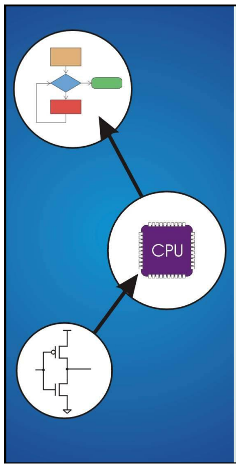
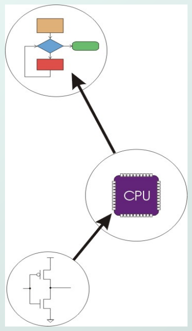


Chapter 7
Assembly Language

Original slides from Gregory Byrd, North Carolina State University

Modified slides by Chris Wilcox, Colorado State University

Computing Layers



Problems

Algorithms

Language

Instruction Set Architecture ⟵

Microarchitecture

Circuits

Devices

Human-Readable Machine Language

- Computers like ones and zeros…

  `0001110010000110`

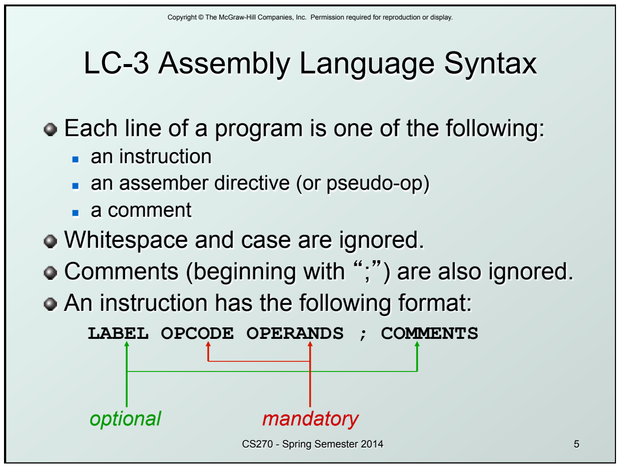
- Humans like symbols…

  `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

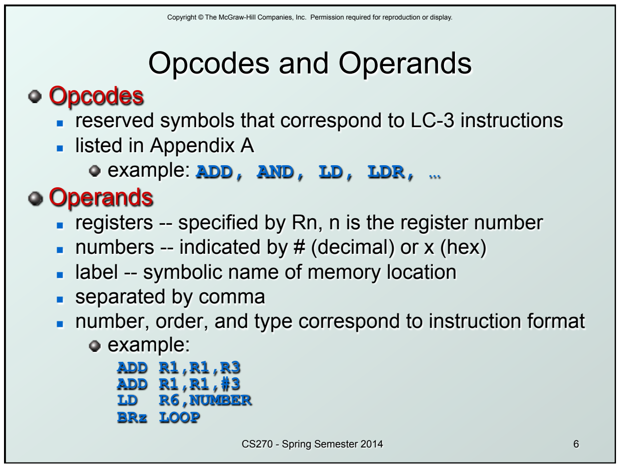
```
;
; Program to multiply a number by six
;
        .ORIG  x3050
        LD     R1, SIX       ; R1 has constant
        LD     R2, NUMBER    ; R2 has variable
        AND    R3, R3, #0    ; R3 has product
;
; The inner loop
;
AGAIN   ADD    R3, R3, R2    ; R3 += R2
        ADD    R1, R1, #-1   ; R1 is loop counter
        BRp    AGAIN         ; conditional branch
;
        HALT
;
NUMBER  .BLKW  1             ; variable
SIX     .FILL  x0006         ; constant
;
   .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 and case are ignored.
- Comments (beginning with ";") are also ignored.
- An instruction has the following format:

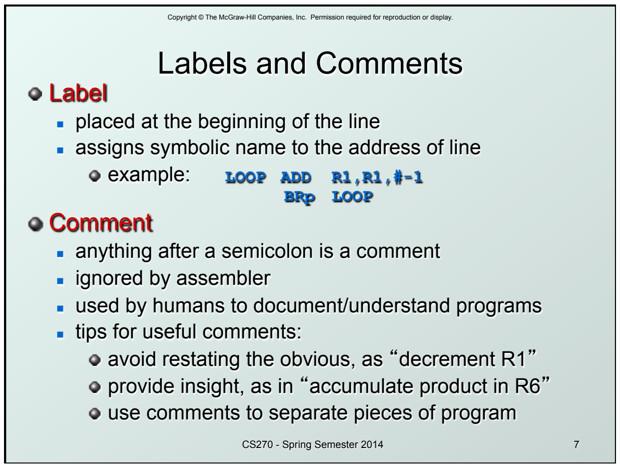
```
LABEL OPCODE OPERANDS ; COMMENTS
```



