

San Jose State University
Department of Computer Engineering

CMPE 200 Lab Report

Assignment 4 Report

Title MIPS Instruction Set Architecture & Programming (3)

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Date 10/02/2022

by

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ABOUT THE AUTHOR

I am Saiteja and I am from Hyderabad, India. I completed my bachelors in Electronics and Communication Engineering from Gokaraju Rangaraju Institute of Engineering and Technology with a CGPA of 9.97/10 in the year 2019. I received a Gold Medal for the academic excellence from my university. Right after that, I got an opportunity to work for Tata Consultancy Services as a Systems Engineer and have worked for 3 years until July 2022. I speak English, Hindi, and Telugu where the last of these is my first language. My interests include but not limited to Cricket, Table-Tennis and learning new languages. Currently I am pursuing my master's in Computer Engineering at San Jose State University.

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INTRODUCTION:

This activity is used to design and develop an assembly code to build a 50-entry array with the base address 0x100 in MARS and gain some familiarity on the MIPS implementation of arrays, stacks, procedures, and recursive procedures by logging few selected registers' values and memory content of selected addresses in a table for the given task.

MY GROUP:

Name: Student_Team 6

Members: Tirumala Saiteja Goruganthu (016707210), Harish Marepalli (016707314)

GIVEN TASK:

The task is to write a MIPS assembly program to perform an arithmetic computation on the given array elements by accessing them and use the result as input to find the factorial using the recursive procedure.

Following are the requirements presented for the task:

- The MIPS code should be under the line “#your code goes in here...”
- Register assignments must be $\$a1 \leftarrow n$, $\$a0 \leftarrow \text{array-base-address}$, and $\$s0 \leftarrow n!$
- Your factorial function must be implemented as a recursive procedure.
- The final value of n obtained from the arithmetic calculation must be written to the memory location at address 0x00.
- The factorial n! must be written to the memory location at address 0x10.

STEPS TAKEN TO COMPLETE THE TASK:

- Spent time to understand the given question carefully.
- Imported the given assembly file into the MARS simulator.
- Revised few topics related to arrays, function calls, procedures, and recursive procedures from the power-point presentations discussed in class.
- Edited the file by making changes at the right place according to the given task.
- Assembled the edited code in the MARS simulator and executed each line of the code step-by-step to check the purpose of that line.
- If found some issues, went back to editing the code and re-assembled it again.
- Check if the output is as expected after the program execution.
- If the output has no errors, then proceed by executing each instruction step-by-step and simultaneously taking the log of the contents of the registers.
- This log is finally dumped into the given test log table.
- Finally, snippets are taken to show the current output along with the screenshots of the stack.

