iFYP

Lab Manual # 02 – Data Transfer, Decision Making, Logical Ops

(Arrays in RISC-V Assembly, Bit Manipulation and Implementation of factorial function)

NAME: Abdul Hadi Afzal
CMS: 413970

Revision History

Revision Number	Revision Date	Revision By	Nature of Revision	Approved By
1.0	04/03/2024	Hira Sohail, Muhammad Bilal	Complete manual	Dr. Waqar

Contents

Objective

The objective of this lab is to:

- Install and get familiar to Venus simulator.
- Write an assembly code translating C to RISCV
- Perform simple tasks using assembly language such as factorial function, bitwise operation.

Tools

- Venus

Assembly Language

Assembly language is a low-level language that helps to communicate directly with computer hardware. It uses mnemonics to represent the operations that a processor must do.

It is an intermediate language between high-level languages like C++ and the machine language.

In an assembly language program, each instruction represents a single operation that the computer's CPU can perform. These can include simple arithmetic and logical operations, such as adding and subtracting values, as well as more complex operations that involve manipulating data stored in the computer's memory. Assembly language programs are typically written in a text editor and then assembled using a specialized software tool called an assembler.

Introduction to Venus

For the next few labs, we will work with several RISC-V assembly files, each of which has a ".s" file extension. To run these, we will be using Venus, an academic RISC-V assembler and simulator. For these labs we will use Venus website for simplicity but we recommend you to go through these instruction for Venus simulator, Venus reference.

Exercise 1: Venus Basics

You can "mount" a folder from your local device onto Venus's web frontend, so that edits you make within the browser Venus editor are reflected in your local file system, and vice versa. If you don't do this step, files created and edited in Venus will be lost each time you close the tab, unless you copy/paste them to a local file.

This exercise will walk you through the process of connecting your file system to Venus, which should save you a lot of trouble copy/pasting files between your local drive and the Venus editor.

1. Firstly, you are required to clone the following repository `https://github.com/61c-teach/sp24-lab-starter.git`

2. In the cloned repository, switch the directory to `tools` and run the script `download.sh` with the command `./download.sh`. This will download all the necessary tools to perform the labs.

3. In your labs folder, **run** `java -jar tools/venus.jar -dm .` This will expose your lab directory to Venus on a network port.

    - You should see a big "Javalin" logo.

    - If you see a message along the lines of "port unable to be bound", then you can specify another port number explicitly by appending `--port PORT_NUM` to the command (for example, `java -jar tools/venus.jar . -dm --port 6162` will expose the file system on port 6162).

4. **Open** https://venus.cs61c.org in your web browser (Chrome or Firefox are recommended).

5. In the Venus web terminal, **run** mount local labs (if you chose a different port, replace "local" with the full URL, such as http://localhost:6162). This connects Venus to your file system.

    - In your browser, you may see a prompt saying Key has been shown in the Venus mount server! Please copy and paste it into here.. You should be able to see a key in the most recent line of your local terminal output; just copy and paste it into the dialog.

6. **Go to** the "Files" tab. You should now be able to see your labs directory under the labs folder.

7. **Navigate** to lab03, and make sure it works by hitting the Edit button next to ex1_hello.s. This should open in the Editor tab.

    - You should see the contents of ex1_hello.s in the editor. This editor behaves like most other text editors, albeit without many of the fancier features.

8. To assemble the program open in the editor, **click** the "Simulator" tab, and **click** "Assemble & Simulate from Editor".

    - In the future, if you already have a program open in the simulator, click "Re-assemble from Editor" instead. Note that this will overwrite everything you have in the simulator tab, such as an existing debugging session.

9. To run the program, **click** "Run".

    - You can see other buttons like "Step", "Prev", and "Reset". You will use these buttons later on in the lab and during your assignments.

10. Go back to the editor tab, and **edit** ex1_hello.s so that the output prints 2023.

    - Hint: The value in a1 is printed when ecall executes. What ecall does is out of scope for this class though.

11. **Save** the changes you just made by hitting Cmd + s on macOS and Ctrl + s on Windows/Linux. This will update your local copy of the file.

12. **Open** the file on your local machine using the text editor of your choice to check and make sure it matches what you have in the web editor.

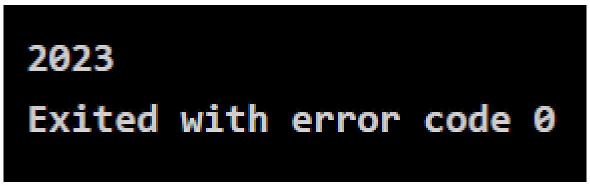
    - **Note:** If you make any changes to a file in your local machine using a text editor, if you had the same file open in the Venus editor, you'll need to reopen it from the "Files" menu to get the new changes.

13. **Run** the program again, you should now see 2023 if you modified the source file correctly.

