

## *Computer Architecture - Lab Assignment 2*

# Performance evaluation of the memory hierarchy of a computer and reverse engineering of the data cache memory

The main objective of this practice consists of manipulate different elements of the architecture of the Basic Computer that it is configured in the DE0-Nano board and they are responsible for implementing various levels of what we call Memory Hierarchy. These levels and implementations of the memory hierarchy on DE0-Nano are the following:

- The level of the main memory can be implemented with DE0-Nano using two different electronic technologies:
  - With electronic circuits of type SDRAM that are located outside of the chip where is the processor (See Fig. 1).
  - With electronic circuits of type SRAM. In DE0-Nano exists one device SRAM that is used in this practice to implement the main memory (See Fig. 1). The on-chip memory is an external memory to the processor but that it is in the same chip where is located the processor which is called FPGA (Field Programmable Gate Array).
- The level of the cache memory:
  - This level is implemented with electronics circuits of type SRAM that are in the same chip where is located the processor (FPGA, see Fig. 1).

In addition, in this practice it will be use two hardware versions of the NIOS V processor that are called **Nios V/m** and **Nios V/g**, respectively. Each type of processor and memory cause that the times of the executions of programs be different.

In this practice it will be carry out the measure of time of execution of a same program called Fibonacci when it is executed with different configurations of the architecture of the Basic Computer in the DE0-Nano Board. These configurations are distinguished in the type of processor configured: Nios V/m or Nios V/g, as well as in the type of the implementation activated for the levels of the memory hierarchy: cache, main memory (SRAM or SDRAM).

The methodology of hands-on exercises consists of four activities with the DE0-Nano board and the software environment Nios V Command Shell. It will be requested to think about the results that you have experimentally obtained.

## Part I. Access to SDRAM memory with Nios V/m processor

The objective of this first activity consists of measure the real time of computation of the Fibonacci program using the SDRAM memory of the DE0-Nano board, also of the Nios V/m, and the Timer which is an input/output device that joins to the hardware components mentioned (see Fig. 1).

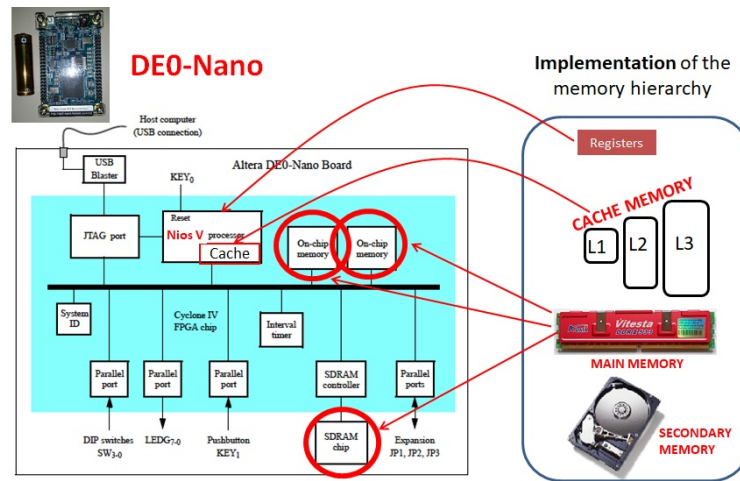


Figure 1: Implementation of the levels of the memory hierarchy integrated in the architecture of the Basic Computer of the DE0-Nano board.

During the execution of the Fibonacci program, the Nios V processor counts the number of intervals of 33 ms that have passed. When the Fibonacci program finishes, the Nios V Command Shell terminal shows the number of complete intervals of 33 ms that have passed, as you can see in Fig. 2.

```

c:/altera/12.isp1/University_Program/nios11_Computer_Systems/DE0-Nano/DE0-Nano_Basic_Computer_NiosVm_conSDRAM/verilog/so
ftware/niosv/ACpractica2niosv # quart-terminal.exe
quart-terminal: connected to hardware target using JTAG UART on cable
quart-terminal: "USB-Blaster [USB-6]", device 1, instance 0
quart-terminal: (Use the IDE stop button or Ctrl-C to terminate)

1 AM AT LAB2_PART1 WITH niosv/m ... RUNNING ...
TIME: 00000000 33-MS INTERVALS
END OF PROGRAM

```

Figure 2: Visualization of the final result of the execution of the program used to measure the time of execution of the programs. The value of the number of 33 ms intervals that is shown in the terminal.