TEST LOG:**Programmer's Names:** Tirumala Saiteja Goruganthu**Date:** 10/02/2022

Addr	MIPS Instruction	Machine Code	Registers				Memory Content	
			\$a1	\$sp	\$ra	\$v0	[0x00]	[0x10]
3034	lw \$t0, 100(\$a0)	0x8c880064	0x00000032	0x00002ffc	0x00000000	0x00000000	0x00000000	0x00000000
3038	lw \$t1, 120(\$a0)	0x8c890078	0x00000032	0x00002ffc	0x00000000	0x00000000	0x00000000	0x00000000
303c	add \$t1, \$t0, \$t1	0x01094820	0x00000032	0x00002ffc	0x00000000	0x00000000	0x00000000	0x00000000
3040	addi \$t0, \$0, 30	0x2008001e	0x00000032	0x00002ffc	0x00000000	0x00000000	0x00000000	0x00000000
3044	divu \$t1, \$t0	0x0128001b	0x00000032	0x00002ffc	0x00000000	0x00000000	0x00000000	0x00000000
3048	mflo \$a1	0x00002812	0x00000005	0x00002ffc	0x00000000	0x00000000	0x00000000	0x00000000
304c	sw \$a1, 0(\$0)	0xac050000	0x00000005	0x00002ffc	0x00000000	0x00000000	0x00000005	0x00000000
3050	jal factorial	0x0c000c19	0x00000005	0x00002ffc	0x00003054	0x00000000	0x00000005	0x00000000
3054	add \$s0, \$v0, \$0	0x00408020	0x00000005	0x00002ffc	0x00003054	0x00000078	0x00000005	0x00000000
3058	sw \$s0, 16(\$0)	0xac100010	0x00000005	0x00002ffc	0x00003054	0x00000078	0x00000005	0x00000078
305c	li \$v0, 10	0x2402000a	0x00000005	0x00002ffc	0x00003054	0x0000000a	0x00000005	0x00000078
3060	syscall	0x0000000c	0x00000005	0x00002ffc	0x00003054	0x0000000a	0x00000005	0x00000078
3064	addi \$sp, \$sp, -8	0x23bdfff8	0x00000001	0x00002fd4	0x00003090	0x00000000	0x00000005	0x00000000
3068	sw \$a1, 4(\$sp)	0xaf500004	0x00000001	0x00002fd4	0x00003090	0x00000000	0x00000005	0x00000000
306c	sw \$ra, 0(\$sp)	0xafbf0000	0x00000001	0x00002fd4	0x00003090	0x00000000	0x00000005	0x00000000
3070	addi \$t0, \$0, 2	0x20080002	0x00000001	0x00002fd4	0x00003090	0x00000000	0x00000005	0x00000000
3074	slt \$t0, \$a1, \$t0	0x00a8402a	0x00000001	0x00002fd4	0x00003090	0x00000000	0x00000005	0x00000000
3078	beq \$t0, \$0, else	0x11000003	0x00000001	0x00002fd4	0x00003090	0x00000000	0x00000005	0x00000000
307c	addi \$v0, \$0, 1	0x20020001	0x00000001	0x00002fd4	0x00003090	0x00000001	0x00000005	0x00000000
3080	addi \$sp, \$sp, 8	0x23bd0008	0x00000001	0x00002fdc	0x00003090	0x00000001	0x00000005	0x00000000
3084	jr \$ra	0x03e00008	0x00000001	0x00002fdc	0x00003090	0x00000001	0x00000005	0x00000000
3088	addi \$a1, \$a1, -1	0x20a5ffff	0x00000001	0x00002fdc	0x00003090	0x00000000	0x00000005	0x00000000
308c	jal factorial	0x0c000c19	0x00000001	0x00002fdc	0x00003090	0x00000000	0x00000005	0x00000000
3090	lw \$ra, 0(\$sp)	0x8fbf0000	0x00000004	0x00002ff4	0x00003054	0x00000018	0x00000005	0x00000000
3094	lw \$a1, 4(\$sp)	0x8fa50004	0x00000005	0x00002ff4	0x00003054	0x00000018	0x00000005	0x00000000
3098	addi \$sp, \$sp, 8	0x23bd0008	0x00000005	0x00002ffc	0x00003054	0x00000018	0x00000005	0x00000000
309c	mul \$v0, \$a1, \$v0	0x70a21002	0x00000005	0x00002ffc	0x00003054	0x00000078	0x00000005	0x00000000
30a0	jr \$ra	0x03e00008	0x00000005	0x00002ffc	0x00003054	0x00000078	0x00000005	0x00000000
30a4								

SCREEN CAPTURES:

- a. Final assembly code in the MARS editor (*Fig6.a*).

```

lab4.asm
1  # $a0 = array base address
2  # $a1 = n
3  # $s0 = n!
4
5  Main:
6      addi $a0, $0, 0x100      # array base address = 0x100
7      addi $a1, $0, 0          # i = 0
8      addi $t0, $0, 3
9      addi $t1, $0, 50         # $t1 = 50
10
11  CreateArray_Loop:
12      slt $t2, $a1, $t1        # i < 50?
13      beq $t2, $0, Exit_Loop   # if not then exit loop
14      sll $t2, $a1, 2          # $t2 = i * 4 (byte offset)
15      add $t2, $t2, $a0        # address of array[i]
16      mult $a1, $t0           # $t3 = i * 3
17      mflo $t3                # save array[i]
18      addi $a1, $a1, 1         # i = i + 1
19      j CreateArray_Loop
20
21  Exit_Loop:
22      # your code goes in here...
23      # arithmetic calculation
24      lw $t0, 100($a0)         #load my_array[25] in $t0 i.e., regaddr = baseaddr + (index)*4 and relative movement is 100
25      lw $t1, 120($a0)         #load my_array[30] in $t1 i.e., regaddr = baseaddr + (index)*4 and relative movement is 120
26      add $t0, $t0, $t1        #add $t0 and $t1 contents
27      addi $t0, $t0, 30        #initialise $t0 to 30
28      divu $t1, $t0            #divide the above added result with $t0($30)
29
30

