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# Computer Architecture 2023-24 (WBCS010-05)

## Lecture 9: Assembly

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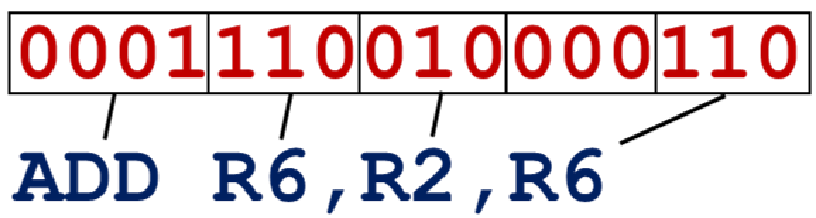
# Human-Friendly Programming (Recap)

- Computers need binary instruction encodings…
  - `0001110010000110`
- Humans prefer symbolic languages…
  - `a = b + c`
- High-level languages allow us to write programs in clear, precise language that is more like English or math. Requires a program (compiler) to translate from symbolic language to machine instructions.
- Examples: C, Python, Fortran, Java, …

# Assembly Language (Recap)

- Very similar format to instructions -- replace bit fields with symbols




- For the most part, one line of assembly language = one instruction
- Some additional features for allocating memory, initializing memory locations, service calls
- Numerical values specified in hexadecimal (x30AB) or decimal (#10)

x10 is not the same as #10 !

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# Assembly Language Syntax (Recap)

› Each line of a program is either 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
```

*optional* *mandatory*

# Mandatory: Opcode and Operands

› Opcodes

Reserved symbols that correspond to LC-3 instructions.

Listed in Appendix A and Figure 5.3.

- For example: `ADD`, `AND`, `LD`, `LDR`, ...

› ***reserved*** means that it cannot be used as a label

› Operands

- Registers -- specified by Rn, where n is the register number.
- Numbers -- indicated by # (decimal) or x (hex).
- Label -- symbolic name of memory location (1 to 20 alphanumeric characters)
- Separated by comma (whitespace ignored).
- Number, order, and type correspond to instruction format.

