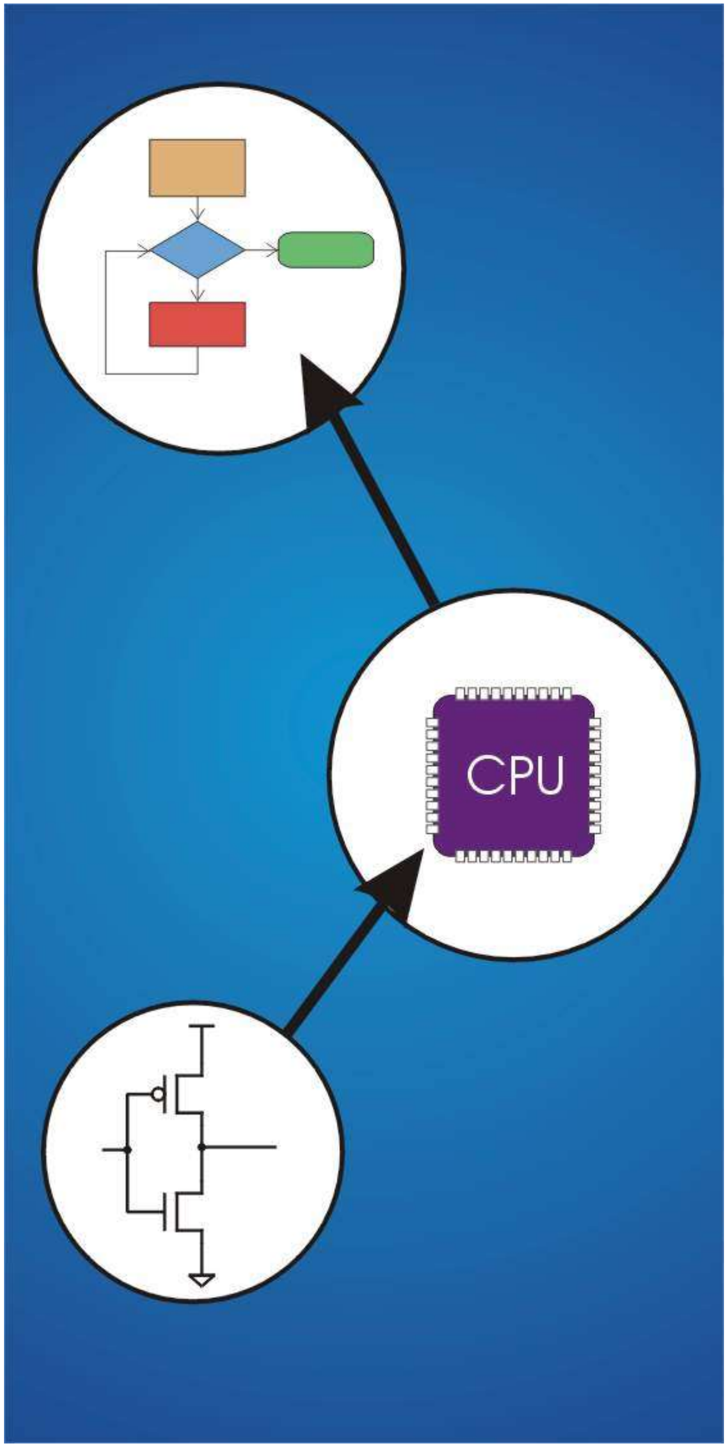
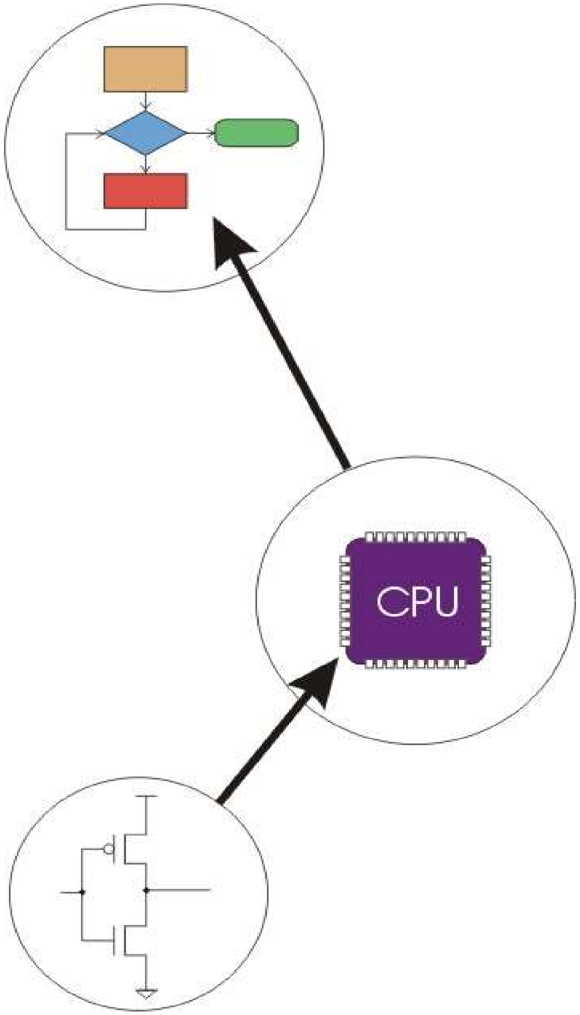