Opcodes and Operands

- Opcodes
  - reserved symbols that correspond to LC-3 instructions
  - listed in Appendix A
    - example: `ADD, AND, LD, LDR, …`
- Operands
  - registers -- specified by Rn, 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
    - example:

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

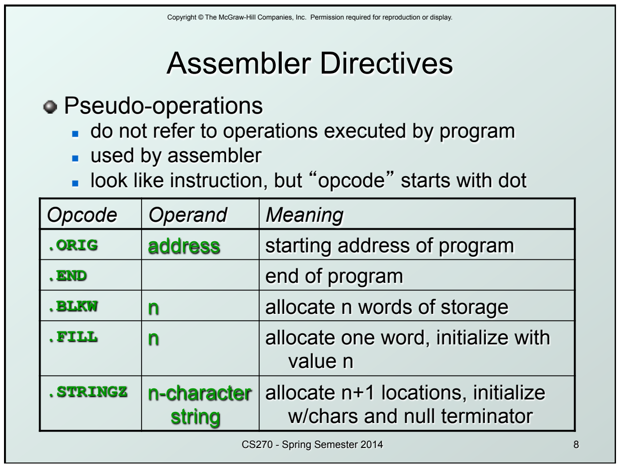


Labels and Comments

- Label
  - placed at the beginning of the line
  - assigns symbolic name to the address of line
    - example:

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

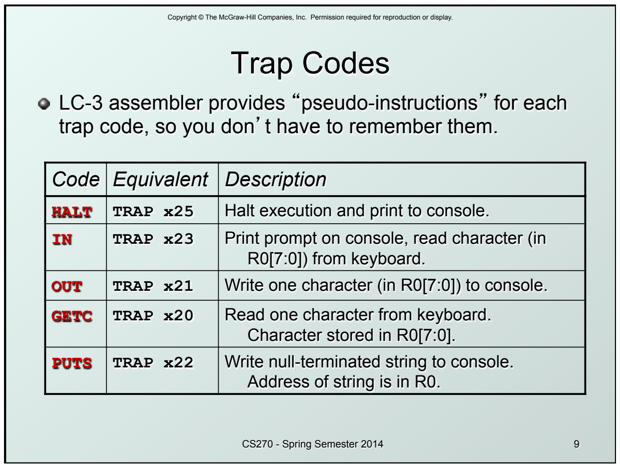
- Comment
  - anything after a semicolon is a comment
  - ignored by assembler
  - used by humans to document/understand programs
  - tips for useful comments:
    - avoid restating the obvious, as "decrement R1"
    - provide insight, as in "accumulate product in R6"
    - use comments to separate pieces 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

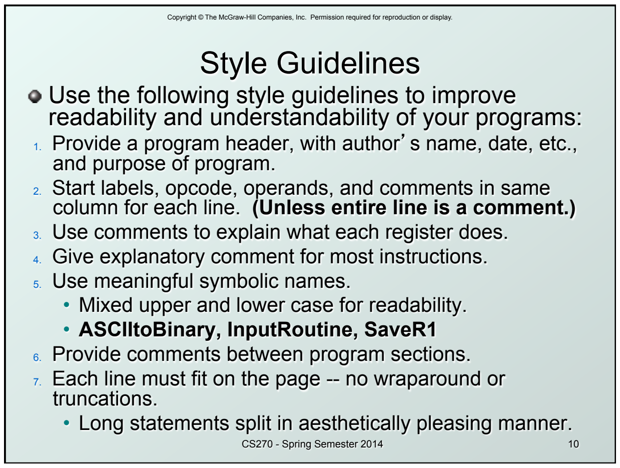
Opcode	*Operand*	*Meaning*
`.ORIG`	address	starting address of program
`.END`		end of program
`.BLKW`	n	allocate n words of storage
`.FILL`	n	allocate one word, initialize with value n
`.STRINGZ`	n-character string	allocate n+1 locations, initialize w/chars and null terminator



Trap Codes

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