```
› ADD     R1,R1,R3    ; DR, SR1, SR2
  ADD     R1,R1,#3    ; DR, SR1, Imm5
  LD      R6,NUMBER   ; DR, address (converted to PCoffset)
  BRz     LOOP        ; nzp becomes part of opcode, address
```

# Optional: Label and Comment

› Label

- Placed at the beginning of the line
- Assigns a symbolic name to the address corresponding to that line

›
```
LOOP ADD   R1,R1,#-1   ; LOOP is address of ADD
     BRp   LOOP
```

› Comment

› A semicolon, and anything after it on the same line, 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 and empty lines to separate pieces of program

# Assembler Directive

› Pseudo-operation
- Does not refer to an actual instruction to be executed
- Tells the assembler to do something
- Looks like an instruction, except "opcode" starts with a 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 with characters and null terminator** |

# .STRINGZ

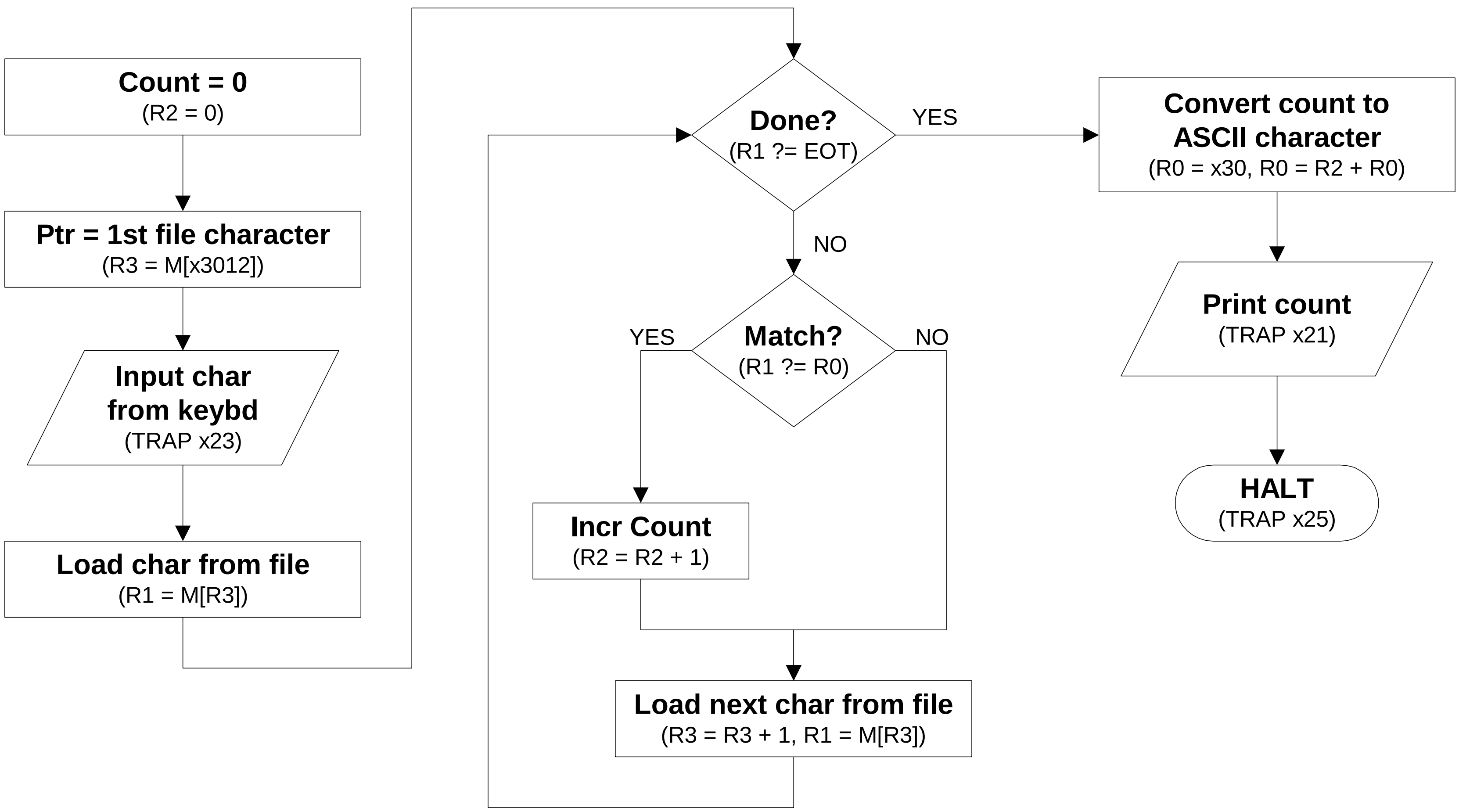
- For example, the code fragment
- .ORIG x3010
- HELLO .STRINGZ "Hello, World!"

- would result in the assembler initializing locations x3010 through x301D to the following values:

- x3010: x0048
- x3011: x0065
- x3012: x006C
- x3013: x006C
- x3014: x006F
- x3015: x002C
- x3016: x0020
- x3017: x0057
- x3018: x006F
- x3019: x0072
- x301A: x006C
- x301B: x0064
- x301C: x0021
- x301D: x0000

# Sample Program: Counting Occurrences in a File

› Once again, we show the program that counts the number of times (up to nine) a user-specified character appears in a file.



# Assembly Language Program 1

```
;
; 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
        TRAP     x23                ; 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
;
; Test character for match.  If a match, increment count.
;
        NOT      R1, R1
        ADD      R1, R1, #1
        ADD      R1, R1, R0     ; Compute R0-R1 to compare
        BRnp     GETCHAR        ; If no match, do not increment count
        ADD      R2, R2, #1
```

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# Assembly Language Program 2

```
;
; 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
        TRAP    x21          ; ASCII code in R0 is displayed.
        TRAP    x25          ; Halt machine

;
; Storage for pointer and ASCII template
;
ASCII   .FILL   x0030
PTR     .FILL   x4000
        .END
```

- What if we don't put HALT (TRAP x25) at the end of the program?

# Data or Instruction?

