

Introduction to the Altera SOPC Builder

Using Verilog Design

This tutorial presents an introduction to Altera's SOPC Builder software, which is used to implement a system that uses the Nios II processor on an Altera FPGA device. The system development flow is illustrated by giving step-by-step instructions for using the SOPC Builder in conjunction with the Quartus II 9.1 software to implement a simple system.

The last step in the development process involves configuring the designed circuit in an actual FPGA device, and running an application program. To show how this is done, it is assumed that the user has access to the Altera DE2-115 Development and Education board connected to a computer that has Quartus II and Nios II software installed.

The screen captures in the tutorial were obtained using the Quartus II version 9.1; if other versions of the software are used, some of the images may be slightly different.

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Altera's Nios II is a soft processor, defined in a hardware description language, which can be implemented in Altera's FPGA devices by using the Quartus II CAD system. To implement a useful system it is necessary to add other functional units such as memories, input/output interfaces, timers, and communications interfaces. To facilitate the implementation of such systems, it is useful to have computer-aided-design (CAD) software for implementing a system-on-a-programmable-chip (SOPC). Altera's SOPC Builder is the software needed for this task.

This tutorial provides a basic introduction to Altera's SOPC Builder, which will allow the reader to quickly implement a simple Nios II system on the Altera DE2-115 board. For a fuller treatment of the SOPC Builder, the reader can consult the Nios II Hardware Development Tutorial. A complete description of the SOPC Builder can be found in the Quartus II Handbook Volume 4: SOPC Builder. These documents are available on the Altera web site.

1 Nios II System

A Nios II system can be implemented on the DE2-115 board as shown in Figure 1.

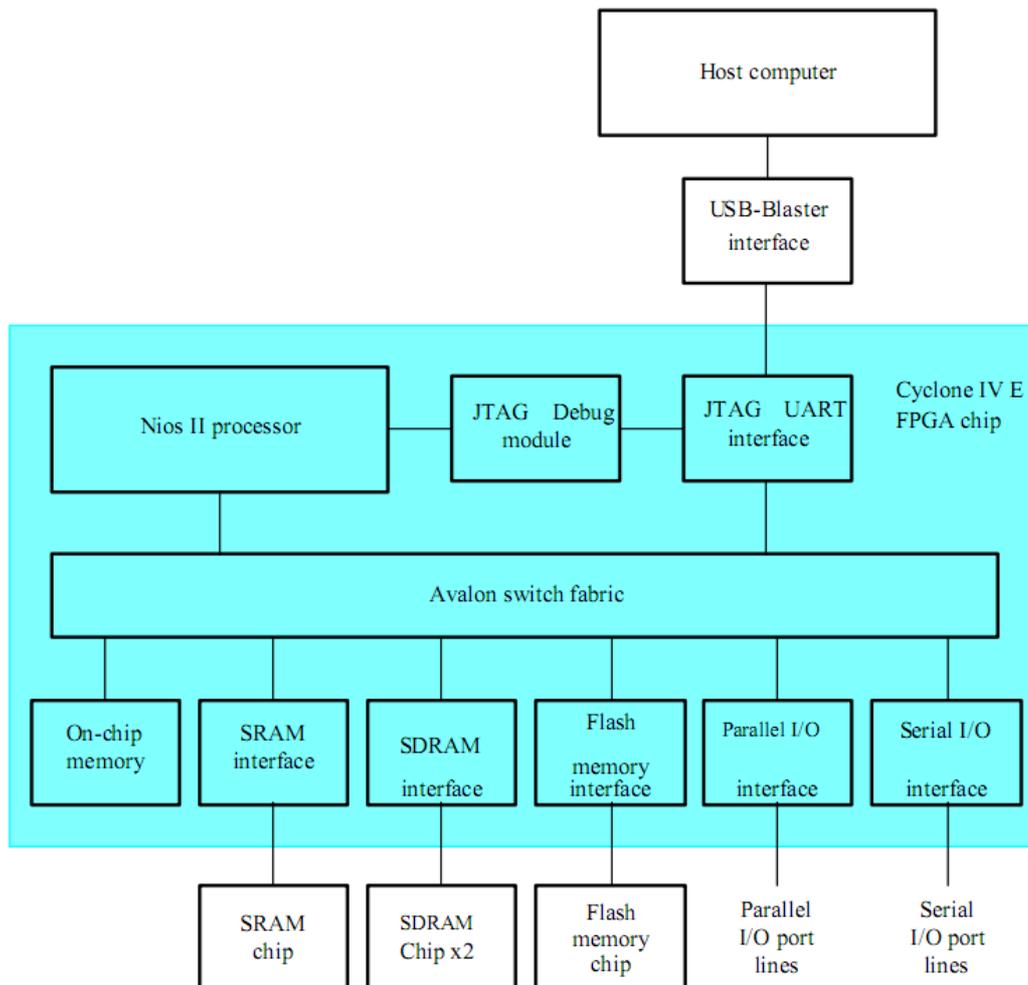


Figure 1. A Nios II system implemented on the DE2-115 board.

The Nios II processor and the interfaces needed to connect to other chips on the DE2-115 board are implemented in the Cyclone IV E FPGA chip. These components are interconnected by means of the interconnection network called the Avalon Switch Fabric. The memory blocks in the Cyclone IV E device can be used to provide an on-chip memory for the Nios II processor. The SRAM, SDRAM and Flash memory chips on the DE2-115 board are accessed through the appropriate interfaces. Parallel and serial input/output interfaces provide typical I/O ports used in computer systems. A special JTAG UART interface is used to connect to the circuitry that provides a Universal Serial Bus (USB) link to the host computer to which the DE2-115 board is connected. This circuitry and the associated software is called the USB-Blaster. Another module, called the JTAG Debug module, is provided to allow the host computer to control the Nios II system. It makes it possible to perform operations such as downloading programs into memory, starting and stopping execution, setting breakpoints, and collecting real-time execution trace data.

Since all parts of the Nios II system implemented on the FPGA chip are defined by using a hardware description language, a knowledgeable user could write such code to implement any part of the system. This would be an onerous and time consuming task. Instead, one can use the SOPC Builder to implement a desired system simply by choosing the required components and specifying the parameters needed to make each component fit the overall requirements of the system. In this tutorial, we will illustrate the capability of the SOPC Builder by designing a very simple system. The same approach is used to design large systems.

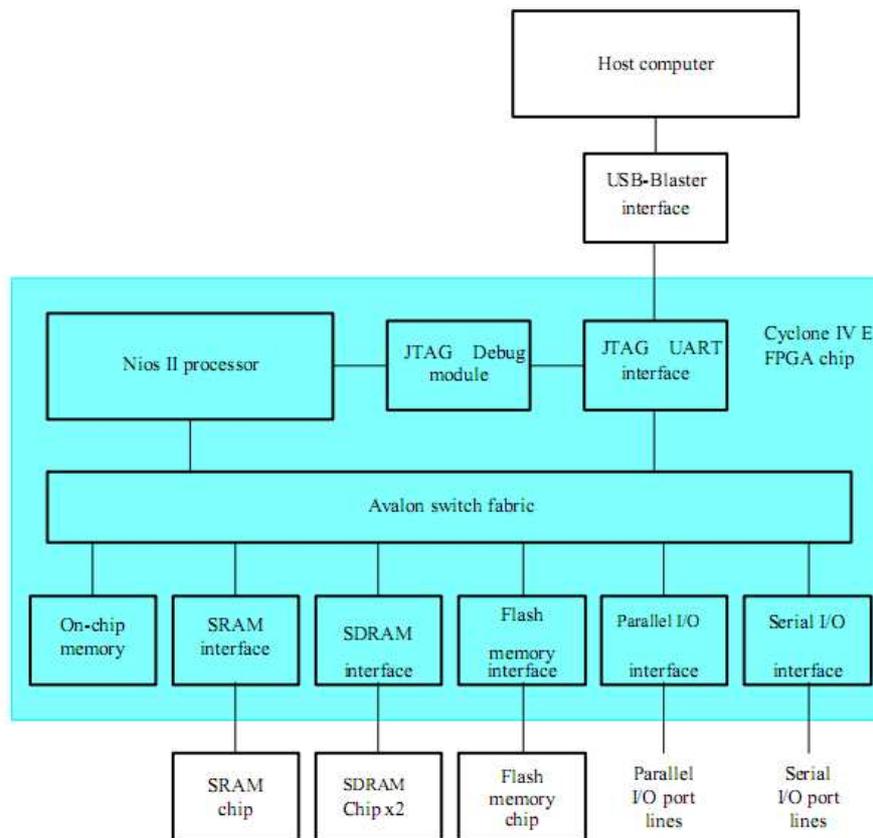


Figure 2 A simple example of a Nios II system.

Our example system is given in Figure 2. The system realizes a trivial task. Eight toggle switches on the DE2-115 board, SW_{7-0} , are used to turn on or off the eight green LEDs, $LEDG_{7-0}$. The switches are connected to the Nios II system by means of a parallel I/O interface configured to act as an input port. The LEDs are driven by the signals from another parallel I/O interface configured to act as an output port. To achieve the desired operation, the eight-bit pattern corresponding to the state of the switches has to be sent to the output port to activate the LEDs. This will be done by having the Nios II processor execute a program stored in the on-chip memory. Continuous operation is required, such that as the switches are toggled the lights change accordingly.

