

Vivado Tutorial

Introduction

This tutorial guides you through the design flow using Xilinx Vivado software to create a simple digital circuit using Verilog HDL. A typical design flow consists of creating model(s), creating user constraint file(s), creating a Vivado project, importing the created models, assigning created constraint file(s), optionally running behavioral simulation, synthesizing the design, implementing the design, generating the bitstream, and finally verifying the functionality in the hardware by downloading the generated bitstream file. You will go through the typical design flow targeting the Artix-7 based Basys3 and Nexys4 DDR boards. The typical design flow is shown below. The circled number indicates the corresponding step in this tutorial.

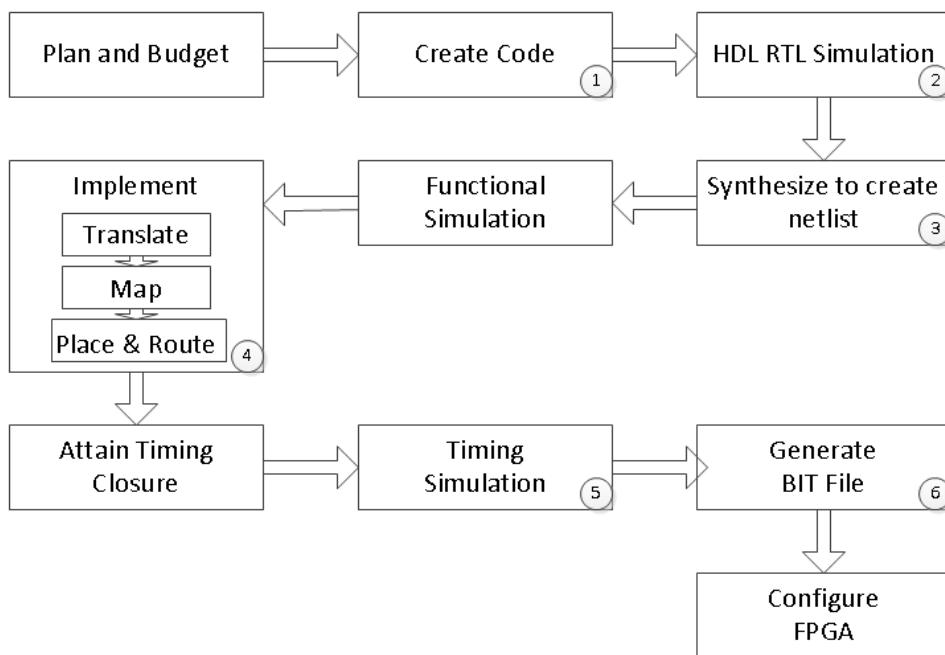


Figure 1. A typical design flow

Objectives

After completing this tutorial, you will be able to:

- Create a Vivado project sourcing HDL model(s) and targeting a specific FPGA device located on the Basys3 and Nexys4 DDR boards
- Use the provided partially completed Xilinx Design Constraint (XDC) file to constrain some of the pin locations
- Add additional constraints using the Tcl scripting feature of Vivado
- Simulate the design using the XSim simulator
- Synthesize and implement the design
- Generate the bitstream
- Configure the FPGA using the generated bitstream and verify the functionality

Procedure

This tutorial is broken into steps that consist of general overview statements providing information on the detailed instructions that follow. Follow these detailed instructions to progress through the tutorial.

Design Description

The design consists of some inputs directly connected to the corresponding output LEDs. Other inputs are logically operated on before the results are output on the remaining LEDs as shown in **Figure 2**.

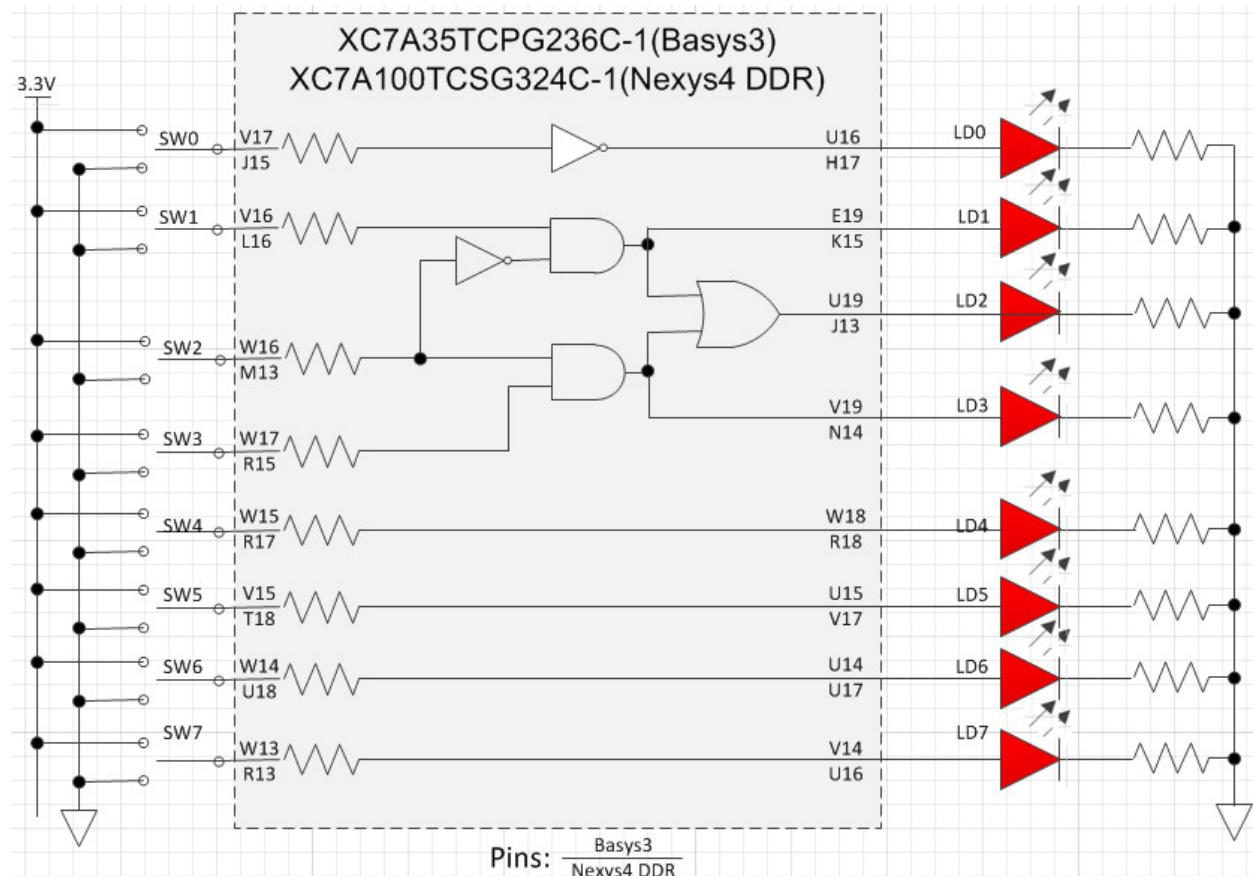


Figure 2. Completed Design

General Flow for this tutorial

- Create a Vivado project and analyze source files
- Simulate the design using XSim simulator
- Synthesize the design
- Implement the design
- Perform the timing simulation
- Verify the functionality in hardware using the Basys3 or Nexys4 DDR board

Create a Vivado Project using IDE

Step 1

- 1-1. Launch Vivado and create a project targeting the xc7a35tcpg236-1 (Basys3) or xc7a100tcsq324-1 (Nexys4 DDR) device and using the Verilog HDL. Use the provided **tutorial.v** and **Nexys4DDR_Master.xdc** or **Basys3_Master.xdc** files from the **sources/tutorial** directory.
 - 1-1-1. Open Vivado by selecting **Start > All Programs > Xilinx Design Tools > Vivado 2015.1 > Vivado 2015.1**
 - 1-1-2. Click **Create New Project** to start the wizard. You will see *Create A New Vivado Project* dialog box. Click **Next**.
 - 1-1-3. Click the **Browse** button of the *Project location* field of the **New Project** form, browse to **c:\xup\digital**, and click **Select**.
 - 1-1-4. Enter **tutorial** in the *Project name* field. Make sure that the *Create Project Subdirectory* box is checked. Click **Next**.

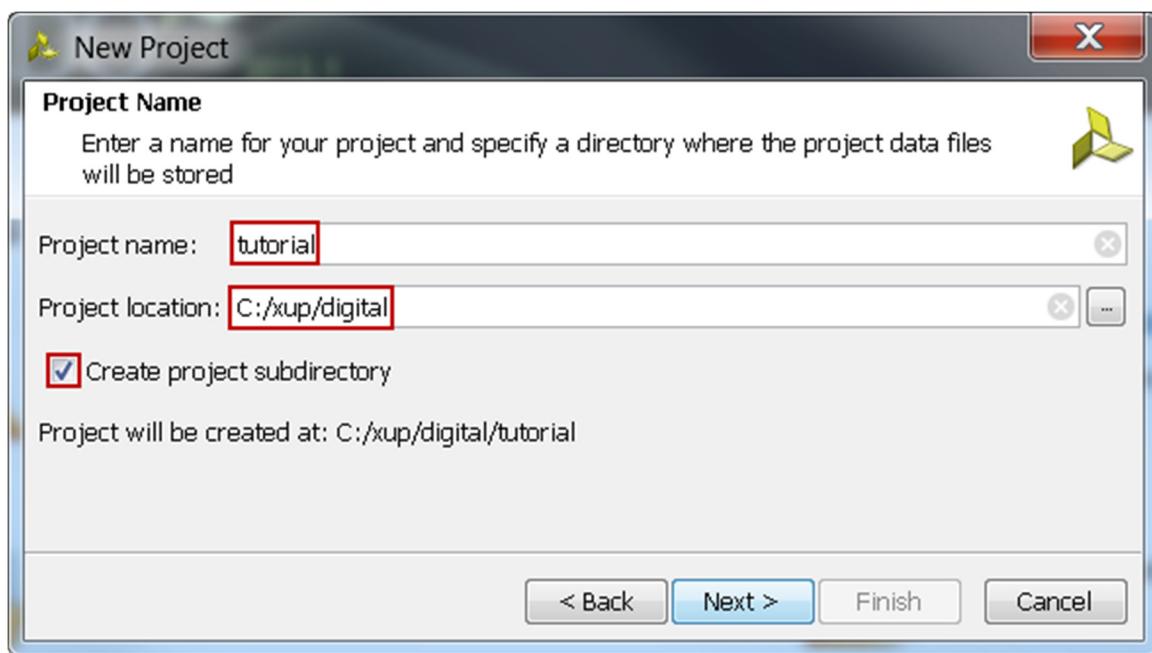


Figure 3. Project Name and Location entry

- 1-1-5. Select **RTL Project** option in the *Project Type* form, and click **Next**.
- 1-1-6. Select **Verilog** as the *Target language* and *Simulator language* in the *Add Sources* form.
- 1-1-7. Click on the **Green Plus** button, then **Add Files...** button, browse to the **c:\xup\digital\sources\tutorial** directory, select **tutorial.v**, click **Open**, and verify the **Copy sources into project** box is checked, then click **Next**.
- 1-1-8. Click **Next** at the *Add Existing IP* form, since we do not have any pre-canned IP to be used in this design.