CODE:

```
.text

addi a0 x0 1
addi a1 x0 2023

# This prints out the integer stored in a1
ecall

# This exits the program
addi a0 x0 17
addi a1 x0 0
ecall
```

OUTPUT:



```
2023
Exited with error code 0
```

Translating from C to RISC-V

In this example, we are going to walk through translating a C program to a RISC-V program. The following program will print out the nth Fibonacci number. Even though this section is a bit long, please read through it!

```
#include <stdio.h>

int n = 12;

// Function to find the nth Fibonacci number
int main(void) {
    int curr_fib = 0, next_fib = 1;
    int new_fib;
    for (int i = n; i > 0; i--) {
        new_fib = curr_fib + next_fib;
        curr_fib = next_fib;
        next_fib = new_fib;
    }
    printf("%d\n", curr_fib);
    return 0;
}
```

Let's break down how we'll translate this step-by-step. Open fib.s in the Venus editor. First, we need to define the global variable n. In RISC-V global variables are declared under the .data directive. This represents the data segment. It will look like this:

```
.data
n: .word 12
```

- n is the name of the variable
- .word means that the size of the data is one word
- 12 is the value that is assigned to n

It is noteworthy that the `.data` section must initialize all the global variable declared under the scope of the section must be initialized with a value.

Quiz Question: How can we declare variables without initialization in RISC-V Assembly?

Ans.

In Venus:

- **Use the .bss section to declare uninitialized variables.**
- **Use .space to reserve bytes.**

Let's move on to initializing curr_fib and next_fib

```
.text
main:
    add t0, x0, x0 # curr_fib = 0
    addi t1, x0, 1 # next_fib = 1
```

Here we have added the .text directive. Everything under this directive is our executable code.

Remember that x0 cannot be modified and always holds the value 0.

We don't need to do anything to declare new_fib (we don't declare variables in RISC-V).

Next, let's get to the loop. We'll start with setting up the loop variables. The following code will set i to n

```
la t3, n # load the address of the label n
lw t3, 0(t3) # get the value that is stored at the adddress denoted by the label n
```

You can think of the code above as doing something along the lines of

```
t3 = &n;
t3 = *t3;
```

We have a new instruction here la. This instruction loads the address of a label. The first line essentially sets t3 to be a pointer to n. Next, we use lw to dereference t3 which will set t3 to the value stored at n.

Now, you're probably thinking, "Why can't we directly set t3 to n?" In the .text section, there is no way that we can directly access n. (Think about it. We can't say add t3, n, x0. The arguments to add must be registers and n is not a register.) The only way that we can access it is by obtaining the address of n. Once we obtain the address of n, we need to dereference it which can be done with lw. lw will reach into memory at the address that you specify and load in the value stored at that address. In this case, we specified the address of n and added an offset of 0.

Let's get down to the loop now. First, we'll create the outer structure below:

```
fib:
    beq t3, x0, finish # exit loop once we have completed n iterations
    ...
    ...
    addi t3, t3, -1 # decrement counter
    j fib # loop
finish:
```

The first line (fib:) is a label that we will use to jump back to the beginning of the loop.

The next line (beq t3, x0, finish) specifies our terminating condition. Here, we will jump to another label, finish, once t3 (which is representing i) reaches 0.

The next line (addi t3, t3, -1) decrements i at the end of the loop body. It's important to do this at the end because i is used in the loop body. If we updated it right after beq, then it would not have the correct value in the loop body.

The next instruction jumps back to the start of the loop.

Now, let's add in the loop body.

```
fib:
    beq t3, x0, finish # exit loop once we have completed n iterations
    add t2, t1, t0 # new_fib = curr_fib + next_fib;
    mv t0, t1 # curr_fib = next_fib;
    mv t1, t2 # next_fib = new_fib;
    addi t3, t3, -1 # decrement counter
    j fib # loop
finish:
```

Nothing special here. The corresponding C lines are written in the comments.

Let's print out the nth Fibonacci number!

```
finish:
    addi a0, x0, 1 # argument to ecall to execute print integer
    addi a1, t0, 0 # argument to ecall, the value to be printed
    ecall # print integer ecall
```

Printing is a system call. You'll learn more about these later in the semester, but a system call is essentially a way for your program to interact with the Operating System. To make a system call in RISC-V, we use a special instruction called ecall. To print out an integer, we need to pass two arguments to ecall. The first argument specifies what we want ecall to do (in this case, print an integer). To specify that we want to print an integer, we pass a 1. The second argument is the integer that we want to print out.

In C, we are used to functions looking like ecall(1, t0). In RISC-V, we cannot pass arguments in this way. To pass an argument, we need to place it in an argument register (a0-a7). When the function executes, it will look in these registers for the arguments. (If you haven't seen this in lecture yet, you will soon). The first argument should be placed in a0, the second in a1, etc.