The assembly programs involved in this Part I of the lab assignment are:

- lab2\_part1\_2.3\_main.s: main program.
- lab2\_part1\_2.3\_fibo.s: benchmark routine of which aims to measure the time of computation.
- excepcionTimer.s: routine which is executed when the timer interruption has fired.
- contador.s: routine which is called from excepcionTimer.s that manages the counter of 33 ms. intervals.
- escribir\_JTAG.s: routine which is called from lab2\_part1\_2.3\_main.s to show in the terminal the number of intervals that have passed until the end of the execution of the benchmark program.
- BCD.s: routine which is called from escribir\_JTAG.s to transform a binary code in BCD format.
- DIV.s: routine that is called from BCD.s to perform the integer division.

The flow of the benchmark program that we will use to measure the time of execution is show in Fig. 3. As we can see, the computer application activates the interrupts system of the timer in the main program (see lab2\_part1\_2.3\_main.s).

The interrupt routine allows to maintain a counter of events in one position of memory called COUNTER (see excepcionTimer.s file). Each event consist of the indication that one interval of 33 ms has passed since the previous interval of time. So, COUNTER records the numbers of 33 ms intervals that have passed since the timer was activated.

Concurrently with the time measurement performed by the Timer, the main program executes the Fibonacci's loop a number of times that is indicated by the constant called ITERATIONS (see lab2\_part1\_2.3\_main.s file). When the loop finishes, the content of the position of the memory that saves COUNTER is consulted

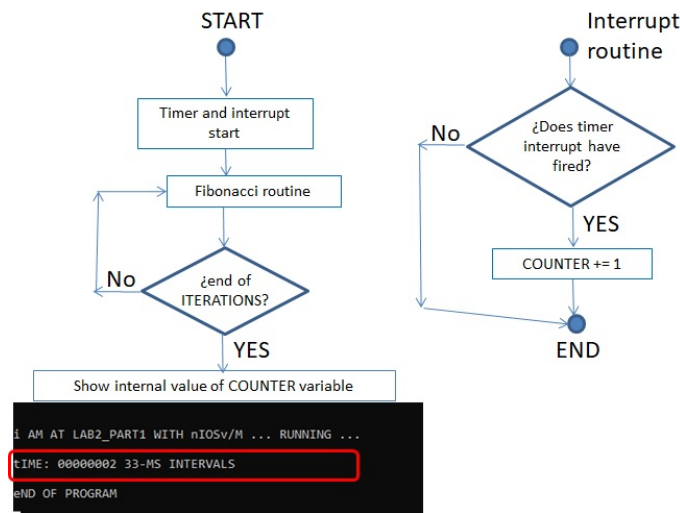


Figure 3: Flow diagram of the benchmark for Parts I, II and III.

and its value is shown in the terminal (see JTAG.s file). For this last process, the binary code is transformed. This binary code represents the value of COUNTER in a number encoded in BCD and, then, in an ASCII code. In the transformation to BCD code, it is necessary to make one or various divisions, for which one routine is included for division because the Nios V/m processor has not the hardware to make division (see JTAG.s file).

Perform the following steps:

1. Turn on the power to the Terasic DE0-Nano board.
2. Open the Nios V Command Shell.  
To run an application program it is necessary to create a new BSP project.
3. Create a new BSP directory called for example: `lab2_bsp`.
4. Select a predesigned *System-on-Chip* File: `nios_system_22jul24.sopcinfo`. This file was obtained by using the *Platform Designer* tool. It integrates a Nios V/m soft processor, a 8 KB on-chip SRAM memory, a 32 KB SDRAM memory, in addition to an I/O controller for a timer that is available in the board.
5. Execute the following command in the Nios V Command Shell Window.

```

$ cd lab2_bsp
$ sh
$ niosv-bsp.exe -c -t=hal -s=nios_system_22jul24.sopcinfo settings.bsp
  
```

The output provides two files called: `settings.bsp` and `linker.x`.

