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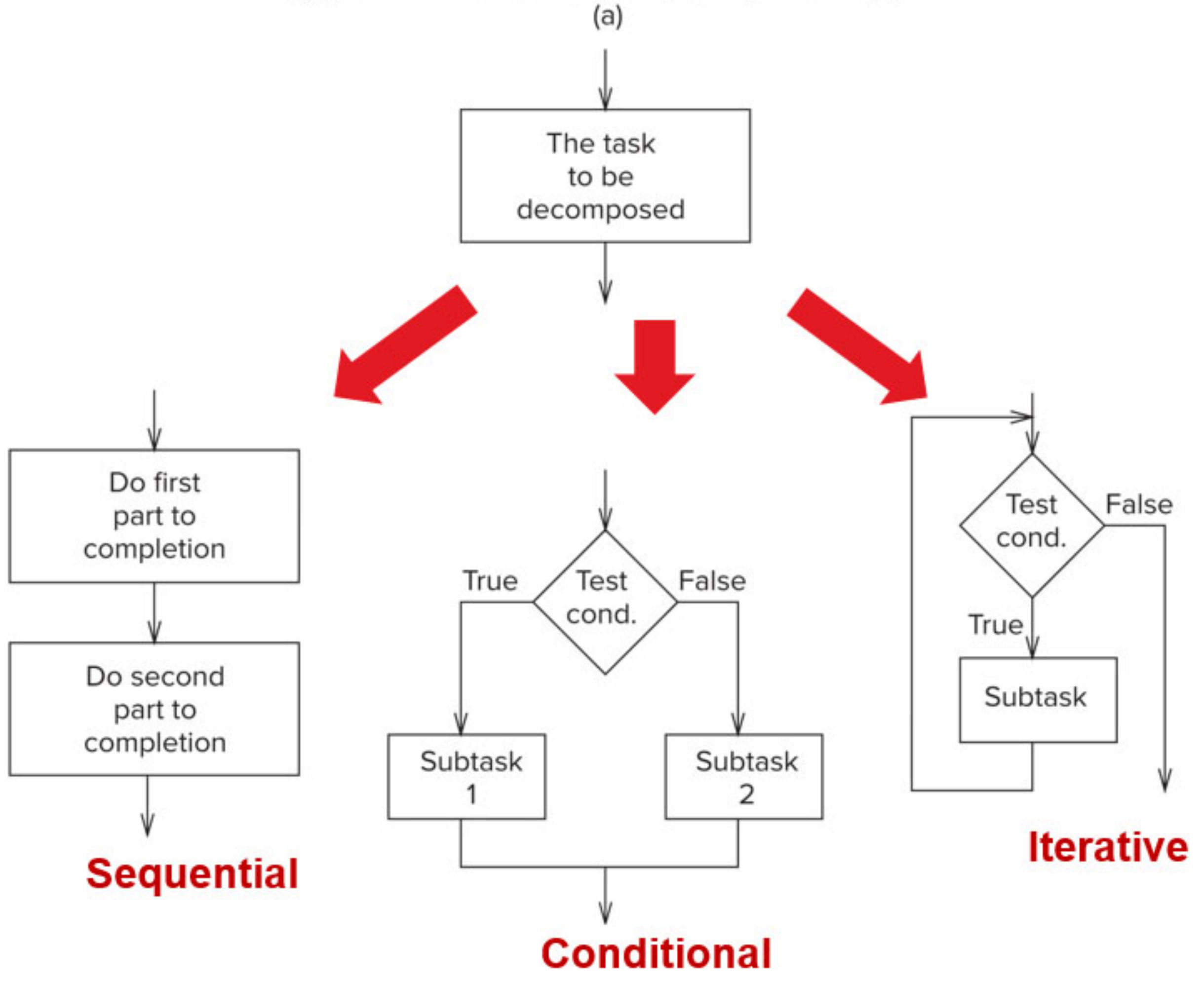
From Bits and Gates to C and Beyond

Programming

Chapter 6

Structured Programming: Three Basic Constructs



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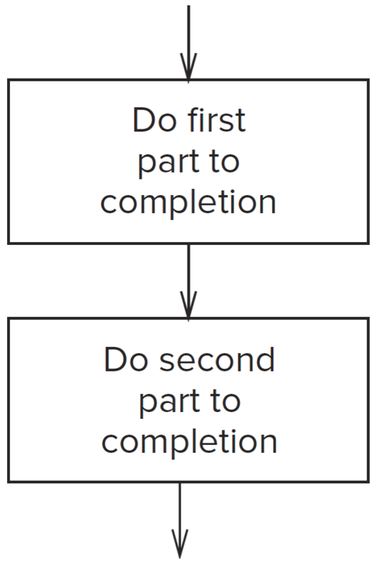
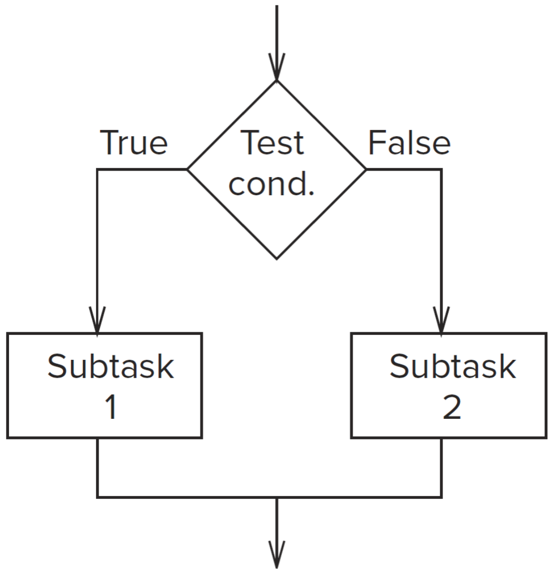
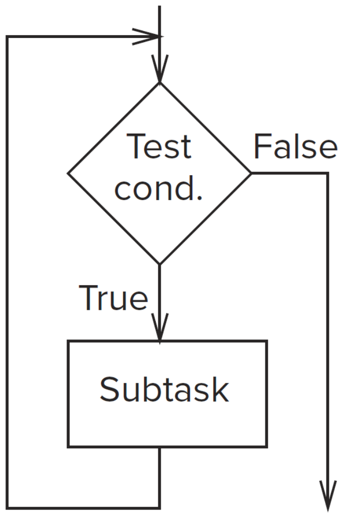
Three Basic Constructs



Sequential: Break into two subtasks, both of which must be performed. Do the first task to completion, then the second.

