



LABORATORY MANUAL

CE/CZ1106
Computer Organization and Architecture

Lab Experiment #2

Modular Programming using VisUAL

by
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SEMESTER 2

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1. **OBJECTIVES**

- 1.1 Understand the concepts of modular programming and the use of subroutines for implementing program modules.
- 1.2 Understand how the stack is used to implement subroutine calls.
- 1.3 Understand the different techniques for passing parameters to a subroutine.

2. **LABORATORY**

This experiment is conducted at the **Hardware Lab 2** at N4-01b-05 (Tel: 67905036).

3. **EQUIPMENT**

3.1 **Hardware**

- Personal Computer with any operating system.

3.2 **Software / User Manuals**

- VisUAL simulator software (<https://salmanarif.bitbucket.io/visual/>)
- Supported instructions in VisUAL

4. **INTRODUCTION**

Good programming techniques dictate that programs be **modular** for **ease of debugging and testing**. Each module or subroutine performs a concisely defined function, which can be called from a main program when needed. The ARM processor provides support for modular programming through. There are three general ways to pass parameters to a subroutine and they are:

- **using registers**
- **using memory block**
- **using the stack**

In this experiment, you will execute ARM assembly language programs that will illustrate how these three parameter-passing techniques can be implemented. For each example, a subroutine call **Mean** will be implemented to add the values in two 32-bit memory variables (**Num1** and **Num2**). The sum is then **divided by 2** to obtain the mean value (remainder is ignored). The result of the 32-bit mean value is to be stored into another memory variable (**Result**). The memory variables **Num1**, **Num2** and **Result** are at **addresses 0x100, 0x104 and 0x108** respective and they are only known to the calling program.

You will also observe in these examples, the two types of parameters that can be passed to a subroutine, namely **passing by value** and **passing by reference**. You will also be given an opportunity to modify a subroutine to ensure that it can be used in a **transparent manner** by a calling program. In other words, using this transparent subroutine will not cause any unintended side-effects in the calling program due to changes in the content of shared registers.

4.1 **Notations used in this manual**

0x20 is used to specify a 32-bit **hexadecimal (hex)** value of 00000020₁₆.

5. EXPERIMENT

5.1 Passing parameters using registers

The first assembly language program (see Figure 1) shows how the values at two variables stored at addresses 0x100 and 0x104 (**Num1** and **Num2**) are passed to the subroutine **Mean** using registers. The result, passed out via a register, is then copied to memory variable (**Result**) at address 0x108.

```

;Calling Program
  ADR R0, Num1
  ADR R1, Num2
  ADR R2, Result      ; setup registers with values
  ADR SP, 0xFFFFF0FC ; (a) initialize Stack Pointer (SP) to top of memory
  LDR R0, [R0]         ; (b) move value of Num1 stored at 0x100 into R0
  LDR R1, [R1]         ; (c) move value of Num2 stored at 0x104 into R1
  BL Mean              ; (d) call subroutine Mean
  STR R1, [R2]         ; move result of mean to memory var at 0x108
  END                  ; Stop emulation

;Subroutine Mean
Mean  ADD  R1, R0, R1   ; add the two parameters in R0 and R1
      ASR  R1, R1, #1   ; divide-by-2 using arithmetic shift right by 1 bit
      MOV  PC, LR       ; return to calling program

```

Figure 1 – The program for passing parameters by registers.

5.1.1 First run up the Visual emulator.

5.1.2 **Type in program** - Enter the mnemonics for the program given in Figure 1. In order to save time, you may want to leave out the comments (i.e. text after the “;” symbol) as they are not necessary for the execution of these instructions. You may want to use the “**Lab2-template**” as it has some memory locations initialized with useful values.

5.1.3 **Initializing the stack pointer (SP)** – Why do you think the stack pointer was initialized to start at the highest memory address 0xFFFFF0FC?

To maximise its possible size since it grows towards a lower memory address

5.1.4 **Parameter passing** – In order to pass the parameters via the registers, the values of **Num1** and **Num2** stored in memory address 0x100 and 0x104 respectively, must be copied to the registers. Likewise, any result passed out by the subroutine via a register needs to be copied to the memory variable **Result** after returning from the subroutine.

(a) Which two registers are being used to pass the parameters to subroutine **Mean**?

R0 and R1

(b) Which register is used to pass out the result to the calling program?

R1

(c) Which other register is well known to return values from subroutine?

LR

5.1.6 **Returning from subroutine** – In order to return to the calling program, the **MOV PC, LR** instruction makes use of link register. Using Figure 2, fill in the contents of the **PC** and **LR** before and immediate after the execution of the **MOV PC, LR** instruction.

