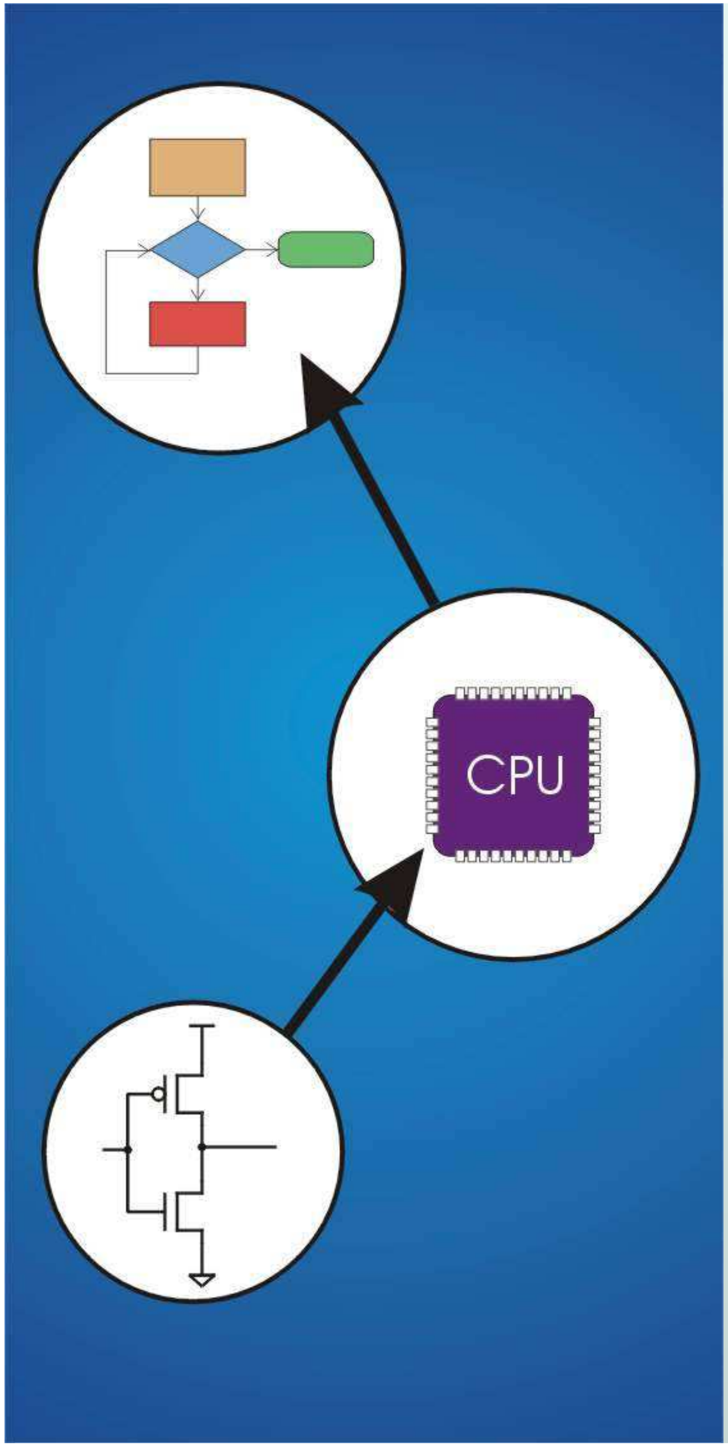
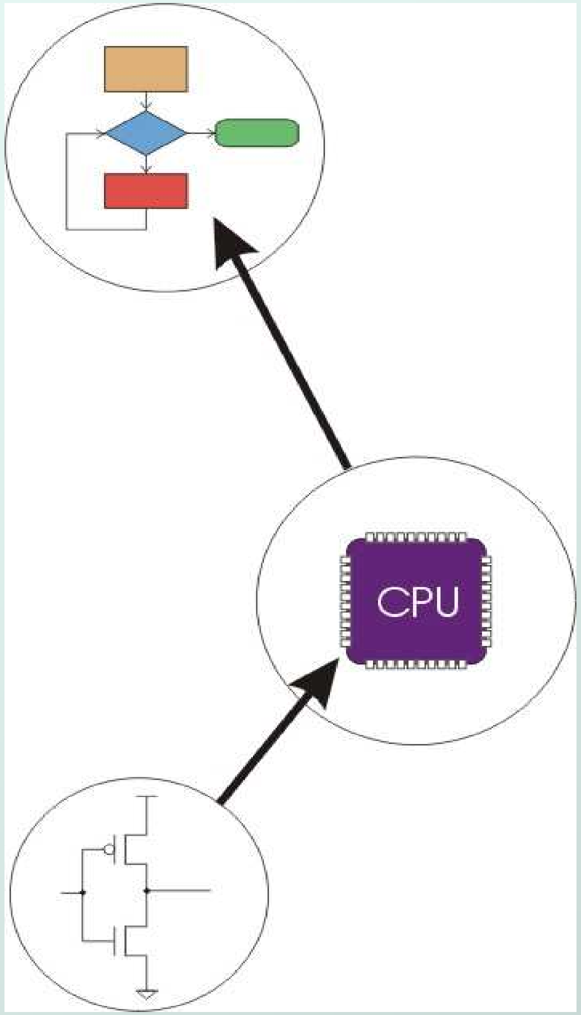


Chapter 6
Programming

Original slides from Gregory Byrd, North Carolina State University

Modified by C. Wilcox, Y. Malaiya
Colorado State University

Computing Layers



Problems

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Algorithms

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Language

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Instruction Set Architecture

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Microarchitecture

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Circuits

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Devices

Solving Problems using a Computer

- Methodologies for creating computer programs that perform a desired function.
- Problem Solving
  - How do we figure out what to tell the computer to do?
  - Convert problem statement into algorithm, using *stepwise refinement*.
  - Convert algorithm into LC-3 machine instructions.
- Debugging
  - How do we figure out why it didn't work?
  - Examine registers and memory, set breakpoints, etc.

Time spent on the first can reduce time spent on the second!

Stepwise Refinement

- Also known as systematic decomposition.
- Start with problem statement:

  "We wish to count the number of occurrences of a character in a file. The character in question is to be input from the keyboard; the result is to be displayed on the monitor."

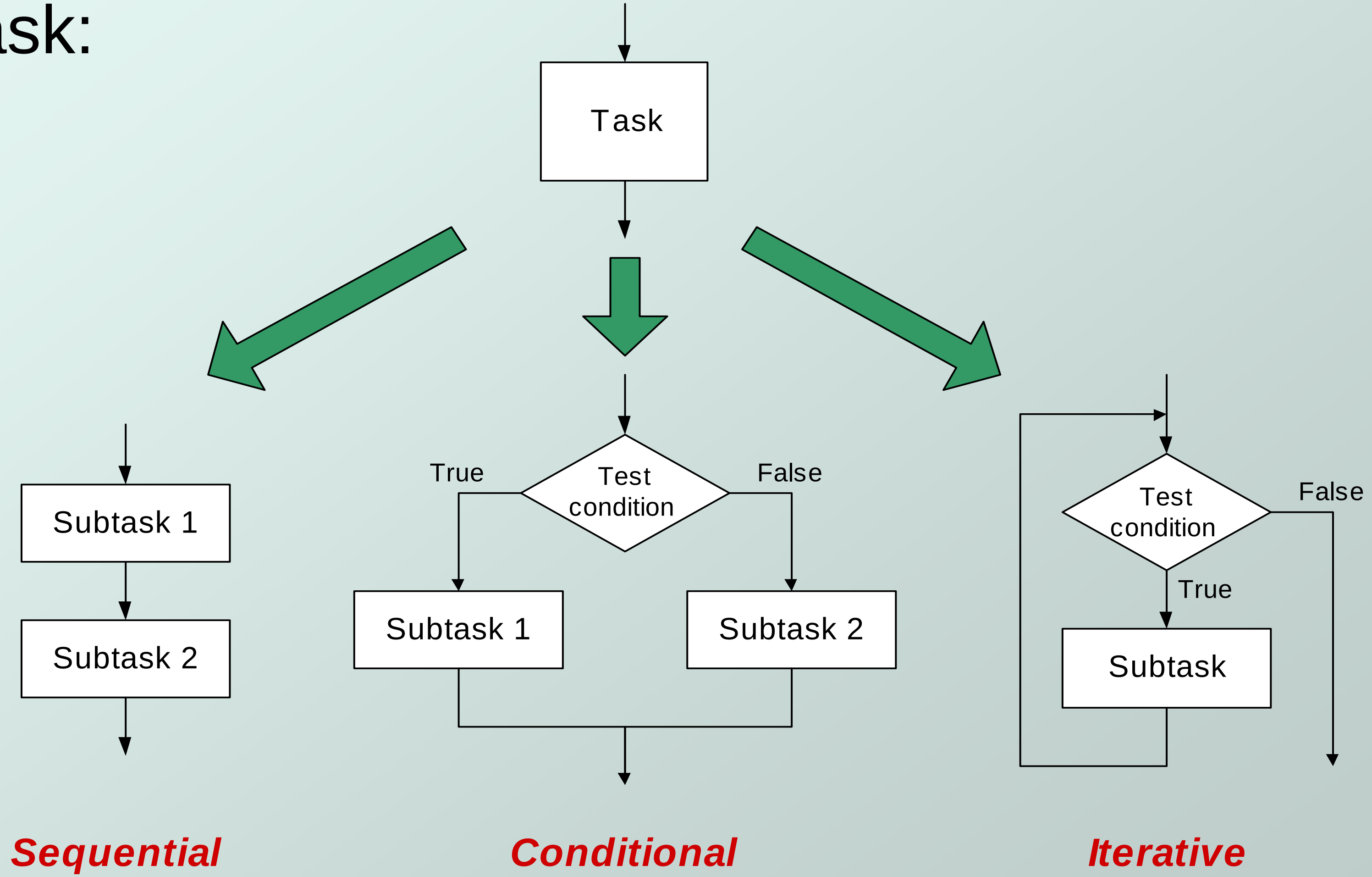
- Decompose task into a few simpler subtasks.
- Decompose each subtask into smaller subtasks, and these into even smaller subtasks, etc.... until you get to the machine instruction level.