```

Registers window (Registers, Coproc 1, Coproc 0):

Name	Number	Value
\$zero	0	0x00000000
\$at	1	0x00000000
\$v0	2	0x00000000
\$v1	3	0x00000000
\$a0	4	0x00000000
\$a1	5	0x00000000
\$a2	6	0x00000000
\$t0	8	0x00000000
\$t1	9	0x00000000
\$t2	10	0x00000000
\$t3	11	0x00000000
\$t4	12	0x00000000
\$t5	13	0x00000000
\$t6	14	0x00000000
\$t7	15	0x00000000
\$s0	16	0x00000000
\$s1	17	0x00000000
\$s2	18	0x00000000
\$s3	19	0x00000000
\$s4	20	0x00000000
\$s5	21	0x00000000
\$s6	22	0x00000000
\$s7	23	0x00000000
\$s8	24	0x00000000
\$s9	25	0x00000000
\$k0	26	0x00000000
\$k1	27	0x00000000
\$gp	28	0x00000000
\$fp	29	0x00000000
\$ra	31	0x00000000
\$lo		0x00000000

Fig6.a – Snippet of the Final assembly code in the MARS editor

- b. Register and memory contents before execution of the program (*Fig6.b*).

Registers window (Registers, Coproc 1, Coproc 0):

Name	Number	Value
\$zero	0	0x00000000
\$at	1	0x00000000
\$v0	2	0x00000000
\$v1	3	0x00000000
\$a0	4	0x00000000
\$a1	5	0x00000000
\$a2	6	0x00000000
\$t0	8	0x00000000
\$t1	9	0x00000000
\$t2	10	0x00000000
\$t3	11	0x00000000
\$t4	12	0x00000000
\$t5	13	0x00000000
\$t6	14	0x00000000
\$t7	15	0x00000000
\$s0	16	0x00000000
\$s1	17	0x00000000
\$s2	18	0x00000000
\$s3	19	0x00000000
\$s4	20	0x00000000
\$s5	21	0x00000000
\$s6	22	0x00000000
\$s7	23	0x00000000
\$s8	24	0x00000000
\$s9	25	0x00000000
\$k0	26	0x00000000
\$k1	27	0x00000000
\$gp	28	0x00000000
\$fp	29	0x00000000
\$ra	31	0x00000000
\$lo		0x00000000

Data Segment window:

Address	Value (+0)	Value (+4)	Value (+8)	Value (+C)	Value (+10)	Value (+14)	Value (+18)	Value (+1C)
0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000004	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000008	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000000C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000010	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000014	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000018	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000001C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000020	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000024	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000028	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000002C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000030	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000034	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000038	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000003C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000040	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000044	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000048	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000004C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000050	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000054	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000058	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000005C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000060	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000064	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000068	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000006C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000070	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000074	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000078	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000007C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000080	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000084	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000088	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000008C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000090	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000094	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000098	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x0000009C	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000A0	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000A4	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000A8	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000AC	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000B0	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000B4	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000B8	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000BC	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000C0	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000C4	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000C8	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000CC	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000D0	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000D4	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000D8	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000DC	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000E0	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000E4	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000E8	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000EC	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000F0	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000F4	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000F8	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x000000FC	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000100	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000	0x00000000
0x00000104	0x00000000	0x00000000						

- c. Register and memory contents after execution of the program (highlighted are the desired outputs in *Fig6.c*).