```
OUTPUT LD      R0, ASCII    ; Load the ASCII template
       ADD     R0, R0, R2   ; Covert binary count to ASCII
       TRAP    x21          ; ASCII code in R0 is displayed.

;
; Storage for pointer and ASCII template
;
ASCII  .FILL   x0030
PTR    .FILL   x4000
       .END
```

- Next memory location after TRAP x21 contains x0030
- In binary: 0000 000 000110000
- Branch to PC + 48 if ?
- x4000 = 0100 000 000 000000 (Jump to subroutine)

# Assembly Language Program 3

```
        .ORIG x3000
        AND R5, R5, #0
        AND R3, R3, #0
        ADD R3, R3, #8
        LDI R1, A
        ADD R2, R1, #0
AG      ADD R2, R2, R2
        ADD R3, R3, #-1
        BRnp AG
        LD R4, B
        AND R1, R1, R4
        NOT R1, R1
        ADD R1, R1, #1
        ADD R2, R2, R1
        BRnp NO
        ADD R5, R5, #1
NO      HALT
B       .FILL xFF00
A       .FILL x4000
        .END
```

Is the sum of the least and the most significant bytes of word equal to zero?

# Assembly Language Program 4 (I)

```
        .ORIG x3000
ONE     LD R0, A
        ADD R1, R1, R0
TWO     LD R0, B
        ADD R1, R1, R0
THREE   LD R0, C
        ADD R1, R1, R0
        ST R1, SUM
        TRAP x25
A       .FILL x0001
B       .FILL x0002
C       .FILL x0003
SUM     .FILL x0004
        .END
```

What is wrong in this example?

# Assembly Language Program 4 (II)

```
      .ORIG x3000
      AND R1, R1, #0
ONE   LD R0, A
      ADD R1, R1, R0
TWO   LD R0, B
      ADD R1, R1, R0
THREE LD R0, C
      ADD R1, R1, R0
      ST R1, SUM
      TRAP x25
A     .FILL x0001
B     .FILL x0002
C     .FILL x0003
SUM   .FILL x0004
      .END
```

- R1 should be initialized (added here)
- What if we add the Load instructions as marked red?

```
.ORIG x3000
      AND R1, R1, #0
ONE   LD R0, A
      ADD R1, R1, R0
TWO   LD R0, B
      ADD R1, R1, R0
THREE LD R0, C
      ADD R1, R1, R0
      LD R0, ONE
      LDI R0, ONE
      ST R1, SUM
      TRAP x25
A     .FILL x0001
B     .FILL x0002
C     .FILL x0003
SUM   .FILL x0004
      .END
```

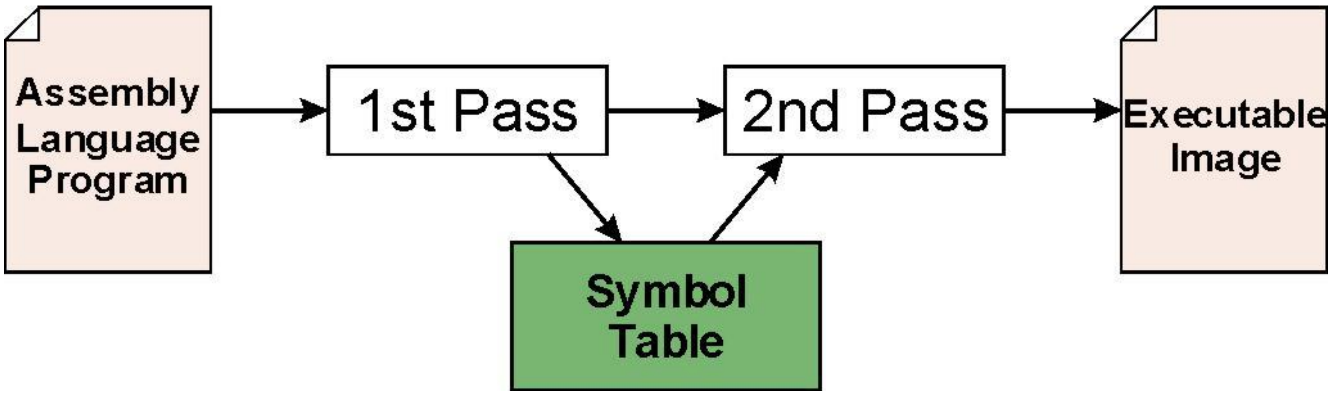
# Assembly Language Program 4 (III)

- LD R0, ONE   will load the value of the location shown by label ONE into R0. In this example, ONE is x3001.
- Content of x3001 is LD R0, A = 0010 000 000001001
- R0 will contain x2009

- LDI R0, ONE  will load the content of the location shown by an address stored at x3001.
- This is equivalent to R0 🡐 M[x2009]

# Assembly Process

› The assembler is a program that translate an assembly language (.asm) file to a binary object (.obj) file that can be loaded into memory.




› **First Pass:**

- Scan program file, check for syntax errors
- Find all labels and calculate the corresponding addresses: the *symbol table*

› **Second Pass:**

- Convert instructions to machine language, using information from symbol table

# First Pass: Construct 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:
   - If line contains a label, add label and LC to symbol table
   - 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

# First Pass on Sample Program (Comments Removed)

