ASHWIN ANAND - COMPUTER ARCHITECTURE LAB 3

Department of Electrical and Computer Engineering
Rutgers, The State University of New Jersey

Course Name: Computer Architecture Lab

Course Number and Section: 14:332:333:01

Experiment: Lab # 3 – C heap functions and Introduction to RISC-V

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Computer Architecture and Assembly Lab
Spring 2021

Lab 3
C heap functions and Introduction to RISC-V

Goals

1. Allocate heap memory using malloc() free()
2. Write RISC-V assembly code

The stack, the heap and static

- stack: local variable storage (automatic, continuous memory)
- heap: dynamic storage (large pool of memory, not allocated in contiguous order) ● static: global variable storage, permanent for the entire run of the program (.data segment, part of the executable file)

```
[uty@u ~]$ ps -A | grep lab3
 157926 pts/3    00:00:00 lab3
[uty@u ~]$ cat /proc/157926/maps
558836ad1000-558836ad2000 r--p 00000000 08:07 5736320                    /home/uty/prjs/testlab/lab3
558836ad2000-558836ad3000 r-xp 00001000 08:07 5736320                    /home/uty/prjs/testlab/lab3
558836ad3000-558836ad4000 r--p 00002000 08:07 5736320                    /home/uty/prjs/testlab/lab3
558836ad4000-558836ad5000 r--p 00002000 08:07 5736320                    /home/uty/prjs/testlab/lab3
558836ad5000-558836ad6000 rw-p 00003000 08:07 5736320      .data         /home/uty/prjs/testlab/lab3
5588370db000-5588370fc000 rw-p 00000000 00:00 0                          [heap]
7f03f94a7000-7f03f94a9000 rw-p 00000000 00:00 0
7f03f94a9000-7f03f94cf000 r--p 00000000 08:07 4721411                    /usr/lib/libc-2.32.so
7f03f94cf000-7f03f961c000 r-xp 00026000 08:07 4721411                    /usr/lib/libc-2.32.so
7f03f961c000-7f03f9668000 r--p 00173000 08:07 4721411                    /usr/lib/libc-2.32.so
7f03f9668000-7f03f966b000 r--p 001be000 08:07 4721411                    /usr/lib/libc-2.32.so
7f03f966b000-7f03f966e000 rw-p 001c1000 08:07 4721411                    /usr/lib/libc-2.32.so
7f03f966e000-7f03f9674000 rw-p 00000000 00:00 0
7f03f96a8000-7f03f96aa000 r--p 00000000 08:07 4721393                    /usr/lib/ld-2.32.so
7f03f96aa000-7f03f96cb000 r-xp 00002000 08:07 4721393                    /usr/lib/ld-2.32.so
7f03f96cb000-7f03f96d4000 r--p 00023000 08:07 4721393                    /usr/lib/ld-2.32.so
7f03f96d4000-7f03f96d5000 r--p 0002b000 08:07 4721393                    /usr/lib/ld-2.32.so
7f03f96d5000-7f03f96d7000 rw-p 0002c000 08:07 4721393                    /usr/lib/ld-2.32.so
7ffd36f52000-7ffd36f73000 rw-p 00000000 00:00 0                          [stack]
7ffd36ff6000-7ffd36ff9000 r--p 00000000 00:00 0                          [vvar]
7ffd36ff9000-7ffd36ffa000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 --xp 00000000 00:00 0                  [vsyscall]
```

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Heap vs. stack, key difference

● Stack is a linear data structure whereas Heap is a hierarchical data structure. ● Stack memory will never become fragmented whereas Heap memory can become fragmented as blocks of memory are first allocated and then freed.
● Stack accesses local variables only while Heap allows you to access variables globally.
● Stack variables can't be resized whereas Heap variables can be resized. ● Stack memory is allocated in a contiguous block whereas Heap memory is allocated in any random order.
● Stack doesn't require to de-allocate variables whereas in Heap de-allocation is needed.
● Stack allocation and deallocation are done by compiler instructions whereas Heap allocation and deallocation is done by the programmer.