We will use the SOPC Builder to design the hardware depicted in Figure 2. Next, we will assign the Cyclone IV E pins to realize the connections between the parallel interfaces and the switches and LEDs which act as I/O devices. Then, we will configure the FPGA to implement the designed system. Finally, we will use the software tool called the Nios II Monitor Program to assemble, download and execute a Nios II program that performs the desired task.

Doing this tutorial, the reader will learn about:

- **Using the SOPC Builder to design a Nios II-based system**
- **Integrating the designed Nios II system into a Quartus II project**
- **Implementing the designed system on the DE2-115 board**
- **Running an application program on the Nios II processor**

2 Altera's SOPC Builder

The SOPC Builder is a tool used in conjunction with the Quartus II CAD software. It allows the user to easily create a system based on the Nios II processor, by simply selecting the desired functional units and specifying their parameters. To implement the system in Figure 2, we have to instantiate the following functional units:

- **Nios II processor, which is referred to as a Central Processing Unit (CPU)**
- **On-chip memory, which consists of the memory blocks in the Cyclone IV E chip; we will specify a 4-Kbyte memory arranged in 32-bit words**
- **Two parallel I/O interfaces**
- **JTAG UART interface for communication with the host computer**

To define the desired system, start the Quartus II software and perform the following steps:

1. Create a new Quartus II project for your system. As shown in Figure 3, we stored our project in a directory called `sopc_builder_tutorial`, and we assigned the name `lights` to both the project and its top-level design entity. You can choose a different directory or project name, but be aware that the SOPC Builder software does not permit the use of spaces in file names. For example, an attempt to use a directory name `sopc builder tutorial` would lead to an error. In your project, choose the EP4CE115F29C7 chip as the target device, because this is the FPGA on the DE2-115 board.

2. Select **Tools > SOPC Builder**, which leads to the pop-up box in Figure 4. Enter **nios_system** as the system name; this will be the name of the system that the SOPC Builder will generate. Choose Verilog as the target HDL, in which the system module will be specified. Click OK to reach the window in Figure 5.

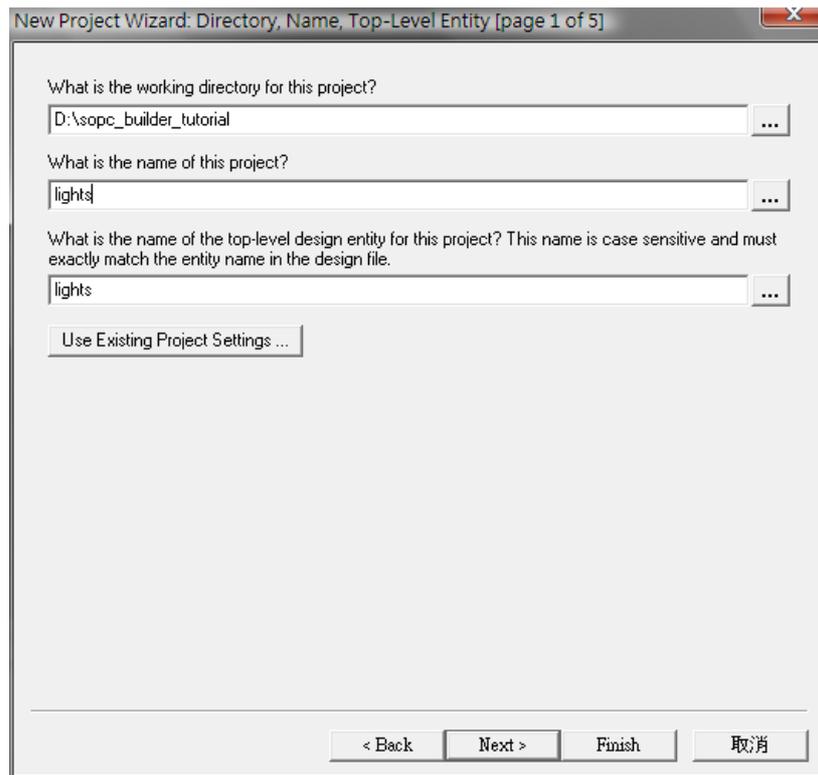


Figure 3. Create a new project.



Figure 4. Create a new Nios II system.

3. Figure 5 displays the System Contents tab of the SOPC Builder, which is used to add components to the system and configure the selected components to meet the design requirements. The available components are listed on the left side of the window. Before choosing our components, examine the area in the figure labeled Target. Check the setting for the Device Family and ensure that Cyclone IV E is selected.

4. The Nios II processor runs under the control of a clock. For this tutorial we will make use of the 50-MHz clock that is provided on the DE2-115 board. As shown in Figure 5, it is possible to specify the names and frequency of clock signals in the SOPC Builder display.

If not already included in this list, specify a clock named **clk_0** with the source designated as External and the frequency set to **50.0 MHz**.

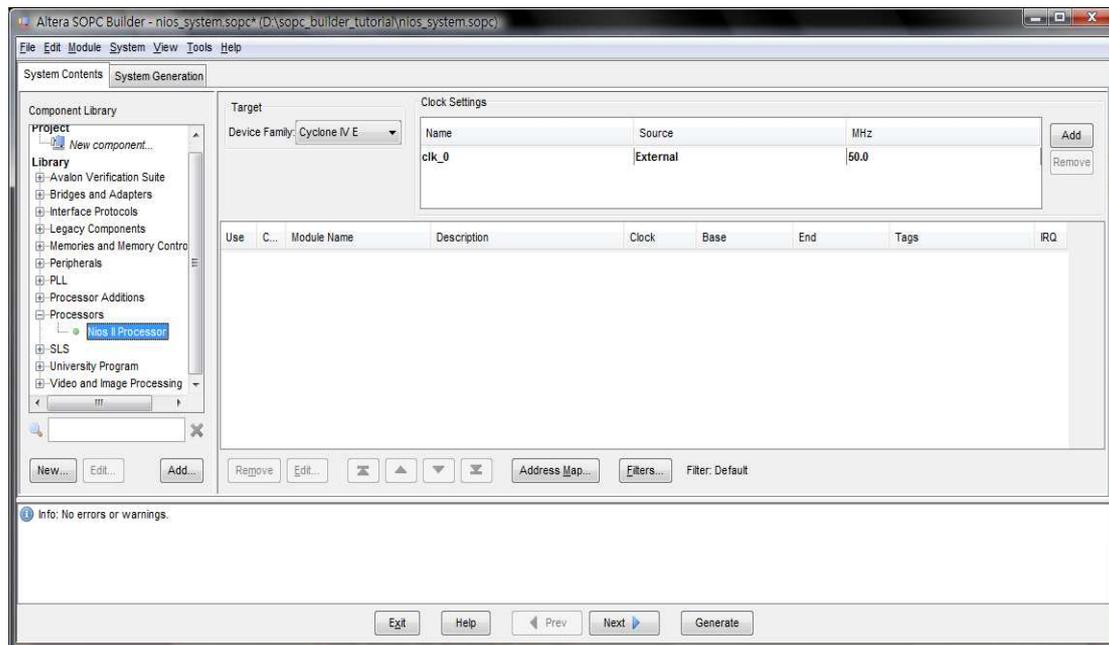


Figure 5. The System Contents tab window.

5. Next, specify the processor as follows:

- On the left side of the window in Figure 5 select **Processors > Nios II Processor** and click Add, which leads to the window in Figure 6.

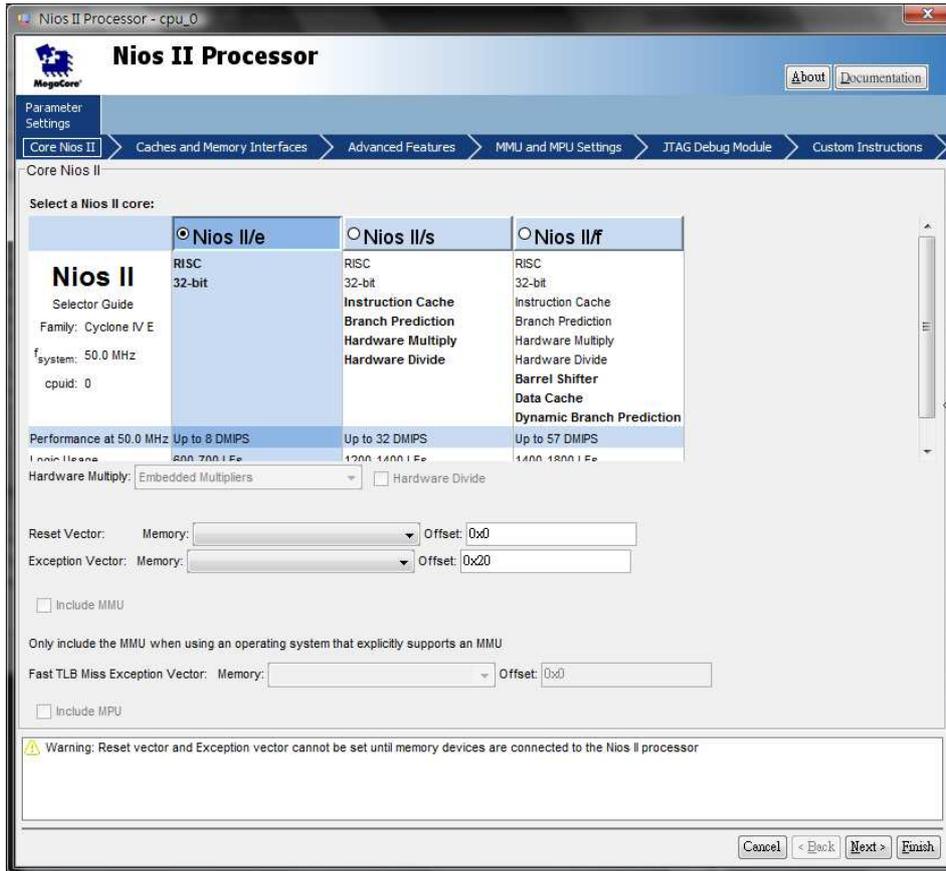


Figure 6. Create a Nios II processor.