- 1-1-9.** In the *Add Constraints* form, click on the **Green Plus** button, then the **Add Files...** button, browse to the **c:\xup\digital\sources\tutorial** directory, select **Basys3_Master.xdc** (for Basys3) or **Nexys4DDR_Master.xdc** (for Nexys4 DDR), click **Open**, and then click **Next**.

The XDC constraint file assigns the physical IO locations on FPGA to the switches and LEDs located on the board. This information can be obtained either through a board's schematic or board's user guide.

- 1-1-10.** In the *Default Part* form, using the **Parts** option and various drop-down fields of the **Filter** section, select the **xc7a35tcpg236-1** part (for Basy3) or **xc7a100tcsg324-1** part (for Nexys4 DDR). Click **Next**.

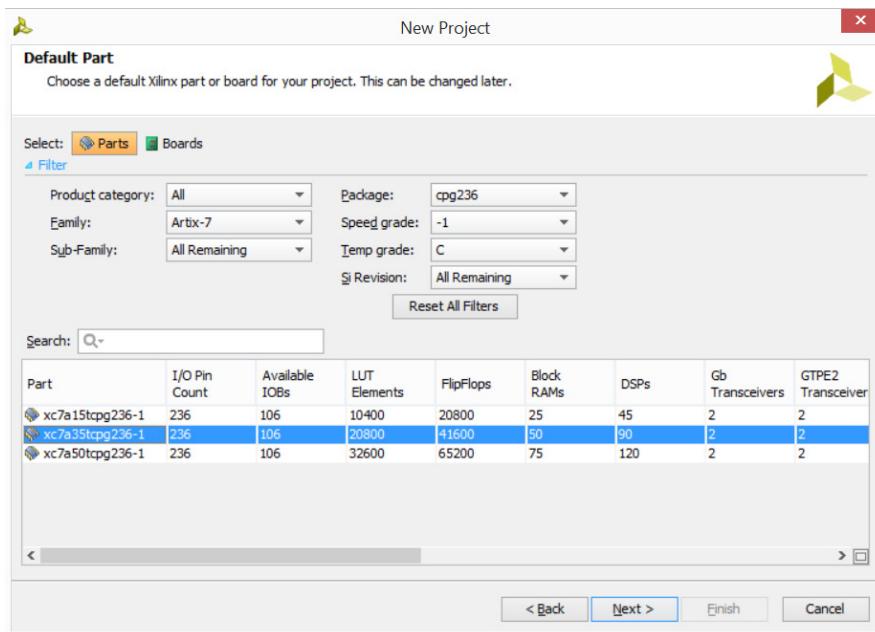


Figure 4. Part Selection for Basys3

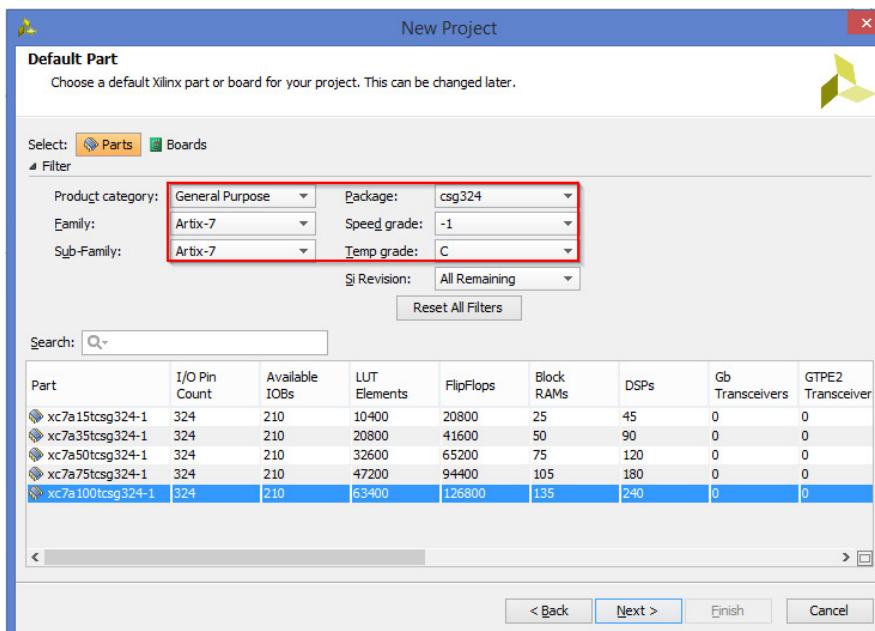


Figure 4. Part Selection for Nexys4 DDR

1-1-11. Click **Finish** to create the Vivado project.

Use the Windows Explorer and look at the **c:\xup\digital\tutorial** directory. You will see that the **tutorial.srcs** and other directories, and the **tutorial.xpr** (Vivado) project file have been created. Two sub-directories, **constrs_1** and **sources_1**, are created under the **tutorial.srcs** directory; deep down under them, the copied *Nexys4DDR_Master.xdc* or *Basys3_Master.xdc* (constraint) and *tutorial.v* (source) files respectively are placed.

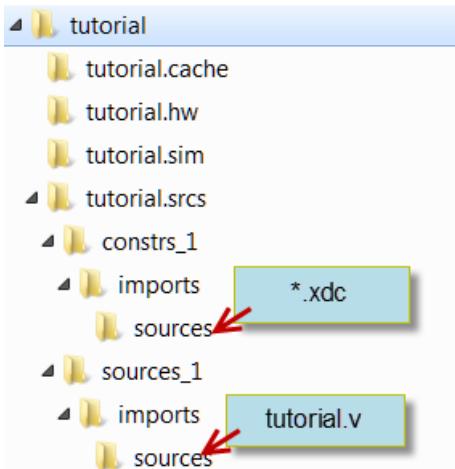


Figure 5. Generated directory structure

1-2. Open the *tutorial.v* source and analyze the content.

1-2-1. In the *Sources* pane, double-click the **tutorial.v** entry to open the file in text mode.

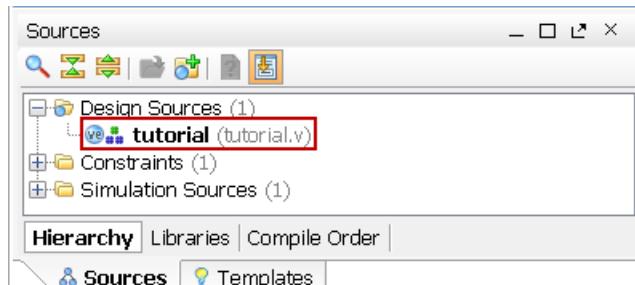


Figure 6. Opening the source file

1-2-2. Notice in the Verilog code that the first line defines the timescale directive for the simulator. Lines 2-5 are comment lines describing the module name and the purpose of the module.

1-2-3. Line 7 defines the beginning (marked with keyword **module**) and Line 19 defines the end of the module (marked with keyword **endmodule**).

1-2-4. Lines 8-9 define the input and output ports whereas lines 12-17 define the actual functionality.

1-3. Open the *Basys3_Master.xdc* or *Nexys4DDR_Master.xdc* source, analyze the content and edit the file.

1-3-1. In the *Sources* pane, expand the *Constraints* folder and double-click the **Basys3_Master.xdc** (*Basys3*) or **Nexys4DDR_Master.xdc** (*Nexys4 DDR*) entry to open the file in text mode.

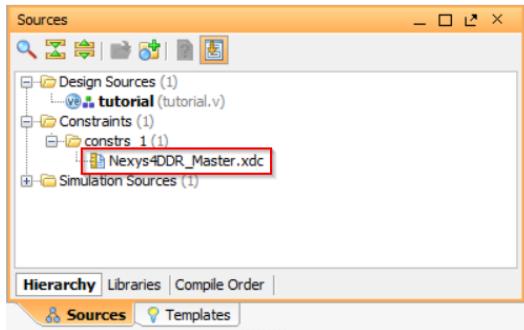


Figure 7. Opening the constraint file

- 1-3-2.** Uncomment the SW[7:0] by deleting the # sign or by highlighting SW[7:0] and pressing CRTL /. Uncomment LED[7:0]. The pin names will need to be changed to match the pin names in the *tutorial.v* file. Change *sw* to *swt* and *LED* to *led*.

```
## LEDs
set_property PACKAGE_PIN U16 [get_ports {led[0]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[0]}]
set_property PACKAGE_PIN E19 [get_ports {led[1]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[1]}]
set_property PACKAGE_PIN U19 [get_ports {led[2]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[2]}]
set_property PACKAGE_PIN V19 [get_ports {led[3]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[3]}]
set_property PACKAGE_PIN W18 [get_ports {led[4]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[4]}]
set_property PACKAGE_PIN U15 [get_ports {led[5]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[5]}]
set_property PACKAGE_PIN U14 [get_ports {led[6]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[6]}]
set_property PACKAGE_PIN V14 [get_ports {led[7]}]
  set_property IOSTANDARD LVCMS33 [get_ports {led[7]}]
#set_property PACKAGE_PIN V13 [get_ports {led[8]}]
  #set_property IOSTANDARD LVCMS33 [get_ports {led[8]}]
## Switches
set_property PACKAGE_PIN V17 [get_ports {sw[0]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[0]}]
set_property PACKAGE_PIN V16 [get_ports {sw[1]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[1]}]
set_property PACKAGE_PIN W16 [get_ports {sw[2]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[2]}]
set_property PACKAGE_PIN W17 [get_ports {sw[3]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[3]}]
set_property PACKAGE_PIN W15 [get_ports {sw[4]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[4]}]
set_property PACKAGE_PIN V15 [get_ports {sw[5]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[5]}]
set_property PACKAGE_PIN W14 [get_ports {sw[6]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[6]}]
set_property PACKAGE_PIN W13 [get_ports {sw[7]}]
  set_property IOSTANDARD LVCMS33 [get_ports {sw[7]}]
#set_property PACKAGE_PIN V12 [get_ports {sw[8]}]
  #set_property IOSTANDARD LVCMS33 [get_ports {sw[8]}]
```