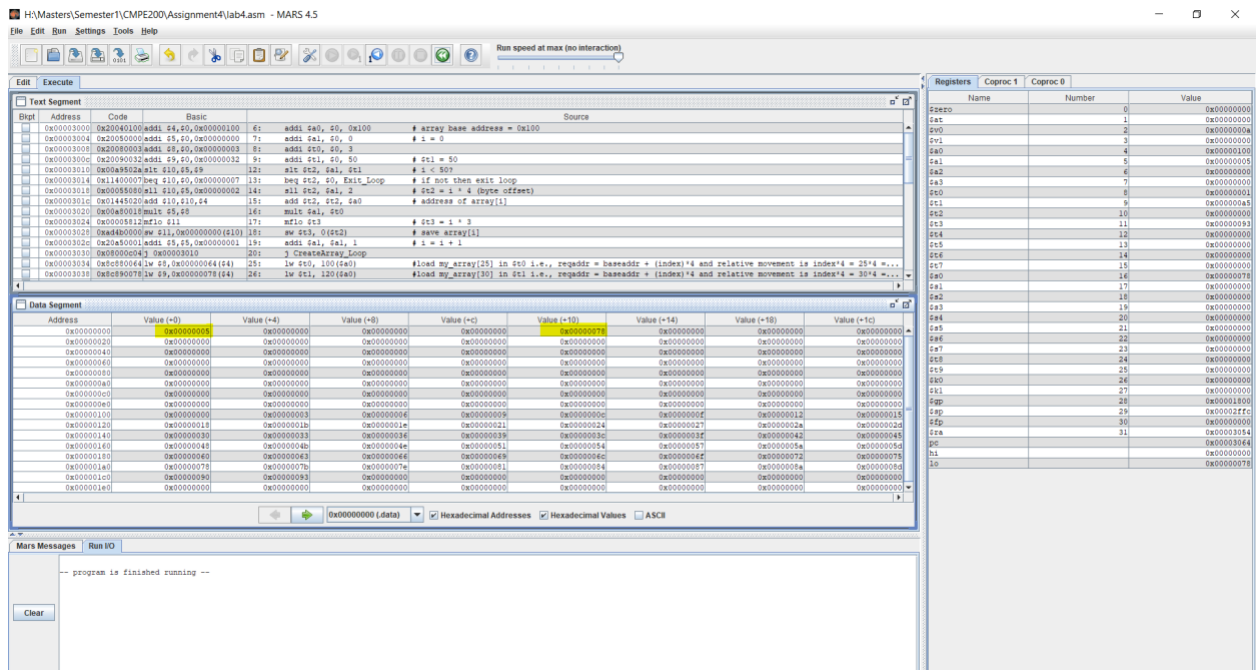


Fig6.c – Snippet of the register and memory contents after execution of the program

- d. Stack memory contents after the execution of the program (*Fig6.d*).