- Choose **Nios II/e** which is the simplest version of the processor. Click **Finish** to return to the window in Figure 5, which now shows the Nios II processor specified as indicated in Figure 7. There may be some warnings or error messages displayed in the SOPC Builder Messages window (at the bottom of the screen), because some parameters have not yet been specified. Ignore these messages as we will provide the necessary data later.

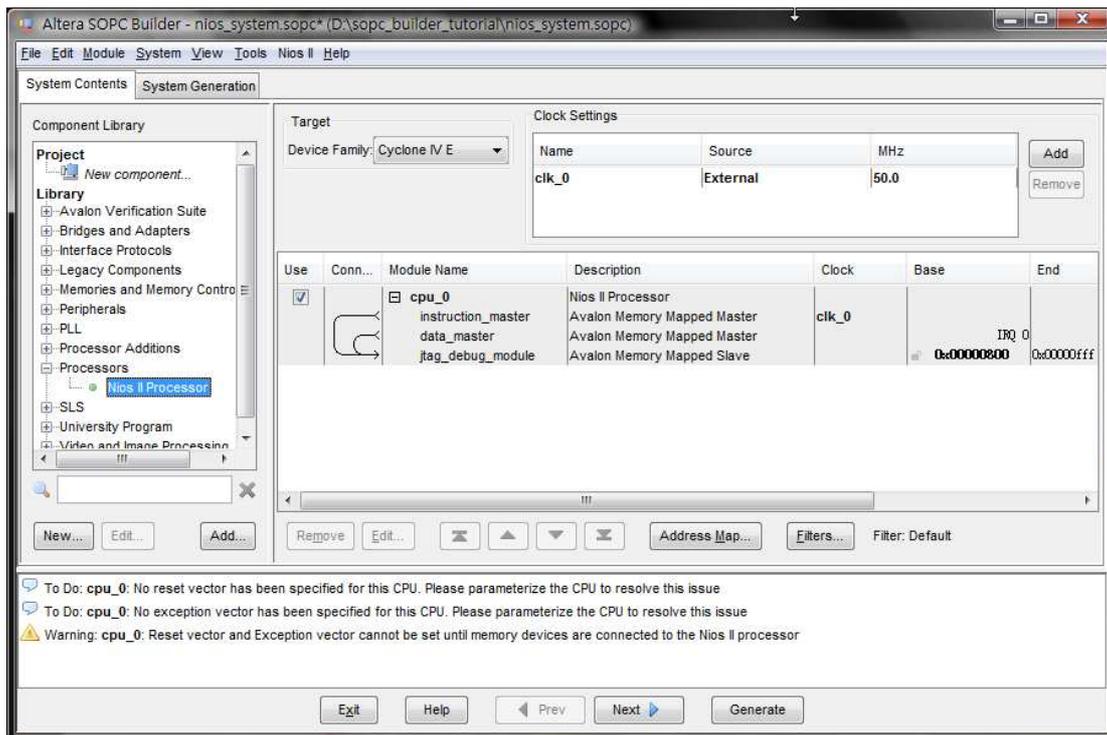


Figure 7. The defined processor.

6. To specify the on-chip memory perform the following:

- Select **Memories and Memory Controllers > On-Chip > On-Chip Memory** (RAM or ROM) and click **Add**
- In the On-Chip Memory Configuration Wizard window, shown in Figure 8, set the memory width to 32 bits and the total memory size to **4 Kbytes**
- Do not change the other default settings
- Click **Finish**, which returns to the System Contents tab as indicated in Figure 9

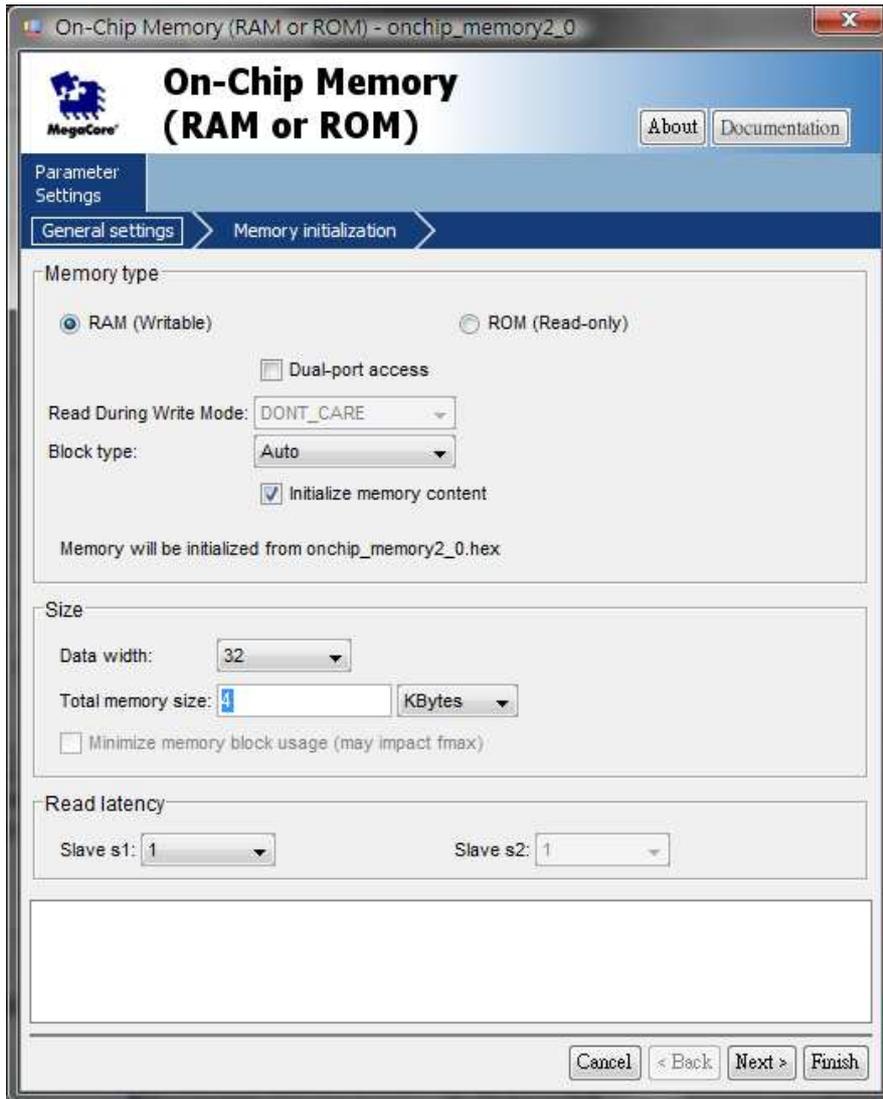


Figure 8. Define the on-chip memory.