Problem Statement

- Because problem statements are written in English, they are sometimes ambiguous and/or incomplete.
  - Where is “file” located? How big is it, or how do I know when I’ve reached the end?
  - How should final count be printed? A decimal number?
  - If the character is a letter, should I count both upper-case and lower-case occurrences?
- How do you resolve these issues?
  - Ask the person who wants the problem solved, or
  - Make a decision and document it.

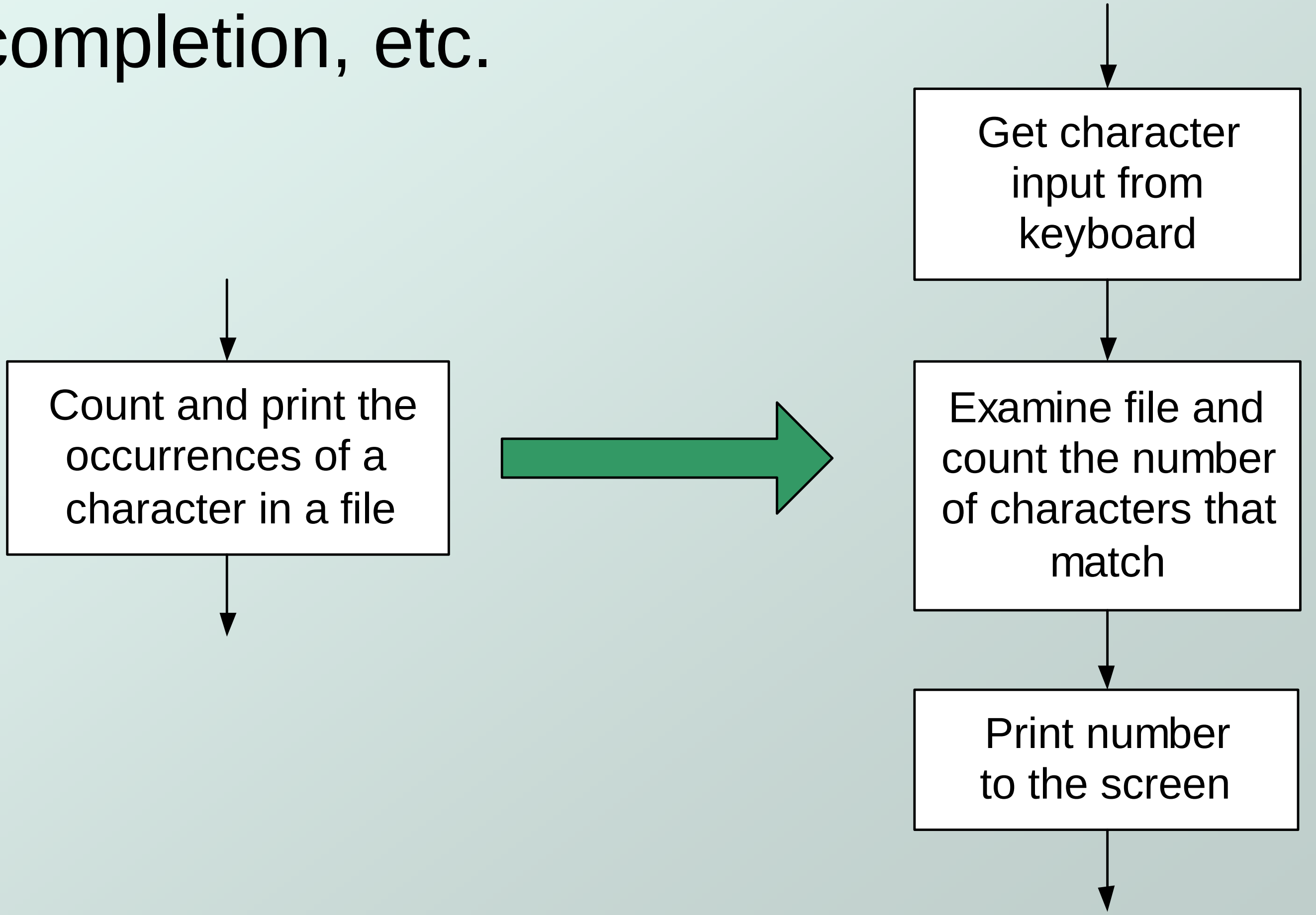
Three Basic Constructs

- There are three basic ways to decompose a task:



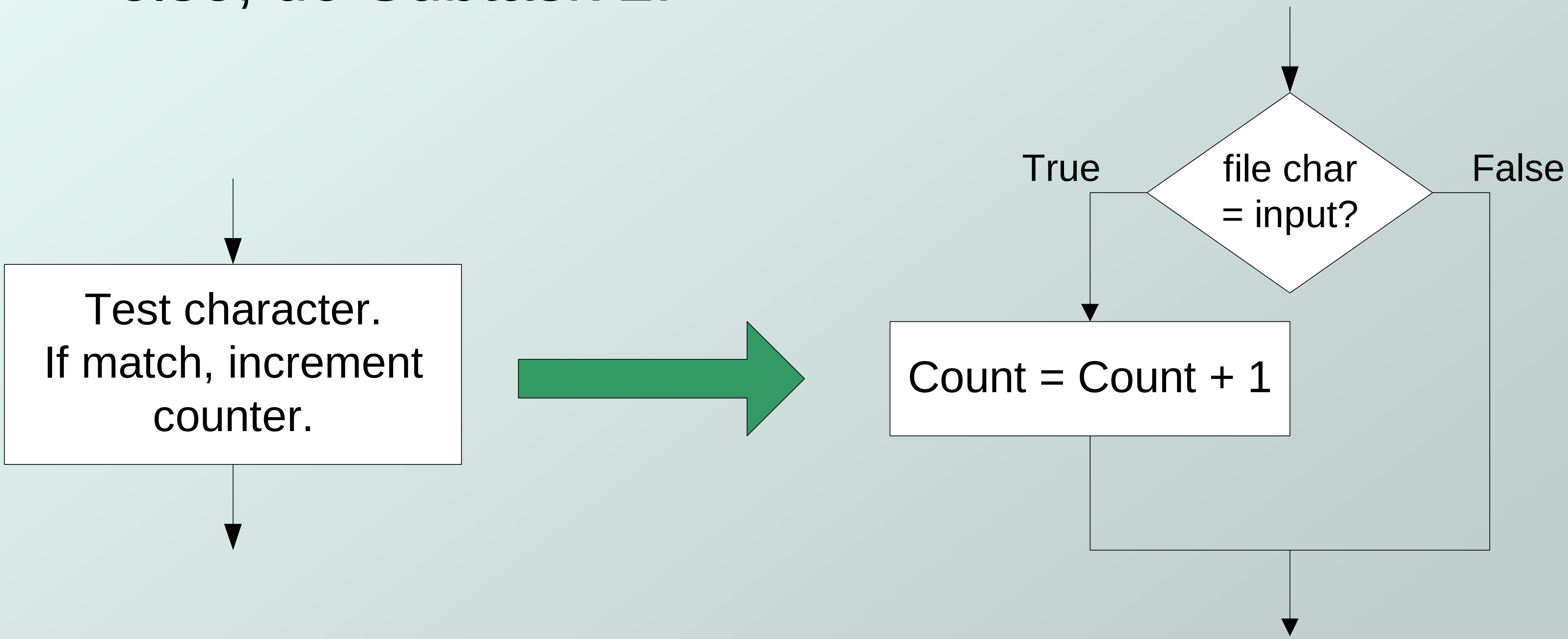
Sequential

- Do Subtask 1 to completion, then do Subtask 2 to completion, etc.



