

CE 435
Embedded Systems

Spring 2018

LAB 1
Implementation of Gray Counter
on an FPGA

Introduction

Lab1 is about functional simulation and implementation of a Gray Counter in Verilog using the Xilinx Vivado toolset. At the end of lab1, you will be able to download and test your design on Zedboard.

The Zedboard digital system development platform features Xilinx's newest Zynq-7000 FPGA, 512 MB external DDR3 memory and enough I/O devices and ports to host a wide variety of digital systems.

Objectives

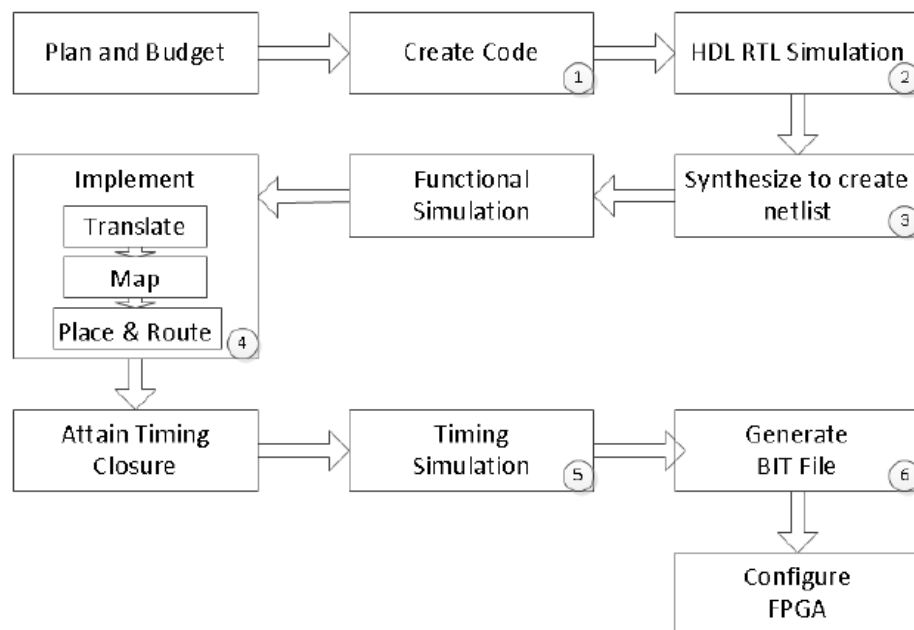
The objective of these lab sessions are the following:

- to introduce the concepts of hardware design using Verilog HDL ,
- to introduce functional and timing simulation and debugging using testbenches and the Xilinx Vivado simulator,
- to introduce the concepts of user-constrained design synthesis, placement, routing and bitmap generation on a Xilinx FPGA board,
- to introduce the downloading and demonstration of the design on the board, and
- to introduce the functionality of the Zedboard.

The diagram shows the typical design flow that will be followed in this lab.

Gray code

The concept of a gray counter is that only one bit changes between 2 successive codes. The 2-bit Gray code is: 00 01 11 10, and the 3-bit Gray code is: 000 001 011 010 110 111 101 100.



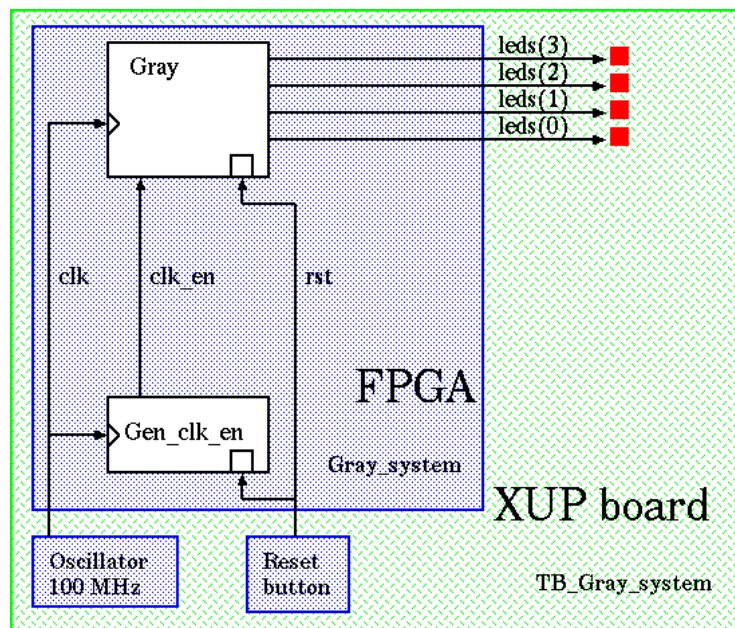
The binary-reflected Gray code for n bits can be generated recursively by reflecting the bits (i.e. listing them in reverse order and concatenating the reverse list onto the original list), prefixing the original bits with a binary 0 and then prefixing the reflected bits with a binary 1. For example, the 4-bit Gray code can be constructed by reflecting the 3-bit code:

0000	0001	0011	0010	0110	0111	0101	0100	1100	1101	1111	1110	1010	1011	1001	1000
(0)+3 bit Gray Code								(1)+reflected 3 bit Gray Code							

Lab overview

The lab will build a 4-bit Gray code for demonstration on the Xilinx Zedboard. This is an evaluation board that includes a Zynq-7000 FPGA (XC7Z020), 512 MB external DDR3 and Flash memories, and a series of peripherals to be used for our demonstration. In this lab, we will use four of the GPIO LEDs (General Purpose I/O Light Emitting Diodes) located at the bottom of the board.

The following Fig. shows the top level of the design. The LEDs will switch every second (freq=1Hz) between successive 4-bit Gray code. Before we implement the design on the FPGA board, we will need to simulate it (step1).



Xilinx tools set up

Make sure that your Linux environment is set up for the Xilinx Vivado toolset. Run (or, even better, place in your start-up shell script) the following commands:

```
setenv XILINXD_LICENSE_FILE 2100@10.64.82.9
source /opt/Xilinx/Vivado/2014.2/settings32.csh #for 32-bit linux OR
```

CE435 Embedded Systems

```
source /opt/Xilinx/Vivado/2014.2/settings64.csh #for 64-bit linux
```

The two previous script commands refer to *csh* shell, and the start-up shell script is *.cshrc*, which should be placed in your home directory. Every time you launch a new *csh* terminal, the *.cshrc* script is automatically executed. The number 14.2 refers to the Xilinx tools version.

Step1 - Design and behavioral simulation of 4-bit Gray counter

In this first step of lab1, you will implement a 4-bit Gray code using a Finite State Machine (FSM) in Verilog. You will write a test bench and simulate, debug and test your design using the builtin Vivado simulator of Xilinx. If you prefer, you can also use *Modelsim* to simulate your designs.

The purpose of this module is to get a general understanding on designing, simulating and debugging your hardware described in Verilog. This task is usually accomplished using a test bench which can also be written in Verilog. Therefore, it is important to understand that a Verilog test bench is as error prone as a Verilog hardware description.

This step requires that you fill in the details of the design and the test bench files and simulate the design until you are convinced that it generates a valid sequence of 4-bit Gray codes.

Start this lab by copying the input files of the module into your local folder and study the two skeleton Verilog files. You have to write Verilog code to generate the sequence described in the Overview Document using an FSM which changes states on the rising edge of the clock. When the asynchronous reset signal is asserted, the state becomes 4'b0000 (*Gray_4bits_RTL.v*).

Now we will turn our attention to the code of the test bench (*TB1_Gray.v*). In the test bench, the gray counter is instantiated and its inputs are connected to signals that are generated in the test bench. The outputs of the gray counter are connected to signals that are verified. Besides the instantiation of the gray counter, there are also some other important behavioral statements (*initial*, *always*):

There is one *initial* statement that initializes system signals such as *reset*, *clk* and *EndOfSimulation* and sets the *EndOfSimulation* after a particular number of clock signals. Another behavioral statement generates the clock signal with a period *cycle*. This requires that the *clk* signal reverses after *cycle/2* ns.