Conditional: Task consists of two subtasks, one of which should be performed and the other not performed. Test condition to choose, then perform subtask to completion. (Either subtask may be empty.)





Iterative: Perform a single subtask multiple times, but only if condition is true. When task is done, go back to retest the condition. The first time condition is not true, program proceeds.

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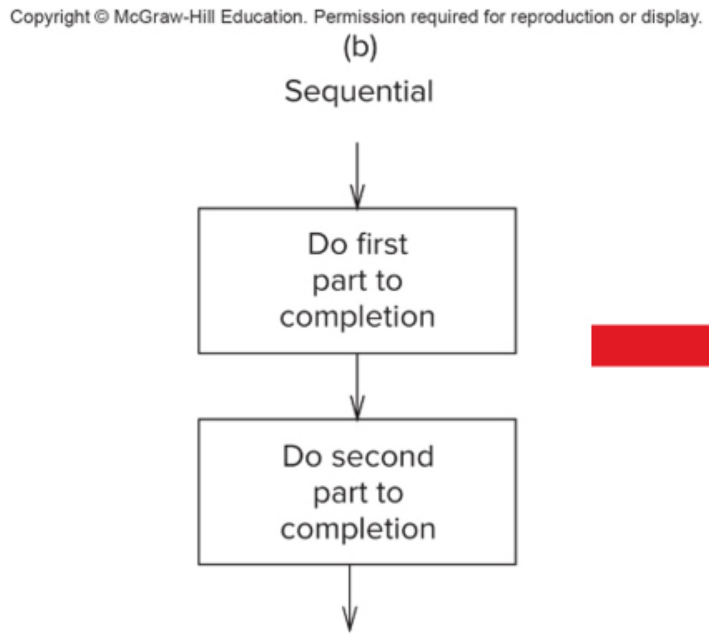
Implementing Constructs with LC-3 Instructions 1

Sequential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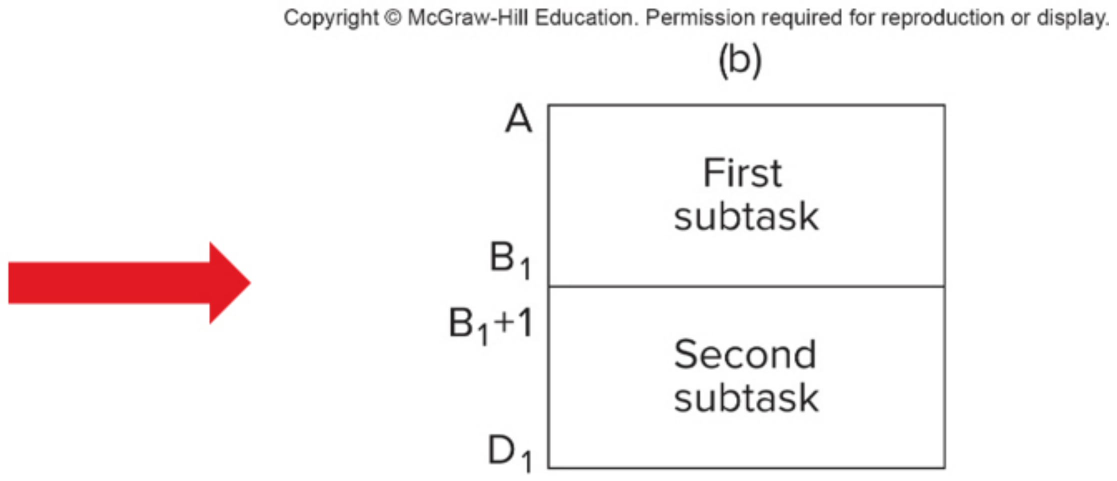
(b)
Sequential
Do first part to completion
Do second part to completion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(b)
A
First subtask
B1
B1+1
Second subtask
D1

No control instructions needed. Execution flows sequentially from one subtask to the next.

Instructions from A to B1 for first subtask.
Instructions from B1+1 to D1 for second subtask.

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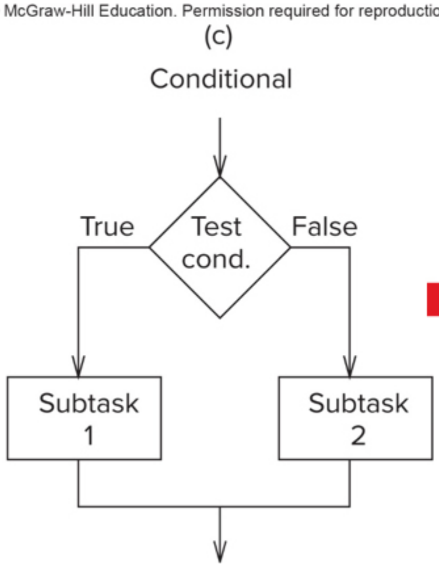
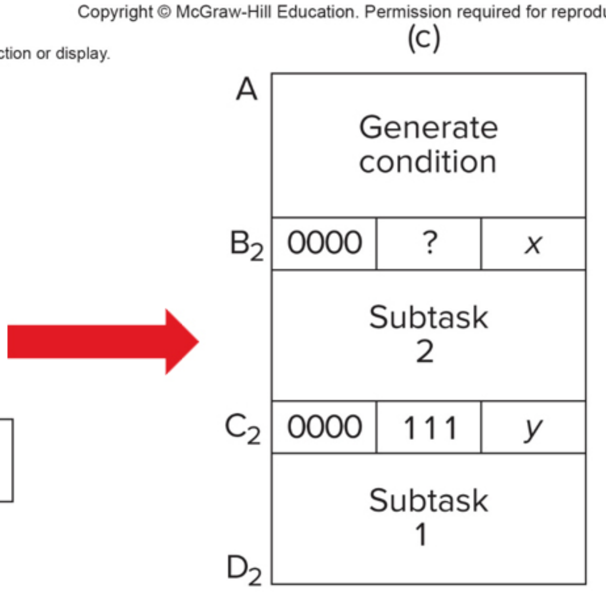
Implementing Constructs with LC-3 Instructions 2

Conditional





First (A), instructions that will set condition codes according to condition.