Libc heap functions

- **void* malloc (size_t size);**
  - Allocate memory block

- **void free (void* ptr);**
  - Deallocate memory block

- **void* calloc (size_t num, size_t size);**
  - Allocate and zero-initialize array

- **void* realloc (void* ptr, size_t size);**
  - Reallocate memory block (realloc() = free() then malloc())

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Exercise 1 [10 pts]: Memory Allocation in C

E1.1. [2 pts] Where in memory would a static integer (global) variable be stored? Explain why.

A static integer is stored in the data segment of the memory. This is because static variable values don't change throughout the program, so it would be part of the virtual address space of the program.

E1.2 [8 pts] Write a C program which dynamically allocates memory to define a float array with 10 entries by using the malloc() function and prints each element out in a for loop. Do not forget to free the memory in the end of your program.

Source code attached to the submission.

```c
// Ashwin Anand

#include <stdio.h>
#include <stdlib.h>

int main()
{

    int a; // creation of globL counter variable for usage in both for loops

    float *ptr; // pointer to a float variable

    ptr = (float*) malloc(10*sizeof(float)); // p point to float with malloc size

    printf("Input 10 numbers: \n"); // message print out to get 10 inputs from user

    for(a=0;a<10;a++)
    {
        scanf("%f", ptr+a); // scans in and stores variable
    }

    printf("Elements are:\n"); // message to print out inputs while it was stored

    for(a=0;a<10;a++)
    {
        printf("%f\n", *(ptr+a)); // prints out input variables
    }

    free(ptr); // free's up space in the memory using the pointer to a float variable


    return 0;
}
```

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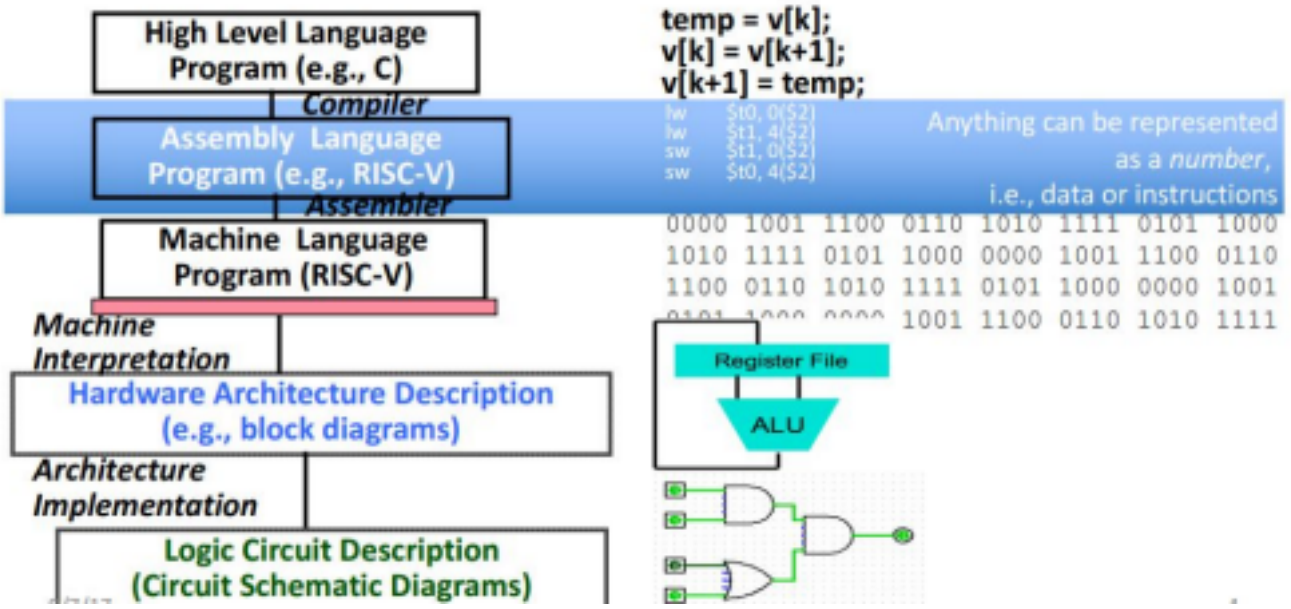
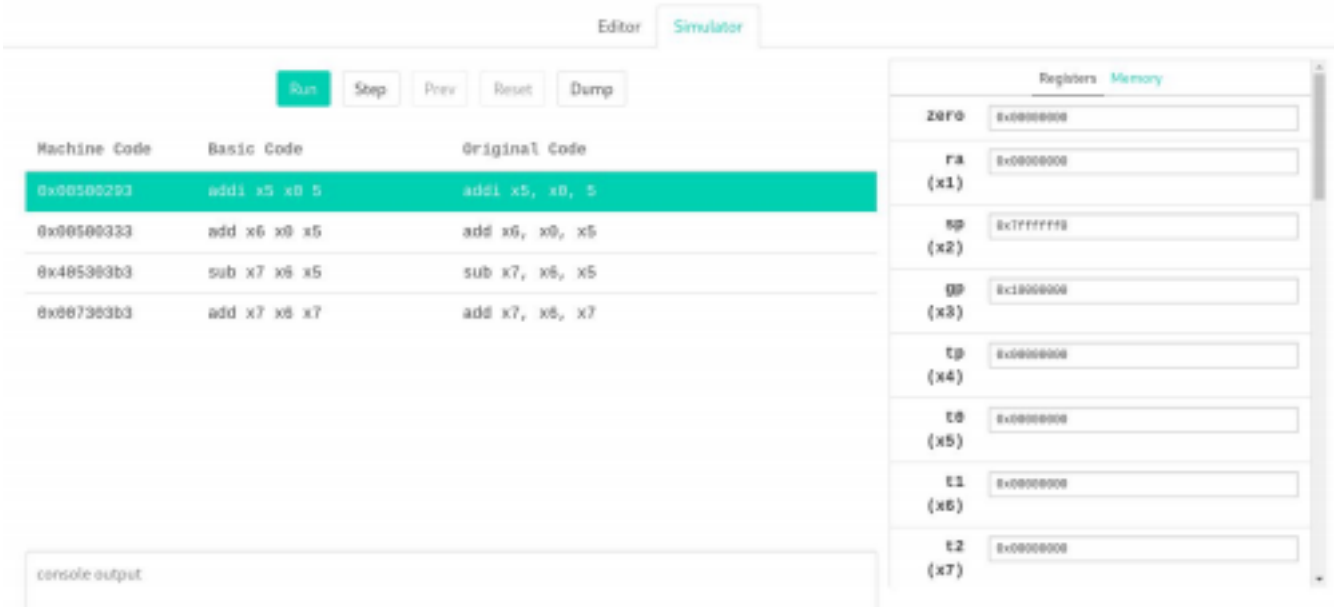
Introduction to RISC-V and the Venus Simulator