```
--                .ORIG   x3000
x3000             AND     R2, R2, #0
x3001             LD      R3, PTR
x3002             TRAP    x23
x3003             LDR     R1, R3, #0
x3004   TEST      ADD     R4, R1, #-4
x3005             BRz     OUTPUT
x3006             NOT     R1, R1
x3007             ADD     R1, R1, #1
x3008             ADD     R1, R1, R0
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
```

| Label | Address |
|---|---|
| TEST | x3004 |
| GETCHAR | x300B |
| OUTPUT | x300E |
| ASCII | x3012 |
| PTR | x3013 |

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# Second Pass: Convert to Machine Instructions

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:
   - If line contains an instruction, translate opcode and operands to binary machine instruction. For label, lookup address in symbol table, subtract (LC+1) and replace label with that. Increment LC
   - If line contains .FILL, convert value/label to binary. Increment LC
   - If line contains .BLKW, create n copies of x0000 (or any arbitrary value). Increment LC by n
   - If line contains .STRINGZ, convert each ASCII character to 16-bit binary value. Add null (x0000). Increment LC by n+1

3. Stop when .END statement is reached

# Example

- .ORIG x3000
- AND R2,R2,#0 ; R2 is counter, initialize to 0
- LD R3,PTR ; R3 is pointer to characters

| Symbol | Address |
|---|---|
| TEST | x3004 |
| GETCHAR | x300B |
| OUTPUT | x300E |
| ASCII | x3012 |
| PTR | x3013 |

- Set LC to x3000
- AND R2,R2,#0 ➔ 0101010010100000
- Increment LC ➔ LC = x3001
- LD R3,PTR ➔ 0010011000010001
- PTR is x3013 from Symbol table
- Subtract LC+1 from x3013 ➔ x3013 – x3002 ➔ x0011
- X0011 ➔ 000010001 (9 bits binary)
- Increment LC ➔ LC = x3002

# Errors during Code Translation

- While assembly language is being translated to machine instructions, several types of errors may be discovered
  - Immediate value too large -- can't fit in Imm5 field
  - Address out of range -- greater than LC+1+255 or less than LC+1-256
  - Symbol not defined, not found in symbol table
- If error is detected, assembly process is stopped and an error message is printed for the user

# Beyond a Single Object File

- Larger programs may be written by multiple programmers, or may use modules written by a third party. Each module is assembled independently, each creating its own object file and symbol table.
- To execute, a program must have all of its modules combined into a single executable image
- **Linking** is the process to combine all of the necessary object files into a single executable

# External Symbols

- In the assembly code we're writing, we may want to symbolically refer to information defined in a different module
- For example, suppose we don't know the starting address of the file in our counting program. The starting address and the file data could be defined in a different module.
- We want to do this:
  - `PTR .FILL  STARTofFILE`
- To tell the assembler that `STARTofFILE` will be defined in a different module, we could do something like this:
  - `.EXTERNAL STARTofFILE`
- This tells the assembler that it's not an error that `STARTofFILE` is not defined. It will be up to the linker to find the symbol in a different module and fill in the information when creating the executable.

# Questions?