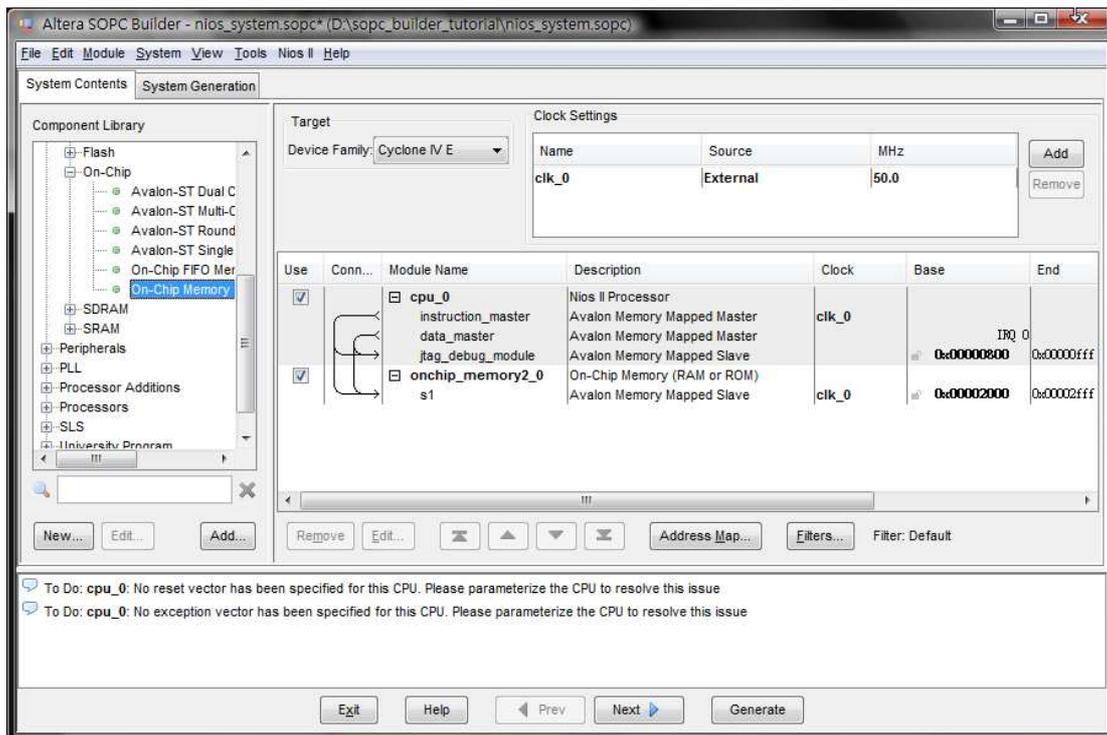


Figure 9. The on-chip memory is included.

7. Specify the input parallel I/O interface as follows:

- Select **Peripherals > Microcontroller Peripherals > PIO** (Parallel I/O) and click **Add** to reach the PIO Configuration Wizard in Figure 10
- Specify the width of the port to be 8 bits and choose the direction of the port to be Input, as shown in the figure
- Click **Finish** to return to the System Contents tab as given in Figure 11



Figure 10. Define a parallel input interface.

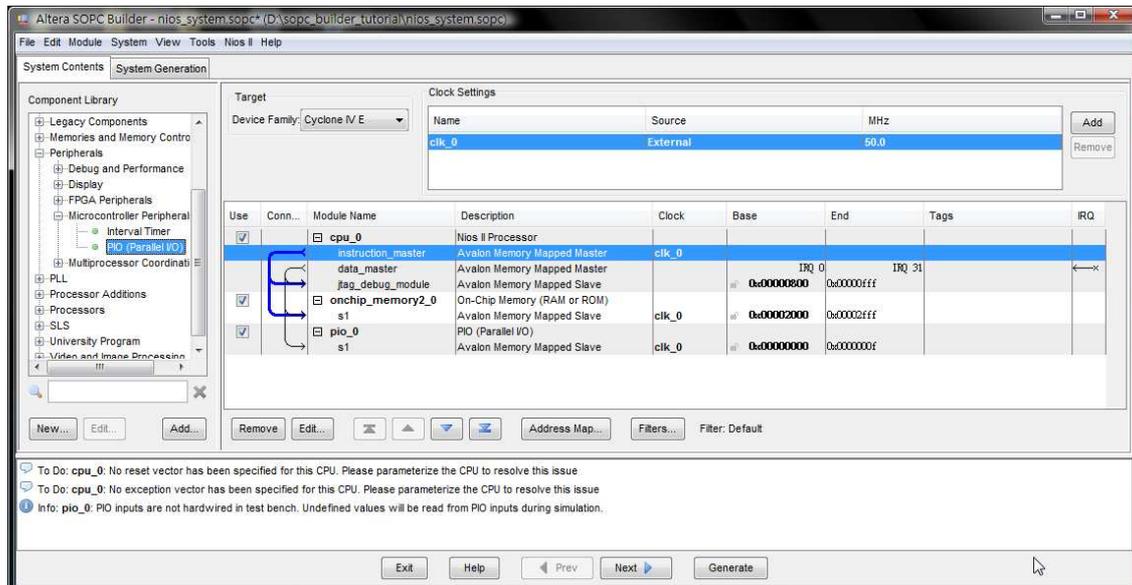


Figure 11. The parallel input interface is included.

8. In the same way, specify the output parallel I/O interface:

- Select **Peripherals > Microcontroller Peripherals > PIO** (Parallel I/O) and click **Add** to reach the PIO Configuration Wizard again
- Specify the width of the port to be 8 bits and choose the direction of the port to be Output
- Click **Finish** to return to the System Contents tab

9. We wish to connect to a host computer and provide a means for communication between the Nios II system and the host computer. This can be accomplished by instantiating the JTAG UART interface as follows:

- Select **Interface Protocols > Serial > JTAG UART** and click **Add** to reach the JTAG UART Configuration Wizard in Figure 12
- Do not change the default settings
- Click **Finish** to return to the System Contents tab



Figure 12. Define the JTAG UART interface.

10. The complete system is depicted in Figure 13. Note that the SOPC Builder automatically chooses names for the various components. The names are not necessarily descriptive enough to be easily associated with the target design, but they can be changed. In Figure 2, we use the names Switches and LEDs for the parallel input and output interfaces, respectively. These names can be used in the implemented system. Right-click on the pio_0 name and then select Rename. Change the name to Switches. Similarly, change pio_1 to LEDs.

11. The base and end addresses of the various components in the designed system can be assigned by the user, but they can also be assigned automatically by the SOPC Builder. We will choose the latter possibility. So, select the command (using the menus at the top of the SOPC Builder window) **System > Auto-Assign Base Addresses**, which produces the assignment shown in Figure 14.

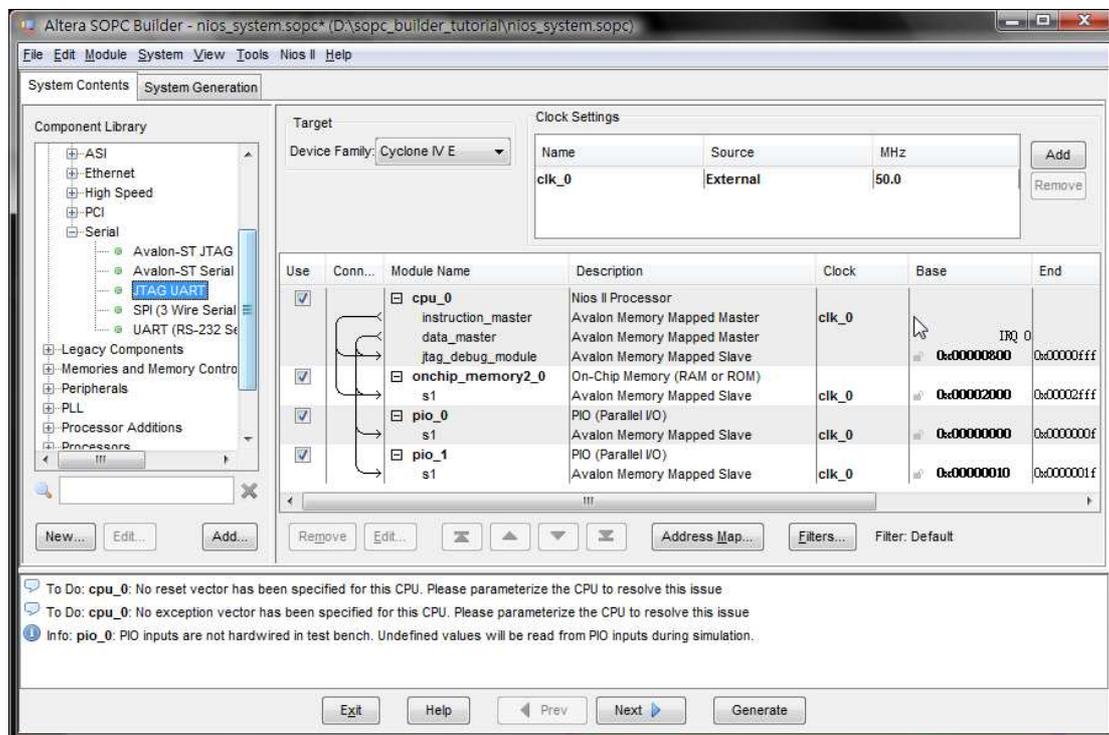


Figure 13. The complete system.

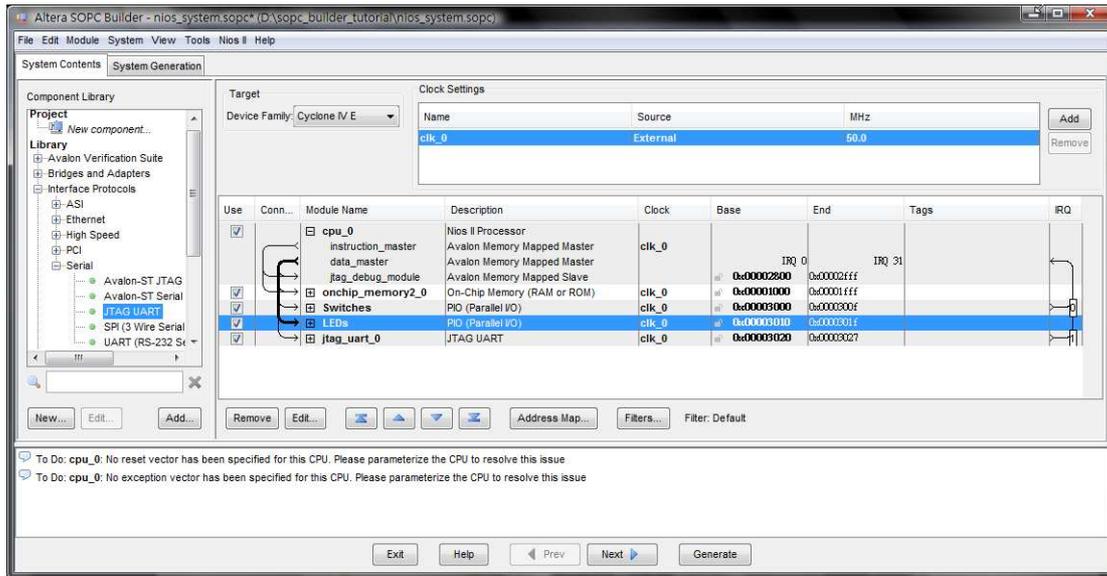


Figure 14. The final specification.