Levels of representation/interpretation



We use the **Venus simulator** (https://www.kvakil.me/venus/) to execute RISC-V assembly programs in a browser with JavaScript enabled.



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Exercise 2 [30 pts]: A Minimal Assembler Program Tutorial
(How to Start Everything Off with Loading Constants)

Start by pasting the following minimal.s assembly program into Venus:

```
# As minimal RISC-V assembly language example (minimal.s)
addi x5, x0, 5
add x6, x0, x5
sub x7, x6, x5
add x7, x6, x7
```

E2.1. [8 pts] Switch to the Simulator and run your program with the Run step, or step through the code with the Step button. You can also clear the registers and the program counter by pressing Reset. Please indicate how the registers x5, x6, and x7 change after running each line.

Code	Machine Code	x5	x6	x7
Line 1 : addi x5 , x0, 5	0x00500293	5	No value stored and not used yet	No value stored and not used yet
Line 2 : add x6 , x0, x5	0x00500333	5	5	No value stored and not used yet
Line 3: sub x7, x6, x5	0x405303b3	5	5	0
Line 4: add x7, x6, x7	0x007303b3	5	5	5

E2.2. [2 pts] Try to use larger constants in your program. What is the largest immediate constant you can use with the ALU operations?

$2^{11} - 1 = 2048 - 1 = 2047$

Largest immediate constant = 2047

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After you finish the E2.1 and E2.2 parts, please extend your program with a handful of more instructions to explore the functionality of the Venus simulator. You can refer to the instructions in the **RISC-V Instruction Set Manual** (https://github.com/riscv/riscv-isa-manual/releases/download/Ratified-IMAFDQC/riscv-spec-20191213.pdf).

Locate all integer ALU instructions of RISC-V (below) and explore them using the simulator.