6. Now, create a new directory for the RISC-V assembler program written in RISC-V assembly language and its building, for example: `lab2_bin`.
7. Copy the files `lab2_part1_2_3_main.s`, `lab2_part1_2_3_fibo.s`, `excepcionTimer.s`, `contador.s`, `escribir_JTAG.s`, `BCD.s`, `DIV.s` to this directory.
8. The source file `lab2_part1_2_3_main.s` contains the application program. This file specifies the starting point in the selected application program. The default symbol is `start`, which is used in the selected sample program.
9. Execute the following command in the Nios V Command Shell window.

```
$ cd lab2.bin
$ riscv32-unknown-elf-as.exe lab2_part1_2_3_main.s -algs -o
lab2_part1_2_3_main.s.obj > lab2_part1_2_3_main.s.log
$ riscv32-unknown-elf-as.exe excepcionTimer.s -algs -o excepcionTimer.s.obj >
excepcionTimer.s.log
$ riscv32-unknown-elf-as.exe escribir_jtag.s -algs -o escribir_jtag.s.obj
> escribir_jtag.s.log $ riscv32-unknown-elf-as.exe contador.s -algs -o
contador.s.obj > contador.s.log
$ riscv32-unknown-elf-as.exe DIV.s -algs -o DIV.s.obj > DIV.s.log
$ riscv32-unknown-elf-as.exe BCD.s -algs -o BCD.s.obj > BCD.s.log
$ riscv32-unknown-elf-as.exe lab2_part1_2_3_fibo.s -algs -o
lab2_part1_2_3_fibo.s.obj > lab2_part1_2_3_fibo.s.log
```

The outputs are files called: lab2\_part1\_2\_3\_main.s.obj, lab2\_part1\_2\_3\_fibo.s.obj, excepcionTimer.s.obj, contador.s.obj, escribir\_JTAG.s.obj, BCD.s.obj, DIV.s.obj.

10. Execute the following command for linking in the Nios V Command Shell window.

```
$ riscv32-unknown-elf-ld.exe -g -T ../lab2.bsp/linker.x -nostdlib
-e _start -u _start --defsym __alt_stack_pointer=0x08001F00 --defsym
__alt_stack_base=0x08002000 --defsym __alt_heap_limit=0x8002000 --defsym
__alt_heap_start=0x8002000 -o lab2_part1_2_3_main.elf lab2_part1_2_3_main.s.obj
lab2_part1_2_3_fibo.s.obj excepcionTimer.s.obj contador.s.obj
escribir_JTAG.s.obj BCD.s.obj DIV.s.obj
$ niosv-stack-report.exe -p riscv32-unknown-elf- lab2_part1_2_3_main.elf
```

The output is a file called: lab2\_part1\_2\_3\_main.elf.

11. Execute the following commands in the Nios V Command Shell window.

```
$ riscv32-unknown-elf-objdump.exe -Sdtx lab2_part1_2_3_main.elf >
lab2_part1_2_3_main.elf.objdump
```

The output is a file called: lab2\_part1\_2\_3\_main.elf.objdump.

Now, it is needed to download the soft SoC system associated with this program onto the DE0-Nano board. Make sure that the power to the DE0-Nano board is turned on.

12. Execute the following command in the Nios V Command Shell window.

```
$ jtagconfig.exe
```

The following message must appear in the Nios V Command Shell window. In the case the message does not show, repeat again the command.

```
1) USB-Blaster [USB-0]
020F30DD 10CL025(Y|Z)/EP3C25/EP4CE22
```

13. Execute the following command in the Nios V Command Shell window.

```
$ quartus_pgm.exe -c 1 -m JTAG -o "p;DE0_Nano_Basic_Computer_22jul24.sof@1"
```

Note the change in the state of the blue LEDs on the DE0-Nano board that correspond to LOAD and GOOD, which will blink as the circuit is being downloaded.

14. Having downloaded the sof configuration DE0-Nano Basic Computer into the FPGA chip on the DE0-Nano board, we can now load and run programs on this SoC computer. In the Nios V Command Shell window, execute the following command.

```
$ niosv-download.exe -g lab2_part1.2.3_main.elf
```

This command also run the program.

15. Observe the messages displayed on the Nios V Command Shell using the following command.

```
$ uart_terminal.exe
```

16. Register the value displayed for the number of 33 *ms.* time intervals that were needed to execute the benchmark. This measure is related with the soft configuration: *Nios V/m + SDRAM memory*. Fill in the Table 1 using this value. This execution time will be compared with the time that will be obtained in the next two parts of this lab assignment. Stop the execution of the sample program by typing "CTRL+c".

Table 1: Runtime measurements.

Soft processor + memory technology	Execution time	Speed-up
Nios V/m + SDRAM memory (Part I)		1x
Nios V/m + on-chip memory (Part II)		
Nios V/g + SDRAM memory (Part III)		
Nios V/g + on-chip memory (Part III)		

**Question 1.** Note that the file lab2\_part1.2.3\_main.s has declared and initialized a constant: ITERATIONS = 1,000,000. Complete the following steps and respond to the question shown at the end of this box.