Chapter 7
Assembly Language

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

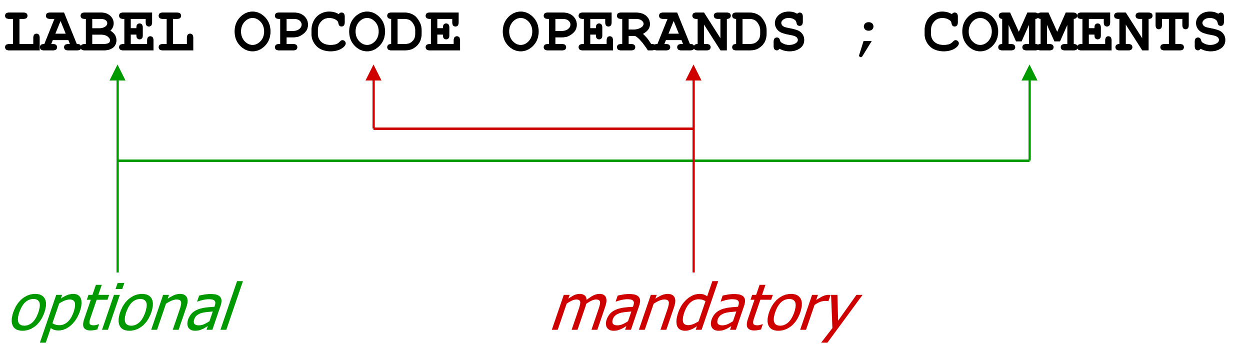
Each line of a program is one of the following:

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

Whitespace (between symbols) and case are ignored.

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

An instruction has the following format:



```
LABEL OPCODE OPERANDS ; COMMENTS
```