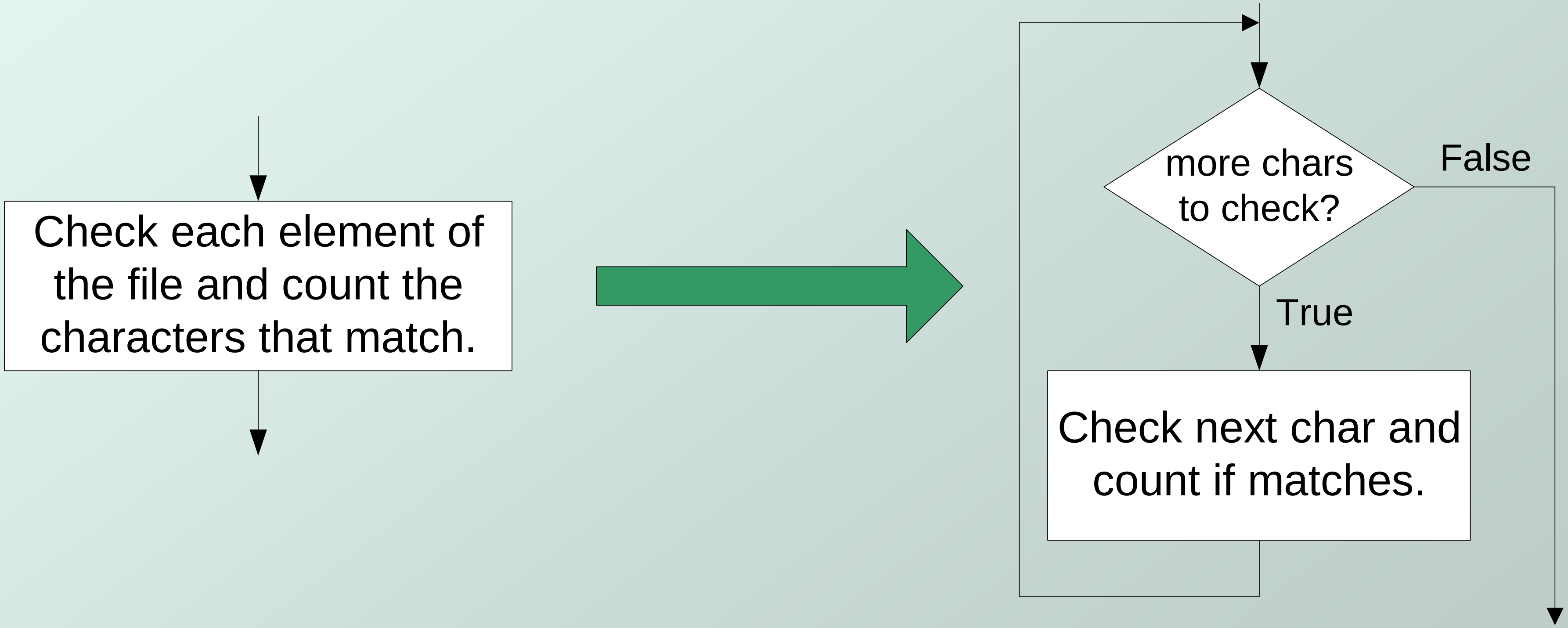
Conditional

- If condition is true, do Subtask 1; else, do Subtask 2.



Iterative

- Do Subtask over and over,
  as long as the test condition is true.



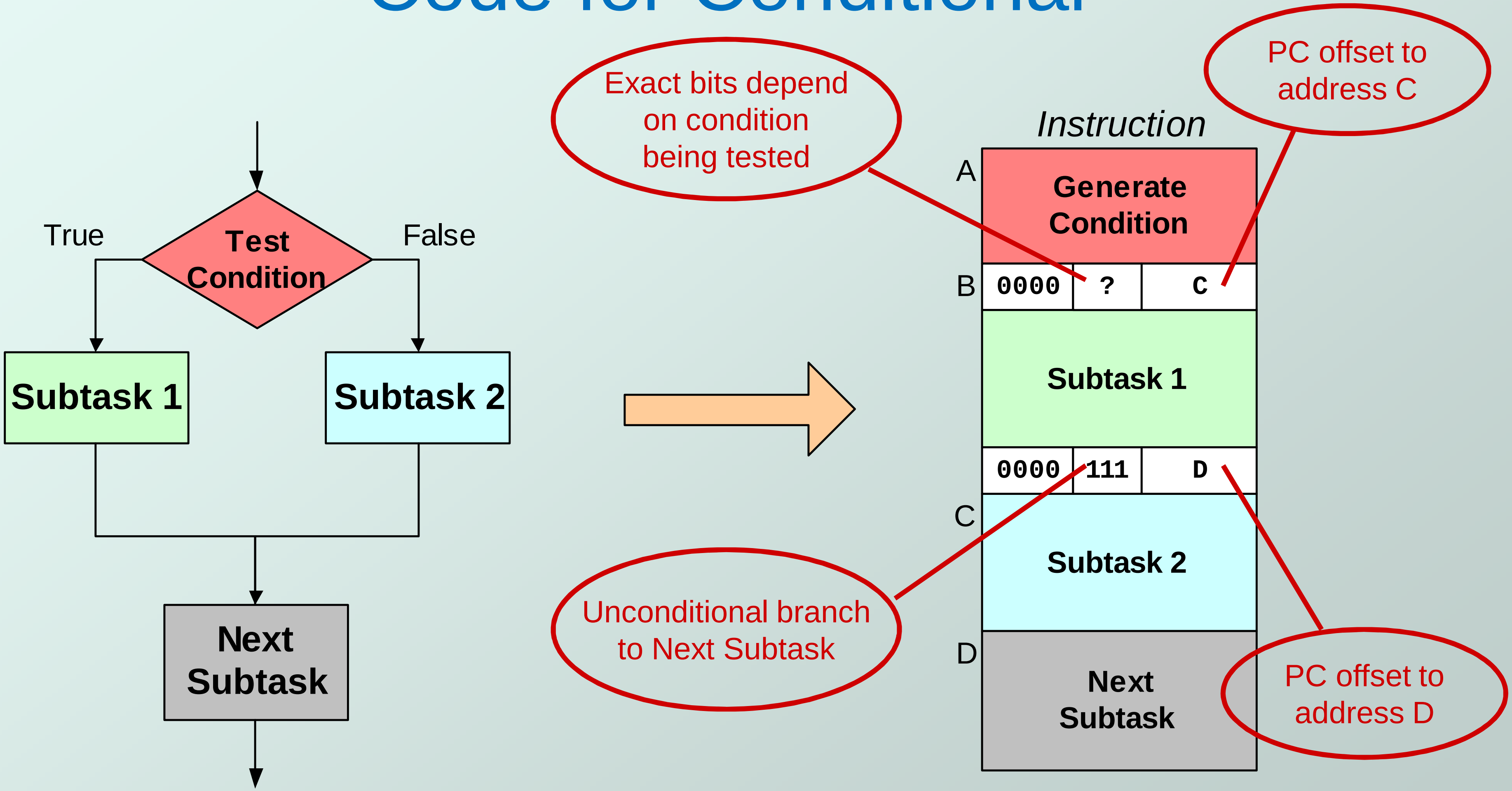
Problem Solving Skills

- Learn to convert problem statement into step-by-step description of subtasks. Like a puzzle, or a "word problem" from elementary school math.
  - What is the starting state of the system?
  - What is the desired ending state?
  - How do we move from one state to another?
- Recognize English words that correlate to three basic constructs:
  - "do A then do B" ⇒ sequential
  - "if G, then do H" ⇒ conditional
  - "for each X, do Y" ⇒ iterative
  - "do Z until W" ⇒ iterative