1. Once you are satisfied that your code makes sense, launch Vivado from a linux terminal to create a new design project (make sure that you have already set the tools up as described in the Overview document):

```
% vivado &
```

The Vivado Project Navigator GUI will open.

2. You create a new project: *Create New Project*
3. At the *Create New Vivado Project* page click *Next*
4. For Project Location, browse to your preferred directory. Type the Project Name (e.g.*GrayCounter_4bit*) and make sure that the *Create Project subdirectory* is checked. Click *Next*.
5. In the *Project Type* form select *RTL Project*. Click *Next*.
6. Click *Next* a few times till you reach the *Default Part* page.

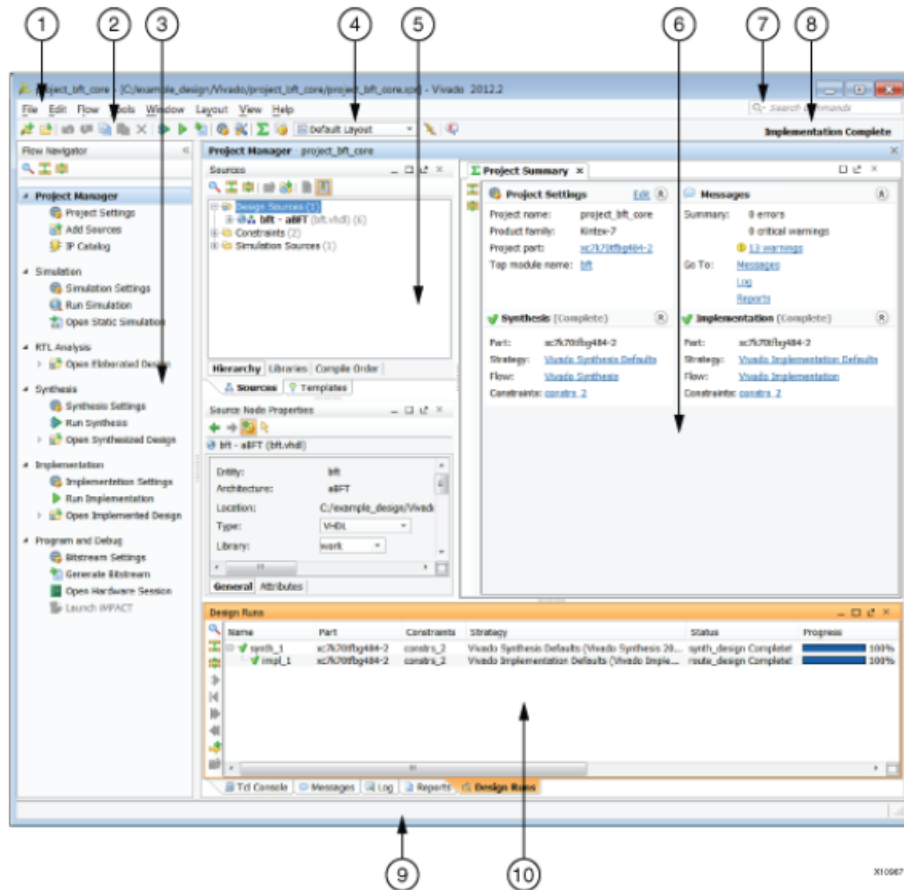


Figure 1. Vivado IDE Viewing Environment

7. In the *Default Part* form specify *Boards* and start searching for *Zedboard*. Select *Zedboard Zynq Evaluation and Development Kit*.
8. In the *New Project Summary* form click *Finish* to create the project.

Figure 1 shows the Vivado IDE environment:

1. Menu Bar
2. Main Toolbar
3. Flow Navigator
4. Layout Selector
5. Data Windows Area
6. Workspace
7. Menu Command Search Field
8. Project Status Bar
9. Status Bar
10. Results Window Area

Select *Add Sources* in the *Flow Navigator*, then select *Add or Create Design Sources* and click *Next*. Select *Add Files*, browse to the directory where your Verilog code resides to add the two Verilog files that you created for this project and click *Next* and *Finish*. The *Project Manager* view will be updated to illustrate the hierarchy of your design.