Category	Instruction	Example	Meaning	Comments
Arithmetic	Add	`add x5, x6, x7`	`x5 = x6 + x7`	Three register operands; add
	Subtract	`sub x5, x6, x7`	`x5 = x6 - x7`	Three register operands; subtract
	Add immediate	`addi x5, x6, 20`	`x5 = x6 + 20`	Used to add constants
Logical	And	`and x5, x6, x7`	`x5 = x6 & x7`	Three reg. operands; bit-by-bit AND
	Inclusive or	`or x5, x6, x8`	`x5 = x6 | x8`	Three reg. operands; bit-by-bit OR
	Exclusive or	`xor x5, x6, x9`	`x5 = x6 ^ x9`	Three reg. operands; bit-by-bit XOR
	And immediate	`andi x5, x6, 20`	`x5 = x6 & 20`	Bit-by-bit AND reg. with constant
	Inclusive or immediate	`ori x5, x6, 20`	`x5 = x6 | 20`	Bit-by-bit OR reg. with constant
	Exclusive or immediate	`xori x5, x6, 20`	`x5 = x6 ^ 20`	Bit-by-bit XOR reg. with constant
Shift	Shift left logical	`sll x5, x6, x7`	`x5 = x6 << x7`	Shift left by register
	Shift right logical	`srl x5, x6, x7`	`x5 = x6 >> x7`	Shift right by register
	Shift right arithmetic	`sra x5, x6, x7`	`x5 = x6 >> x7`	Arithmetic shift right by register
	Shift left logical immediate	`slli x5, x6, 3`	`x5 = x6 << 3`	Shift left by immediate
	Shift right logical immediate	`srli x5, x6, 3`	`x5 = x6 >> 3`	Shift right by immediate
	Shift right arithmetic immediate	`srai x5, x6, 3`	`x5 = x6 >> 3`	Arithmetic shift right by immediate

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E2.3. [10 pts] Assume you need to load the 0xdeadbeef immediate constant from the memory address 0x10000018 as shown in the following screenshot. Please write a RISC-V program and explain how you achieve it.


```
lui x11 , 0xDEADC000        //x11 = 0xDEADC000
addi x11,x11,xEEF           // x11 = 0XDEADBEEF
lui x12, 0x10000            //x12 = 0x10000000
addi x12, x12, 0x018        //x12 = 0x10000018
sw x11, 0(x12)              // mem[0x0000018] = 0xDEADBEEF
```

The term deadbeef has to be loaded into a register is the first step. This will be accomplished using instructions lui and addi. Next, the register address 0x0000018 has to be loaded into the temp register. Following this, the next step would be to load 0xdeadbeef immediate constant value to the memory address 0x0000018 with the sw instruction.

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E2.4. [10 pts] Assume we have an array long int* arr = {3,7,6,4,5}. The values in arr store in the memory of 0(x21), 8(x21),…, 32(x21). Convert the following RISC-V code into a C program. (Name the variable yourself if needed. Notice, on 64-bit system, sizeof(int) is 4, sizeof(long int) is 8)

```
ld x5, 16(x21)
addi x6, x0, 3
sll x5, x5, x6
sd x5, 8(x21)
```

```
int main ()
{
        int arr [4] = {3,7,6,4,5};   // array creation
        int value1 = a[2];           // ld x5, 16(x21)



        int value2 = 0 + 3;          // addi x6, 0, 3 value2 = 3
        value1 = value1*8;           // sll x5, x5, x6
        value1 = a[1];               // sd x5, 8(x21)
        print("%d",value1);          // print value1 (print was not in risc v code given but output is needed)
        return 0;
        }
```

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Exercise 3 [35 pts]: Environment Call

The ECALL instruction is used to make a service request to the execution environment, which might require privileged access. The EEI (execution environment interface) will define how parameters for the service request are passed, but usually these will be in the registers. The ECALL is equivalent to int 0x2e, int 0x80, sysenter and syscall in x86 systems.

Venus contains a simulation of low level operating system functions. The functions in Venus have been inspired by the MIPS simulator MARS. Arguments to the system function are passed via the normal argument register x10 and x11, where x10 contains the function code. Explore io.s to print different kinds of information to the output console. You can use this feature to help you debug your code. For more information about Venus' ECALL, please refer to the wiki page: https://github.com/kvakil/venus/wiki/Environmental-Calls

The following environmental calls are currently supported.