To set up the arguments, we placed a 1 in a0 and we placed the integer that we wanted to print in a1.

Next, let's terminate our program! This also requires ecall

```
addi a0, x0, 10 # argument to ecall to terminate
ecall # terminate ecall
```

In this case, ecall only needs one argument. Setting a0 to 10 specifies that we want to terminate the program.

And there you have it! Here's our full program!

```
.data
n: .word 12
```

```
.text
main:
    add t0, x0, x0 # curr_fib = 0
    addi t1, x0, 1 # next_fib = 1
    la t3, n # load the address of the label n
    lw t3, 0(t3) # get the value that is stored at the adddress denoted by the label n
fib:
    beq t3, x0, finish # exit loop once we have completed n iterations
    add t2, t1, t0 # new_fib = curr_fib + next_fib;
    mv t0, t1 # curr_fib = next_fib;
    mv t1, t2 # next_fib = new_fib;
    addi t3, t3, -1 # decrement counter
    j fib # loop
finish:
    addi a0, x0, 1 # argument to ecall to execute print integer
    addi a1, t0, 0 # argument to ecall, the value to be printed
    ecall # print integer ecall
    addi a0, x0, 10 # argument to ecall to terminate
    ecall # terminate ecall
```

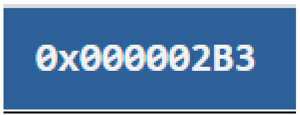
Exercise 2: Using the Venus Debugger

There are two ways of opening a file in the Venus debugger:

1. Through the editor
    1. **Open** fib.s into the Venus editor.
    2. **Click** the "Simulator" tab and **click** the "Assemble & Simulate from Editor" (or the "Re-assemble from Editor") button. The current instruction is highlighted in a light blue color. Similar to cgdb, the current instruction is the instruction has not been executed, but is about to be executed.
2. Through the "Files" tab
    1. **Click** the "Venus" tab, then **click** the "Files" tab.
    2. **Navigate** to the fib.s file, which should be located in the labs folder under lab03.
    3. **Click** the "VDB" button next to the name of the file.

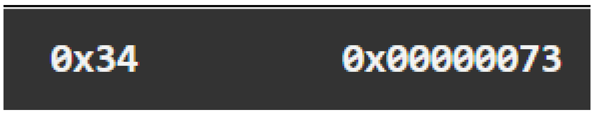
This exercise will ask you to write down your answers in ex2_answers.txt. The question numbers may be different from the step numbers, please be careful!

1. **Open** fib.s in the Venus debugger using one of the two ways listed above.
    - Question 1: What is the machine code of the highlighted instruction? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



0x000002B3

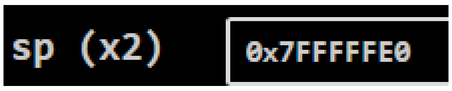
    - Question 2: What is the machine code of the instruction at address 0x34? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



0x34 0x00000073

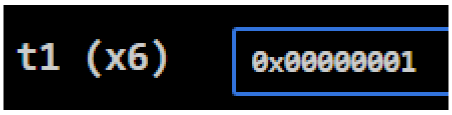
Click the "step" button to advance to the next instruction. The second instruction should now be highlighted.

2. **Click** the "prev" button to undo the last executed instruction. Note that undo may or may not undo operations performed by ecall, such as exiting the program or printing to console.
3. On the right side of the screen, **click** the "Registers" tab to view the values of all 32 registers. This tab may be already selected if it the title is highlighted in yellow. Make sure you look at the integer registers, not the floating-point registers.
    - Question 3: What is the value of the sp register? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



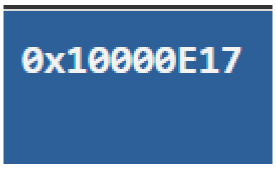
```
sp (x2)   0x7FFFFFE0
```

4. **Continue stepping** until the value in t1 changes.
    - Question 4: What is the new value of the t1 register? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



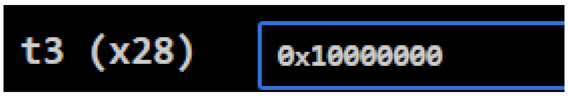
```
t1 (x6)   0x00000001
```

    - Question 5: What is the machine code of the current instruction? The answer should be a 32-bit hexadecimal number, with the 0x prefix.