The next step is to use the Vivado built-in simulator and examine the behavioral simulation results. Behavioral simulation only simulates the Verilog code without any inference to gates or

transistors and is used to prove the logical correctness of your Verilog code. In the *Flow Navigator*, under the *Simulation* tab, select the *Simulation Settings* button and make sure that the Target Simulator is Vivado, the Simulator Language is mixed (or Verilog), and that the top module name is the name of your testbench module. Press OK. In the *Flow Navigator*, press *Run Simulation* and *Run Behavioral Simulation*.

The Verilog code will be compiled and executed using the testbench as the top level module. The workspace of the Vivado IDE will change and new windows will appear when you execute the testbench. One window shows the simulation results as waveforms, another shows the Objects of test bench and yet another the hierarchy of the design and the *glbl* instances (*Scopes*). The *Main Toolbar* can be used to guide the simulation. The most widely used icons are: *restart* which resets the simulation and the waveform and *run <time>* which runs the simulator for time N. For example, *run 10000 ns* will run the design for 10000 ns and will terminate. You can move around the hierarchy of your design from the *Scopes* window, select signals and variables that you want to trace and simulate from the *Objects* window, and drag them to the waveform window.

Test your simulation to ensure that it is correct. Exit when you are done simulating.

Go to the project directory and check to see the directory structure that Vivado created to store the files for project support. The *<Project Name>.srcs* directory contains all project source files and design constraints (to be explained later in step 4). The *<Project Name>.sim* directory contains automatically generated files for each simulation campaign. The *<Project Name>.data* directory is a placeholder for the Vivado program database.

Step 2 - N-bit Gray counter

One of the features of Verilog is that it enables you to create parameterized hardware systems. In this lab you will learn you will how to use such parameter in order to build a general N bit gray counter.

The architecture of an N bit gray counter cannot be easily deduced from the code used in step 1. In order to make a general N bit gray counter you will have to use an N+1 bit register, in which the purpose of the LSB is to act as an auxiliary bit.

This auxiliary bit is not part of the final gray counter but is necessary to calculate the next value of the gray counter. In order to clarify this, let's take a look at an example: a 4 bit gray counter that implements this auxiliary bit.

If you write down the successive gray codes for a 4 bit gray counter and you add an LSB that starts at 1 and toggles, you will get next sequence:

```
0000 1    start value
0001 0    value after first clock edge
0011 1    value after second clock edge
0010 0
0110 1
0111 0
0101 1
0100 0
1100 1
1101 0
1111 1
1110 0
1010 1
1011 0
1001 1
1000 0
0000 1    back to start value
. . .
. . .
```

This can be seen as a 5-bit vector FF(4 downto 0) that consists of 2 parts: the gray counter (bits 4 downto 1) and bit 0 being the auxiliary bit. We can use this to define a finite state machine in which FF(4 downto 0) is the state-variable.

Let's see how this allows us to generate the 4 bit gray counter. Looking at the previous table we can find out when each bit of the gray counter should toggle.

Bit0: toggles on each active clock edge (bit0 = LSB)
Bit1: toggles if bit0 = 1
Bit2: toggles if bit1 = 1 and bit0 = 0
Bit3: toggles if bit2 = 1 and bit1 = 0 and bit0 = 0
Bit4: toggles if bit2 = 0 and bit1 = 0 and bit0 = 0 (bit4 = MSB)

This observation can be expanded to N bits:
Bit0: toggles on each active clock edge (LSB)
Bit1: toggles if bit0 = 1
BitX: toggles if bit(X-1) = 1 and all lower bits = 0, where $X < N$.
BitN: toggles if bit(N-2) and all lower bits = 0 (MSB)

Note that toggling of the MSB (BitN) is independent from the lower bit (Bit(N-1)).

This algorithm can be used to build a general N bit gray counter. Your task is to complete the Verilog code starting from the two given files *TB2_Gray.v* and *GrayCounter_Nbits.v*. Note that your code should run for every N, and not only N=4. In other words, the design should be parameterized.

Note that the code for module 2 is more complicated than the 4-bit Gray counter of module 1. You will need to use structures like for-loops to implement a counter for the general N-bit case.