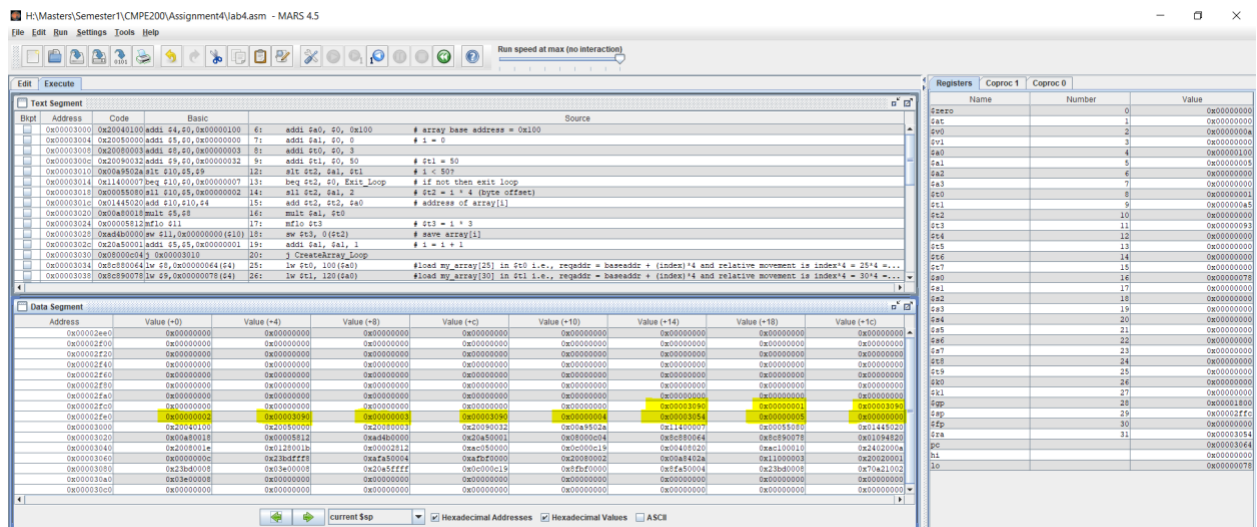


Fig6.d – Snippet of the stack memory after execution of the program

DISCUSSION SECTION:

Following is the explanation behind the arithmetic calculation of the given array elements:

- Since we are talking about the integer arrays, each integer in the array occupies 4 bytes.
- To access the array element at the index 25, we need to use the load word (lw) instruction by pointing to the correct index.
- In general, the target address is calculated using the below formula

Target Address = Base Address + Relative value

Where Relative value = (Index)(Size of the object)*

In our case,

the size of the integer object is 4 bytes

Index is 25

Base address is 0x100

Therefore,

Target Address = $(0x100)_h + (25*4)_d$

$\Rightarrow (0x100)_h + (0x64)_h$

$\Rightarrow (0x164)_h$

- But, while writing the lw instruction, we need to specify the increment/decrement in decimal form relative to the base address. So, we need to calculate only the relative value for the purpose of writing the code.
i.e., relative value = $25*4 = 100$
 $\Rightarrow \text{lw } \$t0, 100(\$a0)$ where \$a0 contains the base address.

Following are the observations with respect to the stack when executing the recursive part of the final assembly code:

- When $n = 5$, the stack memory is as follows

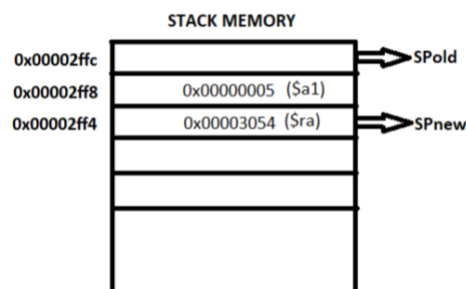


Fig7.a – Stack memory with n=5 case

	0x0000304c	0xac050000	sw \$5,0x00000000(\$0)	31: sw \$a1, 0(\$0)
	0x00003050	0xc000c19	jal 0x00003064	33: jal factorial
	0x00003054	0x00408020	add \$16,\$2,\$0	34: add \$s0, \$v0, \$0
	0x00003058	0xac100010	sw \$16,0x00000010(\$0)	35: sw \$s0, 16(\$0)
	0x0000305c	0x2402000a	addiu \$2,\$0,0x0000000a	36: li \$v0, 10

\$ra (handwritten) with an arrow pointing to the highlighted row (0x00003054).

Fig7.b – Highlighted return address is stored in the stack (n=5 case)

Recursive functions must store their input parameters and return addresses to the stack because all the recursion iterations will try to the same registers for all operations. Hence, in the *Fig7.a*, the stack pointer is incremented down two memory locations which are used to store the input value (n) and return address (\$ra). In the given task, the input value is 0x00000005 and the return address (0x00003054) is shown in the *Fig7.b*.

