

## **CS061 - Lab 2**

### **1 High Level Description**

Today's lab will cover some new LC-3 instructions, introducing the marvels of memory addressing modes, and some more I/O (input/output),

### **2 Goals for This Week**

1. New LC-3 instructions using memory addressing modes *direct*, *indirect*, and *relative*.
2. Exercises 1 – 4:  
Practice using the three memory addressing modes;  
Building a simple loop using the *conditional branch instruction*; and  
Simple input/output using BIOS routines.
3. So what now??

### 3.1 New LC-3 Instructions

As you know, in the LC-3, values can be stored in system memory (RAM), and copied from there to the eight general purpose registers named R0 through R7, or in several special purpose registers (*more about these later on*).

And as you are beginning to see, **all** microprocessor instructions involve getting values from one or other of those places, manipulating them in some fashion, and writing the result to another place - so we need a way to describe this process.

From now on, we will use a standard notation to describe all such actions called **Register Transfer Notation (RTN)**:

- (Rn) means “the contents of Register n” - i.e the value currently stored in that register.
- Mem[ xnnnn ] means “the contents of memory address xnnnn”
- $\leftarrow$  means “copy the value on the right of the arrow to the location on the left”, rather like the C++ assignment operator '='  
(the location on the left may be either a memory address or a local register), so:

$R3 \leftarrow \text{Mem}[ \text{x3042} ]$   
means copy the contents of memory location x3042 to Register 3.

$\text{Mem}[ \text{x3120} ] \leftarrow (R6)$   
means copy the contents of Register 6 to the memory location x3120

$R3 \leftarrow (R1) + (R2)$   
means add the contents of R1 and R2, and write the result to R3.

Also, as we saw last week, a *label* is an alias for a memory location (an address), so:

$\text{Mem}[ \text{myAnswer} ] \leftarrow (R4)$   
means copy the contents of R4 to the memory location corresponding to the label myAnswer.

#### **New LC-3 instructions this week: ST, LDI, STI, LDR, STR, Trap**

Note: further details on all LC-3 instructions can be found [here](#) and in Appendix A of the text.

The **ST (Store)** instruction - see the [ST tutorial](#) (Piazza Resources -> LC3 Instructions)

This is the "inverse" of the LD instruction: it stores the contents of a register directly into a location in memory specified by a label (*overwriting any previous content, of course*).

Before we go on to the other memory addressing modes, we need some background.

Consider the instruction:

LD R1, ADDR\_1 ; as you now know, this means  $R1 \leftarrow \text{Mem}[ \text{ADDR\_1} ]$   
Let's say that ADDR\_1 is an alias for memory address x3100;  
and that the value stored at that address is x4A20 = #18976 = b0100 1010 0010 0000

In other words:  $R1 \leftarrow \text{Mem}[ \text{x3100} ]$  means  $R1 \leftarrow \text{x4A20}$

Now, for reasons that will become clear later on, the label ADDR\_1 **must be no further away from the LD instruction than +/- 256 locations!**

if you attempt to LD or ST with a label further away than that, you will get an assembly error:

"Instruction references label that cannot be represented in a 9-bit signed PC offset" (see [here](#)).

So we need a mode that gets around that limitation - and, in fact, we have two such modes.  
The **LDI (Load Indirect)** instruction - see the [LDI tutorial](#)  
This looks a bit like the LD instruction, except that there is one level of *indirection*:

`LDI R1, ADDR_1` ; loads `Mem[ Mem[ADDR_1] ]` into R1:  
That is, it first fetches `Mem[ ADDR_1 ]` (let's use `ADDR_1 = x3100`; and `Mem[ADDR_1] = x4A20` again).  
Then it uses that value as a **new address**, and fetches `Mem[ x4A20 ]` (i.e. the value stored at `x4A20` – let's say that is `x00C4`), and finally copies that value into R1:  
$$R1 \leftarrow \text{Mem}[\text{Mem}[\text{ADDR\_1}]] \quad \text{i.e.} \quad R1 \leftarrow \text{Mem}[x4A20] \quad \text{i.e.} \quad \underline{R1 \leftarrow x00C4}$$