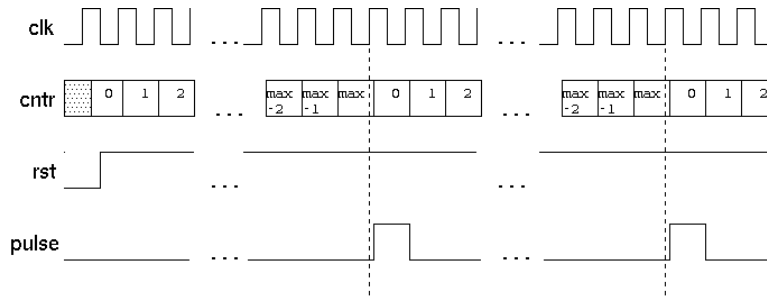
When you are done with your Verilog code, create a new Vivado project, and simulate the design and illustrate the functionality for the case of N=4.

Another thing you should try is to analyze your RTL code. In the *Flow Navigator*, select *RTL Analysis*, expand the *Elaborated Design* and then select *Schematic*. Elaboration is a step during simulation and synthesis in which the design hierarchy is flattened producing an interconnection of modules. The graphical schematic can be viewed in a new window.

Step 3 - N-bit Gray counter with pulse generator

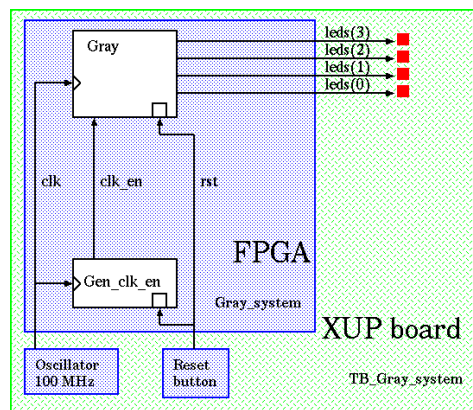
Step 3 is the first step in the implementation of the gray counter on the Zedboard. The outputs of the counter will be connected to the user LEDs (light emitting diodes) on the board. In order to be able to see the count sequence, we will have to lower the frequency of the gray counter to 1 Hz. In a synchronous design this can be done using an enable signal that is only active for 1 clock pulse during each second. This enable signal will be used to enable/disable the gray counter. In this lab you will learn how to write a pulse generator as a means to generate this enable signal. Step 3 is to complete the behavioral model of file *GrayCounter_Nbits_Pulse.v*.

The reset input is asynchronous and active low. The generic "distance" defines the time between 2 pulses. These pulses will drive the signal *clk_en* of the gray counter. Next figure shows how each pulse can be generated:



The time distance between two successive pulses is equal to 1 sec. The complete system is shown below. The *GrayCounter_Nbits_Pulse.v* code implements the *Gen_clk_en* module and connects the pulse signal to *clk_en*.

Next, you will need to implement the *Gray_system.v* module which instantiates the Gray and Pulse modules.



Once you complete the Verilog programs, create a new Vivado project and instantiate the *Gray_system.v* module in the test bench *TB3_Gray.v*, you should simulate the program using *iSIM* and check the correct functionality.

Step 4 - N-bit Gray counter in FPGA

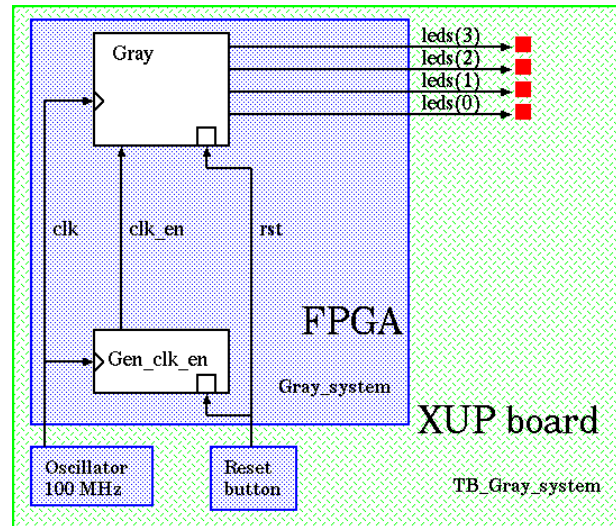
The Gray counter that you verified in the previous module, will now be implemented on the Zedboard board. The outputs of the gray counter will be connected to 4 (or 8) GPIO LEDs of the board. You should have concluded the first three steps before you attempt this step. There is no additional Verilog code for step 4.