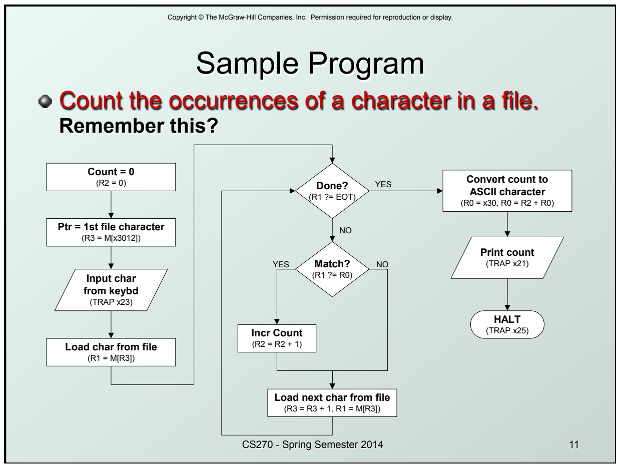
Code	*Equivalent*	*Description*
`HALT`	`TRAP x25`	Halt execution and print to console.
`IN`	`TRAP x23`	Print prompt on console, read character (in R0[7:0]) from keyboard.
`OUT`	`TRAP x21`	Write one character (in R0[7:0]) to console.
`GETC`	`TRAP x20`	Read one character from keyboard. Character stored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



Style Guidelines

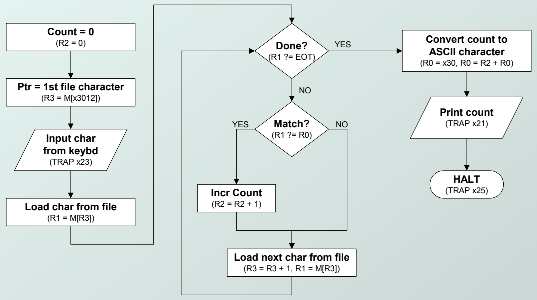
- Use the following style guidelines to improve readability and understandability of your programs:

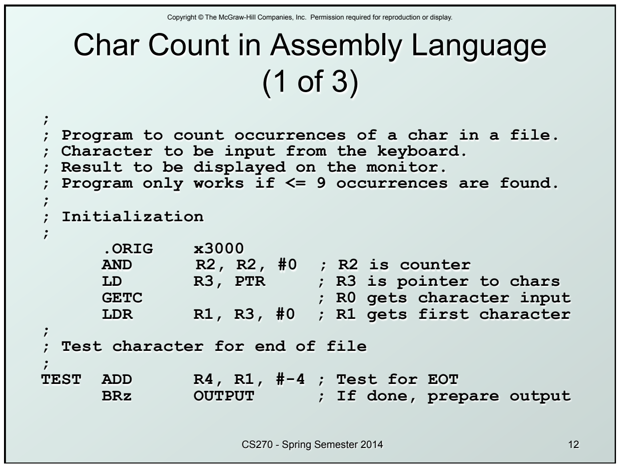
1. Provide a program header, with author's name, date, etc., and purpose of program.
2. Start labels, opcode, operands, and comments in same column for each line. **(Unless entire line is a comment.)**
3. Use comments to explain what each register does.
4. Give explanatory comment for most instructions.
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 char in a file.
; Character to be input from the keyboard.
; Result to be displayed on the monitor.
; Program only works if <= 9 occurrences are found.
;
; Initialization
;
      .ORIG    x3000
      AND      R2, R2, #0  ; R2 is counter
      LD       R3, PTR     ; R3 is pointer to chars
      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
      BRz      OUTPUT      ; If done, prepare output
```