- Change ITERATIONS to 4,000,000 in the lab2\_part1.2.3\_main.s file.
- Compile again the program
- Download the \*.elf file into the board.
- Register the value displayed on the Nios V terminal.
- Obtain the speed-up.

**Is this value a reasonable speed-up? Explain and justify your answer.**

## Part II. Access to SRAM on-chip memory with Nios V/m processor

The goal of this second part consists in measuring the execution time of the Fibonacci program using the SRAM on-chip memory that is located inside the FPGA chip, where the NIOS V/m soft processor is also integrate. The difference between this part and Part I is that the SRAM memory is used. SRAM memory was built using another technology. Additionally, the on-chip memory is located physically nearer the processor. This is a different situation with respect to using the external SDRAM memory of DE0-Nano board. Follow the following steps.

1. Change again the value for ITERATIONS in file `lab2_part1_2_3_main.s` to 1,000,000.
2. Change the immediate value for the `li` instruction at the beginning of the `lab2_part1_2_3_main.s` file. This is the start address of the exception routine.

```
lab2_part1_2_3_main.s
```

```
li s2, 0x08000000
```

3. Modify the `linker.x` file changing the string `new_sdram_controller_0` with the string `Onchip_memory_SRAM` at the end of SECTION: `.exceptions`, `.text`, `.rodata`, `.rdata` and `.bss`.
4. Call this new file for example: `linker.SRAM.x`.
5. Now, compile the file `lab2_part1_2_3_main.s` as explained in Part I.

```
$ riscv32-unknown-elf-as.exe lab2_part1_2_3_main.s -alsg -o  
lab2_part1_2_3_main.s.obj > lab2_part1_2_3_main.s.log
```

6. Link the program as follows.

```
$ riscv32-unknown-elf-ld.exe -g -T ../lab2_bsp/linker.SRAM.x -nostdlib  
-e _start -u _start --defsym __alt_stack_pointer=0x08001F00 --defsym  
__alt_stack_base=0x08002000 --defsym __alt_heap_limit=0x8002000 --defsym  
__alt_heap_start=0x8002000 -o lab2_part1_2_3_main.elf lab2_part1_2_3_main.s.obj  
lab2_part1_2_3_fibo.s.obj excepcionTimer.s.obj contador.s.obj  
escribir_JTAG.s.obj BCD.s.obj DIV.s.obj  
$ niosv-stack-report.exe -p riscv32-unknown-elf- lab2_part1_2_3_main.elf
```

7. Now, download and execute the program. Additionally, display the results of the program using the terminal software.

```
$ niosv-download.exe -g lab2_part1_2_3_main.elf  
$ quart_terminal.exe
```

8. Register the value displayed for the number of 33 *ms.* time intervals that were needed to execute the benchmark. This measure is related with the soft configuration: *Nios V/m + SRAM memory*. Fill in the Table 1 using this value. This execution time will be compared with the time that will be obtained in the previous and next parts I and III of this lab assignment. Stop the execution of the sample program by typing "CTRL+c".

#### Question 2.

**Is this new value a reasonable speed-up respect to the results obtained in Part I? Explain and justify your answer using Fig. 1.**

## Part III. Access to memory hierarchy with Nios V/g processor

The goal of this third part consists in measuring the execution time of the Fibonacci program using the Nios V/g soft processor. Both technologies for main memory will be used: external SDRAM memory and SRAM on-chip memory. The difference between this part and Parts I and II is that the model of Nios V/g processor used. A new configuration file will be used: `DE0_Nano_Basic_Computer_23jul24.sof`.

First of all, the FPGA circuit of DE0-Nano board should be reconfigured.

1. Execute the following command in the Nios V Command Shell window.

```
$ quartus_pgm.exe -c 1 -m JTAG -o "p;DE0_Nano_Basic_Computer_23jul24.sof@1"
```

Follow the following steps when using the external SDRAM memory.