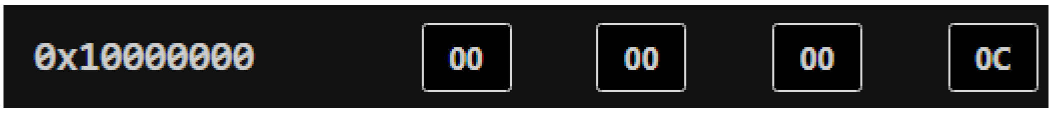
```
0x10000E17
```

5. **Step** until you are at address 0x10. At this point, t3's value has been updated.
    - Question 6: What is the value of the t3 register? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



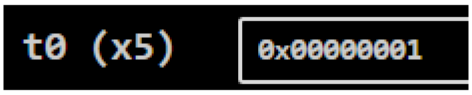
```
t3 (x28)   0x10000000
```

6. If we look at the current instruction, we're loading from the t3 register. **Use** the "Memory" tab (next to the "Registers" tab), and **input** the answer of question 6 (the value of t3) into the "Address" box. You may need to scroll down on the memory tab before it is visible. **Press** "Go" to go to that memory address
    - Question 7: What is the byte that t3 points to? The answer should be an 8 bit (1 byte) hexadecimal number, with the 0x prefix.



```
0x10000000   00   00   00   0C
```

7. **Set a breakpoint** at address 0x28 by clicking the row at that address. The row should turn light red and a breakpoint symbol should appear.
8. **Continue** until the breakpoint by pressing "Run".
    - Question 8: What is the value of the t0 register? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



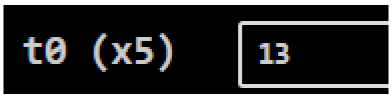
```
t0 (x5)   0x00000001
```

9. **Continue** 6 more times.
    - Question 9: What is the new value of the t0 register? The answer should be a

32 bit hexadecimal number, with the 0x prefix.

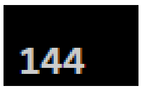
0x0000000D

10. Sometimes, reading hexadecimal values aren't very helpful. **Set** the display settings to "Decimal" by using the dropdown at the bottom of the register tab. This can also be done for the memory tab.
    - Question 10: What is the value of the t0 register in decimal? The answer should be a decimal number without a prefix.



```
t0 (x5)    13
```

11. **Click** the instruction at address 0x28 again to unset the breakpoint.
12. **Click** run to finish running the program, since there are no more breakpoints.
    - Question 11: What is the output of the program? The answer should be a decimal number without a prefix.



```
144
```

Venus: Memcheck

In C programming valgrind was the go-to tool for debugging memory access errors (such as Segmentation fault (core dumped)). For Venus, we have a feature called "memcheck" that accomplishes something similar. The memcheck error messages are designed to mimic valgrind error messages.

Memcheck comes in two modes:

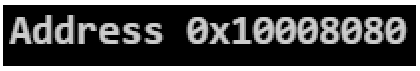
- Normal mode (or just "memcheck"): This mode will show any invalid reads or writes to memory. If there is unfreed memory when the program exits, it will also print out the number of bytes of unfreed memory.
- Verbose mode (or "memcheck verbose"): In addition to normal mode, this mode also prints out every memory read/write, along with a list of blocks that were not freed when the program exits.

You can enable these modes under the Venus tab. If both "Enable Memcheck?" and "Enable Memcheck Verbose?" are selected, memcheck will run in verbose mode.

Lab Task 1- Using Memcheck

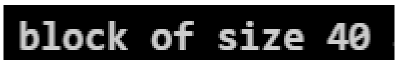
This exercise will ask you to write down your answers in ex3_answers.txt. The question numbers may be different from the step numbers, please be careful!

1. **Open** ex3_memcheck. s in the Venus editor and **read** through the entire program to get an idea of what it does.
2. **Run** the program. Oh no, the program errors! Let's look at the error message.
   - Question 1: What address did the program try to access, but caused the error? The answer should be a 32-bit hexadecimal number, with the 0x prefix.



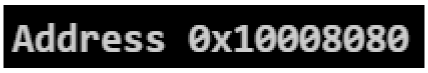
```
Address 0x10008080
```

   - Question 2: How many bytes was the program trying to access? The answer should be a decimal number without a prefix.



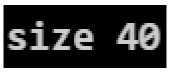
```
block of size 40
```

3. This seems like a memory error, so let's give memcheck a shot. **Enable** memcheck (normal mode) and **reopen** ex3_memcheck.s in VDB.
4. **Run** the program. Look, a memcheck error with more details! **Read** the error carefully.
   - Question 3: What address did the program try to access, but caused the error? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



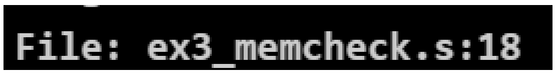
```
Address 0x10008080
```

   - Question 4: How many bytes were allocated in the block related to the error? The answer should be a number without units.