- b. When n=4 , the stack memory is as follows

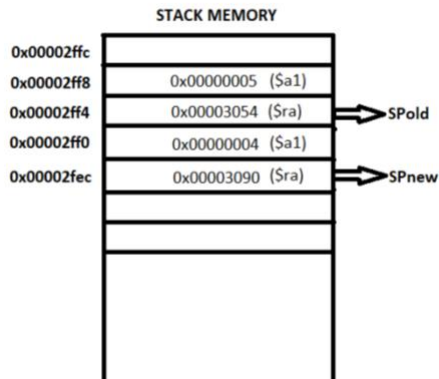


Fig7.c – Stack memory with n=4 case

	0x00003088	0x20a5ffff	addi \$5,\$5,0xffffffff	51: addi \$a1, \$a1, -1
	0x0000308c	0xc000c19	jal 0x00003064	52: jal factorial
	0x00003090	0x8fbf0000	lw \$31,0x00000000(\$29)	53: lw \$ra, 0(\$sp)
	0x00003094	0x8fa50004	lw \$5,0x00000004(\$29)	54: lw \$a1, 4(\$sp)
	0x00003098	0x23bd0008	addi \$29,\$29,0x0000...	55: addi \$sp, \$sp, 8

\$ra (handwritten) with an arrow pointing to the highlighted row (0x00003090).

Fig7.d – Highlighted return address is stored in the stack (n=4 case)

In the next iteration of the recursion, the updated input parameter and the return address will be stored by again incrementing the stack pointer to create two new memory locations. As shown in the *Fig7.c*, the old stack pointer (SP_{old}) is incremented to the new stack pointer (SP_{new}) from the address 0x00002ff4 to address 0x00002fec. One of the new locations will store the updated input parameter (0x00000004) and the other location will store the return address (0x00003090) as shown in *Fig7.d*.

- c. When $n=3$, the stack memory will be as follows

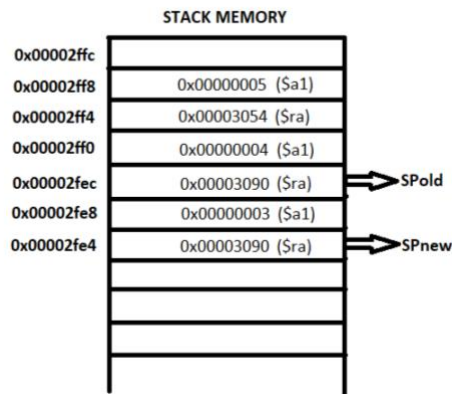


Fig7.e – Stack memory in $n=3$ case

<input type="checkbox"/>	0x00003088	0x20a5ffff	addi \$5,\$5,0xffffffff	51: addi \$a1, \$a1, -1
<input type="checkbox"/>	0x0000308c	0x0c000c19	jal 0x00003064	52: jal factorial
<input type="checkbox"/>	0x00003090	0x8fbf0000	lw \$31,0x00000000(\$29)	53: lw \$ra, 0(\$sp)
<input type="checkbox"/>	0x00003094	0x8fa50004	lw \$5,0x00000004(\$29)	54: lw \$a1, 4(\$sp)
<input type="checkbox"/>	0x00003098	0x23bd0008	addi \$29,\$29,0x0000...	55: addi \$sp, \$sp, 8

Handwritten: \$ra with an arrow pointing to the highlighted row (0x00003090).

Fig7.f – Highlighted return address is stored in the stack ($n=3$ case)

In the next iteration of the recursion, the updated input parameter and the return address will be stored by again incrementing the stack pointer to create two new memory locations. As shown in the *Fig7.e*, the old stack pointer (SP_{old}) is incremented to the new stack pointer (SP_{new}) from the address 0x00002fec to address 0x00002fe4. One of the new locations will store the updated input parameter (0x00000003) and the other location will store the return address (0x00003090) as shown in *Fig7.f*.

