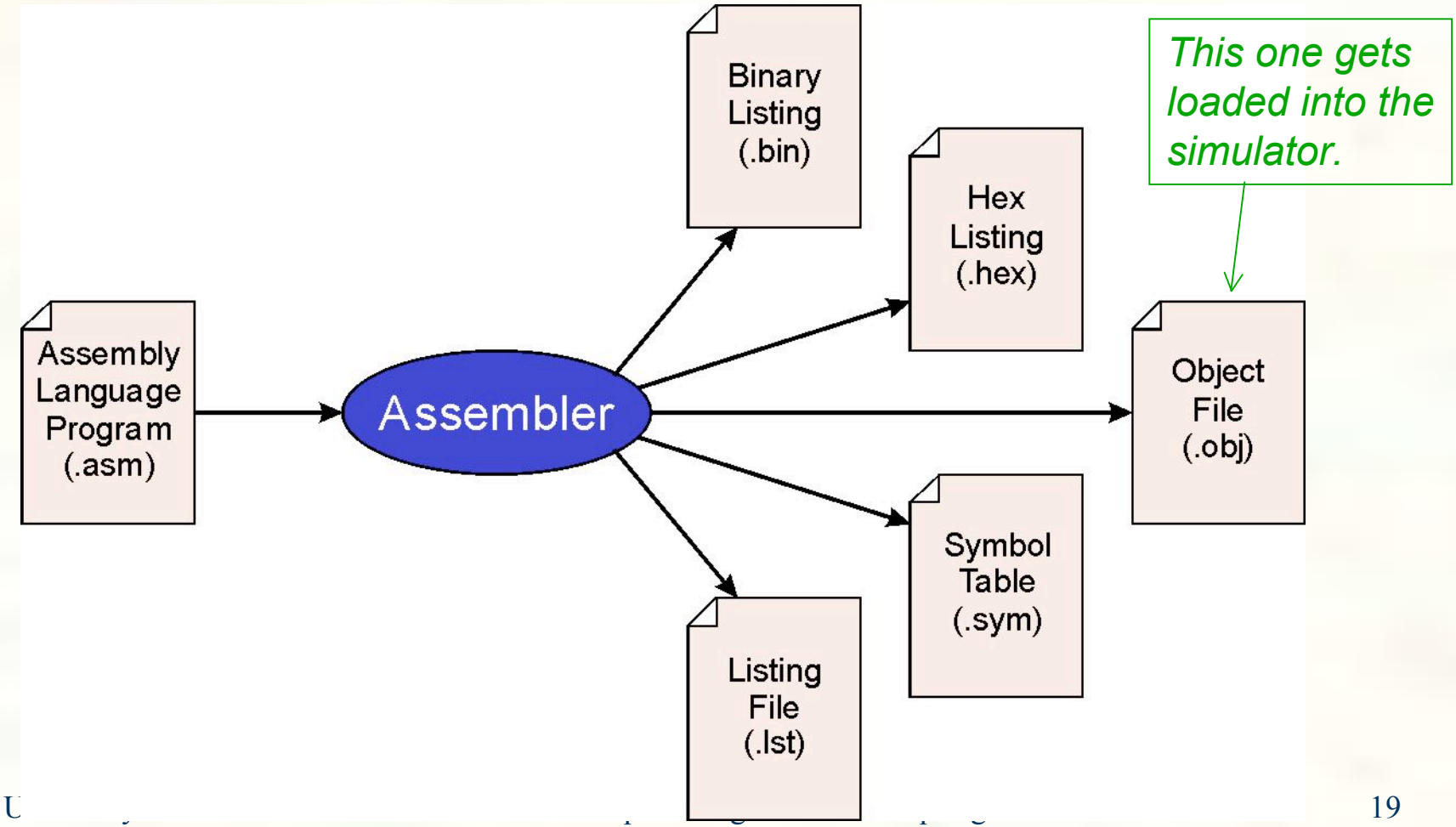
Practice

- 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 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