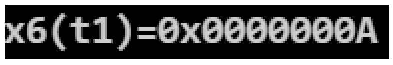
```
size 40
```

   - Question 5: Which line of the source file caused this error? The answer should be a number.



```
File: ex3_memcheck.s:18
```

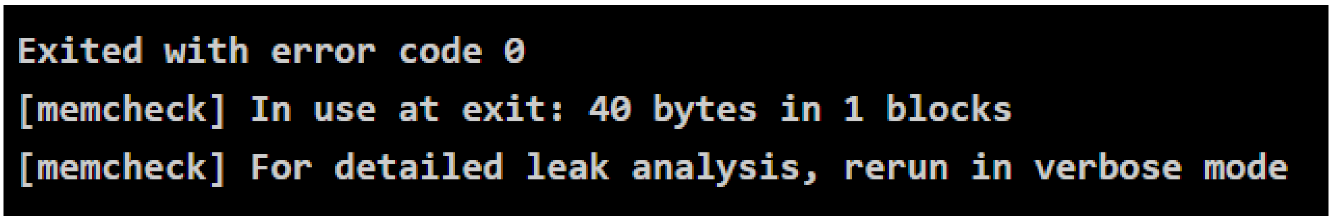
5. **Compare** your answer to Question 2 and Question 4. Note that memcheck may change the memory address that malloc returns.
6. Let's try to debug this error. **Recall** that t1 contains the loop counter.
   - Question 6: What is the value of t1 based on the memcheck error message? The answer should be a decimal number.



```
x6(t1)=0x0000000A
```

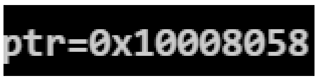
7. **Fix** this error in the source code and **save** the file.
8. **Run** the program again. The process complete without any invalid access errors. However, it complains that there's some unfreed memory.

- Question 7: How many bytes were not freed when the program exited? The answer should be a decimal number without units.



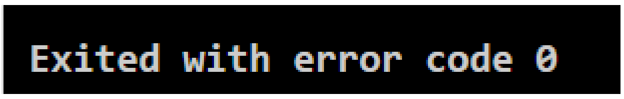
```
Exited with error code 0
[memcheck] In use at exit: 40 bytes in 1 blocks
[memcheck] For detailed leak analysis, rerun in verbose mode
```

9. **Rerun** the program with memcheck in verbose mode. Remember to reopen the file in VDB.
   - Question 8: What is the address of the block that was not freed? The answer should be a 32 bit hexadecimal number, with the 0x prefix.



```
ptr=0x10008058
```

10. **Fix** this error by calling free.
11. **Disable** memcheck for the next two tasks



```
Exited with error code 0
```

CODE:

```
.import utils.s

.text
main:
# This program will fill an array of size 10 with 0's

# Allocate an array of size 10
li a0, 40          # 10 ints, 4 bytes each
jal malloc         # malloc is defined in utils.s
mv t0, a0          # t0 = pointer to allocated memory
mv s0, a0          # save original pointer in s0 to free later

# Fill the array with 0's
li t1, 0           # t1 = index
li t2, 10          # t2 = size of the array

loop:
bge t1, t2, done    # if t1 >= t2, exit loop
sw x0, 0(t0)        # store 0 at address t0
addi t1, t1, 1      # increment index
addi t0, t0, 4      # increment pointer to next int
jal zero, loop      # jump to loop unconditionally

done:
mv a0, s0          # restore original malloc pointer
jal free           # free the allocated memory

# Exit the program
li a0, 0
jal exit
```

Lab Task 2- Arrays In Assembly

Consider the discrete-valued function f defined on integers in the set {-3, -2, -1, 0, 1, 2, 3}. Here's the function definition:

```
f(-3) = 6
f(-2) = 61
f(-1) = 17
f(0) = -38
f(1) = 19
f(2) = 42
f(3) = 5
```

Implement the function in ex4_discrete_fn.s in RISC-V, with the condition that your code may **NOT** use any branch and/or jump instructions! Make sure that your code is saved locally. We have provided some hints in case you get stuck.

All output values are stored in the output array which is passed to f through register a1. You can index into that array to get the output corresponding to the input.

Make sure that you only write to the **t** and **a** register. If you use other registers, strange things may happen (you'll learn about why soon).

HINTS:

1. You can access the values of the array using lw.
2. lw requires that the offset is an immediate value. When we compute the offset for this problem, it will be stored in a register. Since we cannot use a register as the offset, we can add the value stored in the register to the base address to compute the address of the index that we are interested in. Then we can perform a lw with an offset of 0.

In the following example, the index is stored in t0 and the pointer to the array is stored in t1. The size of each element is 4 bytes. In RISC-V, we have to do our own pointer arithmetic, so:

- We need to multiply the index by the size of the elements of the array.
- Then we add this offset to the address of the array to get the address of the element that we wish to read.
- Read the element.

```
slli t2, t0, 2 # step 1 (see above)
add t2, t2, t1 # step 2 (see above)
lw t3, 0(t2)  # step 3 (see above)
```

3. f(-3) should be stored at offset 0, f(-2) should be stored at offset 1, and so on

Testing

To test your function, open ex4_discrete_fn_tester.s and run it through the simulator. make sure that the test passes locally before you submit.