Figure 8. Editing the Basys3 Master XDC

```
set_property -dict { PACKAGE_PIN J15 IOSTANDARD LVCMS33 } [get_ports { swt[0] }]; #IO_L24N_T3_RS0_15 Sch=sv[0]
set_property -dict { PACKAGE_PIN L16 IOSTANDARD LVCMS33 } [get_ports { swt[1] }]; #IO_L3N_TO_DQS_EMCCLK_14 Sch=sv[1]
set_property -dict { PACKAGE_PIN M13 IOSTANDARD LVCMS33 } [get_ports { swt[2] }]; #IO_L6N_TO_D08_VREF_14 Sch=sv[2]
set_property -dict { PACKAGE_PIN R15 IOSTANDARD LVCMS33 } [get_ports { swt[3] }]; #IO_L13N_T2_NRCC_14 Sch=sv[3]
set_property -dict { PACKAGE_PIN R17 IOSTANDARD LVCMS33 } [get_ports { swt[4] }]; #IO_L12N_T1_NRCC_14 Sch=sv[4]
set_property -dict { PACKAGE_PIN T18 IOSTANDARD LVCMS33 } [get_ports { swt[5] }]; #IO_L7N_T1_D10_14 Sch=sv[5]
set_property -dict { PACKAGE_PIN U18 IOSTANDARD LVCMS33 } [get_ports { swt[6] }]; #IO_L17N_T2_A13_D29_14 Sch=sv[6]
set_property -dict { PACKAGE_PIN R13 IOSTANDARD LVCMS33 } [get_ports { swt[7] }]; #IO_L5N_TO_D07_14 Sch=sv[7]
#set_property -dict { PACKAGE_PIN T8 IOSTANDARD LVCMS33 } [get_ports { swt[8] }]; #IO_L24N_T3_34 Sch=sv[8]
#set_property -dict { PACKAGE_PIN P16 IOSTANDARD LVCMS33 } [get_ports { sw[9] }]; #IO_25_34 Sch=sv[9]
#set_property -dict { PACKAGE_PIN R16 IOSTANDARD LVCMS33 } [get_ports { sw[10] }]; #IO_L15P_T2_DOS_RDWR_B_14 Sch=sv[10]
#set_property -dict { PACKAGE_PIN T13 IOSTANDARD LVCMS33 } [get_ports { sw[11] }]; #IO_L23P_T3_A03_D19_14 Sch=sv[11]
#set_property -dict { PACKAGE_PIN H6 IOSTANDARD LVCMS33 } [get_ports { sw[12] }]; #IO_L24P_T3_35 Sch=sv[12]
#set_property -dict { PACKAGE_PIN U12 IOSTANDARD LVCMS33 } [get_ports { sw[13] }]; #IO_L20P_T3_A08_D24_14 Sch=sv[13]
#set_property -dict { PACKAGE_PIN U11 IOSTANDARD LVCMS33 } [get_ports { sw[14] }]; #IO_L19N_T3_A09_D25_VREF_14 Sch=sv[14]
#set_property -dict { PACKAGE_PIN V10 IOSTANDARD LVCMS33 } [get_ports { sw[15] }]; #IO_L21P_T3_D05_14 Sch=sv[15]

## LEDs
set_property -dict { PACKAGE_PIN H17 IOSTANDARD LVCMS33 } [get_ports { led[0] }]; #IO_L18P_T2_A24_15 Sch=led[0]
set_property -dict { PACKAGE_PIN K15 IOSTANDARD LVCMS33 } [get_ports { led[1] }]; #IO_L24P_T3_RS1_15 Sch=led[1]
set_property -dict { PACKAGE_PIN J13 IOSTANDARD LVCMS33 } [get_ports { led[2] }]; #IO_L17N_T2_A25_15 Sch=led[2]
set_property -dict { PACKAGE_PIN N14 IOSTANDARD LVCMS33 } [get_ports { led[3] }]; #IO_L8P_T1_D11_14 Sch=led[3]
set_property -dict { PACKAGE_PIN R18 IOSTANDARD LVCMS33 } [get_ports { led[4] }]; #IO_L7P_T1_D09_14 Sch=led[4]
set_property -dict { PACKAGE_PIN V17 IOSTANDARD LVCMS33 } [get_ports { led[5] }]; #IO_L18N_T2_A11_D27_14 Sch=led[5]
set_property -dict { PACKAGE_PIN U17 IOSTANDARD LVCMS33 } [get_ports { led[6] }]; #IO_L17P_T2_A14_D30_14 Sch=led[6]
set_property -dict { PACKAGE_PIN U16 IOSTANDARD LVCMS33 } [get_ports { led[7] }]; #IO_L18P_T2_A12_D28_14 Sch=led[7]
#set_property -dict { PACKAGE_PIN V16 IOSTANDARD LVCMS33 } [get_ports { LED[8] }]; #IO_L16N_T2_A15_D31_14 Sch=led[8]
#set_property -dict { PACKAGE_PIN T15 IOSTANDARD LVCMS33 } [get_ports { LED[9] }]; #IO_L17N_T2_A16_D32_14 Sch=led[9]
```

Figure 8. Editing the Nexys4 DDR Master XDC

- 1-3-3.** Change the *sw[*]* name to *swt[*]*, and *LED[*]* to *led[*]* as the port names in the model are *swt* and *led*.

- 1-3-4.** Close the *Basys3_Master.xdc* or the *Nexys4DDR_Master.xdc* file saving the changes.

1-4. Perform RTL analysis on the source file.

- 1-4-1. Expand the *Open Elaborated Design* entry under the *RTL Analysis* tasks of the *Flow Navigator* pane and click on **Schematic**.
- 1-4-2. Click **OK** to run the analysis.

The model (design) will be elaborated and a logic view of the design is displayed.

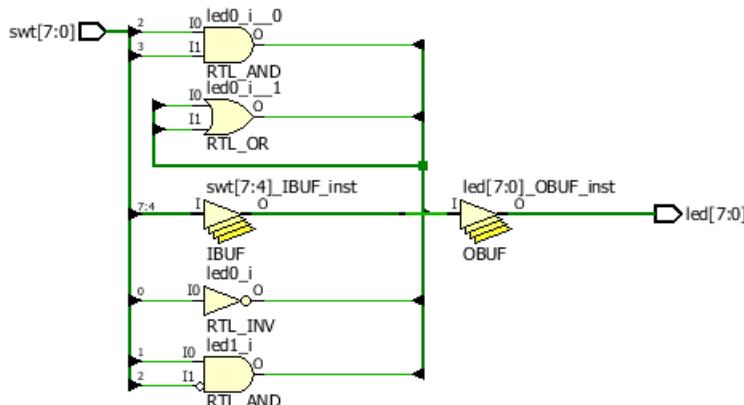


Figure 9. A logic view of the design

Notice that some of the switch inputs go through gates before being output to LEDs and the rest go straight through to LEDs as modeled in the file.

1-5. I/O constraints

- 1-5-1. Once RTL analysis is performed, another standard layout called the *I/O Planning* is available. Click on the drop-down button and select the *I/O Planning* layout.

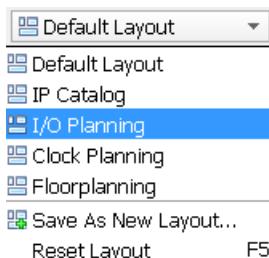


Figure 10. I/O Planning layout selection

Notice that the Package view is displayed in the Auxiliary View area, RTL Netlist tab is selected, and I/O ports tab is displayed in the Console View area. Also notice that design ports (*led* and *swt*) are listed in the I/O Ports tab with both having multiple I/O standards.

Move the mouse cursor over the Package view, highlighting different pins. Notice the pin site number is shown at the bottom of the Vivado GUI, along with the pin type (User IO, GND, VCCO...) and the I/O bank it belongs to.