(a) Has the **stack** has been affected in anyway by the execution of the **MOV PC, LR** instruction?

no

(b) What has been **copied into the PC** after executing the **MOV PC, LR** instruction? With this **PC** content, which instruction do you think will be **executed next**?

Address of the next instruction after BL Mean, stored in LR. STR R1, [R2]

PC =

0x30

LR =

0x1C

Before executing MOV PC, LR

PC =

0x24

LR =

0x1C

After executing MOV PC, LR

Figure 2 - Program counter and LR the MOV PC, LR instruction.

5.2 Passing parameters using memory block

Another method of passing parameters to a subroutine uses a parameter block. A parameter block is a set of **contiguous memory locations containing the parameters**. The **parameters to be passed** can be stored in this block of memory before calling the subroutine and subsequently retrieved from the same block whilst within the subroutine. Since memory is being used, the **number of parameters passed can be numerous and not limited by the available registers**. The program shown in Figure 4 illustrates how a memory block can be used to pass parameters to a subroutine.

;Calling Program

```
ADR SP, 0xFFFFF000 ; initialize Stack Pointer (SP) to top of memory
MOV R0, #0x100      ; (a) move start address of memory block into R0
BL Mean              ; call subroutine Mean
END                  ; End the program
```

;Subroutine Mean

```
Mean LDR R1, [R0]      ; (b) Load value in Num1 into R1
      LDR R2, [R0, #4] ; (c) Load Num2 in R2
      ADD R1, R1, R2    ; Add R2 to R1
      ASR R1, R1, #1    ; divide-by-2 using arithmetic shift right by 1 bit
      STR R1, [R0, #8] ; (d) move result in R1 into memory variable Result
      MOV PC, LR        ; return to calling program
```

Figure 3 – The program for passing parameters using a memory block.

5.2.1 **Type in program** - Enter the mnemonics for the program given in Figure 3. In order to save time, you may want to leave out the comments.

5.2.2 **The memory block** – Using Figure 4(a), draw the contents of the memory block before the start of program execution.

Note: Click the **View memory contents** button on the **Tools** in VISUAL to see the contents in Data Memory.

- 5.2.3 **Base address of memory block** – In order for the subroutine to be able to retrieve parameters stored in the memory block, the base address (i.e. start address) of the memory block must be conveyed to the subroutine.

By observing instruction (a) in Figure 3, describe how the base address of the memory block is passed to the subroutine **Mean**.

Immediate addressing

- 5.2.4 **Retrieving parameters from memory block** – Based on the instructions (b) and (c) in Figure 3, what addressing mode is used to retrieve the values of **Num1** and **Num2** from the memory block? Use a different addressing mode to retrieve the values

Register Indirect, Register indirect with offset

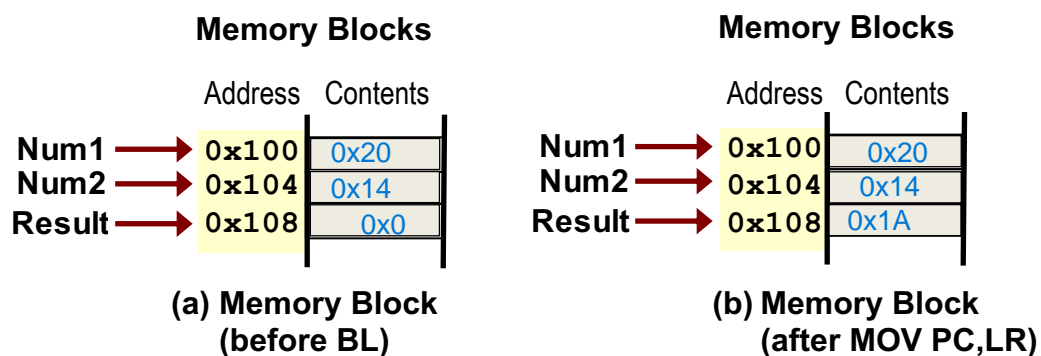


Figure 4 – The contents in the memory block (a) before calling the subroutine **Mean** and (b) after returning from the subroutine.

- 5.2.5 **Returning the result to the calling program** – By observing instruction (d) in Figure 3, describe how the result of the mean value computed within the subroutine **Mean** is returned to the calling program.

(a) Using Figure 4(b), draw the contents of the memory block immediately after execution the **MOV PC, LR** instruction.

