Chapter 7
Assembly Language

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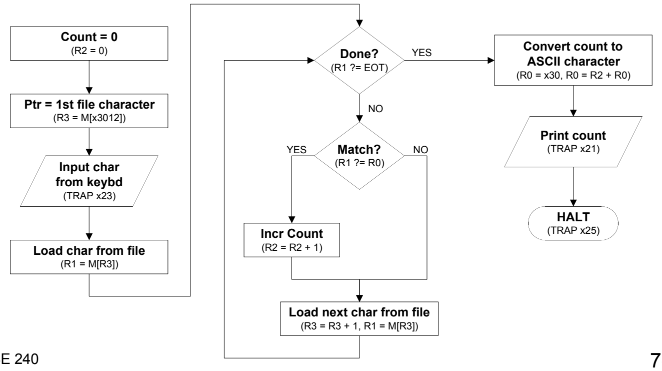
There are 10 kinds of people in the world…
…those that know binary,
and those that don't.

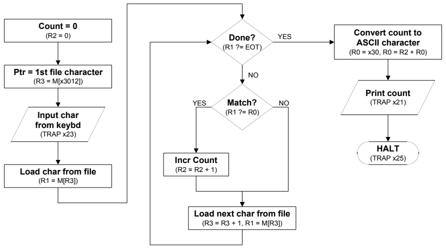
Revisited: Counting Characters (From Ch 5 & 6)

Count the occurrences of a character in a file

Remember this?

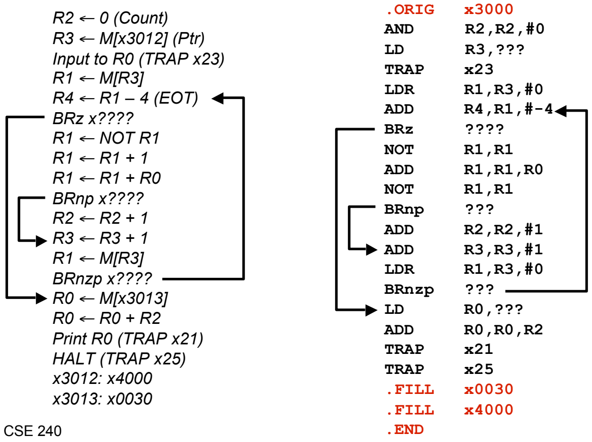


Revisited: Counting Characters (From Ch 5 & 6)



```
R2 ← 0 (Count)
R3 ← M[x3013] (Ptr)
Input to R0 (TRAP x23)
R1 ← M[R3]
R4 ← R1 – 4 (EOT)
BRz x????
R1 ← NOT R1
R1 ← R1 + 1
R1 ← R1 + R0
BRnp x????
R2 ← R2 + 1
R3 ← R3 + 1
R1 ← M[R3]
BRnzp x????
R0 ← M[x3012]
R0 ← R0 + R2
Print R0 (TRAP x21)
HALT (TRAP x25)
x3012: x0030
x3013: x4000
```