Branch at B2 -- taken if condition is true, target = C2+1 (subtask 1).

If condition is not true, branch is not taken, and subtask 2 (B2+1...) is excuted. After subtask 2, C2 is unconditional branch to D2+1, so that subtask 1 is not executed.

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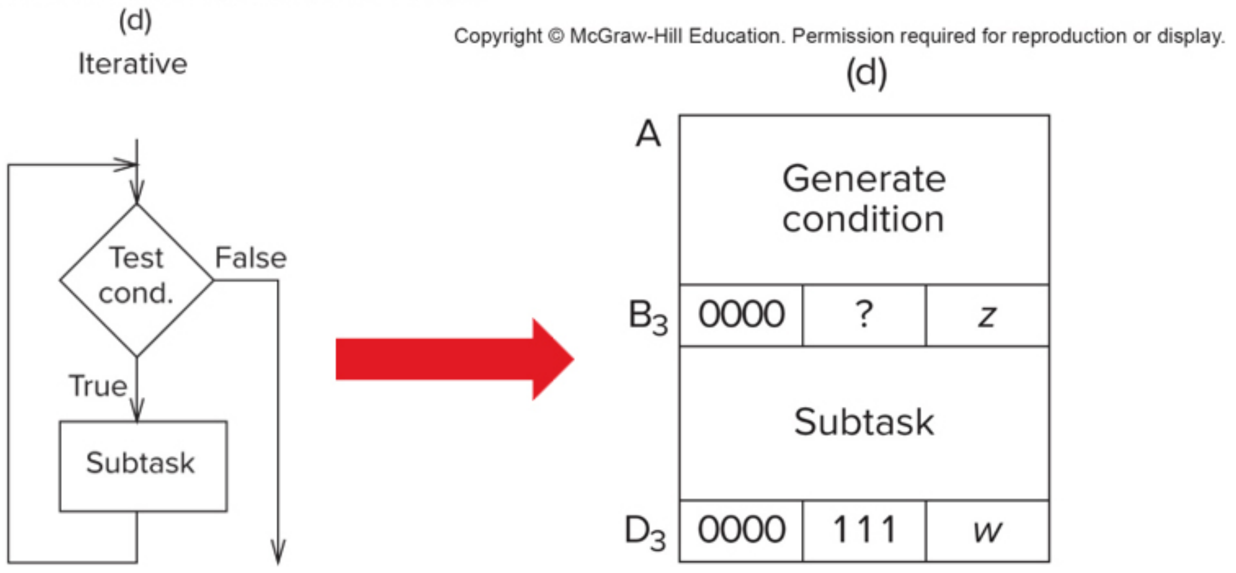
Implementing Constructs with LC-3 Instructions 3

Iterative



First (A), instructions that will set condition codes according to condition.

Branch at B3 -- taken if condition is false, target = D3+1.

If condition is true, branch is not taken, and subtask (B3+1...) is excuted. After subtask 2, D3 is unconditional branch to A, to check the condition again.

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Debugging

Traditionally, a computer error is known as a "bug," and
the process of finding and removing errors is known as "debugging."

How do you know there's an error?

- Run the program with a set of inputs for which the desired output is known or can be confirmed. (This is called "testing.") If you don't get the expected answer, there's an error. Testing with a variety of inputs is essential, because the execution of the program may change with different data -- big numbers, small numbers, negative numbers...
- Sometimes, the behavior of the program itself shows that there's an error. For example, the program runs "forever" without halting. Or a desired output is never displayed on the monitor.

Real-World Analogy

Suppose you want to drive from Raleigh, NC to Washington, DC.

Someone tells you to take I-40 East to I-95, and then go South on I-95, and that it should take about 4.5 hours.

You follow the directions, drive for 4.5 hours, and find yourself in Savannah, GA.

- Error detected -- Savannah is not Washington.
- What went wrong? Retrace your steps. Since there's only one major turn, chances are good that's where the problem is. Should have turned North on I-95, rather than South.
- Note that you (the computer) behaved perfectly. You did exactly what you were told to do. It was the instructions (the program) that was incorrect.

Steps for Debugging

Trace the program

- Record the sequence of events as the program executes
- Check the results of each sequence of events -- are they consistent with what you expect?

When you find a result that does not match your expectation (Why does that sign say "Welcome to South Carolina"?), you can narrow down the location of the bug.

Of course, once the bug is fixed, you have to test again.
There might be multiple bugs!!

Debugging Tools

A **debugger** is an environment for running your program that allows you to do the following:

1. Write values into registers and memory locations.
2. Execute a sequence of instructions.
3. Stop execution when desired (that is, before the program ends).
4. Examine values in memory and register at any point in the program.

For now, we will focus on tools that operate at the instruction level. Other tools will operate at higher levels of abstraction -- program statements and variables in a high-level language.

The **LC-3 simulator** provided for this class allows you to run interactively in debugging mode, providing the capabilities shown above.

Examing and Changing Values

The data for your program is stored in two locations:
memory and **registers**.

The simulator displays the values of all registers and provides a way to look at any memory location. You can also change the values stored in any of those locations.

In the context of the character counting program:

- Set the value of R0 to be an ASCII character of your choice, ignoring the user's input.
- Look at the characters stored in the file. Make sure there's an EOT somewhere that designates the end of file.
- Set the PC to start execution at a specific part of the program.

NOTE: Instructions are stored in memory, too, do you can change an instruction during the debugging session!

Executing a Sequence of Instructions

To debug, you want to (1) set memory and registers as desired, (2) run an "interesting" sequence of instructions, and (3) check the values in memory/registers. Then repeat (2) and (3) until you find something interesting.

There are two fundamental ways of controlling execution:

single-stepping allows you to execute one instruction at a time.

breakpoints allow you to specify a particular instruction where you want to stop execution.

Stepping vs. Breakpoints

Using breakpoints is much faster, because a sequence of instructions can be executed quickly by the simulator. It's a good way to quickly narrow down the likely location of a problem.

Set breakpoints between **modules** of your program -- for example: at the end of each task that you created when you designed the program.

Once you've identified a sequence of interest:

1. **Set a breakpoint** at the beginning of that sequence.
2. **Run** the program from the beginning, quickly executing instructions and stopping when the breakpoint is reached.
3. **Single-step** through one instruction at a time to see exactly what the processor is doing.

