**CS061 – Lab 7**  
**Advanced subroutines!**

**1 High Level Description**

The purpose of this lab is to teach you some advanced subroutine techniques that allow you to write recursive subroutines (a subroutine that calls itself directly or indirectly)!

**2 Our Objectives for This Week**

1. Exercise 1 ~ Demonstrate the shortcomings of subroutine protocols from the book
2. Exercise 2 ~ Improve upon the book’s subroutine protocols and show the shortcomings even with this improvement
3. Exercise 3 ~ Refine the subroutine protocols by using stacks to allow for recursion

**3.1 Exercises**

Exercise 1

Recall that the definition of Factorial is or as the relation Factorial() = Factorial() . This relation is defined as a recursive relation since computing the th factorial relies on computing the th factorial.

We can implement a recursive relation using a recursive subroutine. A recursive subroutine is any subroutine that calls itself either directly or indirectly. A directly recursive subroutine makes a direct call to itself within the subroutine. An indirectly recursive subroutine makes no direct call to itself, but rather calls another subroutine that calls itself. Either way, we need to write our subroutines carefully so that they support recursion, even if we did not deliberately write it to be recursive (in other words, indirectly recursive).

For this exercise, load the provided code from the lab7\_ex1.asm file into the LC-3 tools program, assemble, and run the code in the simulator. What happens? (In order to recover from what happens, hit the pause button in the simulator)

*Ex 1. Q1. What happens when you run this code?*

* *The program runs infinitely.*

Now reset the simulator so you can run the program again. This time, you will step through the

code to discover why the program behaved the way it did. Remember, our eventual goal is to

implement recursion and this program fails when returning from the original subroutine called

after it stops recursing.

Put a breakpoint on address x3003. This should correspond to the instruction ‘JSRR R6’

which calls the first subroutine. Press play and wait for the program to stop at that breakpoint.

Next, press the ‘Step in’ icon (). That’s the icon that looks like a right angle with an arrow pointing to the right. This action will step into the subroutine that is at the address in register R6, which should be x3200.

Next, put a breakpoint on address x3205. This should correspond to the instruction ‘JSR

FACT\_SUB\_START’. Now note the values in R0 and R1.

*Ex 1. Q2. What are the values in registers R0 and R1?*

* *The value in R0 is 0 and the value in R1 is 5.*

Press the play button one more time.

*Ex 1. Q3. What are the values in registers R0 and R1 after pressing play, but before pressing any*

*other buttons?*

* *The value in R0 is 0 and the value in R1 is 4.*

Then from there use the ‘Step in’ button. If you use the ‘Step over’ button you won’t be able to

observe the recursion.

The register R1 will count down from 5 to 0 upon each invocation of the recursion. Once R0 has

the value 0, it will stop recursing and finish executing the last call to the FACT subroutine. It

stops because of the branch instruction in address x3204 which has the instruction ‘BRz

BASE\_3200’. The condition code is finally zero upon the last decrement of R1 in the previous address.

Ex 1. Q4 Write the values of registers R0 and R1 for each iteration of the recursion until the

recursion stops. You’ll know the recursion stops when the program is on the instruction in

address x320B, which corresponds to the BASE\_3200 label.

| **R0** | **R1** |
| --- | --- |
| 0 | 3 |
| 0 | 2 |
| 0 | 1 |
| 0 | 0 |

Now continue pressing the ‘Step in’ button until you reach address x3210 which has the

instruction ‘RET’. The RET instruction is a pseudo-instruction for ‘JMP R7’. That means that it

jumps to the instruction at the address in R7.

*EX 1. Q5. What is the value of R7 before you execute the RET instruction?*

* *The value of R7 before executing RET is x3206.*

Now press ‘Step in’ and you should go back to the address from your answer above and

execution will continue executing from there.

*EX 1. Q6. What is the value of R7 every time you get to return after the first time? (Don’t worry*

*if you miss it the first time, it will be the same forever)*

* *The value of R7 every iteration after the first time is x320A.*

The program is now stuck in an infinite loop of returning to the address from Ex 1. Q 6. Above.

Discuss with the TA why that is and any possible solution to this problem. (Hint: Look at the next

exercise)

Exercise 2

The shortcoming of the code in the previous exercise is that the R7 register was not backed up and restored in the subroutines like the other registers used. We learned in Lab 5 to always back up and restore R7.

For this exercise, copy your code from Lab 7 Exercise 1 above into the file lab7\_ex2.asm. Then modify both the FACT and MUL subroutines to properly backup and restore the R7 register (using the same backup and restore technique from exercise 1).

*Ex 2. Q 1. What happens this time when you run the code?*

* *The program still runs infinitely.*

(You’ll need to press the pause button in the simulator again to recover from what happens)

Again, put a breakpoint on address x3003. This should correspond to the instruction ‘JSRR

R6’ which calls the first subroutine. Press play and wait for the program to stop at that

breakpoint. Next press the ‘Step in’ icon. That’s the icon that looks like a right angle with an

arrow pointing to the right. This action will step into the subroutine that is at the address in

register R6, which should be x3200.

This time, put a breakpoint on the line corresponding to ‘JSR FACT\_SUB\_START’ (it will have moved after adding lines to backup/restore R7). Now note the values in R0 and R1.

*Ex 2. Q2. What are the values in registers R0 and R1?*

* *The value in R0 is 0 and the value in R1 is 5.*

Press the play button one more time.

*Ex 2. Q3. What are the values in registers R0 and R1 after pressing play, but before pressing any*

*other buttons?*

* *The value in R0 is 0 and the value in R1 is 4.*

Then from there use the ‘Step in’ button. If you use the ‘Step over’ button you won’t be able to

observe the recursion.