ID (`a0`)	Name	Description
1	print_int	prints integer in `a1`
4	print_string	prints the null-terminated string whose address is in `a1`
9	sbrk	allocates `a1` bytes on the heap, returns pointer to start in `a0`
10	exit	ends the program
11	print_character	prints ASCII character in `a1`
17	exit2	ends the program with return code in `a1`

```
# Ecall example (io.s)
addi x10, x0, 1
addi x11, x0, 37
ecall
```

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E3.1. [8 pts] What do you see from the console in the simulator when you run the io.s program? Please explain the purpose of each line in the program.

Line 1: register x10 contains the value of 1

Line 2: register x11 contains the value of 37

Line 3: Ecall will display 37 since its displaying value of x11

Output for Risc V code:

```
int a  = 1;     // x10

int b  =  37;  // x11

printf("%d", b);          // display the value of 37 = x11
```

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E3.2 [12 pts] Please convert the following C program into the RISC-V assembly code equivalent.

```
#include <stdio.h>
int main()
{
int x = 30, y = 17;
printf("x + y = ");
printf("%d\n", x + y);
return 0;
}
```

RISC V CODE:

```
.data
output: .asciiz "X+Y="   // prints output
nextline: .asciiz "\n"      // after output makes a separate line
.text
addi x24, x0, 30           // adds 0 and 30 to x24
addi x25, x0, 17           // adds 0 and 17 to x25
addi x10, x0, 4            // adds 0 and 4 to x10
la x11, output             // loads to prints output

ecall

addi x10, x0, 0           // adds 0 and 0 to x10
addi x11, x0, 0           // adds 0 and 0 to x11
addi x10, x0, 1           // adds 0 and 1 to x10
add x11, x24, x25         // adds x24 and x25 to x11

ecall

addi x10, x0, 0           // adds 0 and 0 to x10
addi x10, x0, 4           // adds 0 and 4 to x10
la x11, nextline          // loads next line instruction

ecall
```

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```
.data
output: .asciiz "X+Y="
nextline: .asciiz "\n"
.text
addi x24, x0, 30
addi x25, x0, 17
addi x10, x0, 4
la x11, output

ecall

addi x10, x0, 0
addi x11, x0, 0
addi x10, x0, 1
add x11, x24, x25

ecall

addi x10, x0, 0
addi x10, x0, 4
la x11, nextline

ecall
```

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E3.3 [15 pts] Please convert the following C program into the RISC-V assembly code.

```
#include <stdio.h>
int main()
{
int a = 23, b = 26, c = 5;
if (a < b)
{
printf("%d\n", c*2);
}
else
{
a = a * 4;
}
b = b * 8;
printf("%d\n", c);
return 0;
}
```

RISC V CODE:

```
.data
nextline: .asciiz "\n"          // after output makes a separate line
.text

# declare the variables a,b,c and assigning values to them

addi x29, x0, 23          // adds 0 and 23 to x29
addi x30, x0, 26          // adds 0 and 26 to x30
addi x8, x0, 5            // adds 0 and 5 to x8
addi x10, x0, 1           // adds 0 and 1 to x10

#conditional statements
```

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```
bge x29, x30, Else        // compares x29 and x30 if true heads to Else loop
slli x6, x8, 1            // shifts x8 by 1 to x6
add x11, x0, x6           // adds 0 and x6 to x11

ecall

addi x10, x10, 3          // adds x10 and 3 to x10
la x11, nextline          // loads next line instruction

ecall

beq x0, x0, Exit          // compares x0 and x0 if true it exits loop

Else:
slli x29, x29, 2          // shifts x29 by 2 to x29
beq x0, x0, Exit          // compares x0 and x0 if true it exits loop

Exit:
slli x7, x7, 3            // shifts x7 by 3 to x7
addi x10, x0,0            // adds 0 and 0 to x10
addi x10, x0, 1           // adds 0 and 1 to x10
addi x11, x0,0            // adds 0 and 0 to x11
addi x11, x0,1            // adds 0 and 1 to x11
add x11, x0, x8           // adds 0 and x8 to x11

ecall

addi x10, x10, 3          // adds x10 and 3 to x10
la x11, nextline          // loads next line instruction

ecall
```