(Instead of 1 and 2, you can set the PC to the start of your sequence and set up registers/memory with known initial values.)

Debugging Examples

The best way to learn how to debug is to do it. You'll get plenty of practice, because it's rare to write a program correctly the first time!

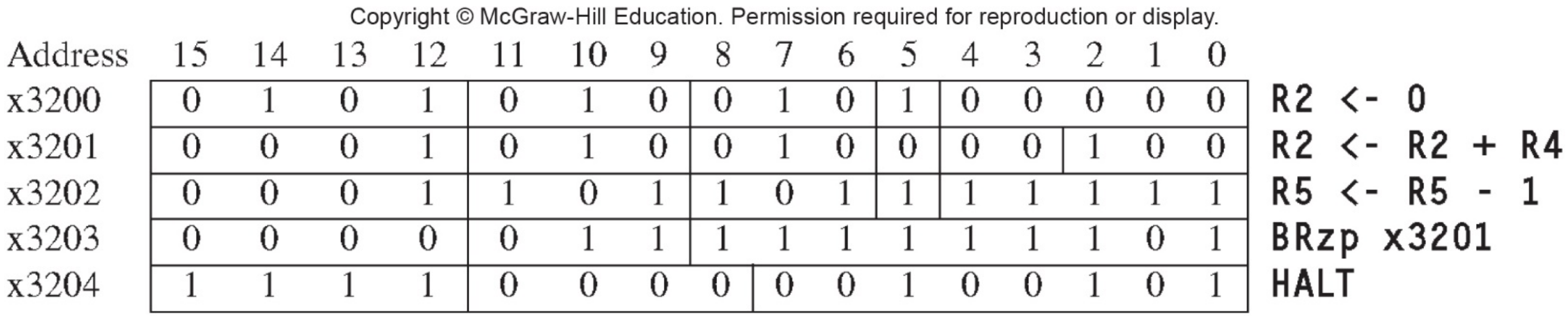
We will show four examples of faulty programs, and show how debugging can find the errors. The examples illustrate several common types of errors:

1. Executing a loop the wrong number of times.
2. Using the wrong opcode.
3. Testing the wrong condition code.
4. Not considering all types of input values.

Example 1: Multiply 1

Program: Registers R4 and R5 contain positive integers. Multiply them and put the result in R2.

Code:



Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3200	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 <- 0
x3201	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	R2 <- R2 + R4
x3202	0	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	R5 <- R5 - 1
x3203	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	BRzp x3201
x3204	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT

Each instruction has an annotation (comment) that tells what the instruction is supposed to do. These comments are not part of the program, but are extremely helpful as you are trying to interpret the execution.

Result: When R4 = 10 and R5 = 3, R2 gets a result of 40.

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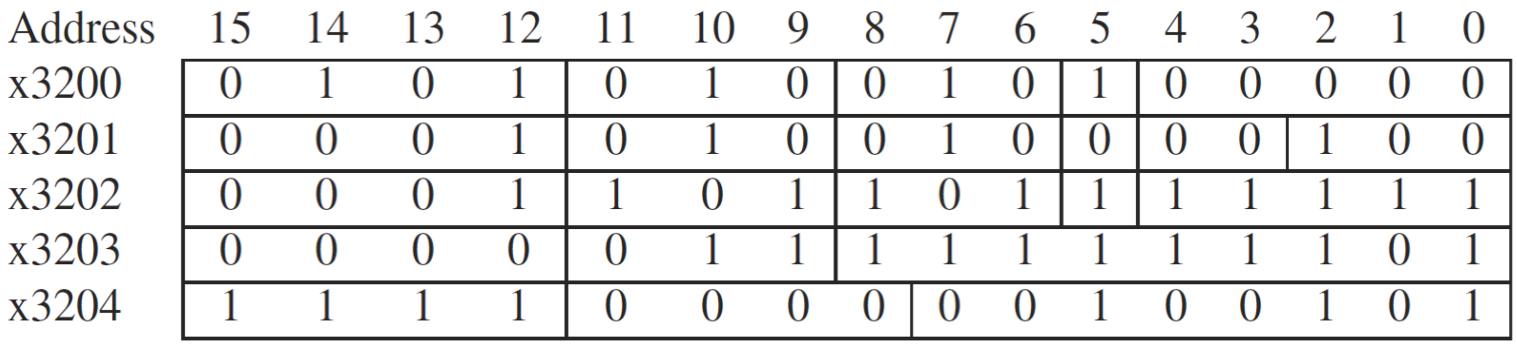
Example 1: Multiply 2

First step: Stare at the code for awhile to see if it makes sense.

Warning: Don't do this too long. It's generally much easier to debug by executing the code and watching its actual behavior. But a careful look to better understand the code is a good practice.



Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3200	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 <- 0
x3201	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	R2 <- R2 + R4
x3202	0	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	R5 <- R5 - 1
x3203	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	BRzp x3201
x3204	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT

R4 gets added to itself multiple times, and R5 gets decreased each time. The loop ends when R5 is zero, so

R2 = 0 + R4 + R4 + R4 = 0 + 10 + 10 + 10 = 30

Looks reasonable -- why doesn't it work? Why do we get 40?

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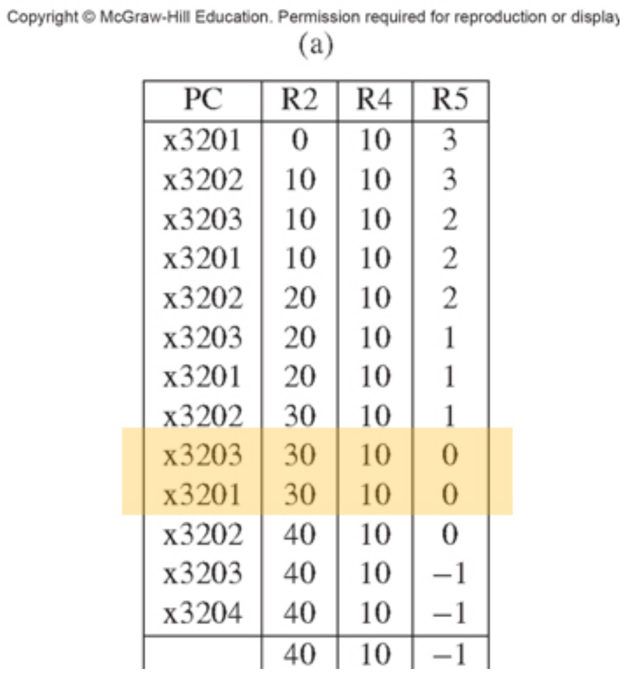
Example 1: Multiply 3

Next step: Trace execution of the code. We'll using single-stepping. The following table shows the PC and the state of the interesting registers after each instruction is executed.