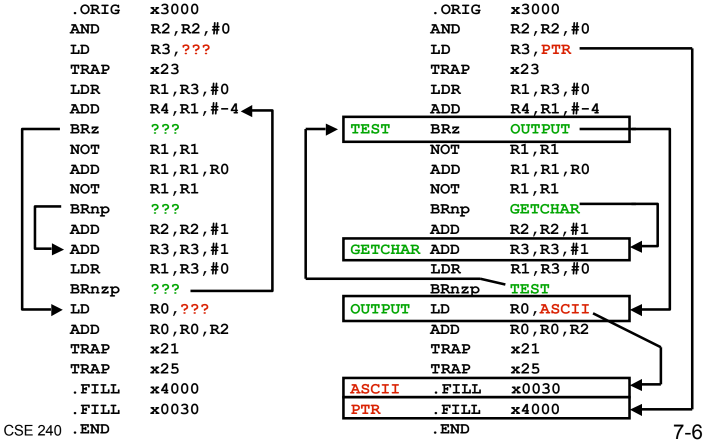
Assembly Language: Opcode + Operands



```
R2 ← 0 (Count)
R3 ← M[x3012] (Ptr)
Input to R0 (TRAP x23)
R1 ← M[R3]
R4 ← R1 – 4 (EOT)
BRz x????
R1 ← NOT R1
R1 ← R1 + 1
R1 ← R1 + R0
BRnp x????
R2 ← R2 + 1
R3 ← R3 + 1
R1 ← M[R3]
BRnzp x????
R0 ← M[x3013]
R0 ← R0 + R2
Print R0 (TRAP x21)
HALT (TRAP x25)
x3012: x4000
x3013: x0030
```

```
.ORIG   x3000
AND     R2,R2,#0
LD      R3,???
TRAP    x23
LDR     R1,R3,#0
ADD     R4,R1,#-4
BRz     ????
NOT     R1,R1
ADD     R1,R1,R0
NOT     R1,R1
BRnp    ???
ADD     R2,R2,#1
ADD     R3,R3,#1
LDR     R1,R3,#0
BRnzp   ???
LD      R0,???
ADD     R0,R0,R2
TRAP    x21
TRAP    x25
.FILL   x0030
.FILL   x4000
.END
```

Introducing Labels for PC-Relative Locations



```
.ORIG   x3000
AND     R2,R2,#0
LD      R3,???
TRAP    x23
LDR     R1,R3,#0
ADD     R4,R1,#-4
BRz     ???
NOT     R1,R1
ADD     R1,R1,R0
NOT     R1,R1
BRnp    ???
ADD     R2,R2,#1
ADD     R3,R3,#1
LDR     R1,R3,#0
BRnzp   ???
LD      R0,???
ADD     R0,R0,R2
TRAP    x21
TRAP    x25
.FILL   x4000
.FILL   x0030
.END
```

```
        .ORIG   x3000
        AND     R2,R2,#0
        LD      R3,PTR
        TRAP    x23
        LDR     R1,R3,#0
        ADD     R4,R1,#-4
TEST    BRz     OUTPUT
        NOT     R1,R1
        ADD     R1,R1,R0
        NOT     R1,R1
        BRnp    GETCHAR
        ADD     R2,R2,#1
GETCHAR ADD     R3,R3,#1
        LDR     R1,R3,#0
        BRnzp   TEST
OUTPUT  LD      R0,ASCII
        ADD     R0,R0,R2
        TRAP    x21
        TRAP    x25
ASCII   .FILL   x0030
PTR     .FILL   x4000
        .END
```

Assembly: Human-Readable Machine Language

Computers like ones and zeros…

`0001110010000110`

Humans like mnemonics …

```
ADD     R6, R2, R6    ; increment index reg.
Opcode  Dest Src1 Src2  Comment
```

Assembler

- A program that turns mnemonics into machine instructions
- ISA-specific
- Mnemonics for opcodes
- One assembly instruction translates to one machine instruction
- 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:

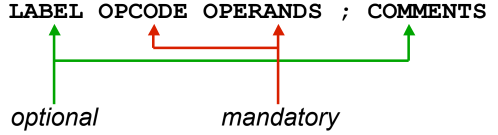
- An instruction
- An assembler directive (or pseudo-op)
- A comment