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```
.data
nextline: .asciiz "\n"
.text

# declare the variables a,b,c and assigning values to them

addi x29, x0, 23
addi x30, x0, 26
addi x8, x0, 5
addi x10, x0, 1

#conditional statements

bge x29, x30, Else
slli x6, x8, 1
add x11, x0, x6

ecall

addi x10, x10, 3
la x11, nextline

ecall

beq x0, x0, Exit

Else:
slli x29, x29, 2
beq x0, x0, Exit

Exit:
slli x7, x7, 3
addi x10, x0,0
addi x10, x0, 1
addi x11, x0,0
addi x11, x0,1
add x11, x0, x8

ecall

addi x10, x10, 3
la x11, nextline

ecall

```

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Exercise 4 [25 pts]: Assembler Directives

Beside instructions in assembler format, an assembler also accepts so-called assembler directives. The code start is usually marked with .text. You can initialize data in the data segment with .data. Each assembler instruction can start with a label such as main: or loop:. This label can then be used as destination for a branch instruction. Also, data can be addressed by using a label. See below some examples:

For more information, check: https://github.com/kvakil/venus/wiki/Assembler-Directives

```
.text
main:
addi x10, x0, 4
la x11, hello
ecall
.data
hello:
.asciiz "Hello"
```

E4.1. [5 pts] What happens when you add the following instruction at the end of your program and run the program? Please explain why.

j main

The purpose of the j main in the program is to make the code run multiple times as without j main the code would print out Hello only once but with j main included in the program it would print out Hello in a loop like infinite times. The j instruction is designed to jump to a specified label (such as main in this situation). The instruction executes in an infinite loop hence it prints out Hello infinite times. The program does not terminate unless users terminate it.

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E4.2 [20 pts] Please convert the following C problem into the RISC-V assembly code.

```
#include <stdio.h>


int exercise4 (int a)
{
        int res = 0;
        for (int i = 0; i < a; i++)
        {
                res += i;
        }
        return res;
}

int main (void)
{
        int a = 10;
        int b;

        b = exercise4(a);
        printf("%d\n", b);
}
```

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RISC V CODE:

```
.data
nextline: .asciiz "\n"          // after output makes a separate line
.text
jal x0 main                     // jumps from x0 to main label

Exercise4:
addi x5, x5, -8                 // adds x5 and -8 to x5
sw x29, 0(x0)                   // shifts x0 by 0 to x29
addi x14, x0, 0                 // adds x0 and 0 to x14
addi x6, x0, 0                  // adds x0 and 0 to x6

loop:
ble x9, x29, exit               // compares x9 and x29 if true exits loop
add x14,x14, x29                // adds x14 and x29 to x14
addi x29, x29, 1                // adds x29 and 1 to x29
jal x0, loop                    // jumps from x0 to loop label

main:
addi x9, x0, 10         // adds x0 and 10 to x9
jal x30, Exercise4      // jumps from x30 to Exercise4 label

addi x30,x0,0           // adds x0 and 0 to x30
```

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```
add x27, x0, x14      // adds x0 and x14 to x27
addi x10, x0, 1       // adds x0 and 1 to x10
add x11, x0, x14      // adds x0 and x14 to x11

ecall

addi x10, x10, 3      // adds x10 and 3 to x10
la x11, nextline      // loads next line instruction

ecall

ret                   // return instruction

exit:
addi x5, x5, 8        // adds x5 and 8 to x5
jalr x0, 0(x30)       // jumps from x30 by 0 to x0
```

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```
.data
nextline: .asciiz "\n"
.text
jal x0 main

Exercise4:
addi x5, x5, -8
sw x29, 0(x0)
addi x14, x0, 0
addi x6, x0, 0

loop:
blc x9, x29, exit
add x14,x14, x29
addi x29, x29, 1
jal x0, loop

main:
addi x9, x0, 10
jal x30, Exercise4

addi x30,x0,0
add x27, x0, x14
addi x10, x0, 1
add x11, x0, x14

ecall

addi x10, x10, 3
la x11, nextline

ecall

ret

exit:
addi x5, x5, 8
jalr x0, 0(x30)

```