Just as in exercise 1, the register R1 will count down from 5 to 0 upon each invocation of the

recursion. Once R1 has the value 0, it will stop recursing and finish executing the last call to the

FACT subroutine. It stops because of the branch instruction in address x3205 which has the

instruction ‘BRz BASE\_3200. The condition code is finally zero upon the last decrement of R1 in the previous address.

Now continue pressing the ‘Step in’ button until you reach address x320E which has the

instruction ‘LD R1, BACKUP\_R1\_3200’. From here, use only the ‘Step over’ button. This

way you don’t have to go through the content of the MULT subroutine. This time, unlike last

time, the return from this subroutine works. That’s what backing up R7 fixed from exercise 1.

Continue pressing ‘Step over’ until you reach the RET instruction. The program is about to return from the last recursive call.

*EX 2. Q4. What is the value of R7 before you execute the RET instruction?*

* *The value of R7 before executing RET is x3207.*

Now press ‘Step over’ and you should go back to the address from your answer above and

execution will continue executing from there.

Continue pressing ‘Step over’ until the value in R0 is 1024.

*EX 2. Q5. Will this program ever finish, or does it just keep going?*

* *The program continues running infinitely.*

Now the program is stuck in a loop trying to return from the recursive subroutine. However,

each time we return we keep overwriting R7 with the value where the recursive subroutine was

called in the subroutine itself. It is never able to go back to where it was originally called in the

main part of the program.

Once more, you’ll be expected to explain what happened that caused the program to not work correctly.

* **The subroutine overwrites the return value because the call to the subroutine sets the return value back inside of the subroutine. This is why the stack method of backing up and restoring the registers is used because it allows us to backup the values from the “main” function (x3000) and restore them based on their original state before entering any subroutine.**

Exercise 3

For this final exercise we’ll fix the shortcomings from the last exercise by using a stack to backup

and restore R7 and any other register we modify instead of a single memory location below the

subroutine as in the previous exercises. In Lab 5 you were told to use the stack to back up the

registers without understanding what a stack is, and without understanding why we need to use

a stack. The last lab, Lab 6, taught you more about programming stacks in assembly. This exercise will now illustrate why you need to backup/restore registers using a stack, namely, to support recursion.

For this exercise, copy your code from lab 7 exercise 2, above, into the file lab7\_ex3.asm. You’ll

then modify the code to back up and restore the registers on the stack instead of memory locations at the end of each subroutine. But first, you’ll need to set up the stack to be used throughout the program.

On the LC3 processor, we usually use R6 to store the top of the stack. In this case, we’ll use R5 to store the top of the stack since we’re using R6 to hold the subroutine address. This stack starts at memory location xFE00. You’ll need to modify the code from the previous exercise starting at address x3000. Change that code to look like the following:

| 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22 | ;========================  ; Main Program  ;========================  .ORIG x3000  ; Load stack  LD R5, STACK\_ADDR    ; Set R1 to 5  AND R1, R1, #0  ADD R1, R1, #5    ; Call the factorial subroutine  LD R6, FACT\_SUB\_ADDR  JSRR R6    HALT  ;========================  ; Local Data  ;========================  FACT\_SUB\_ADDR .FILL x3200  STACK\_ADDR .FILL xFE00  .END |
| --- | --- |

All this additional code does is add a new label, STACK\_ADDR, and load its value, xFE00 into R5. This initializes the stack, readying it for future calls to subroutines.

Next, change the beginning and end of each subroutine to use the stack instead of labels at the end of the subroutine. For example:

| 31  32  33  ...  40  41  42 | ST R7, Save7\_3100  ST R1, Save1\_3100  ; Subroutine code in between  LD R1, Save1\_3100  LD R7, Save7\_3100 |
| --- | --- |

Which backs up and restores R7 and R1 respectively, becomes:

| 31  32  33  34  35  ...  42  43  44  45  46 | ADD R5, R5, #-1  STR R7, R5, #0  ADD R5, R5, #-1  STR R1, R5, #0  ; Subroutine code in between  LDR R1, R5, #0  ADD R5, R5, #1  LDR R7, R5, #0  ADD R5, R5, #1 |
| --- | --- |

Which also backs up the same registers using the stack. Be sure to make this change for both the FACT and MUL subroutines. Also, pay close attention to the order in which you backup and restore the registers. When the registers are restored at the end of the subroutine, they should be restored in the **reverse order** in which they were backed up at the beginning of the subroutine. Also, be sure to do the subtractions and additions in the correct place. A common mistake is to do the addition when you’re restoring the values to the registers before the LDR. It should be after.

Once you're done, assemble the code, put a breakpoint on the HALT instruction and run the

program. Observe what happens. Did it work? (it should) See if you can figure out where the

result of calling the FACT routine is stored.

*Ex 3. Q1. Which register holds the result of calling the FACT subroutine?*

* *Register R0 holds the result of the FACT subroutine.*

*Ex 3. Q2. What value is stored in this register?*

* *The value in R0 is 120.*

*Ex 3. Q3. Is this the correct value for 5!?*

* *Yes, this is the correct value for 5!.*

**3.2 Submission**

Your TA will maintain a Google Sheet for questions and demos.

Demo your lab exercises to your TA ***before you leave the lab***.

If you are unable to complete all exercises in the lab, demo the rest during office hours ***before*** **your next lab** to get full credit. You can demo during the next lab with a 3 point deduction.  
*Office hours are posted on Canvas (under Syllabus -> Office Hours) and Discord (#office-hours).*