- d. When $n=2$, the stack memory is as follows

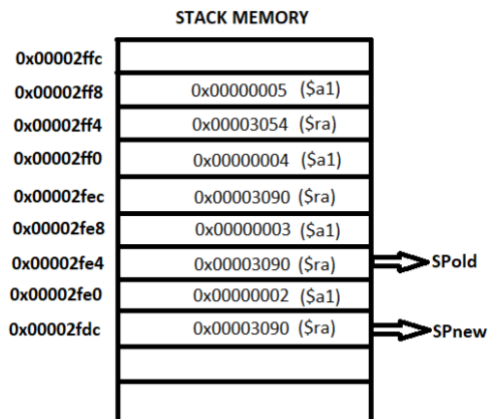


Fig7.g – Stack memory in $n=2$ case

	0x00003088	0x20a5ffff	addi \$5,\$5,0xffffffff	51: addi \$al, \$al, -1
	0x0000308c	0x0c000c19	jal 0x00003064	52: jal factorial
	0x00003090	0x8fbf0000	lw \$31,0x00000000(\$29)	53: lw \$ra, 0(\$sp)
	0x00003094	0x8fa50004	lw \$5,0x00000004(\$29)	54: lw \$al, 4(\$sp)
	0x00003098	0x23bd0008	addi \$29,\$29,0x0000...	55: addi \$sp, \$sp, 8

\$ra

Fig7.h – Highlighted return address is stored in the stack (n=2 case)

In the next iteration of the recursion, the updated input parameter and the return address will be stored by again incrementing the stack pointer to create two new memory locations. As shown in the *Fig7.g*, the old stack pointer (SP_{old}) is incremented to the new stack pointer (SP_{new}) from the address 0x00002fe4 to address 0x00002fdc. One of the new locations will store the updated input parameter (0x00000002) and the other location will store the return address (0x00003090) as shown in *Fig7.h*.

- e. When $n=1$, the stack memory is as follows

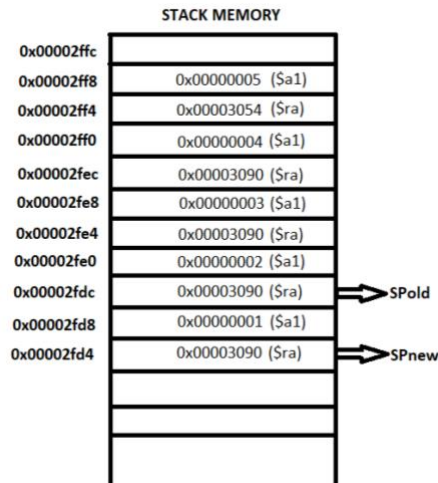


Fig7.i – Stack memory in n=1 case

	0x00003088	0x20a5ffff	addi \$5,\$5,0xffffffff	51: addi \$al, \$al, -1
	0x0000308c	0x0c000c19	jal 0x00003064	52: jal factorial
	0x00003090	0x8fbf0000	lw \$31,0x00000000(\$29)	53: lw \$ra, 0(\$sp)
	0x00003094	0x8fa50004	lw \$5,0x00000004(\$29)	54: lw \$al, 4(\$sp)
	0x00003098	0x23bd0008	addi \$29,\$29,0x0000...	55: addi \$sp, \$sp, 8

\$ra

Fig7.j – Highlighted return address is stored in the stack (n=1 case)

In the next iteration of the recursion, the updated input parameter and the return address will be stored by again incrementing the stack pointer to create two new memory locations. As shown in the *Fig7.i*, the old stack pointer (SP_{old}) is incremented to the new stack pointer (SP_{new}) from the address 0x00002fdc to address 0x00002fd4. One of the new locations will store the updated input parameter (0x00000001) and the other location will store the return address (0x00003090) as shown in *Fig7.j*.

- f. When $n=0$, two more locations are allocated, but due to the $n \geq 1$ condition failure, these two locations are again deallocated.
- g. After the deallocation, the `jr $ra` instruction is executed recursively backwards where the input parameter (n) and the return address (`$ra`) are popped out of the stack with each iteration and the n is multiplied with the current iterative value i.e., $(n-1)$. Similarly, all the n and `$ra` pairs are popped out of the stack and the deallocation of the stack is done using the stack pointer.
Therefore, the factorial is $\Rightarrow n*(n-1)*(n-2)*\dots 1$ stored in `$v0` register.
- h. Finally, the factorial value is copied into `$a0` register and into the memory location `0x10` according to the given requirement.

COLLABORATION SECTION:

1. For the given C++ pseudo code, developed corresponding assembly codes in the MARS software by collaborating with each other.
2. Worked together to execute the code and to observe all the operations and values.
3. Collaborated in understanding the concepts such as arrays, stacks, procedures along with the recursive procedures and discussed and realized few basics of recursion, stack pointer register (`$sp`).
4. By working together, we debugged each line to know the contents of the relevant registers and recorded the memory values at certain addresses in the test log table.