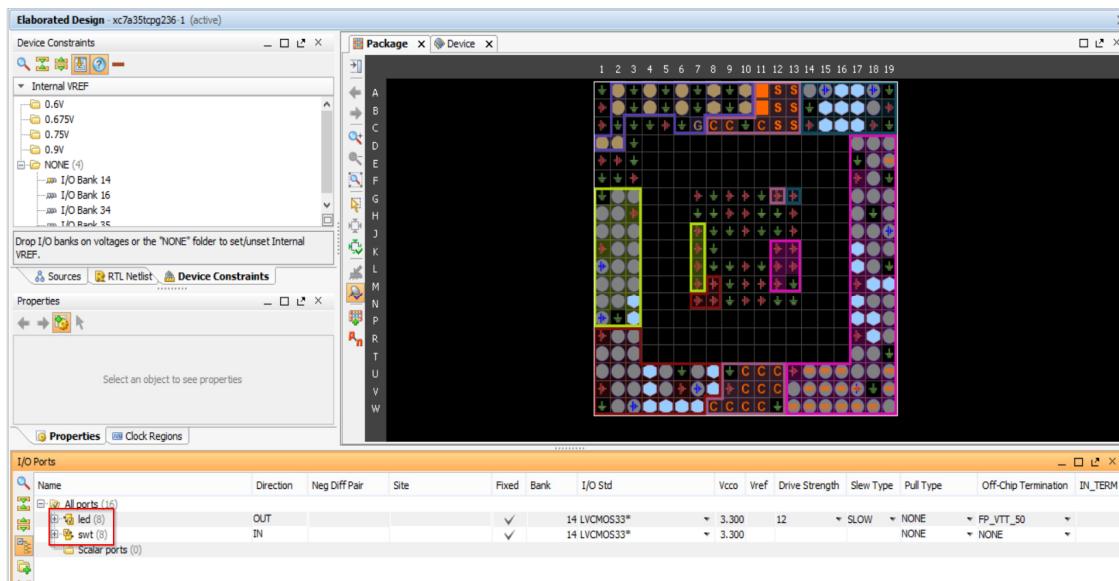


Figure 11. I/O Planning layout view for Basys3

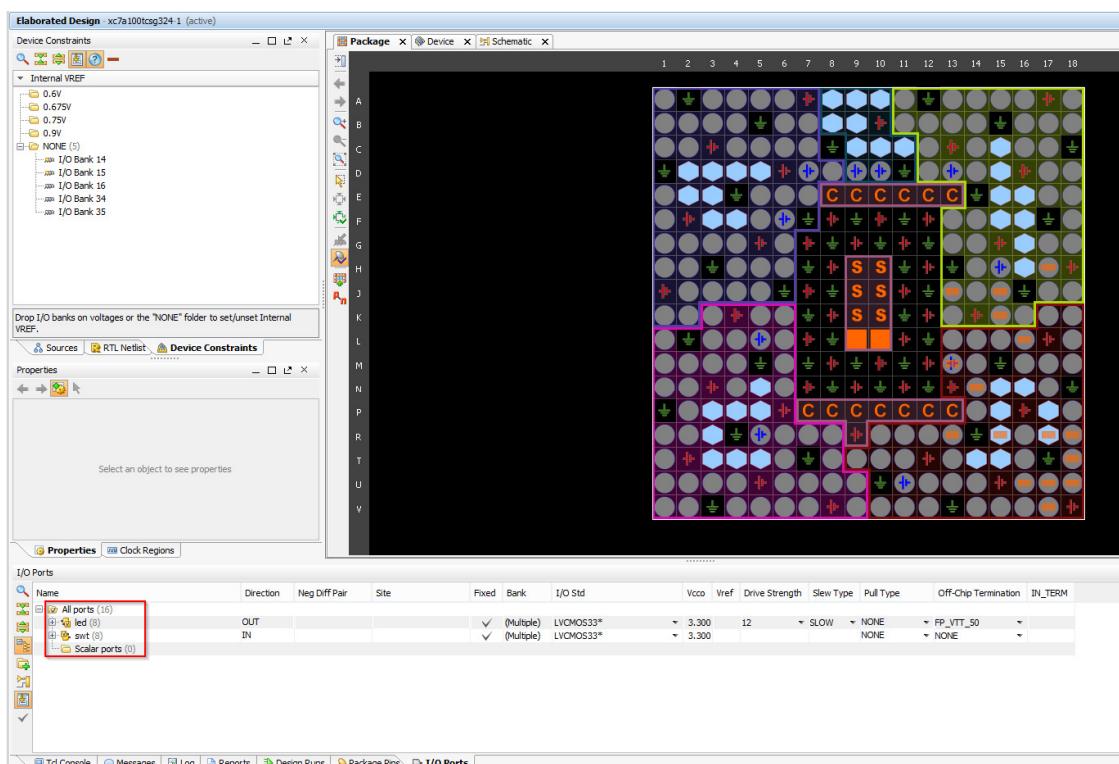


Figure 11. I/O Planning layout view for Nexys4 DDR

You can expand the **led** and **swt** ports by clicking on the + box and observe that **led [7:0]** and **swt[7:0]** have assigned pins and uses LVCMS33 I/O standard. To change the I/O Standard, you would click in the **I/O Std** of the desired port and select the appropriate I/O Standard. The master XDC file already has the correct I/O Standard from editing the file in step 1-3-3.

Name	Direction	Neg Diff Pair	Site	Fixed	Bank	I/O Std	Vcco	Vref	Drive Strength	Slew Type	Pull Type	Off-Chip Termination	IN_TERM
All ports (16)													
led (8)	OUT			✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[7]	OUT		V14	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[6]	OUT		U14	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[5]	OUT		U15	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[4]	OUT		W18	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[3]	OUT		V19	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[2]	OUT		U19	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[1]	OUT		E19	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
led[0]	OUT		U16	✓		14 LVC MOS33*	✓	3.300	12	✓ SLOW	✓ NONE	✓ FP_VTT_50	✓
svt (8)	IN			✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[7]	IN		W13	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[6]	IN		W14	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[5]	IN		V15	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[4]	IN		W15	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[3]	IN		W17	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[2]	IN		W16	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[1]	IN		V16	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
svt[0]	IN		V17	✓		14 LVC MOS33*	✓	3.300		✓ NONE	✓ NONE	✓ NONE	✓
Scalar ports (0)													

Figure 12. I/O Ports tab for Basys3

Name	Direction	Neg Diff Pair	Site	Fixed	Bank	I/O Std
All ports (16)						
led (8)	OUT			✓		(Multiple) LVC MOS33*
led[7]	OUT		U16	✓		14 LVC MOS33*
led[6]	OUT		U17	✓		14 LVC MOS33*
led[5]	OUT		V17	✓		14 LVC MOS33*
led[4]	OUT		R18	✓		14 LVC MOS33*
led[3]	OUT		N14	✓		14 LVC MOS33*
led[2]	OUT		J13	✓		15 LVC MOS33*
led[1]	OUT		K15	✓		15 LVC MOS33*
led[0]	OUT		H17	✓		15 LVC MOS33*
svt (8)	IN			✓		(Multiple) LVC MOS33*
svt[7]	IN		R13	✓		14 LVC MOS33*
svt[6]	IN		U18	✓		14 LVC MOS33*
svt[5]	IN		T18	✓		14 LVC MOS33*
svt[4]	IN		R17	✓		14 LVC MOS33*
svt[3]	IN		R15	✓		14 LVC MOS33*
svt[2]	IN		M13	✓		14 LVC MOS33*
svt[1]	IN		L16	✓		14 LVC MOS33*
svt[0]	IN		J15	✓		15 LVC MOS33*
Scalar ports (0)						

Figure 12. I/O Ports tab for Nexys4 DDR

The ports are already assigned the pins. If you would like to assign pins in this view, you would click under the **Site** column across the desire port row to bring up a drop-down box. Type in the appropriate **Port Variable** to jump to the pins with that variable. Scroll-down until you see the correct port name, and then select it and hit the *Enter* key to assign the pin.

Name	Direction	Neg Diff...	Site	Fixed	Bank	I/O Std	Vco
All ports (16)							
led (8)	OUT			✓		(Mu... LVC MOS33*	3.
led[7]	OUT		U1	✓		14 LVC MOS33*	3.
led[6]	OUT		U1	✓		14 LVC MOS33*	3.
led[5]	OUT		U11	✓		14 LVC MOS33*	3.
led[4]	OUT		U12	✓		14 LVC MOS33*	3.
led[3]	OUT		U13	✓		14 LVC MOS33*	3.
led[2]	OUT		U14	✓		15 LVC MOS33*	3.
led[1]	OUT		U14	✓		15 LVC MOS33*	3.
led[0]	OUT		U17	✓		15 LVC MOS33*	3.
svt (8)	IN		U18	✓		(Mu... LVC MOS33*	3.
Scalar ports (0)							

Figure 13. Assigning pin location

You can also assign the pin by selecting its entry in the I/O ports tab, and dragging it to the Package view, and placing it at the desired location

You can also assign the I/O standard by selecting its entry in the I/O Ports tab, selecting the Configure tab of the I/O Port Properties window, followed by clicking the drop-down button of the I/O standard field, selecting LVCMOS33.

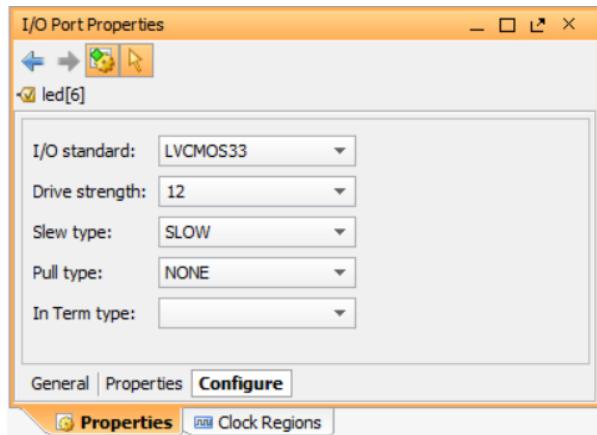


Figure 14. Assigning I/O standard through the I/O Port Properties form

You can also assign the pin constraints and I/O standards using tcl commands, by typing the command in the Tcl Console tab to assign the R13 pin location and the LVCSMOS33 I/O like shown below and hitting the Enter key after the command.

```
set_property -dict { PACKAGE_PIN R13    IO_STANDARD LVCMOS33 } [get_ports
{ swt[7] }];
```

Simulate the Design using the XSim Simulator

Step 2

2-1. Add the tutorial_tb.v testbench file.

- 2-1-1. Click **Add Sources** under the *Project Manager* tasks of the *Flow Navigator* pane.

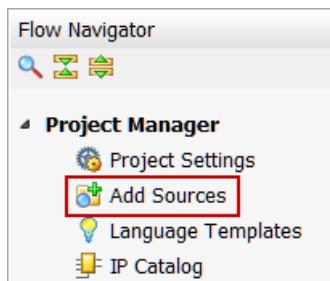


Figure 15. Add Sources

- 2-1-2. Select the *Add or Create Simulation Sources* option and click **Next**.