(a)

PC	R2	R4	R5
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

When R5 = 3, the loop (x3201 to x3203) is executed four times. It should only execute three times to add R4 the correct number of times.

Error: We shouldn't re-execute the loop when R5 becomes zero. We should exit the loop.

Fix: Change BRzp to BRp.

Access the text alternative for slide images.

Example 1: Multiply 4

Using Breakpoints

Because loop errors are very common, it's often enough to stop execution once per iteration, rather than stepping through every instruction. Here's the trace when we set a breakpoint at the BR instruction.

(b)

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

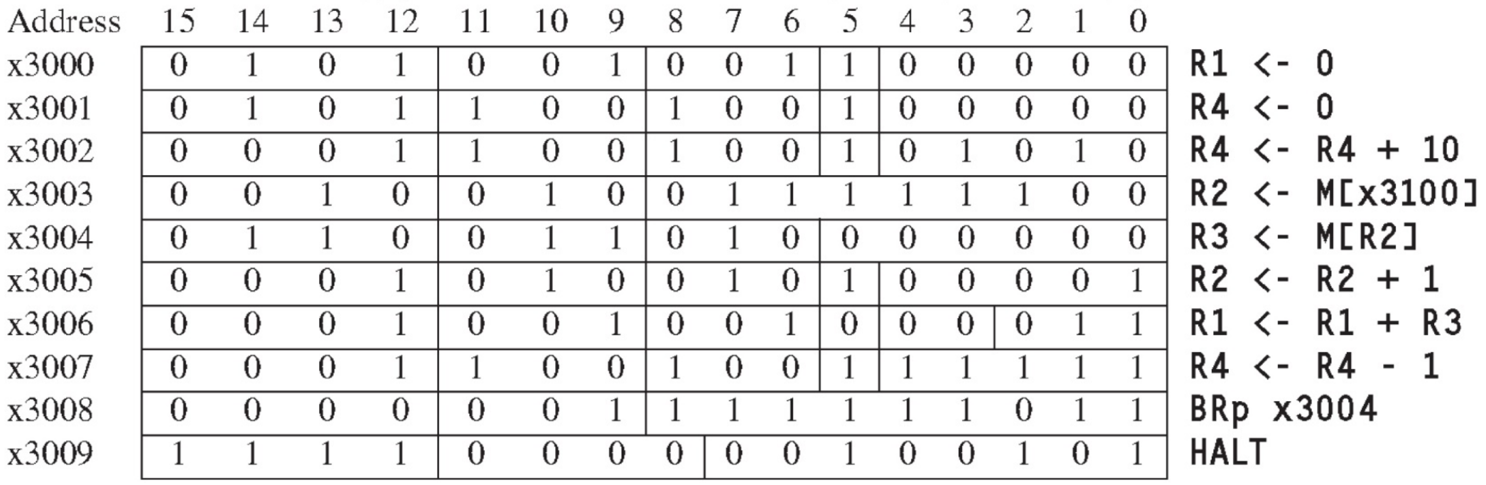
Fewer stopping points means faster debugging and less chance to get lost in the details of the other instructions.

This allows us to quickly check: (a) how many times is the BR being taken? (b) what is the cause of the BR being taken / not taken?

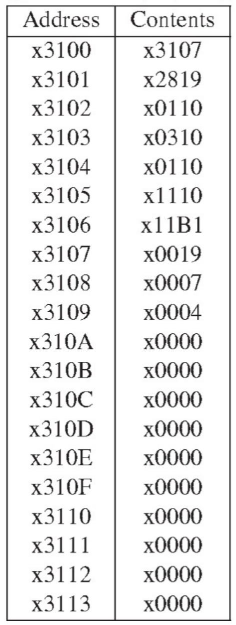
Example 2: Add a Sequence of Numbers 1

Program: Add ten numbers starting at x3100, putting the result in R1.

Code:



Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	R1 <- 0
x3001	0	1	0	1	1	0	0	1	0	0	1	0	0	0	0	0	R4 <- 0
x3002	0	0	0	1	1	0	0	1	0	0	1	0	1	0	1	0	R4 <- R4 + 10
x3003	0	0	1	0	0	1	0	0	1	1	1	1	1	1	0	0	R2 <- M[x3100]
x3004	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	0	R3 <- M[R2]
x3005	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	1	R2 <- R2 + 1
x3006	0	0	0	1	0	0	1	0	0	1	0	0	0	0	1	1	R1 <- R1 + R3
x3007	0	0	0	1	1	0	0	1	0	0	1	1	1	1	1	1	R4 <- R4 - 1
x3008	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	BRp x3004
x3009	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT



Address	Contents
x3100	x3107
x3101	x2819
x3102	x0110
x3103	x0310
x3104	x0110
x3105	x1110
x3106	x11B1
x3107	x0019
x3108	x0007
x3109	x0004
x310A	x0000
x310B	x0000
x310C	x0000
x310D	x0000
x310E	x0000
x310F	x0000
x3110	x0000
x3111	x0000
x3112	x0000
x3113	x0000

Result:

When memory contains the values to the right, result is x0024, but should be x8135.