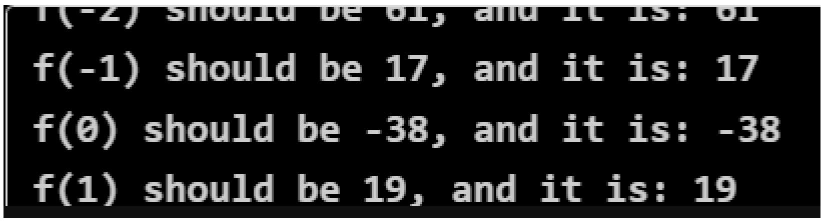
You can also test your code using the command line with the following command.

```
$ java -jar tools/venus.jar lab03/ex4_discrete_fn_tester.s
```

CODE:

```
.globl f

# f takes two arguments:
# a0: the input value to evaluate f at (must be in -3..3)
# a1: pointer to the output array [f(-3), f(-2), ..., f(3)]
# returns value f(a0) in a0

f:
addi t0, a0, 3        # convert domain [-3..3] to index [0..6]
slli t0, t0, 2        # multiply index by 4 (word size)
add t1, a1, t0        # compute effective address of f(a0)
lw a0, 0(t1)          # load the value at that address into a0
jr ra                 # return
```

OUPUT:



```
f(-2) should be 61, and it is: 61
f(-1) should be 17, and it is: 17
f(0) should be -38, and it is: -38
f(1) should be 19, and it is: 19
```

Lab Task 3- Arrays partitioning

An array array1 contains the sequence:

-1 22 8 35 5 4 11 2 1 78

each element of which is word.

Rearrange the element order in this array such that,

- All the elements smaller than the 3rd element (i.e. 8) are on the left of it,
- All the elements bigger than the 3rd element (i.e. 8) are on the right of it.

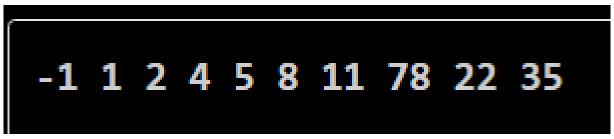
CODE:

```
.data
array1: .word -1, 22, 8, 35, 5, 4, 11, 2, 1, 78
n:      .word 10
```

```
.text
.globl main

main:
la t2, array1        # base address of array
li t1, 10            # array length

# Load pivot (3rd element, index=2)
li t0, 2             # load index 2
slli t0, t0, 2       # t0 = 2 * 4 = 8 bytes offset
add a0, t2, t0       # a0 = &array[2]
lw a1, 0(a0)         # a1 = pivot = 8

# Swap pivot with last element (index 9)
li t3, 9             # index 9
slli t3, t3, 2       # t3 = 9 * 4 = 36 bytes offset
add a2, t2, t3       # a2 = &array[9]
lw a3, 0(a2)         # a3 = array[9] = 78

# Swap pivot and last element
sw a3, 0(a0)         # array[2] = 78
sw a1, 0(a2)         # array[9] = 8

# Initialize pointers for partition
li t4, 0             # i = 0
li t5, 8             # j = 8 (one before last index)

partition_loop:
# Move i forward while array[i] < pivot
i_forward:
slli a0, t4, 2       # offset i * 4
add a2, t2, a0       # &array[i]
lw a3, 0(a2)         # array[i]
bge a3, a1, i_stop   # if array[i] >= pivot, stop
addi t4, t4, 1       # i++
blt t4, t5, i_forward

i_stop:
# Move j backward while array[j] > pivot
j_backward:
slli a0, t5, 2       # offset j * 4
add a2, t2, a0       # &array[j]
lw a3, 0(a2)         # array[j]
ble a3, a1, j_stop   # if array[j] <= pivot, stop
addi t5, t5, -1      # j--
bge t5, t4, j_backward

j_stop:
blt t4, t5, swap_ij  # if i < j, swap

# Otherwise partition done, swap pivot with array[i]
slli a0, t4, 2       # offset i * 4
add a2, t2, a0       # &array[i]
lw a3, 0(a2)         # array[i]

li t6, 9
slli t6, t6, 2       # t6 = 9 * 4
```

```
add a0, t2, t6        # &array[9]
lw a4, 0(a0)          # pivot = 8

# Swap array[i] and pivot
sw a4, 0(a2)          # array[i] = pivot
sw a3, 0(a0)          # array[9] = old array[i]

j print_array

swap_ij:
# Swap array[i] and array[j]
slli a0, t4, 2
add a2, t2, a0
lw a3, 0(a2)

slli a0, t5, 2
add a4, t2, a0
lw a5, 0(a4)

sw a5, 0(a2)
sw a3, 0(a4)

addi t4, t4, 1
addi t5, t5, -1

j partition_loop

print_array:
li t3, 0              # i = 0

print_loop:
blt t3, t1, print_continue
j done

print_continue:
slli t4, t3, 2
add t5, t2, t4
lw a1, 0(t5)

li a0, 1              # syscall print int
ecall

li a0, 11             # syscall print char
li a1, 32             # space
ecall

addi t3, t3, 1
j print_loop

done:
li a0, 10             # syscall exit
ecall
```