12. The behaviors of the Nios II processor when it is reset is defined by its reset vector. It is the location in memory device the processor fetches the next instruction when it is reset. Similarly, the exception vector is the memory address the processor goes to when an interrupt is raised. To specify these two parameters, perform the following:

- Right-click on the **cpu_0** and then select **Edit** to reach the window in Figure 15
- Select **onchip_memory2_0** to be the memory device for both reset vector and exception vector, as shown in the figure
- Do not change the default setting for offset
- Click **Finish** to return to the System Contents tab

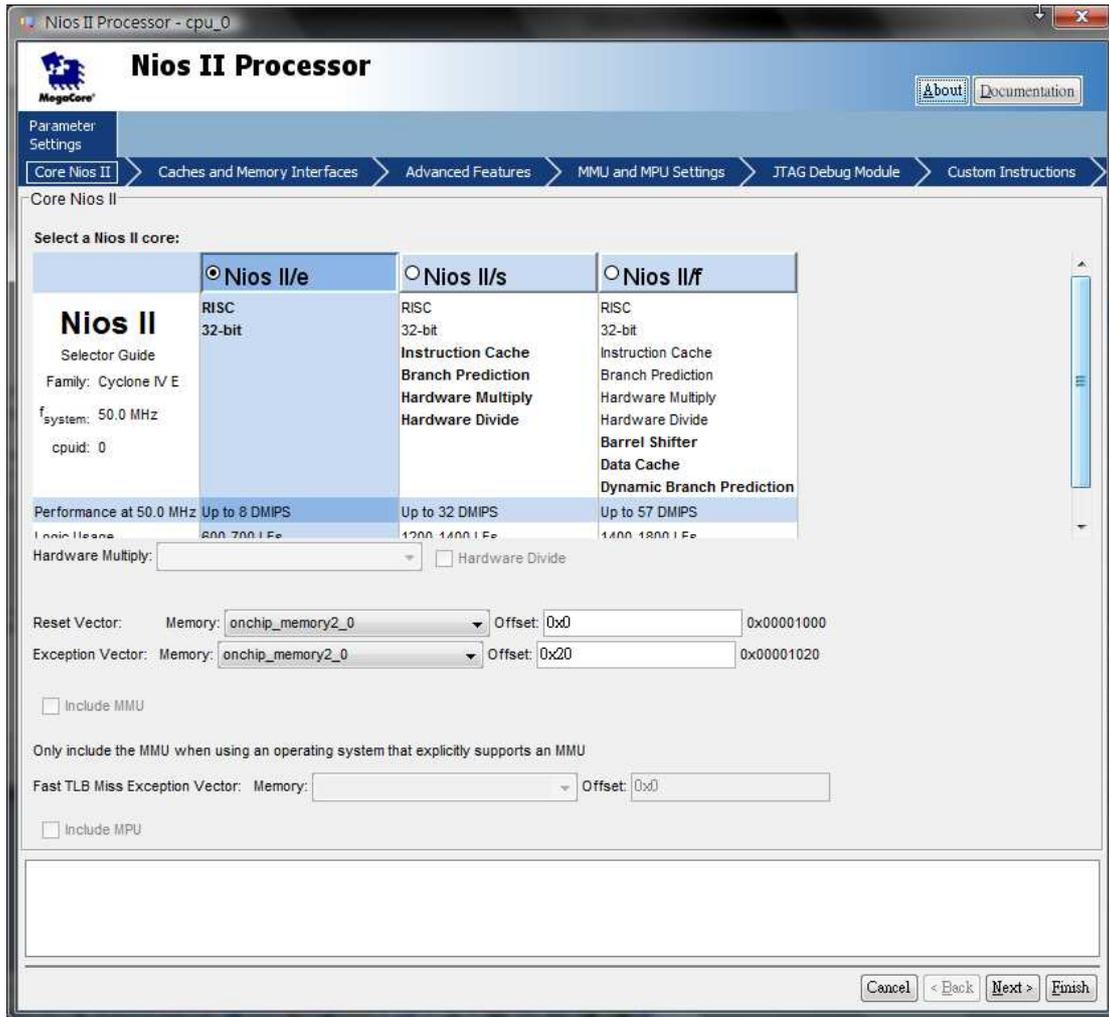


Figure 15. Define the reset vector and exception vector.

13. Having specified all components needed to implement the desired system, it can now be generated. Select the System Generation tab, which leads to the window in Figure 16. Turn off Simulation – Create simulator project files, because in this tutorial we will not deal with the simulation of hardware. Click **Generate** on the bottom of the SOPC Builder window. The generation process produces the messages displayed in the figure. When the message “SUCCESS: SYSTEM GENERATION COMPLETED” appears, click **Exit**. This returns to the main Quartus II window.

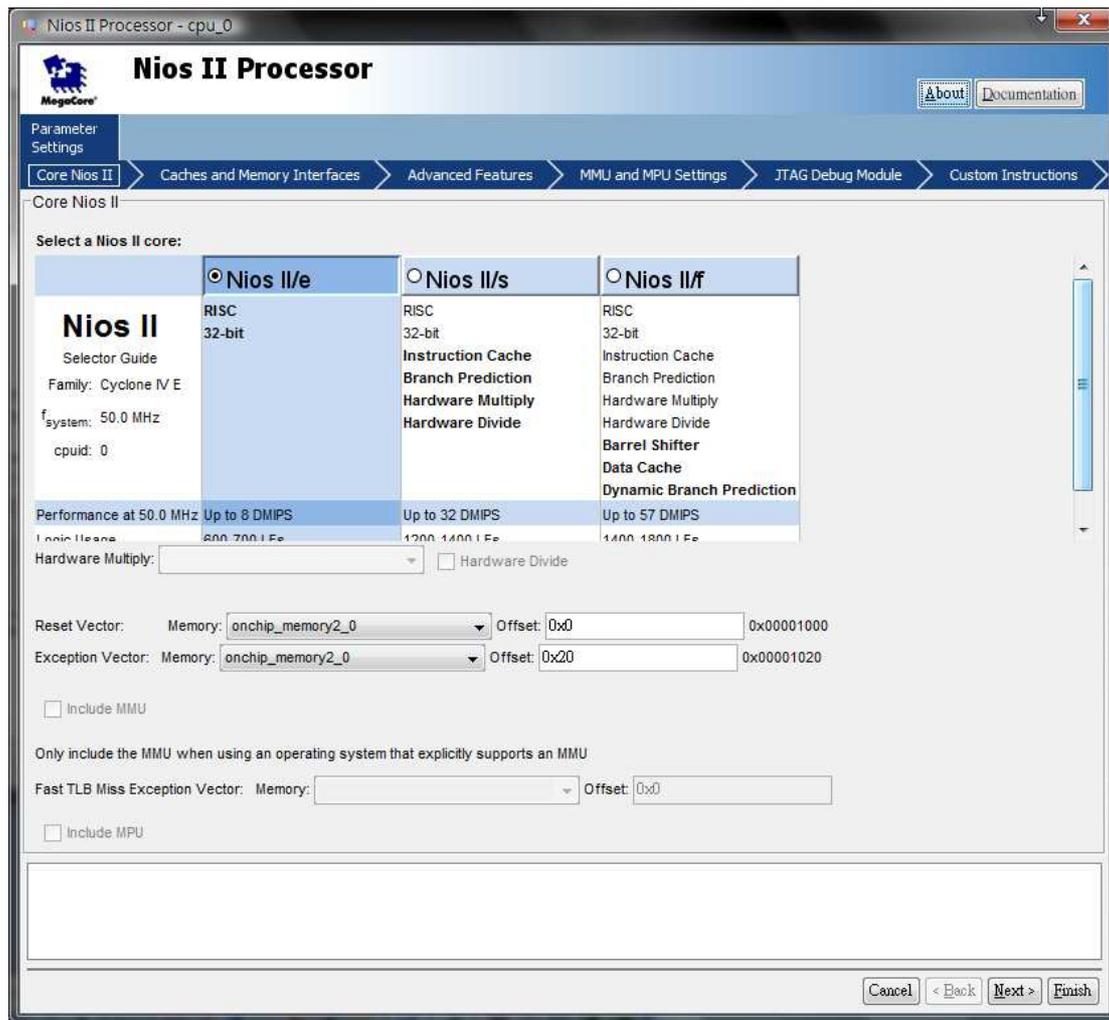


Figure 16.Generation of the system.