CONCLUSION:

In conclusion, we end the report by understanding the arrays, accessing arrays using MIPS assembly, procedures such as function calls, nested function calls, and finally the recursive procedure by taking factorial program as an example. We also gained insight into the concept of jump and link (`jal`) and jump return (`jr`) instructions along with the usage of the stack pointer register (`$sp`).

APPENDIX:

The source code of the given task is as follows

```
# $a0 = array base address
# $a1 = n
# $s0 = n!
```

Main:

```
addi $a0, $0, 0x100    # array base address = 0x100
addi $a1, $0, 0        # i = 0
addi $t0, $0, 3        # initialize $t0 to 3
addi $t1, $0, 50       # $t1 = 50
```

CreateArray_Loop:

```
slt $t2, $a1, $t1      # i < 50?
beq $t2, $0, Exit_Loop # if not then exit loop
sll $t2, $a1, 2        # $t2 = i * 4 (byte offset)
add $t2, $t2, $a0      # address of array[i]
mult $a1, $t0
mflo $t3               # $t3 = i * 3
sw $t3, 0($t2)         # save array[i]
addi $a1, $a1, 1       # i = i + 1
j CreateArray_Loop
```

Exit_Loop:

your code goes in here...

arithmetic calculation

```
lw $t0, 100($a0)       #load my_array[25] in $t0 i.e., reqaddr = baseaddr + (index)*4
                        #and relative movement is index*4 = 25*4 = 100
```

```
lw $t1, 120($a0)       #load my_array[30] in $t1 i.e., reqaddr = baseaddr + (index)*4
                        #and relative movement is index*4 = 30*4 = 120
```

```
add $t1, $t0, $t1      #add $t0 and $t1 contents
```

```
addi $t0, $0, 30       #initialize $t0 to 30
```

```
divu $t1, $t0          #divide the above added result with $t0(30)
```

```
mflo $a1               #capture the quotient from $lo to $a1
```

```
sw $a1, 0($0)          #store the content of $a1 (n) at 0x00 location
```

factorial computation

```
jal factorial          # call procedure
```

```
add $s0, $v0, $0       # return value
```

```
sw $s0, 16($0)         #store the content of $s0 (n!) at 0x10 location
```

```
li $v0, 10             #load the $v0 register with value 10
```

```
syscall               #call the syscall to exit the program
```

factorial:

<i>addi \$sp, \$sp, -8</i>	<i># make room on the stack</i>
<i>sw \$a1, 4(\$sp)</i>	<i># store \$a1</i>
<i>sw \$ra, 0(\$sp)</i>	<i># store \$ra</i>
<i># your code goes in here</i>	
<i>addi \$t0, \$0, 2</i>	<i>#initialize \$t0 to 2</i>
<i>slt \$t0, \$a1, \$t0</i>	<i>#check for $n < 2 \Rightarrow n \leq 1$</i>
<i>beq \$t0, \$0, else</i>	<i>#branch to label 'else' if above condition is false</i>
<i>addi \$v0, \$0, 1</i>	<i>#initialize \$v0 to 1</i>
<i>addi \$sp, \$sp, 8</i>	<i>#deallocate the stack</i>
<i>jr \$ra</i>	<i>#jump to the caller using \$ra</i>

else:

<i>addi \$a1, \$a1, -1</i>	<i>#decrement the n value</i>
<i>jal factorial</i>	<i>#recursive call to the label 'factorial'</i>
<i>lw \$ra, 0(\$sp)</i>	<i>#recursively load back the return address from stack</i>
<i>lw \$a1, 4(\$sp)</i>	<i>#recursively load back the n value from stack</i>
<i>addi \$sp, \$sp, 8</i>	<i>#recursively deallocate the stack memory</i>
<i>mul \$v0, \$a1, \$v0</i>	<i>#recursively multiply the n value to its previous value i.e., $(n-1)$</i>
<i>jr \$ra</i>	<i>#jump to the caller using \$ra</i>