LC-3 Control Instructions

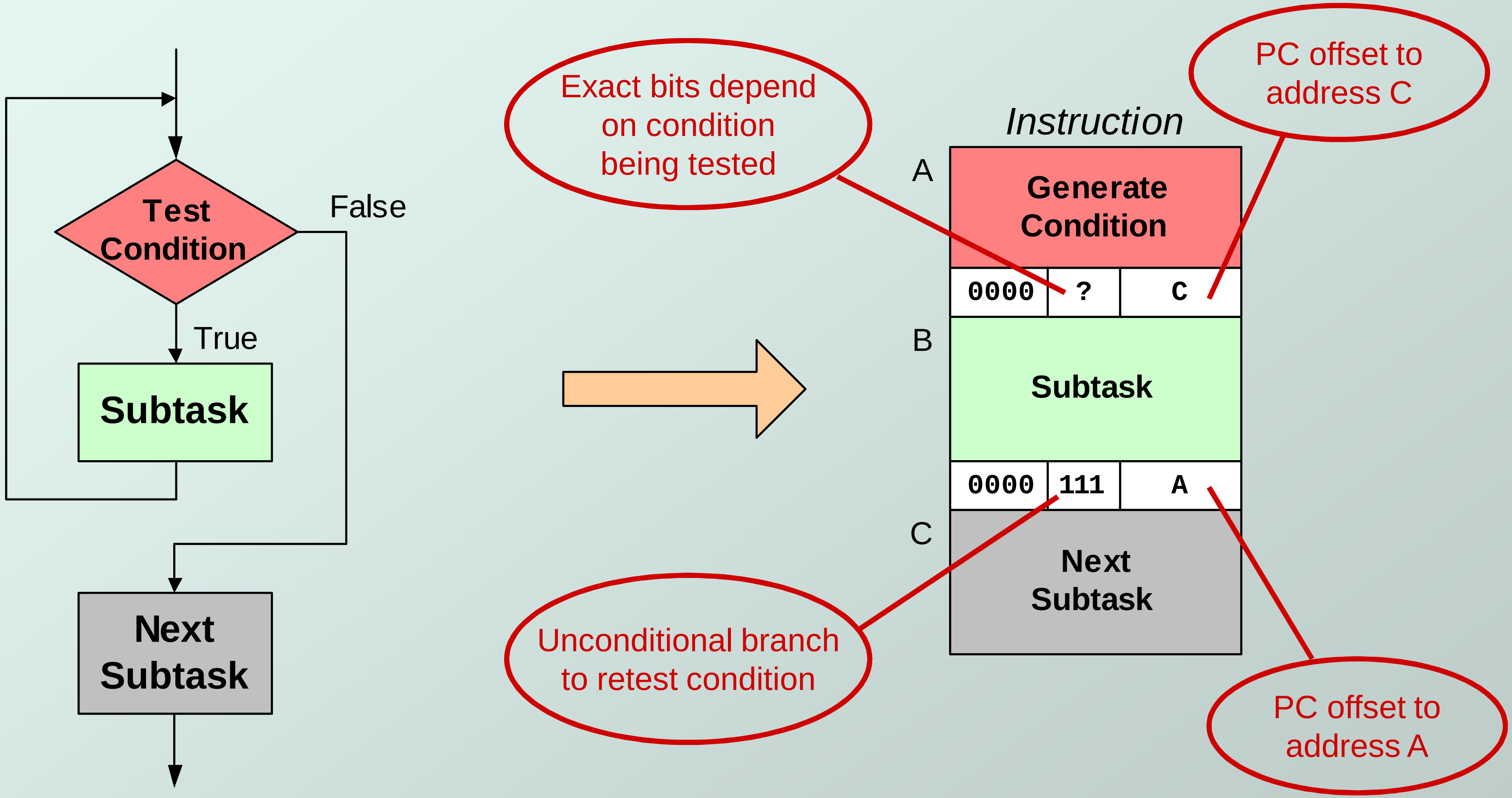
- How do we use LC-3 instructions to encode the three basic constructs?
- Sequential
  - Instructions naturally flow from one to the next, so no special instruction needed to go from one sequential subtask to the next.
- Conditional and Iterative
  - Create code that converts condition into N, Z, or P.
    Example: "Is R0 = R1?"
    Code: Subtract R1 from R0; if equal, Z bit will be set.
  - Use BR instruction to transfer control to proper subtask.

Code for Conditional



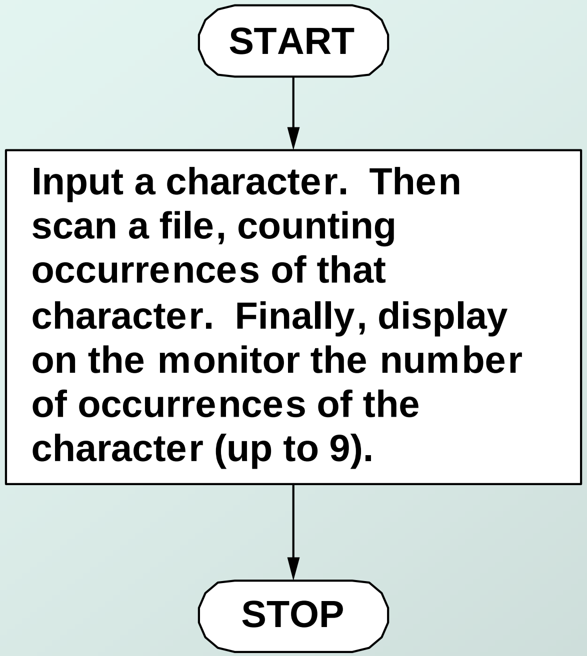
Assuming all addresses are close enough that PC-relative branch can be used.

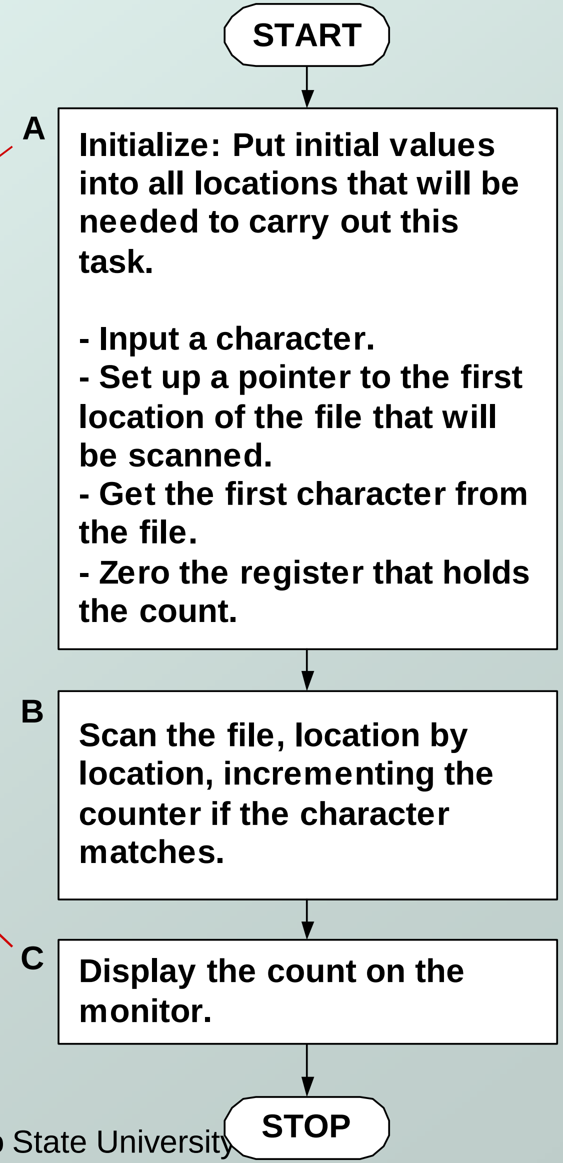
Code for Iteration



Assuming all addresses are on the same page.