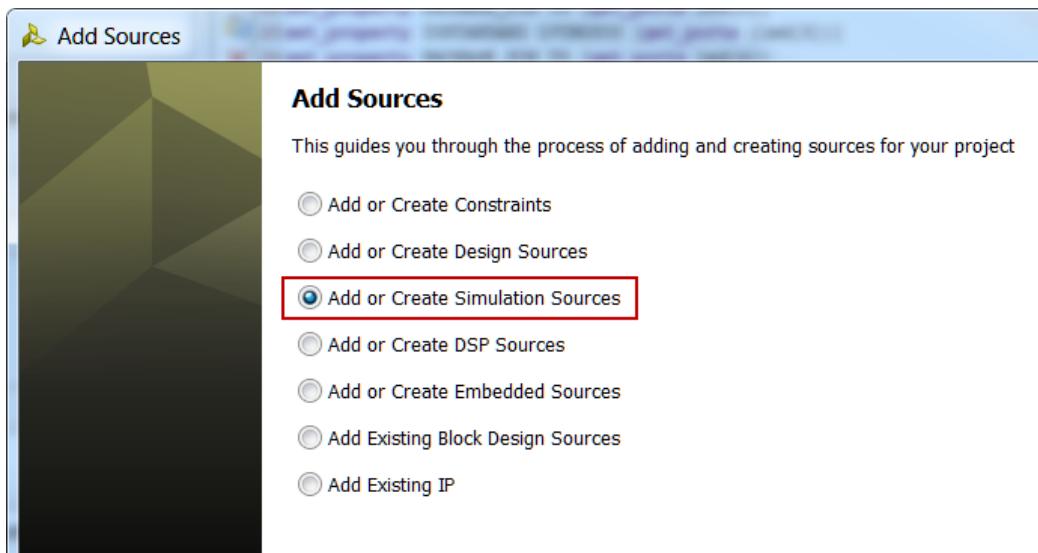


Figure 16. Selecting Simulation Sources option

- 2-1-3. In the *Add Sources Files* form, click the **Green Plus** button then click the **Add Files...** button.
- 2-1-4. Browse to the **c:\xup\digital\sources\tutorial** folder and select **tutorial_tb.v** and click **OK**.
- 2-1-5. Click **Finish**.
- 2-1-6. Select the *Sources* tab and expand the *Simulation Sources* group.

The **tutorial_tb.v** file is added under the *Simulation Sources* group, and **tutorial.v** is automatically placed in its hierarchy as a **tut1** instance.

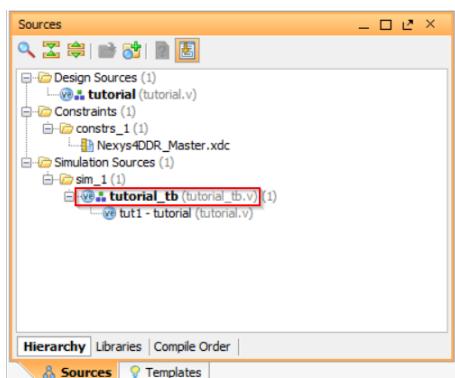


Figure 17. Simulation Sources hierarchy

- 2-1-7. Using the Windows Explorer, verify that the **sim_1** directory is created at the same level as **constrs_1** and **sources_1** directories under the **tutorial.srcs** directory, and that a copy of **tutorial_tb.v** is placed under **tutorial.srcs > sim_1 > imports > sources**.
- 2-1-8. Double-click on the **tutorial_tb** in the *Sources* pane to view its contents.

```

1 `timescale 1ns / 1ps
2 ///////////////////////////////////////////////////////////////////
3 // Module Name: tutorial_tb
4 ///////////////////////////////////////////////////////////////////
5 module tutorial_tb(
6
7     );
8
9     reg [7:0] switches;
10    wire [7:0] leds;
11    reg [7:0] e_led;
12
13    integer i;
14
15    tutorial tutl(.led(leds),.swt(switches));
16
17    function [7:0] expected_led;
18        input [7:0] swt;
19    begin
20        expected_led[0] = ~swt[0];
21        expected_led[1] = swt[1] & ~swt[2];
22        expected_led[3] = swt[2] & swt[3];
23        expected_led[2] = expected_led[1] | expected_led[3];
24        expected_led[7:4] = swt[7:4];
25    end
26    endfunction
27
28    initial
29    begin
30        for (i=0; i < 255; i=i+2)
31        begin
32            #50 switches=i;
33            #10 e_led = expected_led(switches);
34            if(leds == e_led)
35                $display("LED output matched at ", $time);
36            else
37                $display("LED output mis-matched at ", $time, ": expected: %b, actual: %b", e_led, leds);
38        end
39    end
40
41 endmodule

```

Figure 18. The self-checking testbench

The testbench defines the simulation step size and the resolution in line 1. The testbench module definition begins on line 5. Line 15 instantiates the DUT (device/module under test). Lines 17 through 26 define the same module functionality for the expected value computation. Lines 28 through 39 define the stimuli generation and compares the expected output with what the DUT provides. Line 41 ends the testbench. The \$display task will print the message in the simulator console window when the simulation is run.

2-2. Simulate the design for 200 ns using the XSim simulator.

- 2-2-1.** Select **Simulation Settings** under the *Project Manager* tasks of the *Flow Navigator* pane.

A **Project Settings** form will appear showing the **Simulation** properties form.

- 2-2-2.** Select the **Simulation** tab, and set the **Simulation Run Time** value to 200 ns and click **OK**.

- 2-2-3.** Click on **Run Simulation > Run Behavioral Simulation** under the *Flow Navigator* pane.

The testbench and source files will be compiled and the XSim simulator will be run (assuming no errors). You will see a simulator output similar to the one shown below.

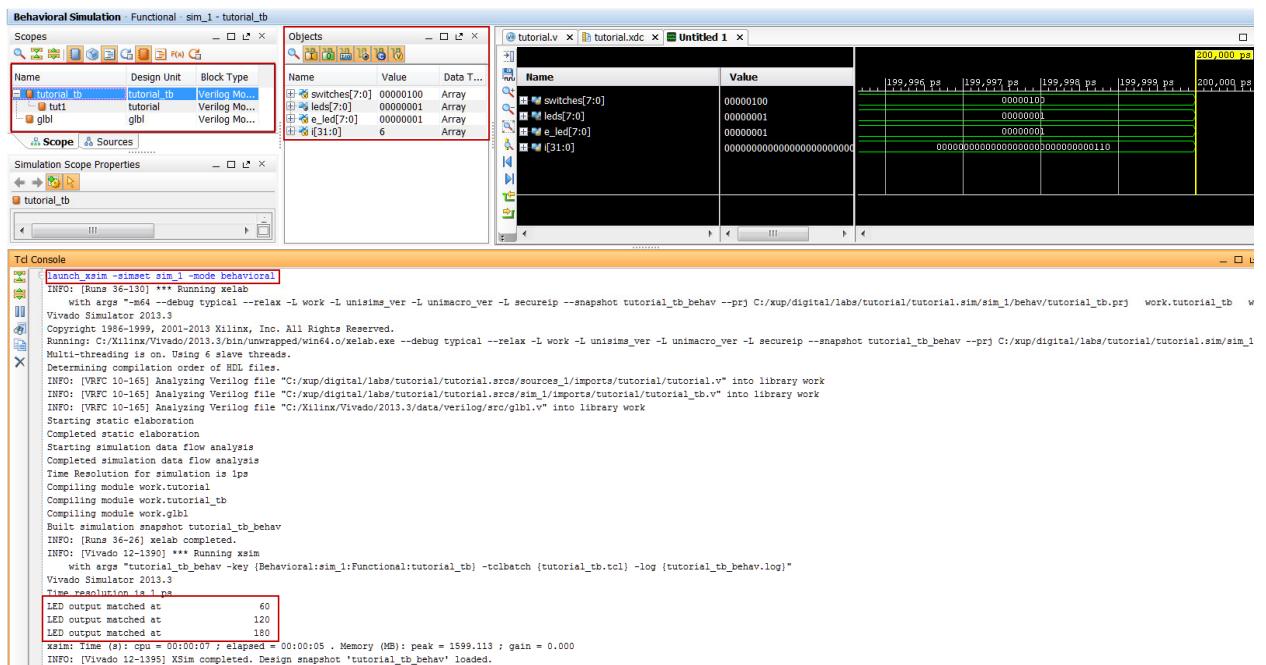


Figure 19. Simulator output

You will see four main views: (i) *Scopes*, where the testbench hierarchy as well as gbl instances are displayed, (ii) *Objects*, where top-level signals are displayed, (iii) the waveform window, and (iv) *Tcl Console* where the simulation activities are displayed. Notice that since the testbench used is self-checking, the results are displayed as the simulation is run.

Notice that the **tutorial.sim** directory is created under the **tutorial** directory, along with several lower-level directories.

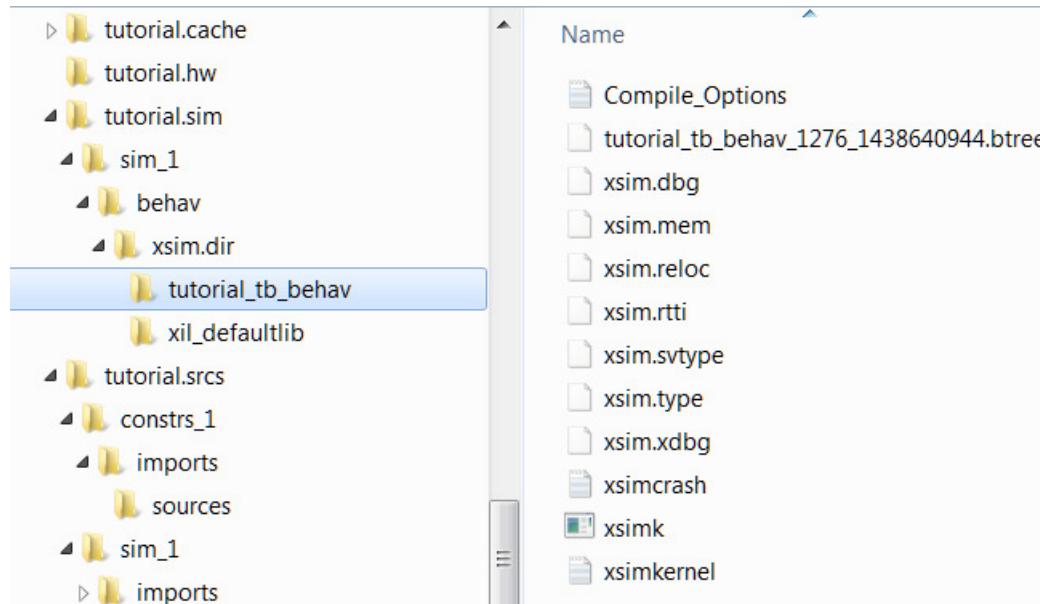


Figure 20. Directory structure after running behavioral simulation

Please refer to the following URL:

http://www.xilinx.com/support/documentation/sw_manuals/xilinx2015_1/ug900-vivado-logic-simulation.pdf to learn more about the Vivado simulator.