Whitespace (between symbols) and case are ignored

Comments (beginning with ";") are also ignored

An instruction has the following format:

```
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 R0, R1, …, R7
- Numbers -- indicated by # (decimal) or x (hex) or b (binary)
  - ➢Examples: "#10" is "xA" is "b1100"
- 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
`.FILL`	value	allocate one word, initialize with value
`.BLKW`	number	allocate multiple words of storage, value unspecified
`.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

Improve the readability of your programs

- Formatting: start labels, opcode, operands in same column
- Use comments to explain what each register does
- Give explanatory comment for most instructions
- Use meaningful symbolic names
- Provide comments between program sections
- Each line must fit on the page -- no wraparound or truncations
  - ➢Long statements split in aesthetically pleasing manner

Use structured programming constructs

- From chapter 6
- Don't be overly clever (may make it harder to change later)

High-level programming style is similar

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)

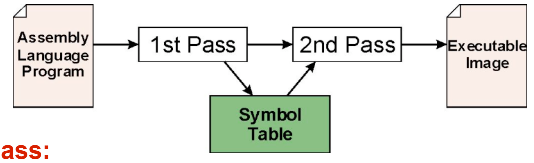
```
;
; Test character for match.  If a match, increment count.
;
        NOT     R1, R1
        ADD     R1, R1, R0  ; If match, R1 = xFFFF
        NOT     R1, R1      ; If match, R1 = x0000
        BRnp    GETCHAR     ; If no match, do not increment
        ADD     R2, R2, #1
;
; Get next character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

Program that converts 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. **Begin with 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-blank line in the program:**
   a) If line contains a label, put label/LC pair into symbol table
   b) Increment LC
      – NOTE: If statement is `.BLKW` or `.STRINGZ`, increment LC by the number of words allocated
      – A line with only a comment is considered "blank"

3. **Stop when `.END` statement is reached**

Second Pass: Generating Machine Code

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 errors:

- 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

Assembly Process Example: First Pass

```
                .ORIG   x3000
x3000           AND     R2,R2,#0
x3001           LD      R3,PTR
x3002           TRAP    x23
x3003           LDR     R1,R3,#0
x3004           ADD     R4,R1,#-4
x3005 TEST      BRz     OUTPUT
x3006           NOT     R1,R1
x3007           ADD     R1,R1,R0
x3008           NOT     R1,R1
x3009           BRnp    GETCHAR
x300A           ADD     R2,R2,#1
x300B GETCHAR   ADD     R3,R3,#1
x300C           LDR     R1,R3,#0
x300D           BRnzp   TEST
x300E OUTPUT    LD      R0,ASCII
x300F           ADD     R0,R0,R2
x3010           TRAP    x21
x3011           TRAP    x25
x3012 ASCII     .FILL   x0030
x3013 PTR       .FILL   x4000
                .END
```

Symbol	Address
TEST	x3005
GETCHAR	x300B
OUTPUT	x300E
ASCII	x3012
PTR	x3013

Assembly Process Example: Second Pass

```
                .ORIG   x3000
x3000           AND     R2,R2,#0  →  0101 010 010 1 00000
x3001           LD      R3,PTR    →  0010 011 000010001
x3002           TRAP    x23       →  1111 0000 00100011
x3003           LDR     R1,R3,#0     .
x3004           ADD     R4,R1,#-4    .
x3005 TEST      BRz     OUTPUT
x3006           NOT     R1,R1
x3007           ADD     R1,R1,R0
x3008           NOT     R1,R1
x3009           BRnp    GETCHAR
x300A           ADD     R2,R2,#1
x300B GETCHAR   ADD     R3,R3,#1
x300C           LDR     R1,R3,#0
x300D           BRnzp   TEST
x300E OUTPUT    LD      R0,ASCII
x300F           ADD     R0,R0,R2
x3010           TRAP    x21
x3011           TRAP    x25
x3012 ASCII     .FILL   x0030
x3013 PTR       .FILL   x4000
                .END
```

Symbol	Address
TEST	x3005
GETCHAR	x300B
OUTPUT	x300E
ASCII	x3012
PTR	x3013

LC-3 Assembler

Generates two different output files

Object file (.obj)

- Binary representation of the program

Symbol file (.sym)

- Includes names of labels (also known as symbols)
- Used by simulator to make code easier to read
- A text file of symbol mappings

Object File Format

LC-3 object file contains

- Starting address (location where program must be loaded), followed by…
- Machine instructions
- (Real-world object file formats are more complicated)

LC-3 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
        .
        .
        .
```

Using 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

- Load multiple object files into memory, then start executing at a desired address
- System routines, such as keyboard input, are loaded with OS
  - ➢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