Char Count in Assembly Language (2 of 3)

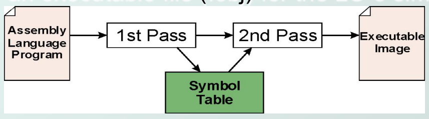
```
;
; Test character for match, if so increment count.
;
        NOT   R1, R1
        ADD   R1, R1, R0 ; If match, R1 = xFFFF
        NOT   R1, R1     ; If match, R1 = x0000
        BRnp  GETCHAR    ; No match, no increment
        ADD   R2, R2, #1
;
; Get next character from file.
;
GETCHAR ADD   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 to ASCII
        OUT              ; ASCII code 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 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

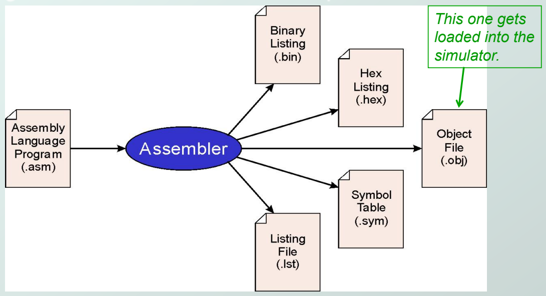
Practice

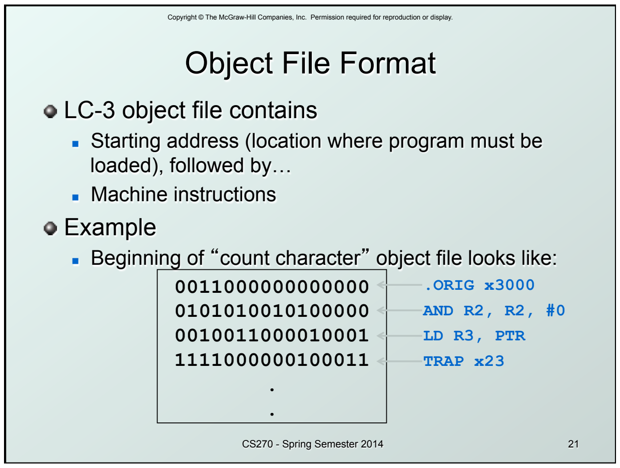
- Using the symbol table constructed earlier, translate these statements into LC-3 machine language.

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.

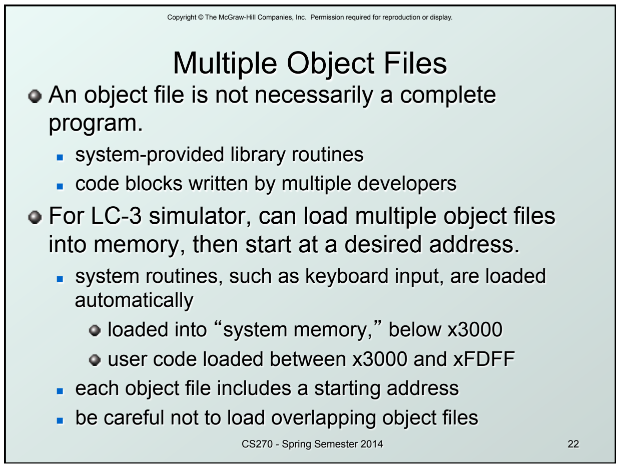




Object File Format

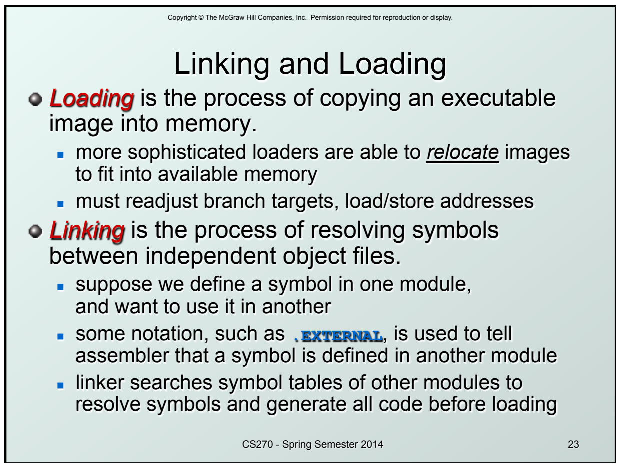
- LC-3 object file contains
  - Starting address (location where program must be loaded), followed by…
  - Machine instructions
- Example
  - Beginning of "count character" object file looks like:

```
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 at a desired address.
  - system routines, such as keyboard input, are loaded automatically
    - loaded into "system memory," below x3000
    - user code 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 searches symbol tables of other modules to resolve symbols and generate all code before loading