- 2-2-4.** Click on the *Zoom Fit* button () located left of the waveform window to see the entire waveform.

Notice that the output changes when the input changes.

You can also float the simulation waveform window by clicking on the **Float** button on the upper right hand side of the view. This will allow you to have a wider window to view the simulation waveforms. To reintegrate the floating window back into the GUI, simply click on the **Dock Window** button.

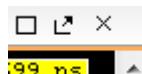


Figure 21. Float Button



Figure 22. Dock Window Button

2-3. Change display format if desired.

- 2-3-1.** Select **i[31:0]** in the waveform window, right-click, select *Radix*, and then select *Unsigned Decimal* to view the for-loop index in *integer* form. Similarly, change the radix of **switches[7:0]** to *Hexadecimal*. Leave the **leds[7:0]** and **e_led[7:0]** radix to *binary* as we want to see each output bit.
- 2-4. Add more signals to monitor lower-level signals and continue to run the simulation for 500 ns.**

- 2-4-1.** Expand the **tutorial_tb** instance, if necessary, in the **Scopes** window and select the **tut1** instance.

The **swt[7:0]** and **led[7:0]** signals will be displayed in the **Objects** window.

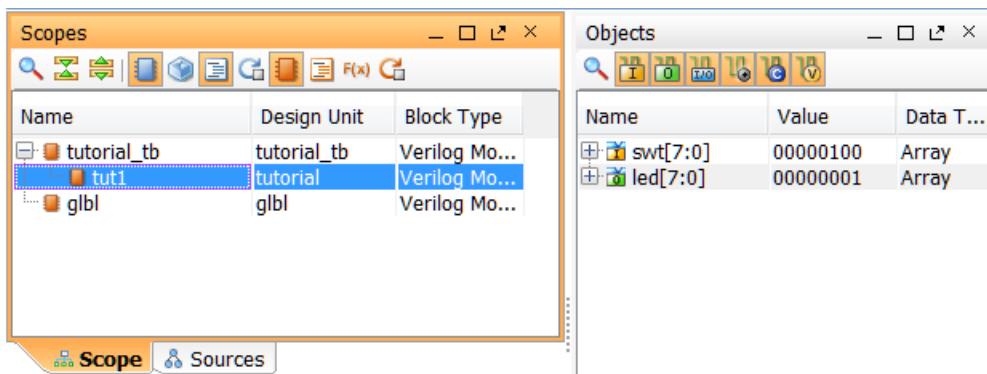


Figure 23. Selecting lower-level signals

- 2-4-2.** Select **swt[7:0]** and **led[7:0]** and drag them into the waveform window to monitor those lower-level signals. You can also add the signals by right-clicking and selecting **Add to Wave Window**.

- 2-4-3.** On the simulator tool buttons ribbon bar, type 500 in the  time window, click on the drop-down button of the units field and select ns, and click on the () button.

The simulation will run for an additional 500 ns.

- 2-4-4.** Click on the *Zoom Fit* button and observe the output.

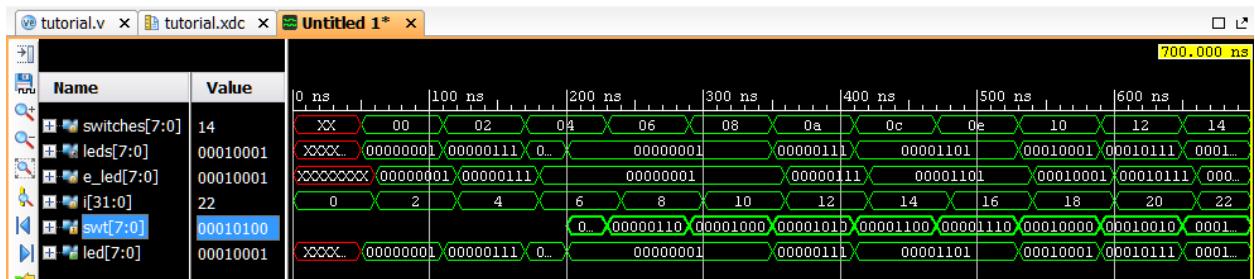


Figure 24. Running simulation for additional 500 ns

- 2-4-5.** Close the simulator by selecting **File > Close Simulation**.

- 2-4-6.** Click **OK** and then click **Discard** to close it without saving the waveform.

Synthesize the Design

Step 3

- 3-1. Synthesize the design with the Vivado synthesis tool and analyze the Project Summary output.**

- 3-1-1.** Click on **Run Synthesis** under the *Synthesis* tasks of the *Flow Navigator* pane.

The synthesis process will be run on the tutorial.v file (and all its hierarchical files if they exist). When the process is completed a *Synthesis Completed* dialog box with three options will be displayed.

- 3-1-2.** Select the *Open Synthesized Design* option and click **OK** as we want to look at the synthesis output before progressing to the implementation stage.

Click **Yes** to close the elaborated design if the dialog box is displayed.

- 3-1-3.** Select the **Project Summary**  tab (Select default layout if the tab is not visible) and understand the various windows.

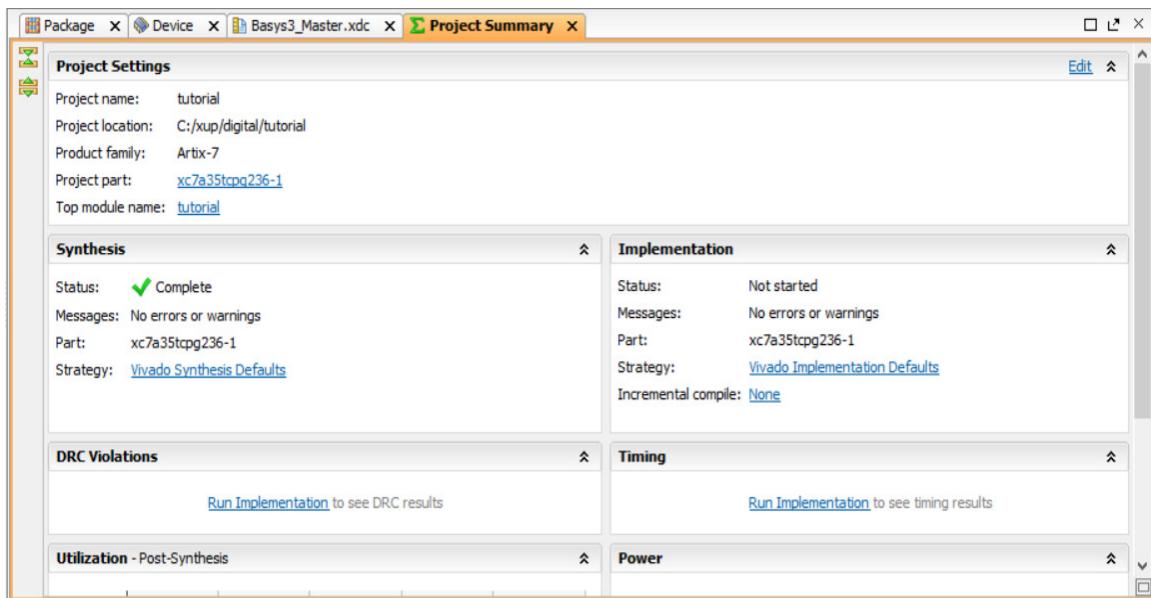


Figure 25. Project Summary view for Basys3

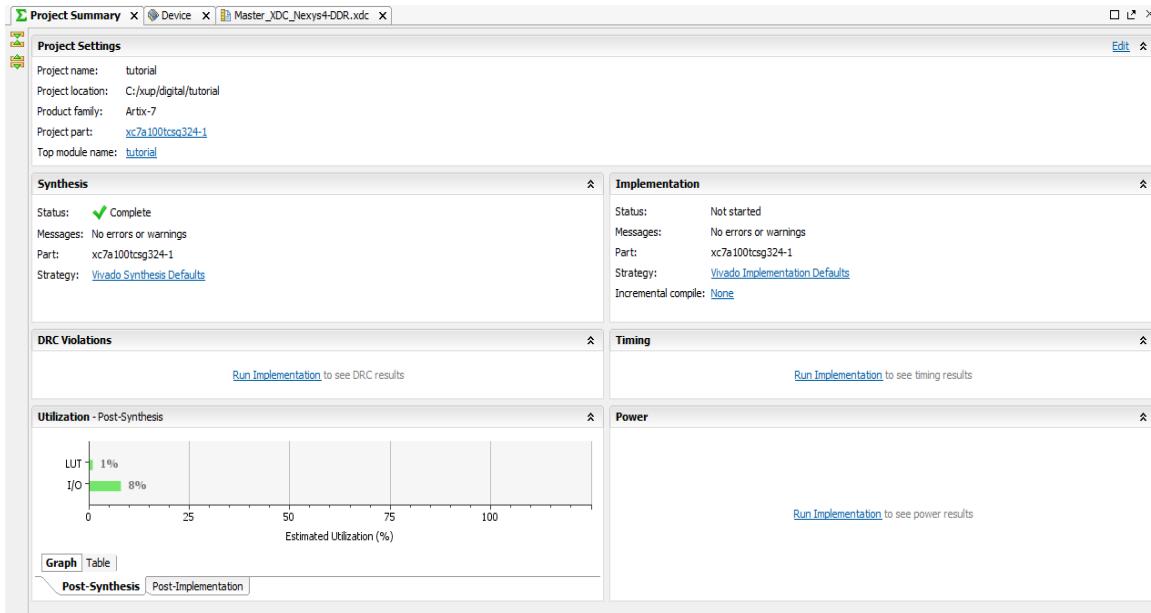


Figure 25. Project Summary view for Nexys4 DDR

Click on the various links to see what information they provide and which allows you to change the synthesis settings.

3-1-4. Click on the **Table** tab in the **Project Summary** tab.

Notice that there are an estimated three LUTs and 16 IOs (8 input and 8 output) that are used.