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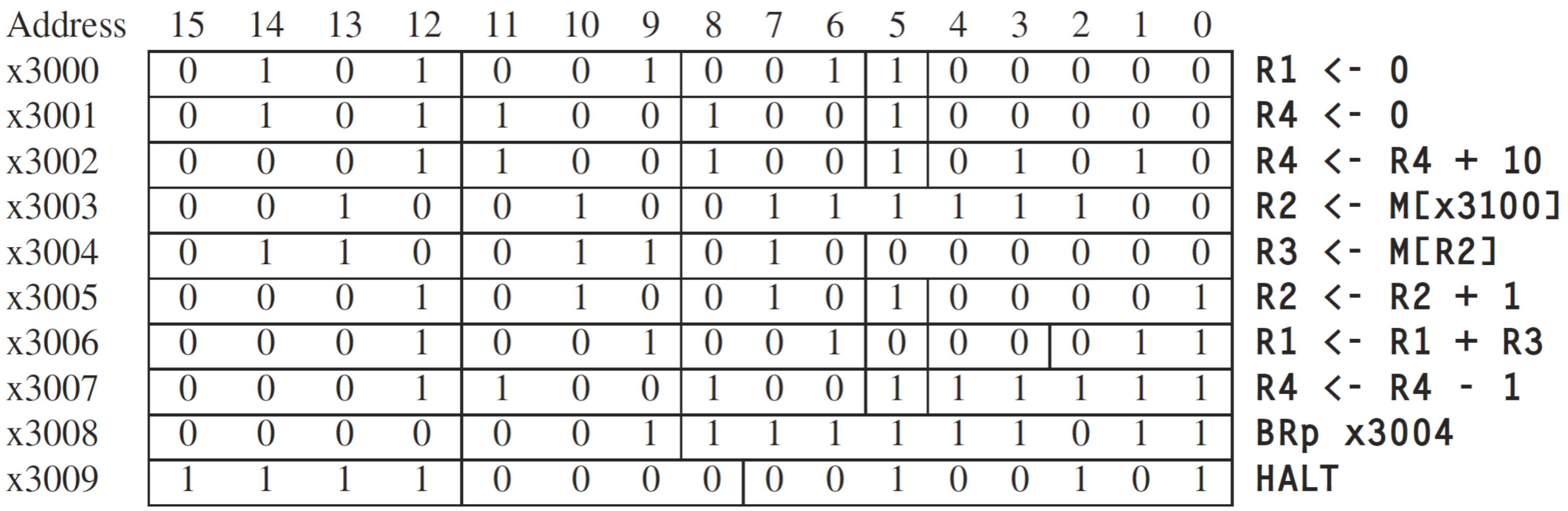
Example 2: Add a Sequence of Numbers 2

Step 1: Examine code -- what is the algorithm?



Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	R1 <- 0
x3001	0	1	0	1	1	0	0	1	0	0	1	0	0	0	0	0	R4 <- 0
x3002	0	0	0	1	1	0	0	1	0	0	1	0	1	0	1	0	R4 <- R4 + 10
x3003	0	0	1	0	0	1	0	0	1	1	1	1	1	1	0	0	R2 <- M[x3100]
x3004	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	0	R3 <- M[R2]
x3005	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	1	R2 <- R2 + 1
x3006	0	0	0	1	0	0	1	0	0	1	0	0	0	0	1	1	R1 <- R1 + R3
x3007	0	0	0	1	1	0	0	1	0	0	1	1	1	1	1	1	R4 <- R4 - 1
x3008	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	BRp x3004
x3009	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT

R1 (sum) initialized to zero. R4 (counter) initialized to 10.

R2 (address) initialized to x3100.

R3 gets value from M[R2], added to R1. Increment R2 for next address. Decrement R4 and exit when counter is zero.

Access the text alternative for slide images.

Example 2: Add a Sequence of Numbers 3

Stepping through the code, we see the following:

PC	R1	R2	R4
x3001	0	x	x
x3002	0	x	0
x3003	0	x	#10
x3004	0	x3107	#10

After x3004, R2 should contain x3100, the starting address of the numbers. Why does it contain x3107?

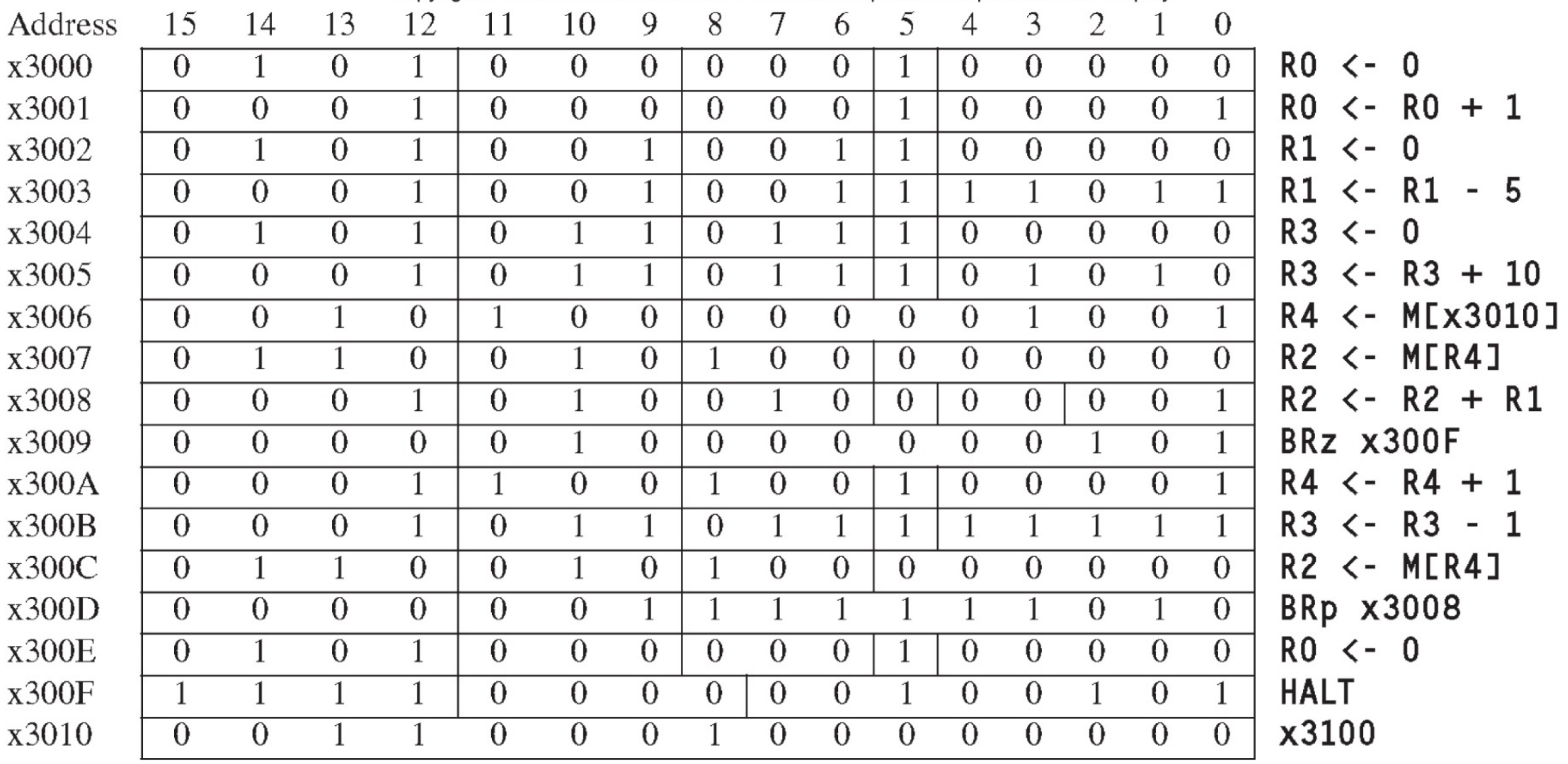
Opcode at x3004 is **LD**. Therefore, it loads the content of memory location x3100, which is x3107.