OUTPUT:



```
-1 1 2 4 5 8 11 78 22 35
```

Lab Task 4- Factorial

In this task, you will be implementing the factorial function in RISC-V using assembly. This function takes in a single integer parameter n and returns n!. A stub of this function can be found in the file factorial.s.

The argument that is passed into the function is located at the label n. You can modify n to test different factorials. To implement, you will need to add instructions under the factorial label. Note that you may find it helpful to add additional labels to simplify control flow. We recommend that you implement the iterative solution, but you are welcome to implement the recursive solution. You can assume that the factorial function will only be called on positive values with results that won't overflow a 32-bit two's complement integer.

At the start of the factorial call, the register a0 contains the number which we want to compute the factorial of. Then, place your return value in register a0 before returning from the function.

Make sure that you only write to the **t** and **a** registers. If you use other registers, strange things may happen (you'll learn about why soon).

Also, make sure you initialize the registers you are using! Venus might show that the registers are initially 0, but in real life they can contain garbage data. Make sure you set the register values that you will be using to some defined number before using them**.**

Testing

To test your code, you can make sure your function properly returns the correct output. Some examples are 0! = 1, 3! = 6, 7! = 5040 and 8! = 40320.

To test your function, open ex5_factorial.s and run it through the simulator. This will be how we test your function on the autograder, so make sure that the test passes locally before you submit.

You can also test your code using the command line with the following command.

```
java -jar tools/venus.jar lab03/ex5_factorial.s
```

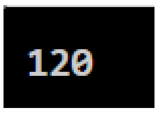
- The report should include your thinking, illustration of implementations, and results of the source code.

CODE:

```
.data
n: .word 5           # Change this value to test different factorials

.text
.globl main

main:
la t0, n
lw a0, 0(t0)         # Load n into a0
jal ra, factorial    # Call factorial function

addi a1, a0, 0       # Prepare argument for print int syscall
li a0, 1             # Syscall code for print integer
ecall

addi a1, x0, '\n'    # Prepare newline char
li a0, 11            # Syscall code for print char
ecall

li a0, 10            # Syscall code for exit
ecall

# factorial: iterative factorial function
# Input: a0 = n
# Output: a0 = n!
factorial:
li t0, 1             # i = 1
li t1, 1             # result = 1

loop:
bgt t0, a0, end_loop    # if i > n, end loop

mul t1, t1, t0          # result *= i
addi t0, t0, 1          # i++

j loop

end_loop:
```

```
            mv a0, t1                  # Move result to a0 to return
                jr ra                      # Return to caller
```

OUTPUT:



```
120
```

Lab Task 5 – Bit Manipulation

Write a RISC-V assembly program that performs various bit manipulation operations on integers. The program should implement a set of operations based on the user's choice:

Toggle Bit: Toggle a specific bit in a given integer.

Check Bit: Check if a specific bit is set in a given integer.

Set Bit: Set a specific bit in a given integer.

Clear Bit: Clear a specific bit in a given integer.

The program should prompt the user for the operation they want to perform and then execute the corresponding function. Each function should take two arguments: the integer to manipulate and the position of the bit to manipulate.

Steps:

Write a RISC-V assembly program that starts by displaying a menu with the options to toggle a bit, check a bit, set a bit, or clear a bit.

Prompt the user for the desired operation.

Prompt the user for the integer to manipulate and the bit position (0-based index).

Based on the user's choice, perform the requested operation using arithmetic operators (addition, subtraction) and bitwise operations (AND, OR, XOR).

Display the result of the operation to the user.

Loop back to the menu to allow the user to perform additional operations.

- XOR (xor) can be used to toggle a bit.
- AND (and) can be used to check if a bit is set.
- OR (or) can be used to set a bit.
- AND with a mask can be used to clear a bit.