After this step, the student should be able to implement a small hardware system on an FPGA board. You will also learn details on the implementation flow of the Vivado toolset. Since this is the first time that you use the Xilinx implementation tools, this lab is described as a walk-through in which all steps are explained. Launch Vivado from a Linux terminal and create a new design project (e.g. *GrayCounter_Nbit_fpga*):

% vivado &

Create the new project which includes the three Verilog files you created in Lab3 without the test bench (refer to step1 for details on how to do this). We will not need a test bench file because we will run the design on the board instead of simulating it. The file *GrayCounter_System.v* is the top

level of the design.



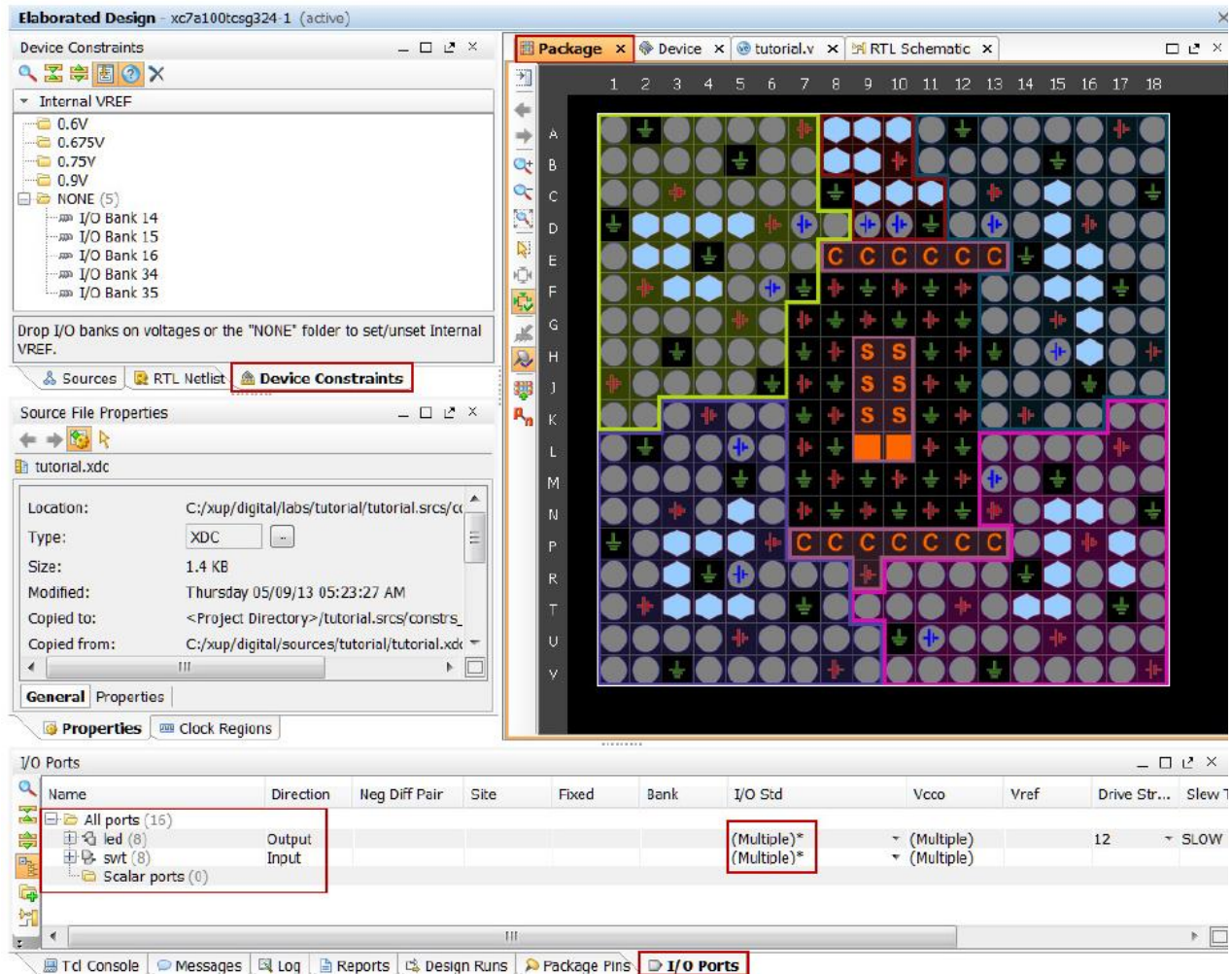
Design Constraints

Besides the verilog source code, an implementation to an FPGA bitstream requires that the designer defines design constraints. These constraints specify the FPGA I/O pins which will be assigned to the I/O module ports (e.g. clock, leds, etc.), their physical characteristics, timing constraints such as clock period and clock duty cycle and so on. In particular timing are the most important constraints of a design since they have a direct impact to the speed and area of the generated circuit. There is an inverse relationship between area (i.e. number of LUTs) and speed (i.e. clock frequency): aggressive clock frequencies typically result into circuits that are larger.

Select *Add Sources* in the *Flow Navigator*, then select *Add or Create Constraints* and click *Next*. Select *Add Files*, and select the *GrayCounter_System.xdc* text file. For this lab, the incomplete XDC file (XDC stands for Xilinx Design Constraints) is given to you. You will need to fill in the details, i.e. the entries that contain *XXX*. You will have to consult the Zedboard schematic for the pin locations of the *clk*, *rst* and *leds* (named LD0 to LD7) in the Zedboard schematic. It is actually even easier in the Zedboard because the pin locations are the small codes near the leds. For example led[0] is electrically connected to pin T22 of the FPGA. Study the syntax of the Tcl script (pronounced as tikl) language that is used in the XDC file and try to extend it to all I/O pins.