Instead, we need to use **LEA** to put the address x3100 into R2, not the data at M[x3100].

Example 3: Look for a Value in a Sequence 1

Program: Look for the value 5 in the sequence of ten numbers starting at address x3100. If the value is there, put 1 in R0; else put 0 in R0.

Code:



Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	R0 <- 0
x3001	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	R0 <- R0 + 1
x3002	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	R1 <- 0
x3003	0	0	0	1	0	0	1	0	0	1	1	1	1	0	1	1	R1 <- R1 - 5
x3004	0	1	0	1	0	1	1	0	1	1	1	0	0	0	0	0	R3 <- 0
x3005	0	0	0	1	0	1	1	0	1	1	1	0	1	0	1	0	R3 <- R3 + 10
x3006	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	1	R4 <- M[x3010]
x3007	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	R2 <- M[R4]
x3008	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	1	R2 <- R2 + R1
x3009	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	BRz x300F
x300A	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0	1	R4 <- R4 + 1
x300B	0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	R3 <- R3 - 1
x300C	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	R2 <- M[R4]
x300D	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	0	BRp x3008
x300E	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	R0 <- 0
x300F	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT
x3010	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	x3100

Access the text alternative for slide images.

Example 3: Look for a Value in a Sequence 2

Result:

When tested with data that includes one or more 5's, R0 set to 0.

Algorithm:

```
R0 = 1 -- assuming that we will see a 5
R1 = −5  -- used to test if value = 5
R3 = 10  -- counter
R4 = x3100 -- starting address
Load M[R4] into R2.
LOOP:
    Test if R2 equals 5.  If so, branch to x300F -- halt (with R1=1).
    Increment R4 to next address.  Decrement loop counter (R3).
    Load M[R4] into R2.  Branch to back to LOOP if R3 not zero.
Set R0=0 -- counter hit zero before seeing any 5's.
```

Example 3: Look for a Value in a Sequence 3

Learning from our earlier loop bug, we set a breakpoint at the bottom of the loop, to see how many times it executes.

PC	R1	R2	R3	R4
x300D	−5	7	9	3101
x300D	−5	32	8	3102
x300D	−5	0	7	3103

After three breakpoints, the execution does not hit this BR again, even though R3 is 7.

Why?? R2 shows that we did not load 5.

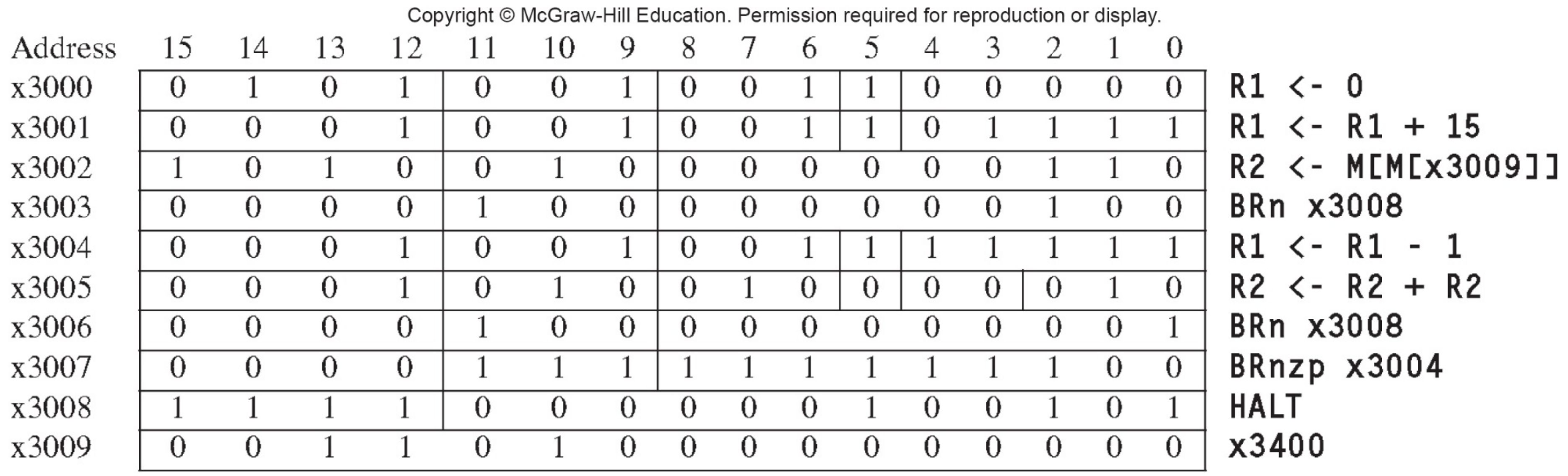
Looking more closely, the simulator shows that the Z bit is set at the last breakpoint. Why? Because the LD at x300C loaded a zero into R2.
We were thinking the BR would be based on the previous ADD instruction (decrementing R3) and forgot that LD also sets the condition codes.

Fix: Move the LD before the decrement of R3, so that the condition code is set by the relevant instruction.

Example 4: Find the First 1 in a Word 1

Program: Load a data word from a far-away memory location (x3400). From left to right, look for the first one bit in the value, and put the bit position of that one in R1. If no 1's, make R1 = −1.