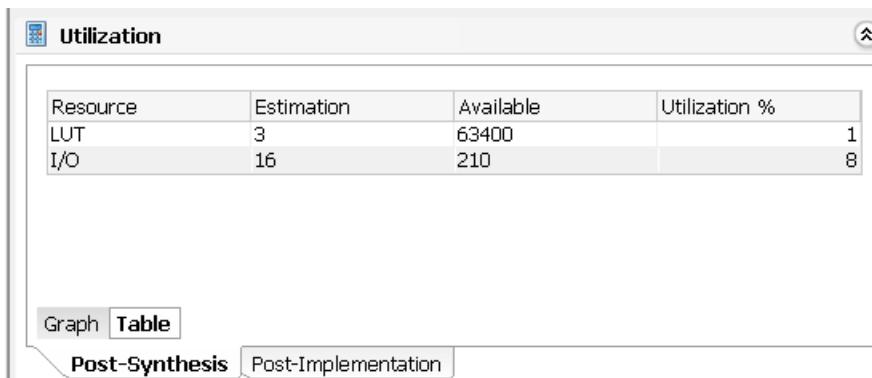


Figure 26. Resource utilization estimation summary

- 3-1-5. Click on **Schematic** under the *Open Synthesized Design* tasks of *Synthesis* tasks of the *Flow Navigator* pane to view the synthesized design in a schematic view.

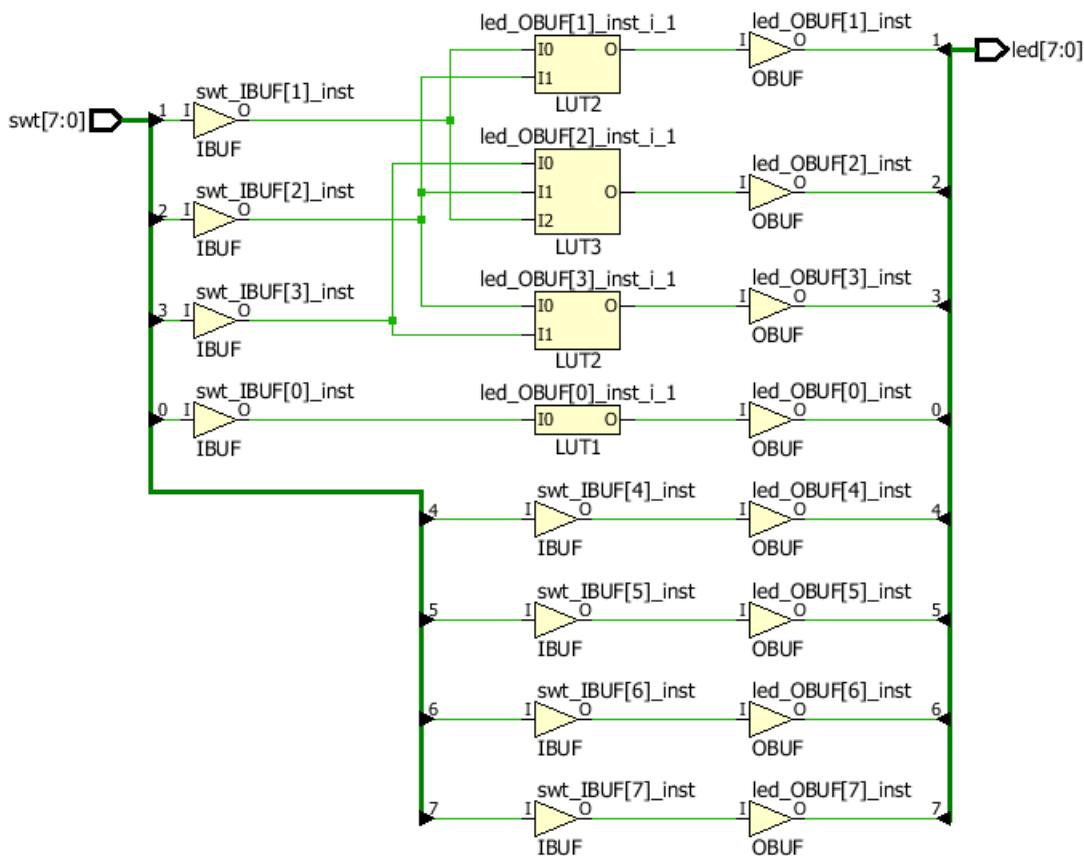


Figure 27. Synthesized design's schematic view

Notice that `IBUF` and `OBUF` are automatically instantiated (added) to the design as the input and output are buffered. The logical gates are implemented in LUTs (1 input is listed as LUT1, 2 input is listed as LUT2, and 3 input is listed as LUT3). Four gates in RTL analysis output is mapped into four LUTs in the synthesized output.

Using the Windows Explorer, verify that `tutorial.runs` directory is created under `tutorial`. Under the `runs` directory, `synth_1` directory is created which holds several temporary sub-directories.

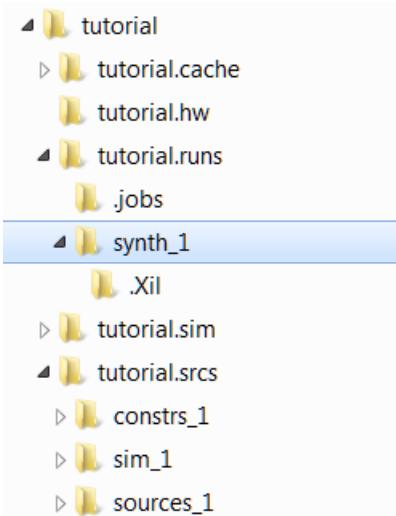


Figure 28. Directory structure after synthesizing the design

Implement the Design

Step 4

4-1. Implement the design with the Vivado Defaults Implementation settings and analyze the Project Summary output.

- 4-1-1. Click on **Run Implementation** under the *Implementation* tasks of the *Flow Navigator* pane.

The implementation process will be run on the synthesis output files. When the process is completed an *Implementation Completed* dialog box with three options will be displayed.

- 4-1-2. Select **Open implemented design** and click **OK** as we want to look at the implemented design in a Device view tab.

- 4-1-3. Click **Yes** to close the synthesized design.

The implemented design will be opened.

- 4-1-4. In the *Netlist* pane, select one of the nets (e.g. led_OBUF[1]) and notice that the net displayed in the X0Y0 clock region for Basys3 and the X0Y1 and X0Y2 clock regions for Nexys4 DDR in the Device view tab (you may have to zoom in to see it).

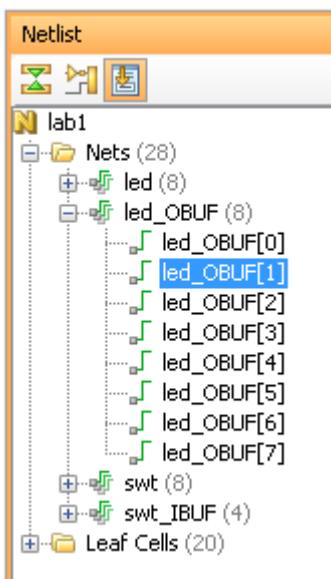


Figure 29. Selecting a net

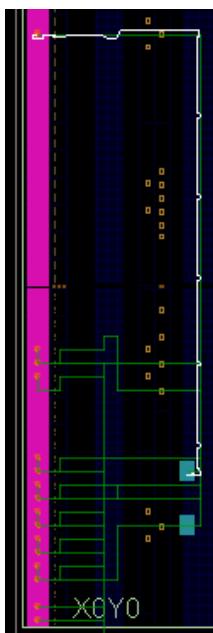


Figure 29. Viewing implemented design for Basys3

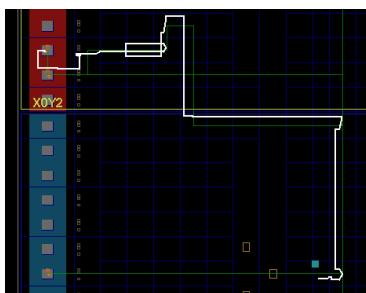


Figure 29. Viewing implemented design for Nexys4 DDR

- 4-1-5.** Close the implemented design view by selecting **File > Close Implemented Design**, and select the **Project Summary** tab (you may have to change to the Default Layout view) and observe the results.

Notice that the actual resource utilization is three LUTs and 16 IOs. Also, it indicates that no timing constraints were defined for this design (since the design is combinatorial). Select the **Post-implementation** tabs under the *Timing* and *Utilization* windows.

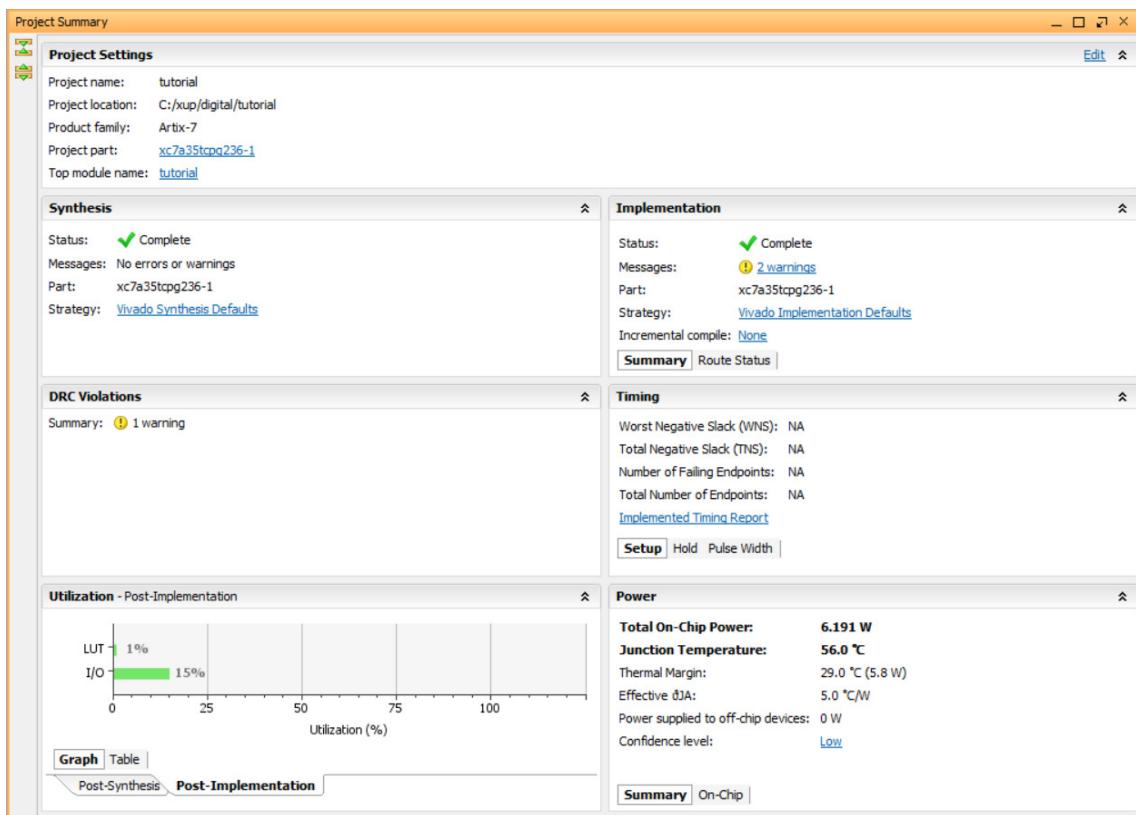


Figure 30. Implementation results

Using the Windows Explorer, verify that **impl_1** directory is created at the same level as **synth_1** under the **tutorial_runs** directory. The **impl_1** directory contains several files including the report files.