This round-about process is called “**indirection**”, and the label is called a “**pointer**” (sound familiar?), and it allows us to get around the +/- 256 line limitation (although the label itself must still be within that range)

The **STI (Store Indirect)** instruction - see the [STI tutorial](#)  
This works just like LDI, only in the opposite direction.  
It takes the value from a register and copies (stores) it to memory at the address given by `Mem[ someLabel ]` (overwriting previous content).  
$$\text{Mem}[\text{Mem}[\text{ADDR\_1}]] \leftarrow (R1) \quad \Rightarrow \quad \text{address } x4A20 \leftarrow (R1)$$
  
(i.e. the value currently stored in R1 is copied to the address stored in `ADDR_1 = x3100`, which is `x4A20`)

The **LDR (Load Relative)** instruction - see the [LDR tutorial](#)  
This uses indirection like LDI, except that it uses a *register* as the pointer rather than a memory address:

The instruction  
`LDR R1, R6, #0` ; For this course, we will always set the offset (the third parameter) to 0.  
This copies the value from `Mem[ (R6) + offset 0 ]` into R1:  
(let's say `(R6) = x3100`, and `Mem[ x3100 ]` is again `x4A20`)  
$$R1 \leftarrow \text{Mem}[(R6)+x0] \quad \text{i.e.} \quad R1 \leftarrow \text{Mem}[x3100] \quad \text{i.e.} \quad \underline{R1 \leftarrow x4A20}$$

The **STR (Store Relative)** instruction - see the [STR tutorial](#)  
This works just like LDR, only in the opposite direction.  
In the example, the instruction stores the value from R1 into the address stored in R5 (`x3100`):

The instruction  
`STR R1, R6, #0`  
copies the value currently stored in R1 into the address stored in R5:  
(Again, let's say `(R6) == x3100`, as above)  
$$\text{Mem}[(R6)] \leftarrow (R1) \quad \text{i.e.} \quad \underline{\text{address } x3100 \leftarrow (R1)}$$

By convention, we usually use **R6** as a “Base Register”, i.e. the pointer register in LDR/STR instructions.

The **Trap** instruction - see Table 1 below and the [TRAP tutorial](#) and p. 543 in the text.

**Trap** instructions are actually calls to a set of **BIOS subroutines** (a bit like what C++ calls “functions”). You saw one of them (PUTS) last week. You may use either the “TRAP xnn” form or the alias in your code.

Table 1: Trap instructions

Invocation	Alias	Effect
TRAP x20	GETC	<b>R0</b> ← one character of input (ascii) from the keyboard (no echo)
TRAP x21	OUT	print ( <b>R0</b> ) to the screen as an ascii character
TRAP x22	PUTS	Jump to memory location ( <b>R0</b> ) and print the contents of that and each succeeding memory location until a 0 is encountered. <i>Used for printing strings.</i>
TRAP x23	IN	<b><i>You will never use this instruction!</i></b> Prompt the user to input a single character; get the input from the keyboard & store it in R0, and echo it to the console.
TRAP x25	HALT	Terminates the program

### 3.2 Exercises 1 – 4

**REMINDER: Always open the Text Window of your simpl LC-3 emulator!**

*(by checking the "Text Window" box at the bottom as soon as you open simpl)*

Keep an eye on it for run-time error messages!

#### **Exercise 1: Direct memory addressing mode (LD and ST)**

Write a program in lab-02\_ex1.asm that uses .FILL pseudo-ops to load the values #65 (decimal 65) and x41 (hexadecimal 41) into two memory locations with the labels DEC\_65 and HEX\_41 respectively. *Check the binary values stored in the two locations - what do you notice?*

Look up an ASCII table (*use the back of your text or [this table](#)*) to see what these values represent when interpreted as characters rather than numbers.

Then use the **LD** instruction to load these two values into registers R3 and R4 respectively. Run the program, and inspect those registers to make sure it did what you expected.

#### **Exercise 2: Indirect memory addressing mode (LDI and STI)**

Sometimes, the data we need is located in some remote region of memory.

Copy the program from exercise 1 into your lab-02\_ex2.asm file and replace the data stored at DEC\_65 and HEX\_41 with two far away addresses such as x4000 and x4001 respectively, and rename the labels to DEC\_65\_PTR and HEX\_41\_PTR (*because your labels are now pointers to remote data*).