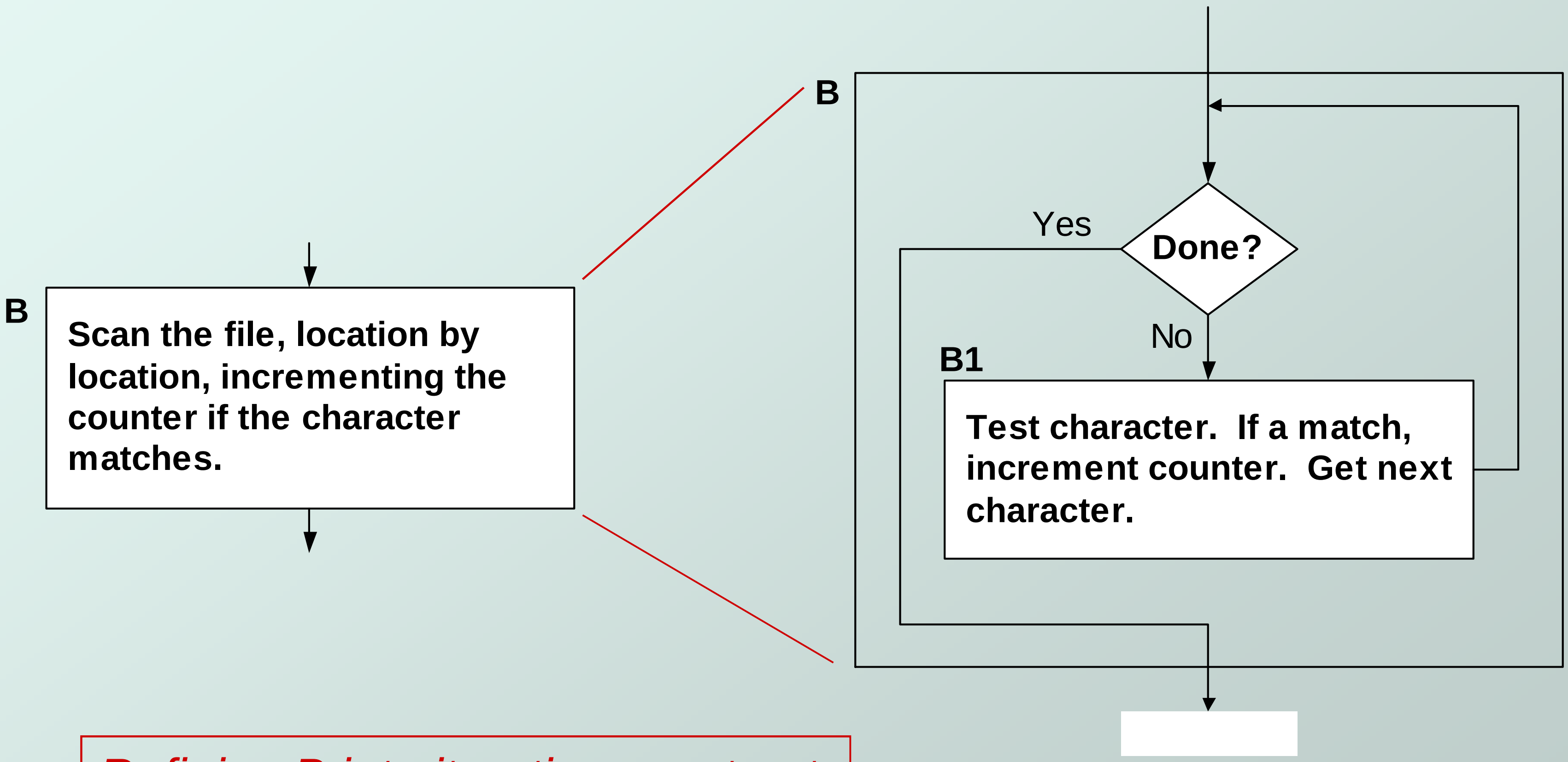
Example: Counting Characters





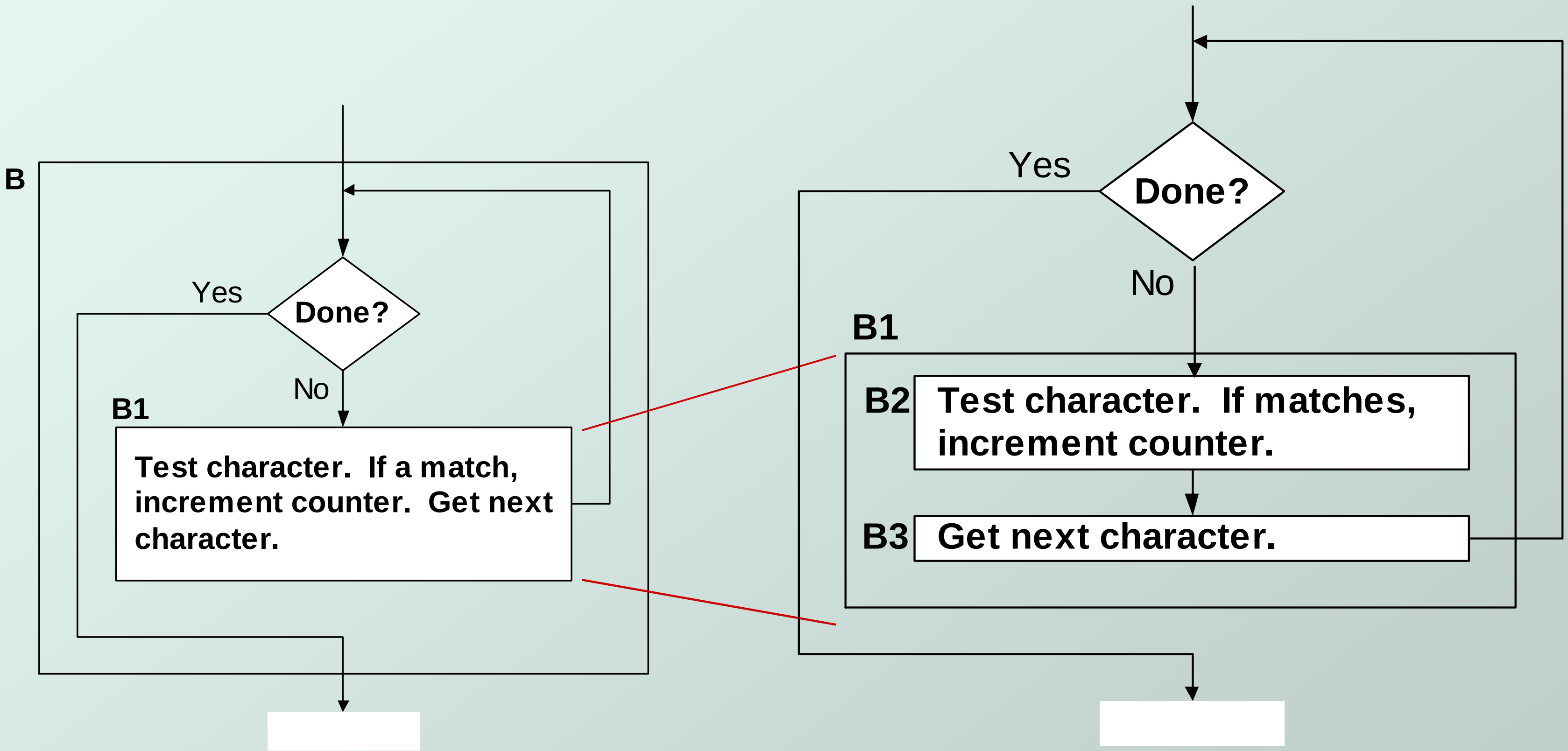
Initial refinement: Big task into three sequential subtasks.

Refining B



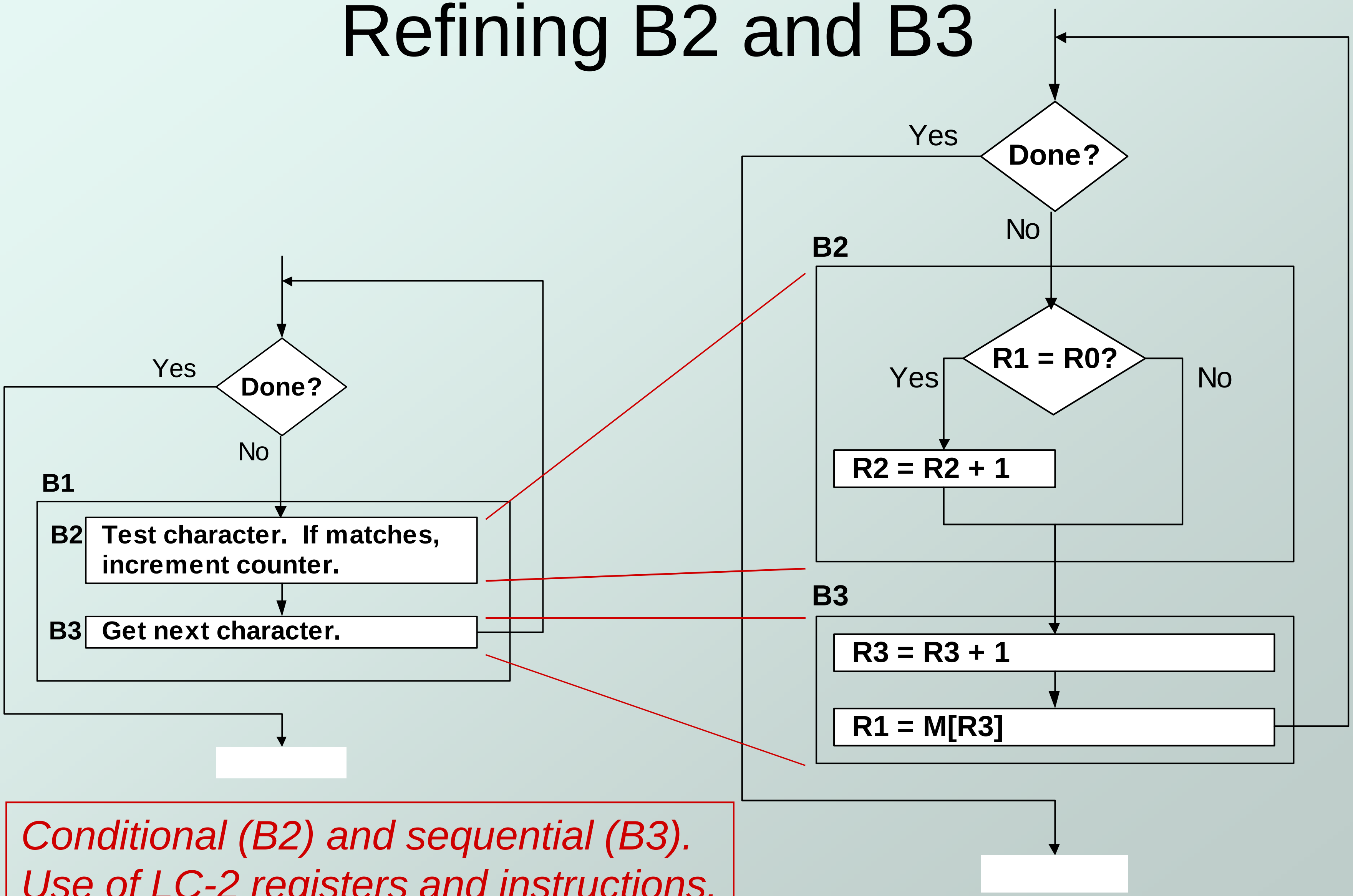
Refining B into iterative construct.