- 4-1-6.** Select the *Report Utilization* entry under the *Synthesized Design* under the Flow Navigator. The report will be displayed in the auxiliary view pane showing resources utilization. Note that since the design is combinatorial no registers are used.

Perform Timing Simulation

Step 5

5-1. Run a timing simulation.

- 5-1-1.** Select **Run Simulation > Run Post-Implementation Timing Simulation** process under the *Simulation* tasks of the *Flow Navigator* pane.

The XSim simulator will be launched using the implemented design and **tutorial_tb** as the top-level module.

Using the Windows Explorer, verify that **timing** directory is created under the **tutorial.sim > sim_1 > impl** directory. The **timing** directory contains generated files to run the timing simulation.

- 5-1-2. Click on the **Zoom Fit** button to see the waveform window from 0 to 200 ns.
- 5-1-3. Right-click at 50 ns (where the switch input is set to 0000000b) and select **Markers > Add Marker**.
- 5-1-4. Similarly, right-click and add a marker at around 55.000 ns where the **leds** changes.
- 5-1-5. You can also add a marker by clicking on the Add Marker button (). Click on the **Add Marker** button and left-click at around 60 ns where **e_led** changes.

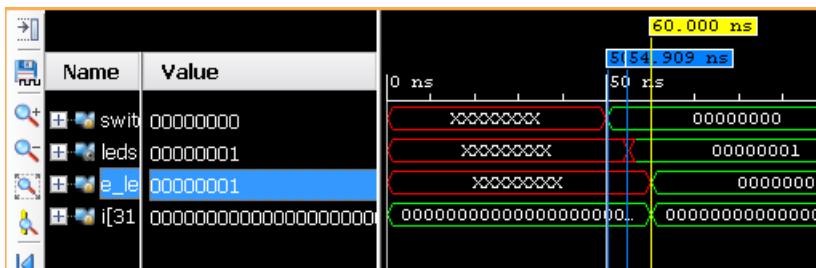


Figure 31. Timing simulation output

Notice that we monitored the expected led output at 10 ns after the input is changed (see the testbench) whereas the actual delay is about 5.000 ns.

- 5-1-6. Close the simulator by selecting **File > Close Simulation** without saving any changes.

Generate the Bitstream and Verify Functionality

Step 6

- 6-1. Make sure that the power supply source jumper is set to **USB**. Connect the board and power it **ON**. Generate the bitstream, open a hardware session, and program the FPGA.
- 6-1-1. Make sure that the power supply source jumper is set to **USB** and the provided Micro-USB cable is connected between the board and the PC. Note that you do not need to connect the power jack and the board can be powered and configured via USB alone.

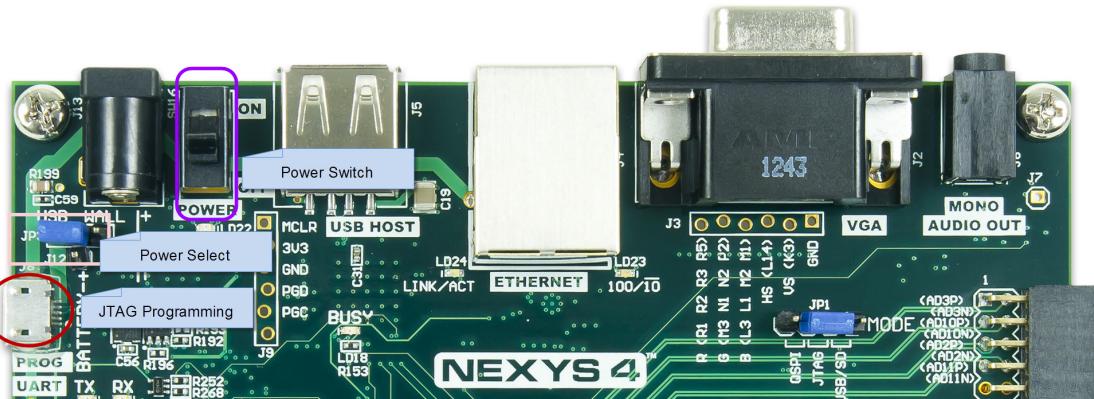


Figure 32. Board settings for Nexys4 DDR

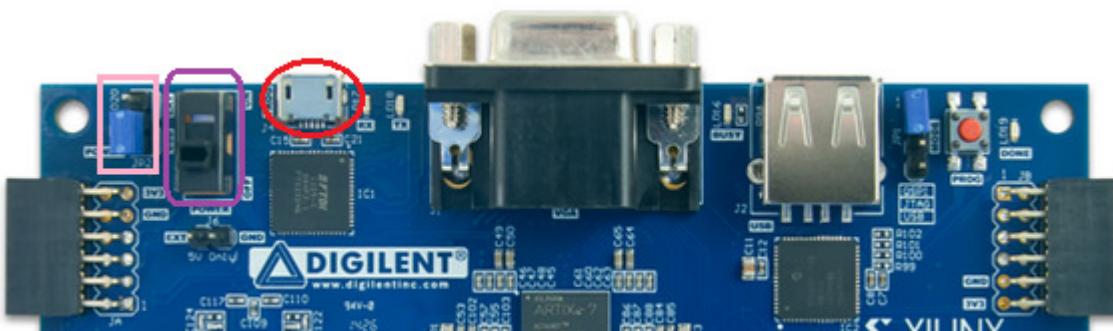


Figure 32. Boards settings for Basys3

- 6-1-2. Power **ON** the switch on the board.
- 6-1-3. Click on the **Generate Bitstream** entry under the *Program and Debug* tasks of the *Flow Navigator* pane.

The bitstream generation process will be run on the implemented design. When the process is completed a *Bitstream Generation Completed* dialog box with three options will be displayed.

This process will have **tutorial.bit** file generated under **impl_1** directory which was generated under the **tutorial.runs** directory.

- 6-1-4. Select the *Open Hardware Manager* option and click **OK**.

The Hardware Manager window will open indicating “unconnected” status.

- 6-1-5. Click on the **Open target** link.

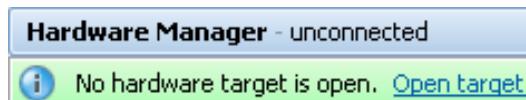


Figure 33. Opening new hardware target

- 6-1-6. From the dropdown menu, click **Auto Connect**.

The Hardware Session status changes from Unconnected to the server name and the device is highlighted. Also notice that the Status indicates that it is not programmed.

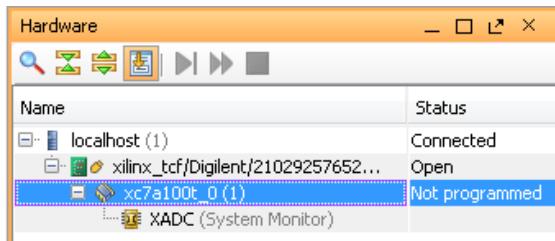


Figure 34. Opened hardware session for the Nexys4 DDR

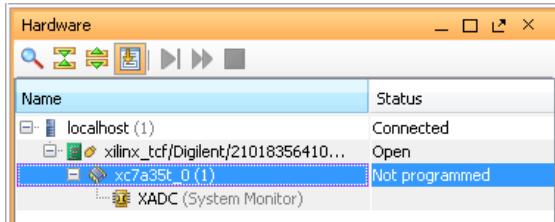


Figure 34. Opened hardware session for the Basys3

- 6-1-7.** Select the device and verify that the lab1.bit is selected as the programming file in the General tab.

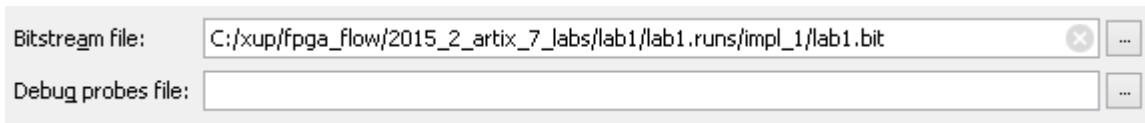


Figure 35. Programming file

- 6-1-8.** Click on the *Program device > XC7A100T_0* or the *XC7A35T_0* link in the green information bar to program the target FPGA device.

Another way is to right click on the device and select *Program Device...*



Figure 36. Selecting to program the FPGA

- 6-1-9.** Click **Program** to program the FPGA.

The DONE light will light when the device is programmed. You may see some other LEDs lit depending on switch positions.

- 6-1-10.** Verify the functionality by flipping switches and observing the output on the LEDs.

- 6-1-11.** Close the hardware session by selecting **File > Close Hardware Manager**.

- 6-1-12.** Click **OK** to close the session.

6-1-13. Power **OFF** the board.

6-1-14. Close the **Vivado** program by selecting **File > Exit** and click **OK**.

Conclusion

The Vivado software tool can be used to perform a complete design flow. The project was created using the supplied source files (HDL model and user constraint file). A behavioral simulation was done to verify the model functionality. The model was then synthesized, implemented, and a bitstream was generated. The timing simulation was run on the implemented design using the same testbench. The functionality was verified in hardware using the generated bitstream.