Changes to the designed system are easily made at any time by reopening the SOPC Builder tool. Any component in the System Contents tab of the SOPC Builder can be selected and deleted, or a new component can be added and the system regenerated.

3 Integration of the Nios II System into a Quartus II Project

To complete the hardware design, we have to perform the following:

- **Instantiate the module generated by the SOPC Builder into the Quartus II project**
- **Assign the FPGA pins**
- **Compile the designed circuit**
- **Program and configure the Cyclone IV E device on the DE2-115 board**

3.1 Instantiation of the Module Generated by the SOPC Builder

The instantiation of the generated module depends on the design entry method chosen for the overall Quartus II project.

We have chosen to use Verilog HDL, but the approach is similar for both VHDL and schematic entry methods. Normally, the Nios II module is likely to be a part of a larger design. However, in the case of our simple example there is no other circuitry needed. All we need to do is instantiate the Nios II system in our top-level Verilog file, and connect inputs and outputs of the parallel I/O ports, as well as the clock and reset inputs, to the appropriate pins on the Cyclone IV E device.

The Verilog module generated by the SOPC Builder is in the file `nios_system.v` in the directory of the project. Note that the name of the Verilog module is the same as the system name specified when first using the SOPC Builder. The Verilog code is quite large. Figure 17 depicts the portion of the code that defines the input and output signals for the module `nios_system`. The 8-bit vector that is the input to the parallel port Switches is called `in_port_to_the_Switches`. The 8-bit output vector is called `out_port_from_the_LEDs`. The clock and reset signals are called `clk_0` and `reset_n`, respectively. Note that the reset signal is added automatically by the SOPC Builder; it is called `reset_n` because it is active low.

```

2124 module nios_system (
2125     // 1) global signals:
2126     clk_0,
2127     reset_n,
2128
2129     // the_LEDs
2130     out_port_from_the_LEDs,
2131
2132     // the_Switches
2133     in_port_to_the_Switches
2134 );
2135
2136 ;
2137
2138 output [ 7: 0] out_port_from_the_LEDs;
2139 input clk_0;
2140 input [ 7: 0] in_port_to_the_Switches;
2141 input reset_n;
2142
2143 wire [ 1: 0] LEDs_sl_address;
2144 wire LEDs_sl_chipselect;
2145 wire [ 7: 0] LEDs_sl_readdata;
2146 wire [ 7: 0] LEDs_sl_readdata_from_sa;
2147 wire LEDs_sl_reset_n;
2148 wire LEDs_sl_write_n;
2149 wire [ 7: 0] LEDs_sl_writedata;

```

Figure 17. A part of the generated Verilog module.

Figure 18 shows a top-level Verilog module that instantiates the Nios II system. This module is named `lights`, because this is the name we specified in Figure 3 for the top-level design entity in our Quartus II project. Note that the input and output ports of the module use the pin names for the 50-MHz clock, `CLOCK_50`, pushbutton switches, `KEY`, toggle switches, `SW`, and green LEDs, `LEDG`, that are specified in the DE2-115 User Manual. Type this code into a file called `lights.v`. Add this file and all the `*.v` files produced by the SOPC Builder to your Quartus II project. Also, add the necessary pin assignments on the DE2-115 board to your project. The procedure for making pin assignments is described in the tutorial `Quartus II Introduction Using Verilog Design`.

Note that an easy way of making the pin assignments when we use the same pin names as in the DE2-115 User Manual is to import the assignments given in the file called DE2-115_pin_assignments.csv in the directory DE2-115_tutorials\design_files, which is included on the CD-ROM that accompanies the DE2-115 board and can also be found on Altera's DE2-115 web pages. Since the system we are designing needs to operate at a 50-MHz clock frequency, add the needed timing assignment in your Quartus II project. The tutorial Timing Considerations with Verilog-Based Designs shows how this is done.

```
// Implements a simple Nios II system for the DE2-115 board.
// Inputs: SW7-0 are parallel port inputs to the Nios II system
// CLOCK_50 is the system clock
// KEY0 is the active-low system reset
// Outputs: LEDG7-0 are parallel port outputs from the Nios II system
module lights (SW, KEY, CLOCK_50, LEDG);
input    [7:0] SW;
input    [0:0] KEY;
input    CLOCK_50;
output  [7:0] LEDG;

// Instantiate the Nios II system module generated by the SOPC Builder:
// nios_system (clk_0, reset_n, out_port_from_the_LEDs, in_port_to_the_Switches)
// nios_system Nios II (CLOCK_50, KEY[0], LEDG, SW);

endmodule
```

Figure 18. Instantiating the Nios II system.

Having made the necessary settings compile the code. You may see some warning messages associated with the Nios II system, such as some signals being unused or having wrong bit-lengths of vectors; these warnings can be ignored.

3.2 Programming and Configuration

Program and configure the Cyclone IV E FPGA in the JTAG programming mode as follows:

1. Connect the DE2-115 board to the host computer by means of a USB cable plugged into the USB-Blaster port. Turn on the power to the DE2-115 board. Ensure that the **RUN/PROG** switch is in the **RUN** position.
2. Select **Tools > Programmer** to reach the window in Figure 19.
3. If not already chosen by default, select **JTAG** in the Mode box. Also, if the USB-Blaster is not chosen by default, press the **Hardware Setup...** button and select the USB-Blaster in the window that pops up.
4. The configuration file lights.sof should be listed in the window. If the file is not already listed, then click **Add File** and select it.

5. Click the box under **Program/Configure** to select this action.

6. At this point the window settings should appear as indicated in Figure 19. Press **Start** to configure the FPGA.

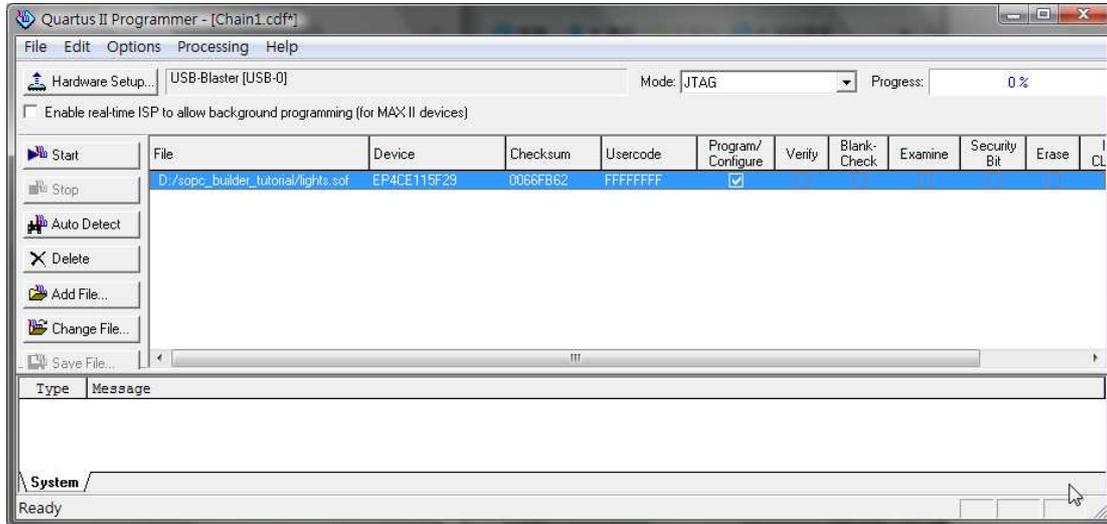


Figure 19. The Programmer window.

4 Running the Application Program

Having configured the required hardware in the FPGA device, it is now necessary to create and execute an application program that performs the desired operation. This can be done by writing the required program either in the Nios II assembly language or in a high-level language such as C. We will illustrate both approaches.

A parallel I/O interface generated by the SOPC Builder is accessible by means of registers in the interface. Depending on how the PIO is configured, there may be as many as four registers. One of these registers is called the Data register. In a PIO configured as an input interface, the data read from the Data register is the data currently present on the PIO input lines. In a PIO configured as an output interface, the data written (by the Nios II processor) into the Data register drives the PIO output lines. If a PIO is configured as a bidirectional interface, then the PIO inputs and outputs use the same physical lines. In this case there is a Data Direction register included, which determines the direction of the input/output transfer. In our unidirectional PIOs, it is only necessary to have the Data register. The addresses assigned by the SOPC Builder are 0x00003000 for the Data register in the PIO called Switches and 0x00003010 for the Data register in the PIO called LEDs, as indicated in Figure 14.

4.1 Using a Nios II Assembly Language Program

Figure 20 gives a Nios II assembly-language program that implements our trivial task. The program loads the addresses of the Data registers in the two PIOs into processor registers r2 and r3. It then has an infinite loop that merely transfers the data from the input PIO, Switches, to the output PIO, LEDs.