Make also sure to specify a clock period of 10 ns (100M MHz target frequency). The XDC file is where the Vivado tool is instructed by the user to perform time-constrained placement and routing and to place the I/O ports of the design onto specific FPGA pins that have a dedicated function in the board (e.g. they are connected to the LEDs or buttons). This is where you specify the target clock frequency that you want your system to run.

An alternative way to specify design constraints is by the drop-down *Layout Selector* menu. In the Flow Navigator, open the Elaborated Design, select *I/O Planning* and notice that the *Package* GUI view is displayed in the *Workspace* area and the I/O ports tab in the *Results Window Area* (see figure). Move the 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 type of the I/O bank it belongs to.



Expand the led ports by clicking on the + box and make sure that led[3:0] use the LVCMOS33 I/O standard (change it if they do not). To assign a pin location for led[0], click under the site column across led[0] row to see a drop-down box appear. Type T22, tick *Fixed* and hit the Enter key to assign the pin.

Notice that any selection that you perform in this GUI automatically updated the XDC file which has to be reloaded every time you make a change. In fact, the *Package* GUI is just a more user-friendly method to specify design constraints. The specification of pin site T22 and LVCMOS33 I/O standard for led[0] is specified by the following two Tcl commands in the *GatewayCounter_System.xdc* file:

```
set_property package_pin T22 [get_ports{led[0]}]
set_property ionstandard_LVCMOS33 [get_ports{led[0]}]
```

Select *File* → *Save Constraints* and click *OK* to update the existing constraints file.

Synthesis

Synthesis is a process which parses the Verilog design files and generate a gate-level netlist for the whole design. After synthesis there is no immediate correspondence between the gate level

netlist (*GrayCounter_System.ngc*) and the FPGA architecture. In other words, the netlist is in a generic gate level format.

Click on *Run Synthesis* under *Synthesis* tab. The synthesis process will be run on the top level *GrayCounter_System.v* file (and all its hierarchical files). When the process is completed after a few minutes a *Synthesis Completed* dialog box with three options is displayed. 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.