Code:

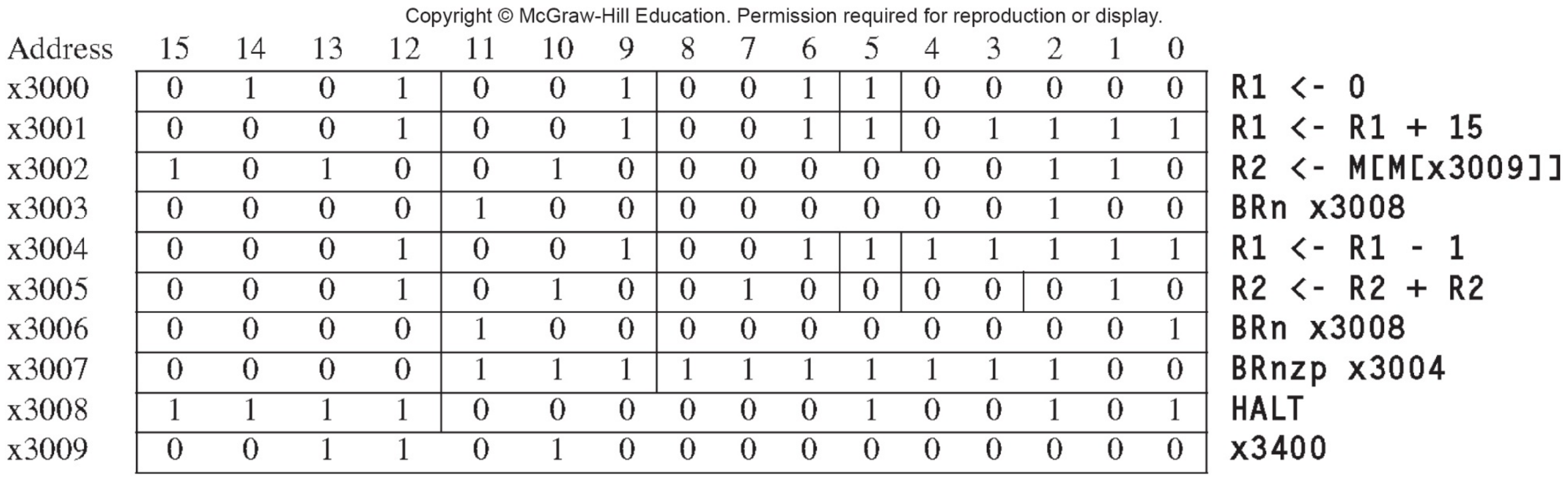


Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	R1 <- 0
x3001	0	0	0	1	0	0	1	0	0	1	1	0	1	1	1	1	R1 <- R1 + 15
x3002	1	0	1	0	0	1	0	0	0	0	0	0	0	1	1	0	R2 <- M[M[x3009]]
x3003	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	BRn x3008
x3004	0	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	R1 <- R1 - 1
x3005	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1	0	R2 <- R2 + R2
x3006	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	BRn x3008
x3007	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	BRnzp x3004
x3008	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT
x3009	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	x3400

Result: Program usually works, but sometimes fails to terminate.

Access the text alternative for slide images.

Example 4: Find the First 1 in a Word 2



Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	0	1	0	1	0	0	1	0	0	1	1	0	0	0	0	0	R1 <- 0
x3001	0	0	0	1	0	0	1	0	0	1	1	0	1	1	1	1	R1 <- R1 + 15
x3002	1	0	1	0	0	1	0	0	0	0	0	0	0	1	1	0	R2 <- M[M[x3009]]
x3003	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	BRn x3008
x3004	0	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	R1 <- R1 - 1
x3005	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1	0	R2 <- R2 + R2
x3006	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	BRn x3008
x3007	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	BRnzp x3004
x3008	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT
x3009	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	x3400

Algorithm:

R1 = 15, leftmost bit position

R2 = data value (memory address is in x3009, using LDI to load M[x3400])

If value is negative, then 15 is the first 1 --> branch to HALT.

LOOP:
- Decrement R1 (next bit position). Shift value (R2) to the left.
- If negative, then a 1 was shifted into position 15 --> exit loop.

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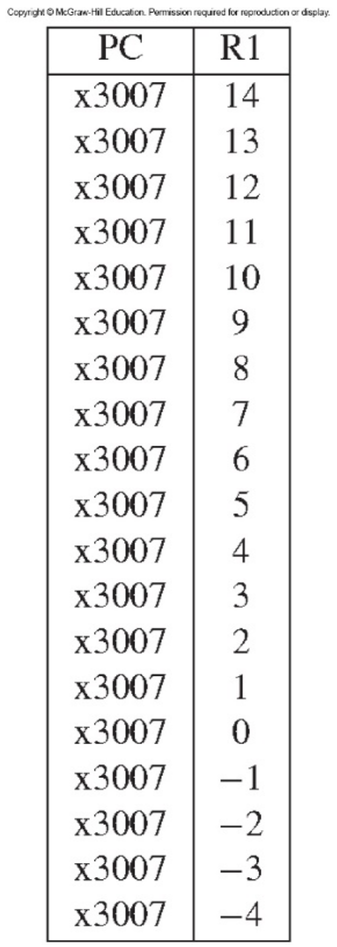
Example 4: Find the First 1 in a Word 3

Set breakpoint at bottom of loop, to see how many times it's executed.



PC	R1
x3007	14
x3007	13
x3007	12
x3007	11
x3007	10
x3007	9
x3007	8
x3007	7
x3007	6
x3007	5
x3007	4
x3007	3
x3007	2
x3007	1
x3007	0
x3007	−1
x3007	−2
x3007	−3
x3007	−4

Loop should execute at most 16 times. Why does it keep going?

Problem: A value of zero is loaded into R2. Therefore, a 1 is never shifted into the sign bit. Therefore, the loop is never exited -- INFINITE LOOP.

Fix: Add a check for zero when value is first loaded. Exit and set R1 = −1.

NOTE: This only fails when value is zero. If you didn't happen to test that case, then your customer will find the bug instead!

Access the text alternative for slide images.

Lessons

Use breakpoints to observe the behavior of the program,
paying special attention to register values that affect control flow.

Single-step through code as needed, to understand why register are getting their value. (Wrong opcode, wrong operand, ...?)

Test with a variety of input data.

- Especially look for corner cases that may behave differently, such as negative numbers, or zero.

Don't assume that comments are correct!

- Comments express what the programmer intended, but only the instructions determine how the program actually behaves.

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