The program includes the assembler directive `.include`

```
"nios_macros.s"
```

which informs the Assembler to use the Nios II macros that specify how the movia pseudo instructions can be assembled.

```
.include "nios_macros.s"

.equ Switches, 0x00003000
.equ LEDs, 0x00003010

.global _start
_start:
movia r2, Switches
movia r3, LEDs
loop:  ldbio  r4, 0(r2)
      stbio  r4, 0(r3)
      br    loop
```

Figure 20. Assembly language code to control the lights.

The directive

```
.global _start
```

indicates to the Assembler that the label `_start` is accessible outside the assembled object file. This label is the default label we use to indicate to the Linker program the beginning of the application program.

For a detailed explanation of the Nios II assembly language instructions see the tutorial Introduction to the Altera Nios II Soft Processor.

Enter this code into a file `lights.s` and place the file into a working directory. We placed the file into the directory `sopc_builder_tutorial\app_software`. The program has to be assembled and converted into an S-Record file, `lights.srec`, suitable for downloading into the implemented Nios II system. Altera provides the monitor software, called Altera Monitor Program, for use with the DE2-115 board. This software provides a simple means for compiling, assembling and downloading of programs into a Nios II system implemented on a DE2-115 board. It also makes it possible for the user to perform debugging tasks. A description of this software is available in the Altera Monitor Program tutorial. Open the Altera Monitor Program, which leads to the window in Figure 21. This software needs to know the characteristics of the designed Nios II system, which are given in the ptf file `nios_system.ptf`. Click the **File > New Project** menu item to display the New Project Wizard window, shown in Figure 22, and perform the following steps:

1. Enter the `sopc_builder_tutorial` directory as the Project directory by typing it directly into the Project directory field, or by browsing to it using the **Browse...** button.
2. Enter `lights` as the Project name and click **Next >**, leading to Figure 23.
3. From the Select a System drop down box, select **<Custom System>**.
4. Click **Browse...** beside the System Description field to display a file selection window and choose the `nios_system.ptf` file. Note that this file is in the design directory `sopc_builder_tutorial`.
5. Specifying the `.sof` file in the Quartus II Programming (SOF) File field allows the user to download the programming file onto the board from the Altera Monitor Program. Note that we need not specify this file as we have already downloaded the programming file onto the board.
6. Click **Next >**.
7. Select Assembly Program as the program type from the drop down menu and click **Next >**, leading to Figure 24.
8. Click **Add...** to display a file selection window and choose the `lights.s` file and click **Next >**. Note that this file is in the directory `sopc_builder_tutorial/app_software`.
9. Ensure that the Host Connection is set to the USB-Blaster, the Processor is set to **cpu_0** and the Terminal Device is set to the **JTAG UART**, and click **Next >**
10. The Altera Monitor Program also needs to know where to load the application program. In our case, this is the memory block in the FPGA device. The SOPC Builder assigned the name **onchip_memory2_0** to this block. As shown in Figure 25, the Monitor Program has already selected the correct memory device.
11. Having provided the necessary information, click **Finish** to confirm the system configuration.

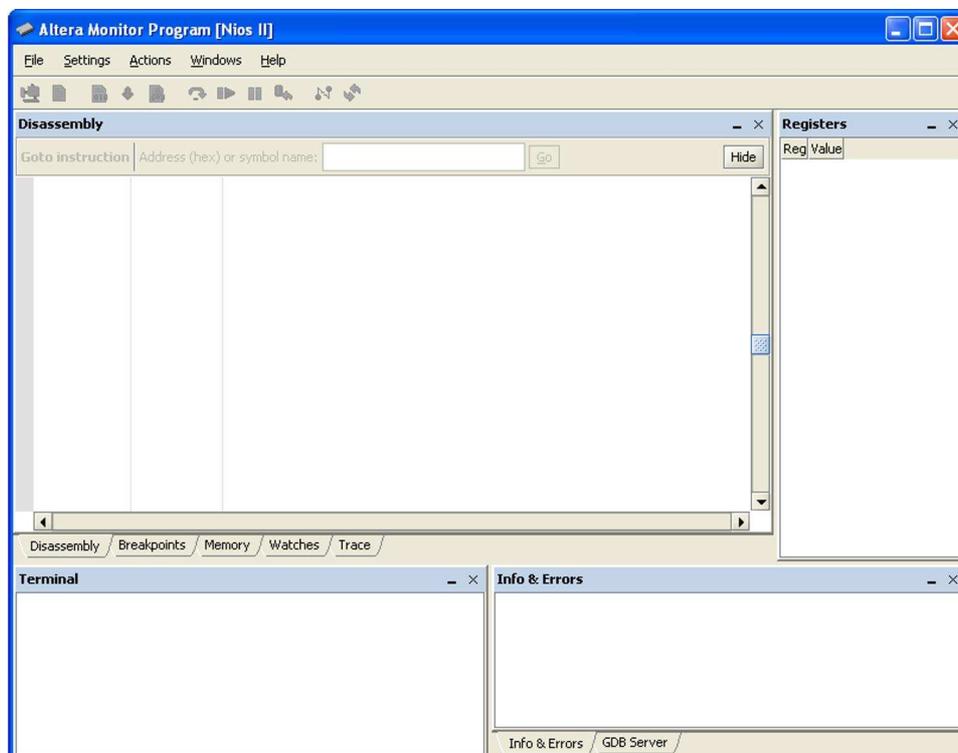


Figure 21. The Altera Monitor Program window on startup.

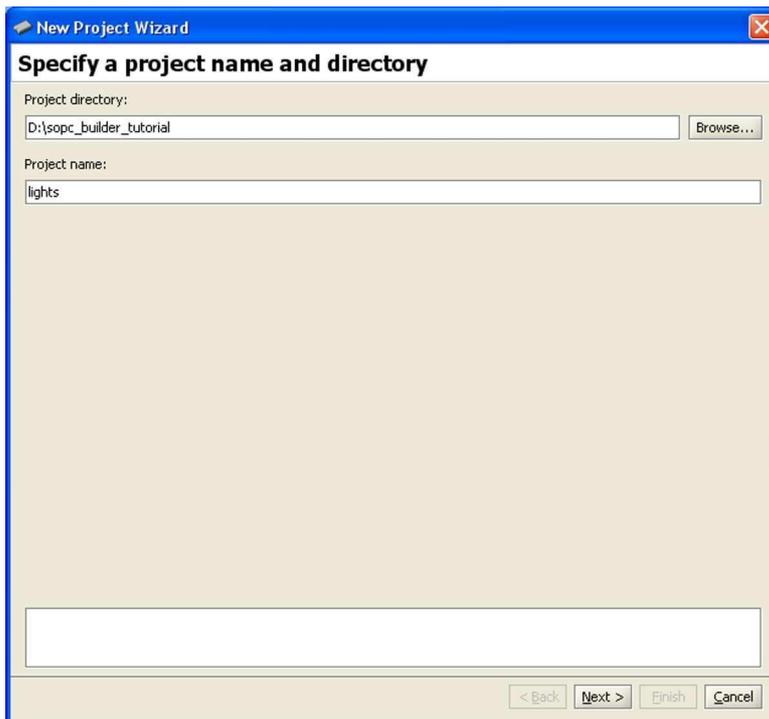


Figure 22. Specify the project directory and name.

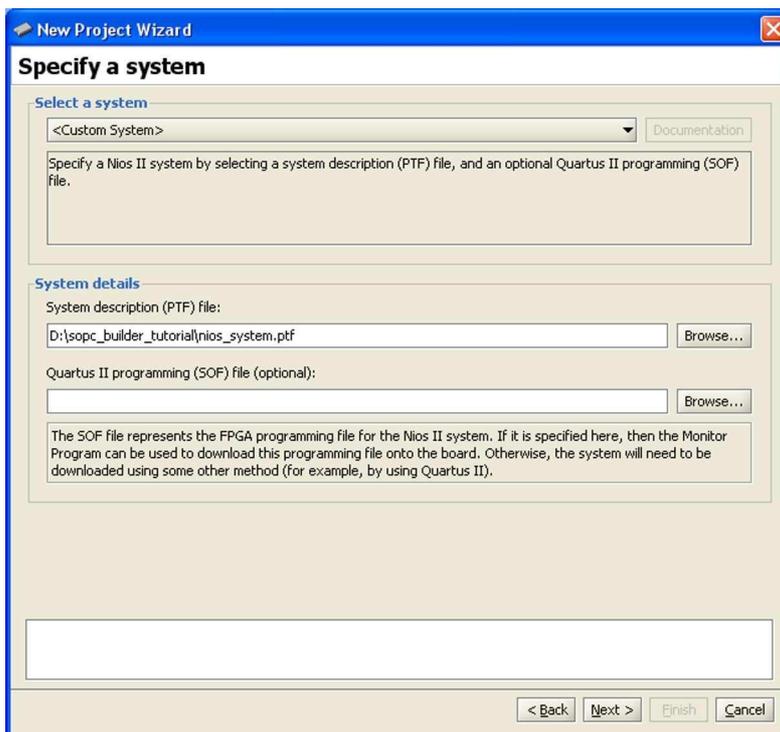


Figure 23. The System Specification window.