Refining B1



Refining B1 into sequential subtasks.

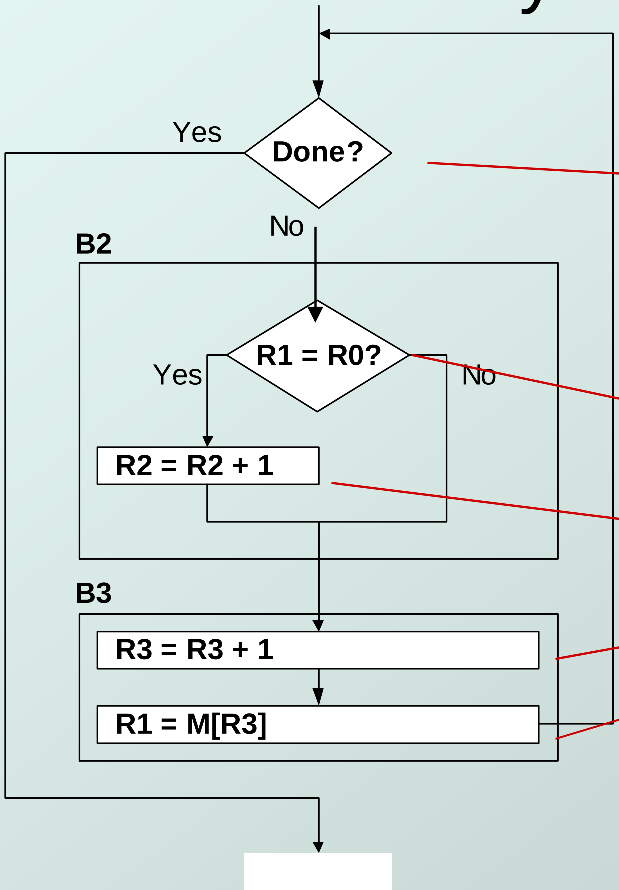
Refining B2 and B3



Conditional (B2) and sequential (B3).
Use of LC-2 registers and instructions.

The Last Step: LC-3 Instructions

- Use comments to separate into modules and to document your code.




```
; Look at each char in file.
0001100001111100  ; is R1 = EOT?
0000010xxxxxxxxx  ; if so, exit loop
; Check for match with R0.
1001001001111111  ; R1 = -char
0001001001100001
0001001000000001  ; R1 = R0 – char
0000101xxxxxxxxx  ; no match, skip incr
0001010010100001  ; R2 = R2 + 1
; Incr file ptr and get next char
0001011011100001  ; R3 = R3 + 1
0110001011000000  ; R1 = M[R3]
```

Don't know PCoffset bits until all the code is done

Debugging

- You've written your program and it doesn't work.
- Now what?
- What do you do when you're lost in a city?
  - Drive around randomly and hope you find it?
  - ✓ Return to a known point and look at a map?
  - ✓ In debugging, the equivalent to looking at a map is *tracing* your program.
  - Examine the sequence of instructions being executed.
  - Keep track of results being produced.
  - Compare result from instructions to the *expected* result.

Debugging Operations

- Any debugger should provide means to:
  1. Display values in memory and registers.
  2. Deposit values in memory and registers.
  3. Execute instruction sequence in a program.
  4. Stop execution when desired.

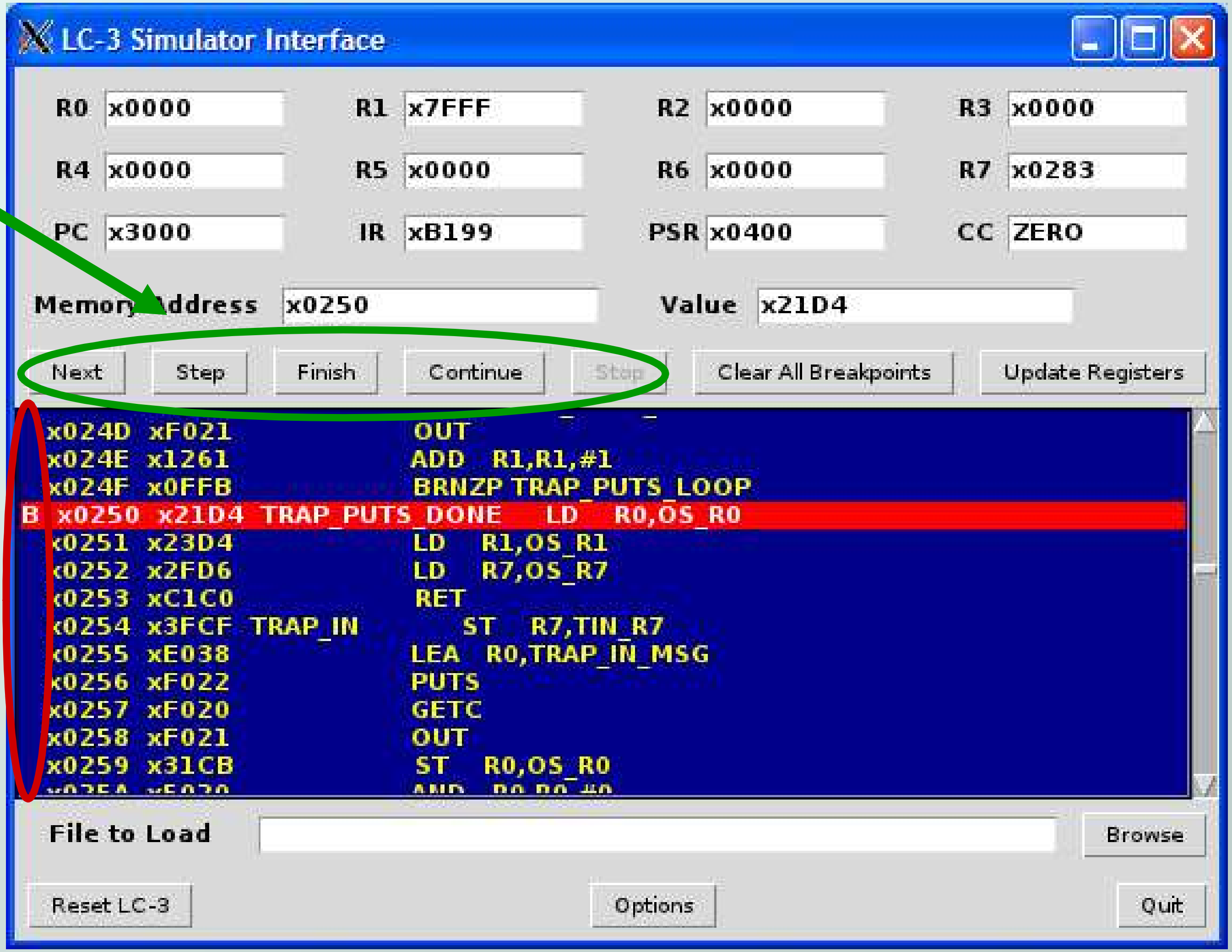
1. Different programming levels offer different tools.
   - High-level languages (C, Java, ...)
     usually have source-code debugging tools.
   - For debugging at the machine instruction level:
     - simulators
     - operating system “monitor” tools
     - in-circuit emulators (ICE)
       - plug-in hardware replacements that give instruction-level control