optional

mandatory

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

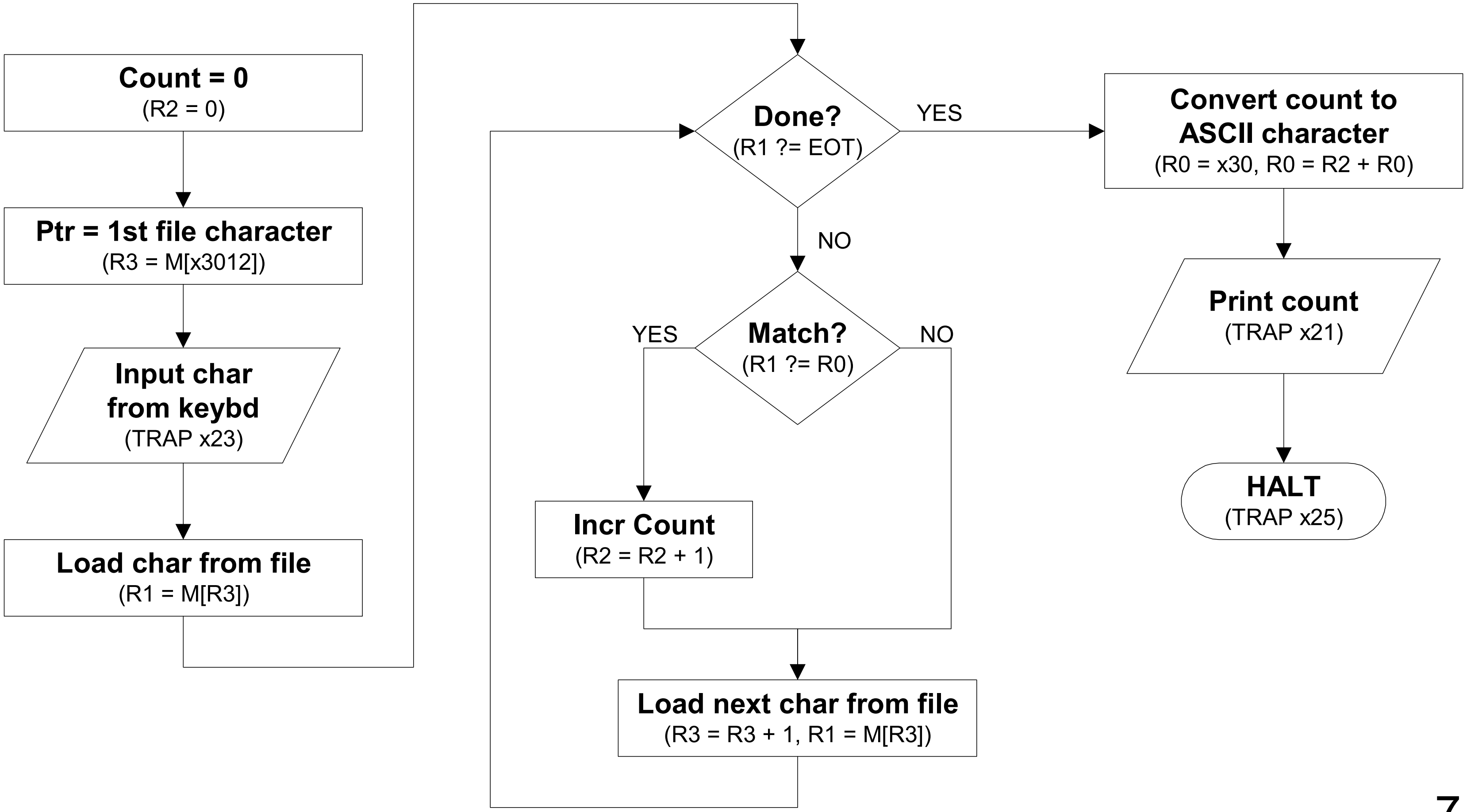
Use the following style guidelines to improve the readability and understandability of your programs:

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)

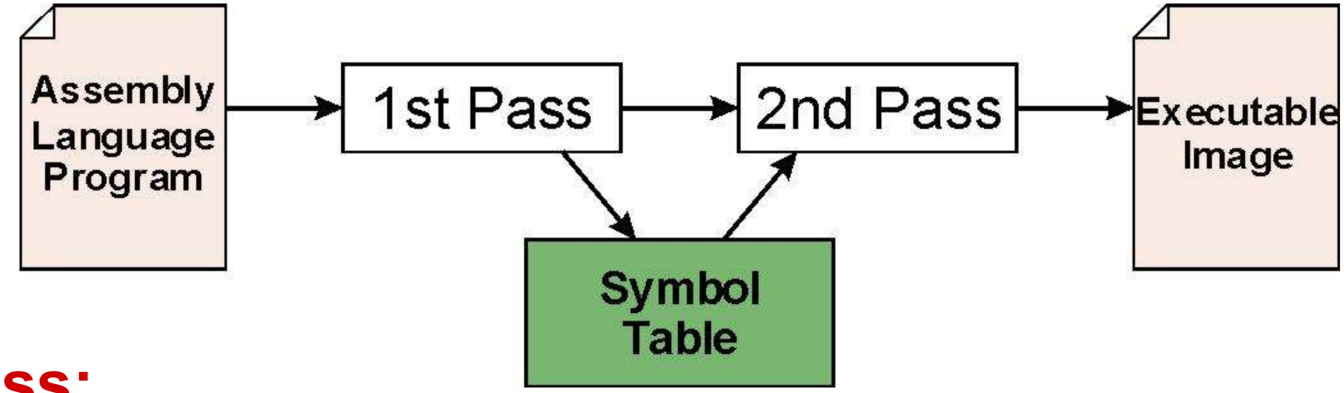
```
;
; Test character for match.  If a match, increment count.
;
        NOT     R1, R1
        ADD     R1, R1, R0  ; If match, R1 = xFFFF
        NOT     R1, R1      ; If match, R1 = x0000
        BRnp    GETCHAR     ; If no match, do not increment
        ADD     R2, R2, #1
;
; Get next character 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 7-12 through 7-14).

Symbol	Address
Test	x3004
…	…
PTR	x3103