A pseudo code is provided:

```
.data

menu: .asciiz "Choose an option:\n1. Toggle Bit\n2. Check Bit\n3. Set Bit\n4. Clear Bit\n"

.text

.global _start

_start:

    # Display menu and get user input

    la a0, menu

    li a7, 64  # syscall for print string

    ecall

    # Get user choice and integer and bit position

    # ...

    # Perform operations based on user choice

    # Call the appropriate function for each choice

toggle_bit:

    # Code to toggle the specified bit

    # ...

check_bit:

    # Code to check if the specified bit is set

    # ...

set_bit:

    # Code to set the specified bit

    # ...

clear_bit:

    # Code to clear the specified bit

    # ...

# Add more functions and loops as needed
```

CODE:

```
.data

menu:       .asciiz "\nSelect operation:\n1. Toggle Bit\n2. Check
Bit\n3. Set Bit\n4. Clear Bit\n5. Exit\nChoice: "

prompt_int: .asciiz "Enter the integer: "

prompt_pos: .asciiz "Enter the bit position (0-based): "

result_msg: .asciiz "Result: "

check_set:  .asciiz "Bit is set.\n"

check_clear:.asciiz "Bit is clear.\n"

invalid_pos_msg: .asciiz "Invalid bit position! Must be between 0 and
31.\n"


.text

.globl main


main:

menu_loop:

# Print menu string

li a0, 4

la a1, menu

ecall


# Read choice integer

li a0, 5

ecall

mv s0, a0          # Save choice in s0


# Exit if choice == 5
```

```
li t0, 5
beq s0, t0, exit

# Prompt for integer
li a0, 4
la a1, prompt_int
ecall

# Read integer
li a0, 5
ecall
mv s1, a0          # Save input integer in s1

# Prompt for bit position
li a0, 4
la a1, prompt_pos
ecall

# Read bit position
li a0, 5
ecall
mv s2, a0          # Save bit position in s2

# Validate bit position: must be less than 32
li t1, 32
bge s2, t1, invalid_pos
```

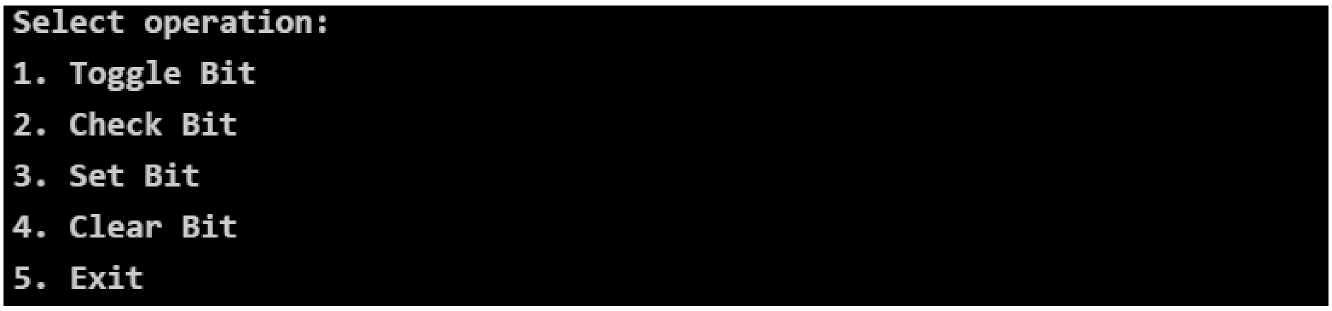
```
# mask = 1 << bit position
li t2, 1
sll t2, t2, s2     # create mask in t2

# Branch based on choice (s0)
li t3, 1
beq s0, t3, do_toggle
li t3, 2
beq s0, t3, do_check
li t3, 3
beq s0, t3, do_set
li t3, 4
beq s0, t3, do_clear

# Invalid choice - loop again
j menu_loop

invalid_pos:
# Print invalid position message
li a0, 4
la a1, invalid_pos_msg
ecall
j menu_loop

do_toggle:
xor t4, s1, t2     # toggled result in t4
```

```
# Print result message
li a0, 4
la a1, result_msg
ecall

# Print integer result
li a0, 1
mv a1, t4
ecall

j menu_loop

do_check:
and t4, s1, t2
bnez t4, bit_set

# Bit is clear
li a0, 4
la a1, check_clear
ecall
j menu_loop

bit_set:
li a0, 4
la a1, check_set
ecall
j menu_loop
```

```
do_set:
or t4, s1, t2

# Print result message
li a0, 4
la a1, result_msg
ecall

# Print integer result
li a0, 1
mv a1, t4
ecall
j menu_loop

do_clear:
xori t5, t2, -1        # bitwise NOT of mask
and t4, s1, t5         # clear the selected bit in s1

# Print result message
li a0, 4
la a1, result_msg
ecall

# Print integer result
li a0, 1
mv a1, t4
```

```
ecall

j menu_loop

exit:
li a0, 10          # syscall exit
ecall
```

OUTPUT:



```
Select operation:
1. Toggle Bit
2. Check Bit
3. Set Bit
4. Clear Bit
5. Exit
```

Reference

https://inst.eecs.berkeley.edu/~cs61c/fa23/

https://www.cse.cuhk.edu.hk/~byu/CENG3420/2022Spring/slides/lab1-2.pdf