LC-3 Simulator

execute instruction sequences

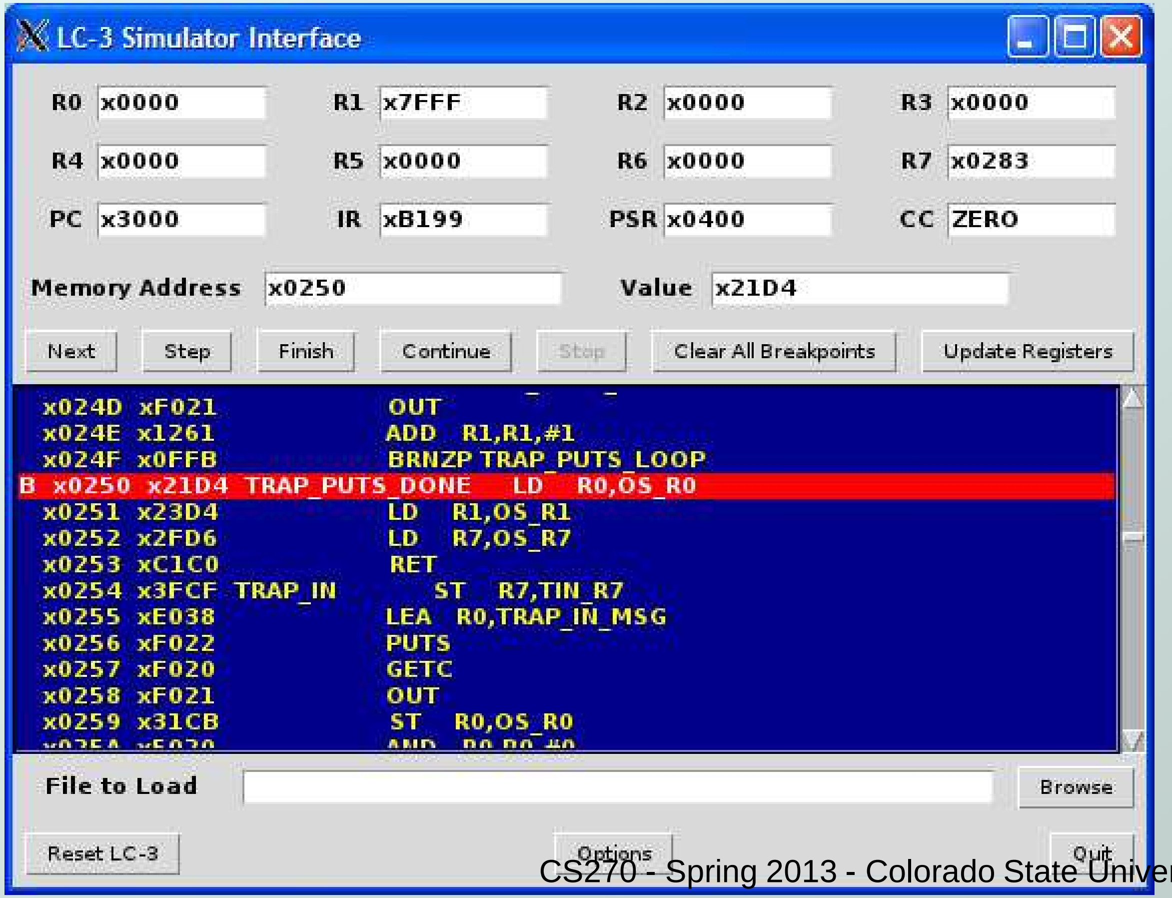
stop execution, set breakpoints

set/display registers and memory



LC-3 Simulator

Step: single stepping into routines
Finish: to the end of the routine
Similar buttons in the PC version



Types of Errors

- Syntax Errors
  - You made a typing error that resulted in an illegal operation.
  - Not usually an issue with machine language, because almost any bit pattern corresponds to a legal instruction.
  - In high-level languages, these are often caught during the translation from language to machine code.
- Logic Errors
  - Your program is legal, but wrong, so the results don't match the problem statement.
  - Trace the program to see what's really happening and determine how to get the proper behavior.
- Data Errors
  - Input data is different than what you expected.
  - Test the program with a wide variety of inputs.

Tracing the Program

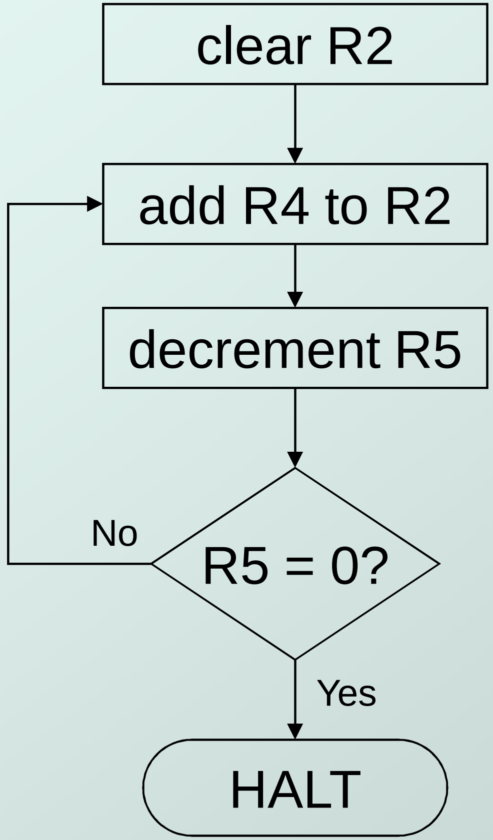
- Execute the program one piece at a time, examining register and memory to see results at each step.
- Single-Stepping
  - Execute one instruction at a time.
  - Tedious, but useful to help you verify each step of your program.
- Breakpoints
  - Tell the simulator to stop executing when it reaches a specific instruction.
  - Check overall results at specific points in the program.
    - Quickly execute sequences to get an overview of the behavior.
    - Quickly execute sequences that your believe are correct.
- Watchpoints
  - Tell the simulator to stop when a register or memory location changes or when it equals a specific value.
  - Useful when you don't know <u>where</u> or <u>when</u> a value is changed.

Tracing the Program

- Single-Stepping
  - Educational
  - When you suspect the problem is within a sequential block
- Breakpoints
  - Set a breakpoint at the end of a sequential block in a loop or or conditional block
    - To see what the block is doing

Example 1: Multiply

- This program is supposed to multiply the two unsigned integers in R4 and R5.




```
x3200 0101010010100000
x3201 0001010010000100
x3202 0001101101111111
x3203 0000011111111101
x3204 1111000000100101
```

Set R4 = 10, R5 =3.
Run program.
Result: R2 = 40, not 30.

Debugging the Multiply Program

PC and registers at the beginning of each instruction

Single-stepping

PC	R2	R4	R5
x3200	--	10	3
x3201	0	10	3
x3202	10	10	3
x3203	10	10	2
x3201	10	10	2
x3202	20	10	2
x3203	20	10	1
x3201	20	10	1
x3202	30	10	1
x3203	30	10	0
x3201	30	10	0
x3202	40	10	0
x3203	40	10	-1
x3204	40	10	-1
	40	10	-1

Breakpoint at branch (x3203)

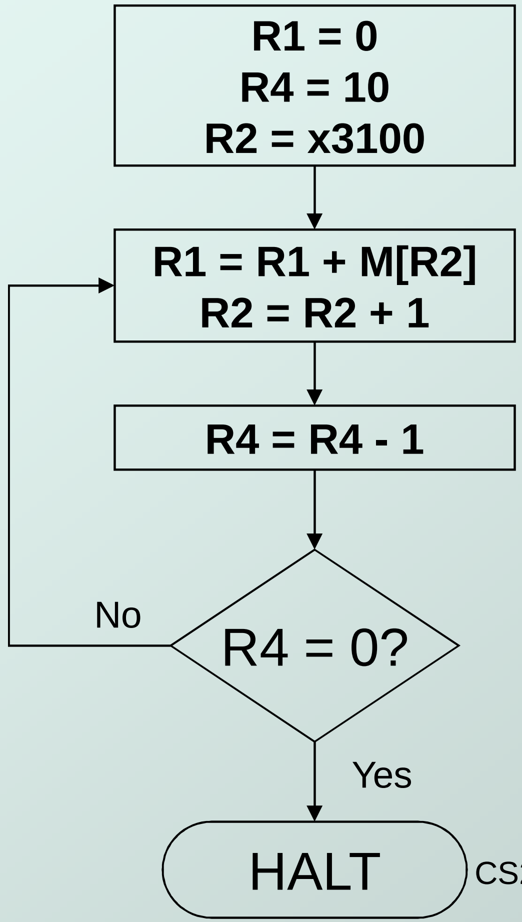
PC	R2	R4	R5
x3203	10	10	2
x3203	20	10	1
x3203	30	10	0
x3203	40	10	-1
	40	10	-1

Should stop looping here!