```
                .ORIG   x3000
                AND             R2, R2, #0  ; init counter
                 LD     R3, PTR    ; R3  pointer to chars
                 GETC            ; R0 gets char input
                 LDR     R1, R3, #0  ; R1 gets first char
TEST            ADD     R4, R1, #-4 ; Test for EOT
                BRz     OUTPUT     ; done?
;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 cha.
                LDR   R1, R3, #0 ; R1 gets next char
                BRnzp TEST
; Output the count.
OUTPUT           LD    R0, ASCII  ; Load ASCII template
                 ADD   R0, R0, R2 ; Covert binary to ASCII
                 OUT            ; ASCII code is displayed
                HALT           ; Halt machine
; Storage for pointer and ASCII template
ASCII                               .FILL                   x0030
PTR                                 .FILL                   x4000
                                    .END
```

Symbol Table

Symbol	Address
TEST	x3004
GETCHAR	
OUTPUT	
ASCII	
PTR	x3013

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

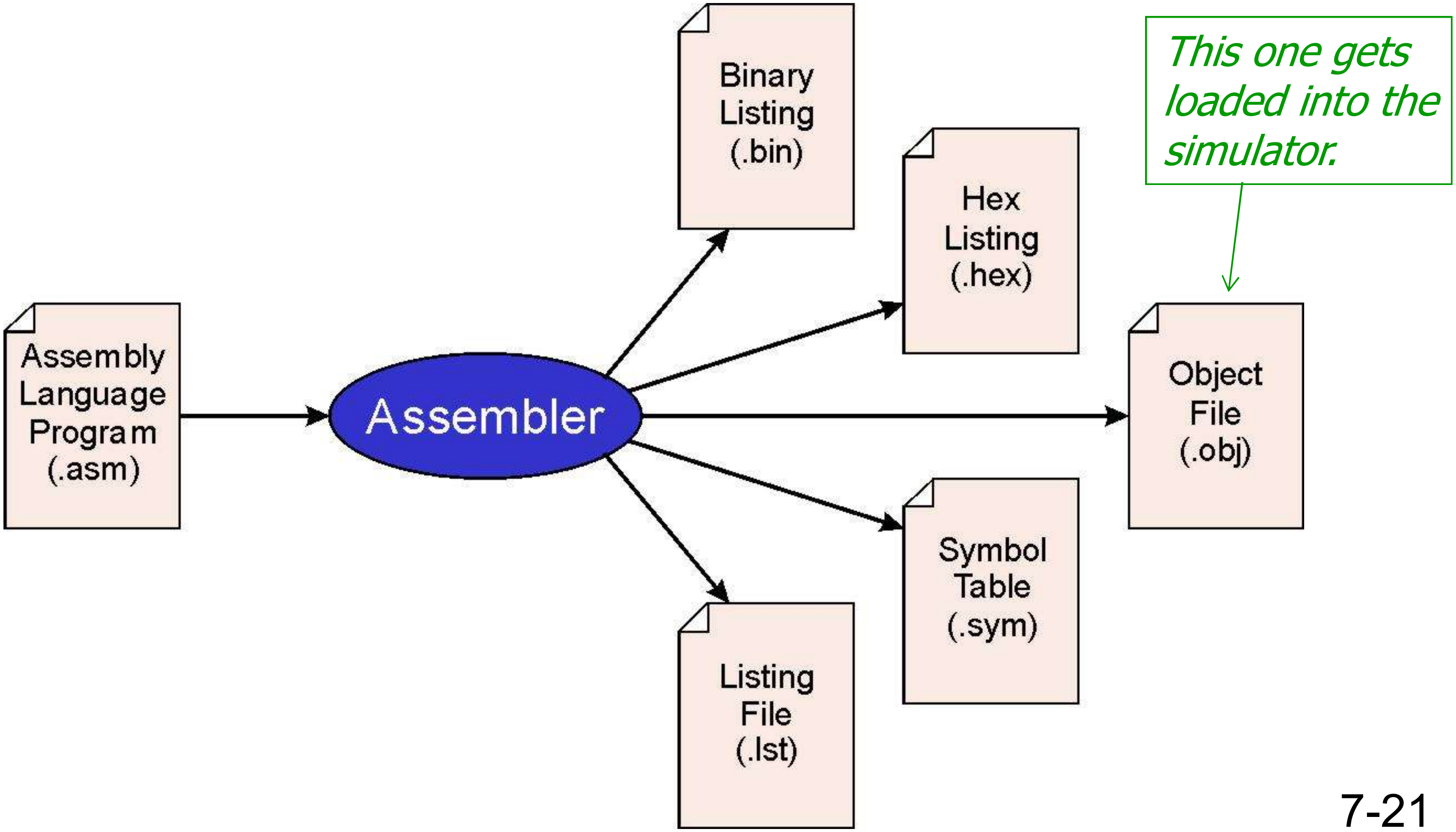
Symbol ptr: x3013, LD is at x3001
Offset needed: x13 - x02 (PC incremented)