2. Change the immediate value for the `li` instruction at the beginning of the `lab2_part1_2_3_main.s` file. This is the start address of the exception routine when the SDRAM memory is used. Additionally, change the output message sent to terminal.

```
lab2_part1_2_3_main.s

li s2, 0x0

TEXT0_MAIN:
.asciz "\nI am at lab2_part3 with NiosV/g ... running ... \n"
```

3. Now, compile the file `lab2_part1_2_3_main.s` as explained in Part I.

```
$ riscv32-unknown-elf-as.exe lab2_part1_2_3_main.s -alsh -o
lab2_part1_2_3_main.s.obj > lab2_part1_2_3_main.s.log
```

4. Link the program using the `linker.x` file as follows.

```
$ riscv32-unknown-elf-ld.exe -g -T ../lab2_esp/linker.x -nostdlib
-e _start -u _start --defsym __alt_stack_pointer=0x08001F00 --defsym
__alt_stack_base=0x08002000 --defsym __alt_heap_limit=0x8002000 --defsym
__alt_heap_start=0x8002000 -o lab2_part1_2_3_main.elf lab2_part1_2_3_main.s.obj
lab2_part1_2_3_fibo.s.obj excepcionTimer.s.obj contador.s.obj
escribir_JTAG.s.obj BCD.s.obj DIV.s.obj
$ niosv-stack-report.exe -p riscv32-unknown-elf- lab2_part1_2_3_main.elf
```

5. Now, download and execute the program. Additionally, display the results of the program using the terminal software.

```
$ niosv-download.exe -g lab2_part1_2_3_main.elf
$ juart_terminal.exe
```

6. Register the value displayed for the number of 33 *ms*. time intervals that were needed to execute the benchmark. This measure is related with the soft configuration: *Nios V/g + SDRAM memory*. Fill in the Table 1 using this value. This execution time will be compared with the times that were obtained in Parts I and II of this lab assignment. Stop the execution of the sample program by typing "CTRL+c".

Follow the following steps when using the external on-chip SRAM memory.

7. Change the immediate value for the `li` instruction at the beginning of the `lab2_part1_2_3_main.s` file. This is the start address of the exception routine when the on-chip SRAM memory is used. Additionally, change the output message sent to terminal.

```
lab2_part1_2_3_main.s

li s2, 0x08000000

TEXT0_MAIN:
.asciz "\nI am at lab2_part3 with NiosV/g ... running ... \n"
```

8. Now, compile the file `lab2_part1_2_3_main.s` as explained in Part I.

```
$ riscv32-unknown-elf-as.exe lab2_part1.2.3_main.s -alsg -o
lab2_part1.2.3_main.s.obj > lab2_part1.2.3_main.s.log
```

9. Link the program using the linker\_SRAM.x file that was generated in Part II as follows.

```
$ riscv32-unknown-elf-ld.exe -g -T ../lab2.bsp/linker_SRAM.x -nostdlib
-e _start -u _start --defsym __alt_stack_pointer=0x08001F00 --defsym
__alt_stack_base=0x08002000 --defsym __alt_heap_limit=0x8002000 --defsym
__alt_heap_start=0x8002000 -o lab2_part1.2.3_main.elf lab2_part1.2.3_main.s.obj
lab2_part1.2.3_fibo.s.obj excepcionTimer.s.obj contador.s.obj
escribir_JTAG.s.obj BCD.s.obj DIV.s.obj
$ niosv-stack-report.exe -p riscv32-unknown-elf- lab2_part1.2.3_main.elf
```

10. Now, download and execute the program. Additionally, display the results of the program using the terminal software.

```
$ niosv-download.exe -g lab2_part1.2.3_main.elf
$ uart_terminal.exe
```

11. Register the value displayed for the number of 33 *ms.* time intervals that were needed to execute the benchmark. This measure is related with the soft configuration: *Nios V/g + SRAM memory*. Fill in the Table 1 using this value. Calculate the speed-up of each soft SoC configuration using as reference the SoC configuration based on Nios V/m and external SDRAM memory, which is takes as  $SpeedUp = 1$ . This execution time will be compared with the times that were obtained in Parts I and II of this lab assignment. Stop the execution of the sample program by typing "CTRL+c".
12. Now, please, answer the following questions.

**Question 3. Why do different versions of soft SoC systems based on Nios V/m processor provide such values of speed-up? Explain and justify your answer.**

**Question 4. Why do the executions times of the two versiones of soft SoC systems based on Nios V/g processor provide the same execution time? Explain and justify your answer.**

**Question 5. Why does the soft SoC systems based on Nios V/m processor provide lower performance than the SoC system based on Nios V/g? Explain and justify your answer.**

## Part IV. Reverse engineering of the data cache memory