(b) Has the correct mean value been updated into the memory variable **Result** in address 0x108?

yes



With reference to the program in Figure 3, would you say the parameters were passed by value or passed by reference? (Hint: see section 5.3)

Passed by value

5.3 Passing parameters using the stack

The most general method of passing parameters to a subroutine is by using the stack. The parameters to be passed can be **pushed** onto the stack before calling the subroutine and subsequently retrieved from the stack whilst within the subroutine. Since a system stack is accessed via a **stack pointer (SP)**, there is **no need to pass the start address of a memory block to the subroutine**. The **number of parameters that can be passed is only limited by the maximum size of the system stack**. The program shown in Figure 6 illustrates how the stack can be used to pass parameters to a subroutine.

In this example, the two numbers (**Num1** and **Num2**) whose mean is to be computed is passed by **value** (i.e. actual values stored in these memory variables are passed to the subroutine). In order to get the subroutine to directly update the result into memory variable **Result** at address 0x108, the variable **Result** is **passed by reference** (i.e. the address of the variable is passed to the subroutine).

```

;Calling Program
    ADR SP, 0xFFFFF0FC ; initialize Stack Pointer (SP) to top of memory
    MOV R0, #0x100      ;
    LDR R1, [R0], #4
    STR R1, [SP, #-4] ! ; (a) push value at memory variable Num1 to stack
    LDR R1, [R0], #4
    STR R1, [SP, #-4] ! ; (b) push value at memory variable Num2 to stack
    STR R0, [SP, #-4] ! ; (c) push address at memory variable Result to stack
    BL Mean              ; call subroutine Mean
    ADD SP, SP, #12      ; (h) remove the 3 parameters push to the stack earlier
    END                  ; Stop emulation

;Subroutine Mean
Mean    LDR R0, [SP, #8] ; (d) move value of Num1 that is on the stack into R0
        LDR R1, [SP, #4] ; (e) move value of Num2 that is on the stack to R1
        ADD R0, R0, R1   ; Add R1 to R0
        ASR R0, R0, #1   ; divide-by-2 using arithmetic shift right by 1 bit
        LDR R2, [SP]     ; (f) move address of Result that is on the stack into R2
        STR R0, [R2]     ; (g) move result in R0 into memory variable Result
        MOV PC, LR       ; return to calling program

```

Figure 5 – The program for passing parameters using the stack.

5.3.1 **Type in program** - Enter the mnemonics for the program given in Figure 5. In order to save time, you may want to leave out the comments.

5.3.2 **Parameters on the stack** – Reset the **PC** to that start of the program and single step through the program till you reach instruction (d) in Figure 5. Using Figure 6, fill in all the known items on the stack. Label these items with appropriate names such as **Num1**, **Num2**, and address of **Result**. Also indicate where **SP** is currently pointing to. Modify the caller to push all results, in their right sequence, to the stack in a single instruction.

STMFD SP!,{R0-R2}

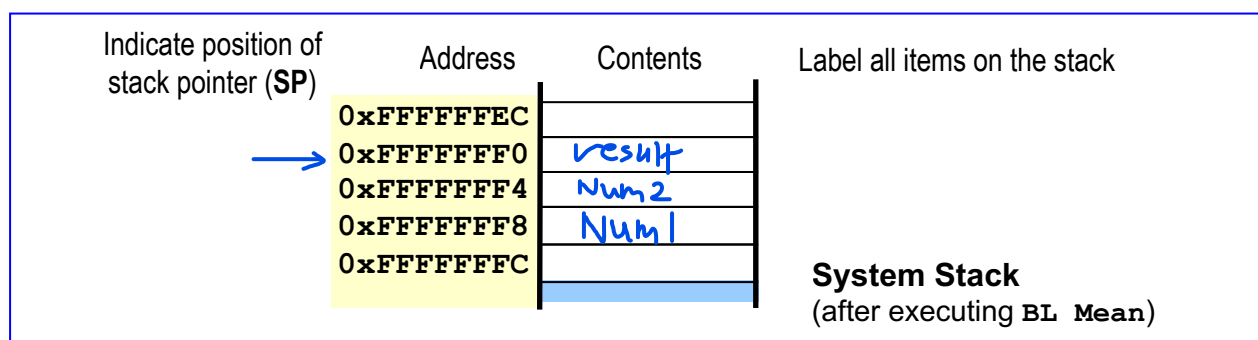


Figure 6 – The items on the system stack just after entering subroutine Mean.

5.3.3 Assessing parameters on the stack – Continue to step through instructions (d) to (g) in Figure 5 as you answer the following questions:

- (a) What type of addressing mode is used to access the value of **Num1** and **Num2** that was pushed to the stack earlier in the calling program?

Register Indirect with Offset

- (b) Using the Figure 6 that you have filled in with the items on the stack, explain why the offsets values 8 and 4 were used to fetch the value of **Num1** and **Num2** on the stack respectively?