You can load the data into the new locations by putting the following code at the end of your current data block, after the HALT instruction, and before the .END pseudo-op:

```
;; Remote data
.orig x4000
NEW_DEC_65 .FILL #65
NEW_HEX_41 .FILL x41
```

### ***But now we have a problem!***

As we have already seen, the LC-3 Direct memory addressing mode (LD, ST instructions) only works with labels that are within +/- #256 memory locations of the instruction (see [here](#) for full details) – so our new data locations are too far away from the code to be accessed with LD and ST, even though we have provided new labels for them.

**Try using the LD instruction with these new labels and see what happens!**

But never fear – the **indirect** and **relative** addressing modes will come to the rescue!

Replace the LD instruction with one using **LDI** to load the data into R3 and R4

*(Hint: use the \_PTR labels, not the NEW\_ ones – in fact you can now remove those, they are of no use!)*

Next, add code to increment the values in R3 and R4 by 1.

*(What ascii characters do they correspond to now?)*

Finally, store the incremented values back into addresses x4000 and x4001 using **STI**.

Again, inspect the registers to make sure it worked as expected!

### **Exercise 3: Relative memory addressing mode (LDR and STR)**

Use your lab02\_ex3.asm file

Start with the same setup as in exercise 02: You have two labeled locations (“pointers”), which contain two “remote” memory addresses; your actual data is stored at those remote addresses.

Directly load (**LD**) the values of the pointers (i.e. the actual remote memory addresses) into R5 and R6 respectively.

Now, use the relative memory addressing mode (**LDR**) to load the remote data into R3 and R4, using R5 and R6 as “Base Registers” - i.e. the registers that hold the memory pointers.

Perform the same manipulation as in exercise 02 – i.e. increment the values in R3 & R4, then store those incremented values back into x4000 and x4001, this time using **STR** (*inspect your registers to confirm, as always*).

### **SUCCESS!!**

You have now used the two memory addressing modes indirect (**LDI**, **STI**) and relative (**LDR**, **STR**) to accomplish exactly the same goal – each uses indirection (“pointers”) to access memory locations that were too far away to be reached by LD:

The Indirect memory addressing mode uses a label (aliased memory location) as a pointer.

The Relative memory addressing mode uses a register containing a memory address as a pointer.

*(The downside of both is that they require one more memory read than direct addressing).*

## **Exercise 4: Loops**

Use the conditional branch instruction (**BR**) to construct a counter-controlled loop (the same control structure you learned in lab 1 and assn 1)

Hard-code (i.e. use *.FILL*) local data values x61 and x1A, and load them into R0 and R1 respectively. Inside a loop, output to console the contents of R0 (Trap x21, or OUT), then immediately increment R0 by 1.

Use R1 as the loop counter by decrementing it by 1 each iteration, just as you did in lab 1 – i.e. the loop should be executed exactly x1A times.

Think carefully about how and when to terminate the loop: do you use BRn or BRnz or BRz or BRzp or ??

*What does this loop do? Can you figure it out **before** you run it?*

### **3.3 Submission**

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

If you are unable to complete all exercises in lab, show your TA how far you got (you may be given a partial grade for it), and request permission to demo in office hours: you will have 1 week to do so (i.e. you must go to office hours before your next lab: you may not demo a previous lab in a lab session).

**Note:** if you do not get permission from your TA in lab, your work will not be graded.

*Office hours are posted on Piazza, under the "Staff" tab.*

## **4 So what do I know now?**

You should now ...

- Be totally familiar with the Register Transfer Notation (RTN) as a way of describing instructions. *This will become fundamental to our understanding of how a microprocessor functions, which is the ultimate purpose of the entire course – so make sure you get the hang of it!*
- understand the three LC-3 memory addressing modes – direct, indirect, and relative
- master the LD/ST, LDI/STI, LDR/STR instructions, and the concept of indirection (pointers) – specifically, how to load from and store to locations in memory that are too far away from your code to be reached by the direct addressing mode (LD/ST).
- know how to build a simple counter-controlled loop
- Be able to use the bios routines – i.e. the Trap instructions that manage console i/o: GETC, OUT, PUTS and HALT.