Executing loop one time too many.
Branch at x3203 should be based on Z bit only, not Z and P.

Example 2: Sum an Array of Numbers

- This program is supposed to sum the numbers stored in 10 locations beginning with x3100, leaving the result in R1.




```
x3000 0101001001100000
x3001 0101100100100000
x3002 0001100100101010
x3003 0010010011111100
x3004 0110011010000000
x3005 0001010010100001
x3006 0001001001000011
x3007 0001100100111111
x3008 0000001111111011
x3009 1111000000100101
```

Debugging the Summing Program

- Running the the data below yields R1 = x0024, but the sum should be x8135. What happened?

Address	***Contents***
x3100	x3107
x3101	x2819
x3102	x0110
x3103	x0310
x3104	x0110
x3105	x1110
x3106	x11B1
x3107	x0019
x3108	x0007
x3109	x0004

Start single-stepping program...

PC	R1	R2	R4
x3000	--	--	--
x3001	0	--	--
x3002	0	--	0
x3003	0	--	10
x3004	0	x3107	10

Should be x3100!

Loading contents of M[x3100], not address.
Change opcode of x3003
from 0010 (LD) to 1110 (LEA).

Debugging the Summing Program

```
        AND R1, R1, #0
        AND R4, R4, #0
        ADD R4, R4, #10
        LD R2, START
LOOP    LDR R3, R2, #0
        ADD R2, R2, #1
        ADD R1, R1, R3
        ADD R4, R4, #-1
        BRP LOOP
        HALT
...
START   .FILL x3107
        ......
```

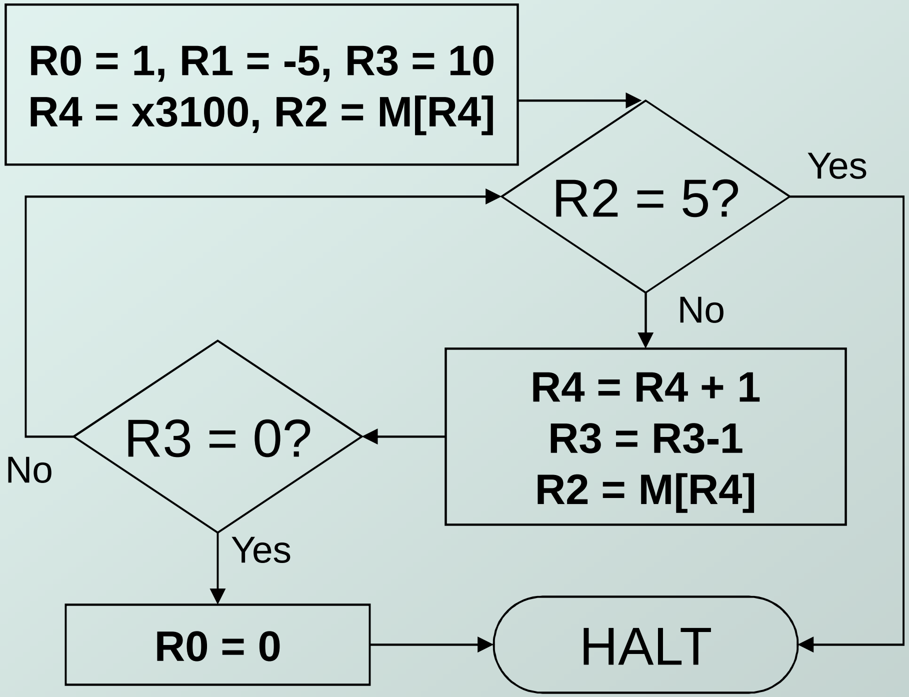
→

```
        AND R1, R1, #0
        AND R4, R4, #0
        ADD R4, R4, #10
        LEA  R2, START
LOOP    LDR R3, R2, #0
        ADD R2, R2, #1
        ADD R1, R1, R3
        ADD R4, R4, #-1
        BRP LOOP
        HALT
...
START   .FILL x3107
        ......
```

Loading <u>contents</u> of M[x3100], not address.
Change opcode of x3003
from 0010 (LD) to 1110 (LEA).

Example 3: Looking for a 5

- This program is supposed to set R0=1 if there's a 5 in one of ten memory locations, starting at x3100.
- Else, it should set R0 to 0.



x3000	**0101000000100000**
x3001	**0001000000100001**
x3002	**0101001001100000**
x3003	**0001001001111011**
x3004	**0101011011100000**
x3005	**0001011011101010**
x3006	**0010100000001001**
x3007	**0110010100000000**
x3008	**0001010010000001**
x3009	**0000010000000101**
x300A	**0001100100100001**
x300B	**0001011011111111**
x300C	**0110010100000000**
x300D	**0000001111111010**
x300E	**0101000000100000**
x300F	**1111000000100101**
x3010	**0011000100000000**

Debugging the Fives Program

- Running the program with a 5 in location x3108 results in R0 = 0, not R0 = 1. What happened?

Address	*Contents*
x3100	9
x3101	7
x3102	32
x3103	0
x3104	-8
x3105	19
x3106	6
x3107	13
x3108	5
x3109	61

Perhaps we didn't look at all the data?
Put a breakpoint at x300D to see how many times we branch back.

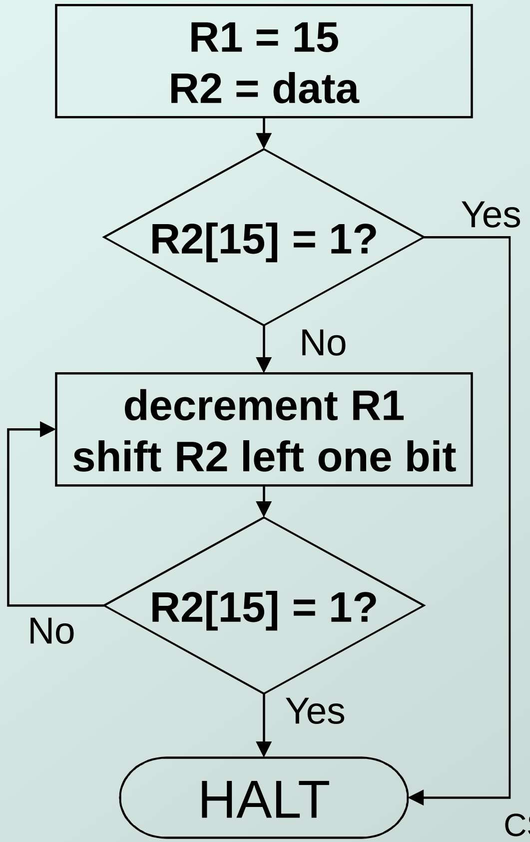
PC	R0	R2	R3	R4
x300D	1	7	9	x3101
x300D	1	32	8	x3102
x300D	1	0	7	x3103
	0	0	7	x3103

Didn't branch back, even though R3 > 0?

Branch uses condition code set by loading R2 with M[R4], not by decrementing R3.
Swap x300B and x300C, or remove x300C and branch back to x3007.

Example 4: Finding First 1 in a Word

- This program is supposed to return (in R1) the bit position of the first 1 in a word. The address of the word is in location x3009 (just past the end of the program). If there are no ones, R1 should be set to –1.



x3000	0101001001100000
x3001	0001001001101111
x3002	1010010000000110
x3003	0000100000000100
x3004	0001001001111111
x3005	0001010010000010
x3006	0000100000000001
x3007	0000111111111100
x3008	1111000000100101
x3009	0011000100000000

Debugging the First-One Program

- Program works most of the time, but if data is zero, it never seems to HALT.

PC	R1
x3007	14
x3007	13
x3007	12
x3007	11
x3007	10
x3007	9
x3007	8
x3007	7
x3007	6
x3007	5

PC	R1
x3007	4
x3007	3
x3007	2
x3007	1
x3007	0
x3007	-1
x3007	-2
x3007	-3
x3007	-4
x3007	-5

Breakpoint at backwards branch (x3007)

If no ones, then branch to HALT never occurs!
This is called an “infinite loop.”
Must change algorithm to either
(a) check for special case (R2=0), or
(b) exit loop if R1 < 0.

Debugging: Lessons Learned

- Trace program to see what's going on.
  - Breakpoints, single-stepping
- When tracing, make sure to notice what's *really* happening, not what you think *should* happen.
  - In summing program, it would be easy to not notice that address x3107 was loaded instead of x3100.
- Test your program using a variety of input data.
  - In Examples 3 and 4, the program works for many (but not all) data sets.
  - Be sure to test extreme cases (all ones, no ones, ...).