Using the symbol table constructed earlier, translate these statements into LC-3 machi guage.

Statement	Machine La guage
`LD R3,PTR`	0010 011 0 0001 0001
`ADD R4,R1,#-4`	
`LDR R1,R3,#0`	
`BRnp GETCHAR`	

LC-3 Assembler

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



This one gets loaded into the simulator.

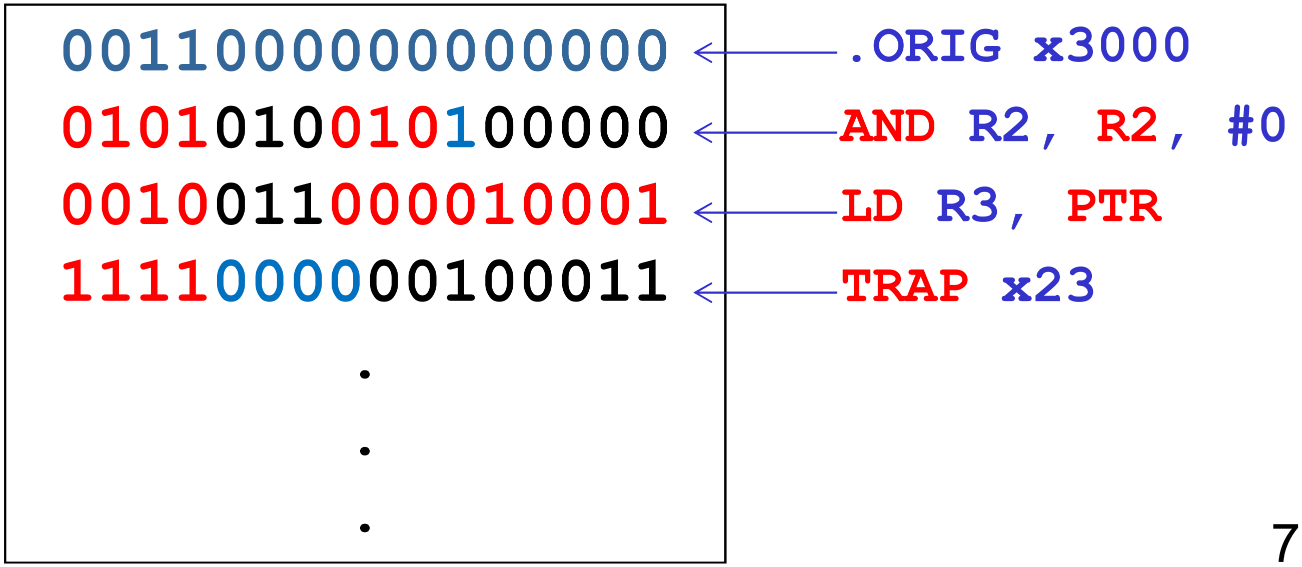
Object File Format

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

LC-3 tools Local Modifications

The following LC-3 assembly instructions will only work with the local tools in the CS department (they will not work with the tools at the text book web site).

Pseudoinstructions: macros that are replaced by one or more actual machine instructions during assembly.

- .ZERO DR (AND DR,DR,#0) ,
- .COPY DR,SR1 (ADD DR,SR1,#0)

Instruction set Extension:

- PUSH
- POP

The authors had chosen to not implement these in accordance with the minimalist RISC approach (see page 254).

Additional traps:

- GETS (Trap #26)
- NEWLN (Trap #27)

The authors had implemented the all 0 instruction (BRnzp with offset 0) so that it is a NOP. In the modified tools the instruction is illegal. A NOP is sometimes used for inserting delays.