Num1 and Num2 are on a higher memory address from SP, separated by 4 bytes each

- (c) Describe what instructions (f) and (g) do? What item is being assessed from the stack and how is this item used to return the result calling program? Can we use fewer registers than R0-R2?

They get the address of R2 so the result can be stored in it. R1 can be used instead of R2

5.3.4 Removing parameters from the stack after subroutine call – Identify which instruction in Figure 5 was used to perform the necessary housekeeping of getting rid of parameters that were pushed to the stack when they are no longer needed.

ADD SP,SP,#12

- (a) Describe why this instruction is equivalent to the operation of popping off the 3 items that was pushed to the stack before the subroutine?

It returns the stack pointer to the original address so the lower memory address can be reassigned values

- (b) What would happen if parameters were repeatedly pushed to the stack before subroutine calls but not removed from the stack after returning from the subroutine?

It will cause stack overflow when the stack runs out of space.

5.4 Writing a transparent subroutine

An important characteristic of a subroutine is that it should be **transparent**. In other words, it does not affect the proper execution of a program after it has been called within the program. One way of achieving transparency is to ensure that before one exits the subroutine, all registers used within the subroutine (except the register used to pass out the result) are restored with the original contents they had just before entering the subroutine.

The **STMFD** and **LDMFD** instructions can be used to efficiently save all used registers to the stack on entry, and restore them before returning from the subroutine.

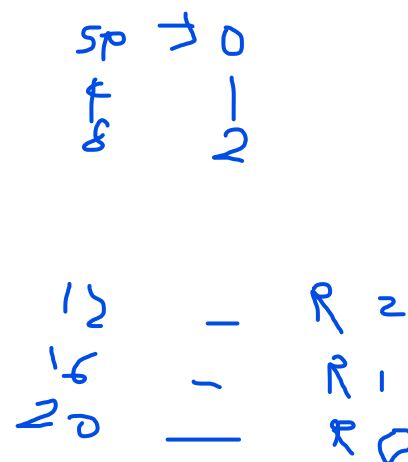
Modify the subroutine **Mean** in Figure 6 to save away registers **R0**, **R1**, and **R2** to the stack on entry into the subroutine and then restore their original values from the stack just before executing the **MOV PC, LR** instruction. Do note that additional items have been pushed to the stack when you carry out this operation. Think carefully about what **new offset values** (i.e. instructions (d), (e) and (f) in Figure 5) are required to correctly access the stack-based parameters **Num1**, **Num2** and address of **Result** as there are now additional items on the stack.

Step through your modified program to verify that your subroutine still works correctly and the values of **R0** and **R1** and **R2** before and after your subroutine call remains unchanged.

```
Mean  STMFD SP!,{R0-R2,LR}
      LDR R0,[SP,#20]
      LDR R1,[SP,#16]
      LDR R2,[SP,#12]

      ADD R0,R0,R1
      ASR R0,R0,#1
      STR R0,[R2]

      LDMFD SP!,{R0-R2}
      MOV PC,LR
```



Note: The remaining sections are optional. You should proceed to complete it if you have already completed section 5.1 to 5.3.

5.5 Programming Exercise

A C string can be found starting at address 0x100. The end of a C string is terminated with a character of value of 0x000. Using the template given to you in the VIPAS project file “**Lab2-5_5-template**”, complete the subroutine **strlen** that will return the length of the string in register **R0** to the calling program. The length of your string should **include** the count for the terminator character 0x000. The start address of the string is passed to **strlen** using the stack.

The template for “**Lab2-5_5-template**” is given in Figure 7 but use the provided VISUAL project file as the data memory has been filled with appropriate values. If you have written **strlen** correctly, it should return the value of 21 or 0x15.

```

;Calling Program
    ADR    SP,0xFFFFF0FC ; initialize Stack Pointer (SP) to top of memory
    MOV    R0,#0x100      ; Fill R0 with start address
    STMFD  SP!,{R0}       ; push start address of string to stack
    BL     Strlen          ; call subroutine Mean
    ?      ; perform appropriate housekeeping of the stack
    END    ; Terminate

;Subroutine Strlen
Strlen  ??                ; save registers used in Strlen subroutine to stack
        ??
        :                ; complete the subroutine Strlen
        ??

```

Figure 7 – The program template for the Strlen programming exercise.

6. LOG BOOK

Record your results, observations and analysis in section 5 into your **log book**. You may find some of this information helpful in the open book quiz that you will be taking before the end of this laboratory session

7. REFERENCES

- 7.1 CE1106/CZ1106 Lecture Notes on Modular Programming by Asst. Prof. Mohamed M. Sabry Aly (2022)
- 7.2 The VISUAL User Guide