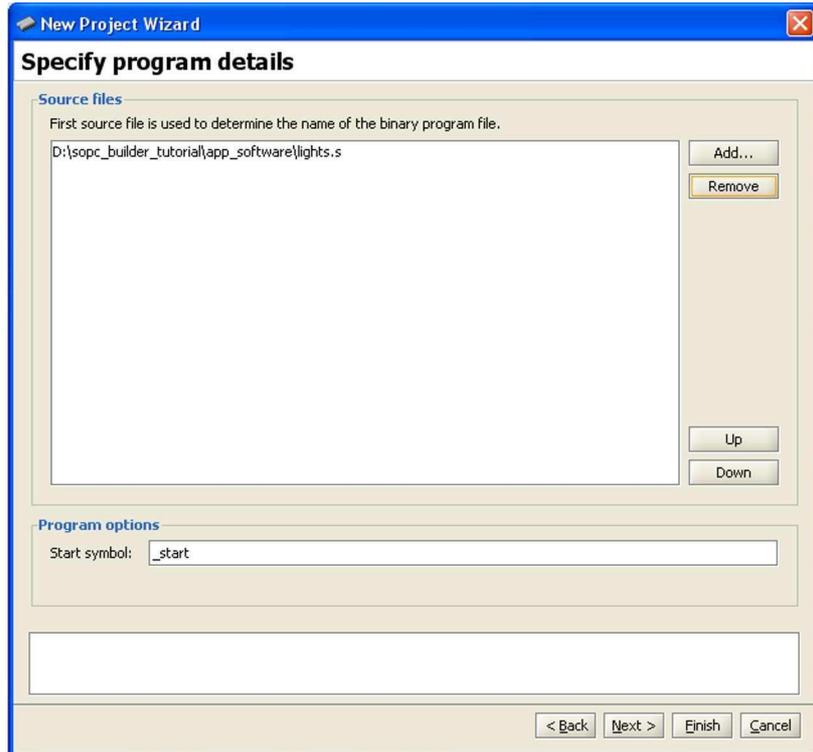


Figure 24. Specify the binary file to use.

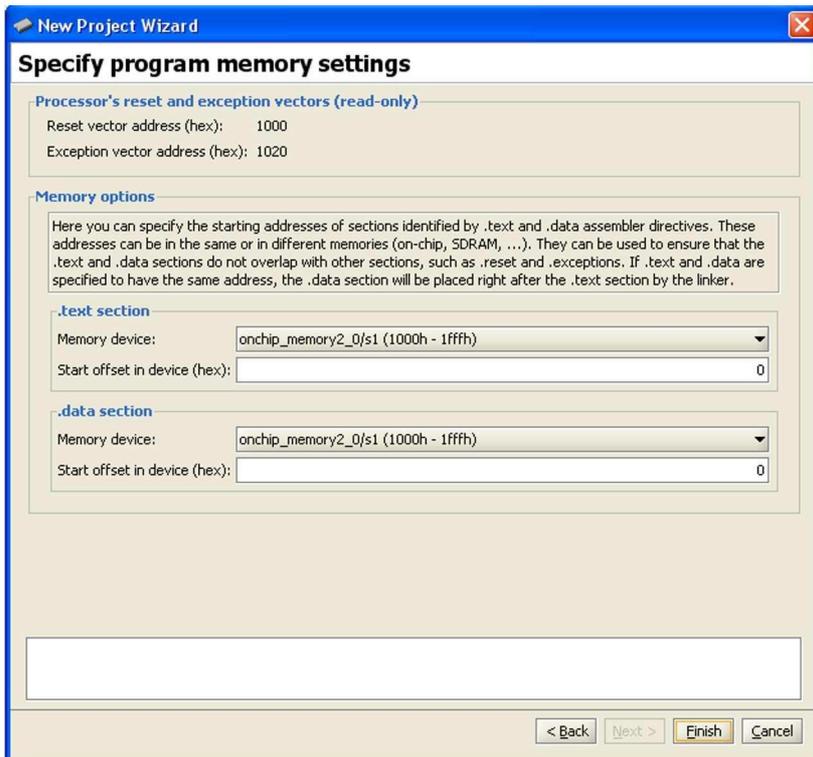


Figure 25. The program memory settings window.

Next, to assemble and download the light.s program, click the **Actions > Compile & Load** menu item. The Altera Monitor Program will invoke an assembler program, followed by a linker program. The commands used to invoke these programs, and the output they produce, can be viewed in the Info & Errors window of the Monitor Program window. After the program has been downloaded onto the board, the program is displayed in the Disassembly window of the Monitor Program as illustrated in Figure 26. Observe that movia is a pseudoinstruction which is implemented as two separate instructions.

Click the **Actions > Continue** menu item to execute the program. With the program running, you can now test the design by turning the switches, SW 7 to SW 0 on and off; the LEDs should respond accordingly.

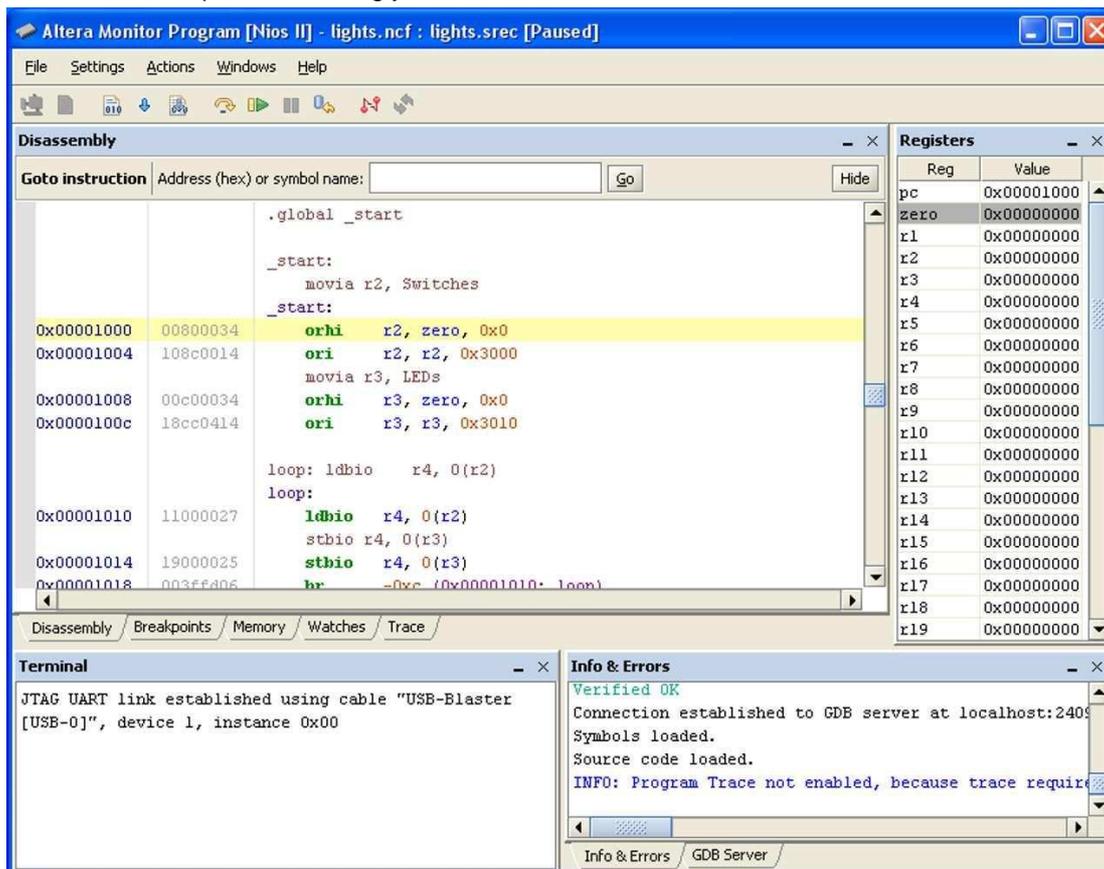


Figure 26. Display of the downloaded program.

The Monitor Program allows a number of useful functions to be performed in a simple manner. They include:

- **single stepping through the program**
- **examining the contents of processor registers**
- **examining the contents of the memory**
- **setting breakpoints for debugging purposes**
- **disassembling the downloaded program**

A description of this software and all of its features is available in the Altera Monitor Program tutorial.

4.2 Using a C-Language Program

An application program written in the C language can be handled in the same way as the assembly-language program. A C program that implements our simple task is given in Figure 25. Enter this code into a file called `lights.c`.

```
#define Switches (volatile char *) 0x0003000
#define LEDs (char *) 0x0003010

void main()
{   while (1)
    *LEDs = *Switches;
}
```

Figure 27.C language code to control the lights.

Perform the following steps to use this program:

1. Disconnect from the current debugging session by clicking the **Actions > Disconnect** menu item.
2. Click the **Settings > Program Settings...** menu item to launch the Project settings window with the Program settings tab selected.
3. Select C Program as the Program Type in the drop-down list. The Monitor Program may prompt you to clear any currently selected source files. Click **Yes** to proceed. Note that `lights.s` has been removed from the list of source files.
4. Click **Add...** and choose the **lights.c** file.
5. Click **Ok** to confirm the new program configuration.

The steps to compile, load, and run the program are the same as for an assembly language program.

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