Select the *Project Summary* tab (Default Layout) and understand the various windows. You can see useful information such as the utilization of the FPGA in terms of various resources such as LUT, I/Os both in Graph and Table format. Click on the *Schematic* tab under the *Open Synthesized Design* to view the synthesized design in schematic view. Study the schematics of both the gray counter and pulse generator and observe that IBUF and OBUF gates are automatically instantiated to the design as the input and output is buffered. These gates will be later mapped to LUTs and Flip flops in the FPGA CLBs.

Verify that the *<Project Name>.runs* directory has been created by Vivado under the *<Project Name>* directory. Under the *runs* directory, *synth_1* directory is created which holds several temporary subdirectories.

Implementation (Translation, Mapping, Placement & Routing)

The *implementation* is a multi-step phase that transforms the synthesized gate level netlist into a Xilinx proprietary bitstream that can be downloaded to program the FPGA.

The *translation* phase merges multiple design files into a single netlist called *GrayCounter_System.ngd*. This is the main data base of the netlist which also includes the constraint file (XDC).

The *Mapping* phase groups gates from the netlist into physical components of the FPGA (LUTs, Flip-flops, DSP modules, IO buffers, etc.).

The *Placement* and *Routing* phase places the physical components onto the 2D chip, connects the components, and extract timing data into reports. This is the most time-consuming task of the implementation phase.

Once a design is implemented, the user should create a file that can be downloaded and program the FPGA. This file is called a bitstream: a BIT file (.bit extension), which can program the FPGA in one of two different ways:

- By a download cable such as a Platform USB. The bitstream is downloaded from the computer hard disk to the FPGA.
- By writing a non-volatile memory such as a Xilinx Platform Flash PROM. The bit file should first be converted into a PROM file.

Click on *Run Implementation* under the *Implementation* tab. The implementation task will run on the synthesis output files. When the process is completed an *Implementation Completed* dialog box with three options is displayed. Select the *Open Implemented Design* option and click *OK* as we want to look at the implementation output in the *Device* view tab. Click *Yes* to close the synthesized design.

Study the implemented design in the *Device* view and zoom in to look at the details of the final design and how it is mapped on the FPGA fabric. At the *Netlist* panel, select one of the nets and notice that the net is highlighted in the FPGA.

Close the implemented view and select the *Project Summary* (Default Layout view) and observe

the results. How much is the actual resource utilization? Select the *Post-implementation* tabs under the *Timing and Utilization* Windows.

Verify that the *impl_1* directory has been created under the *<Project Name>.runs* directory. The *impl_1* directory contains several files including the report files.

Timing simulation

Now that the N-bit gray counter has been placed and routed in the Zynq-7000 FPGA fabric, we have all the information to perform a detailed timing simulation. Click on *Run Simulation* → *Run Post-implementation Timing Simulation* under the *Simulation* tab. The Vivado simulator will be launched using the implemented design and your testbench as the top level module. Note that you have to resort to a previous project with a testbench in order to be able to run the simulation.

Run again the testbench and notice that the waveform show the real and not the zero delay of the behavioral simulation. Close the simulator by selecting *File* → *Close simulation*

Bitstream generation and FPGA Programming

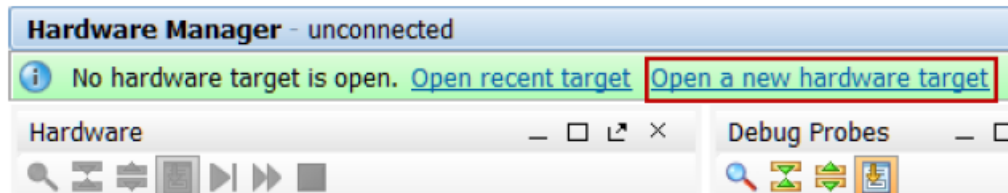
This step will allow us to download the design to the FPGA and see the N-bit gray counter running on the Zedboard. First, you should connect the board, power it ON and make sure that the micro-USB cable is connected between the board and the PC. All the jumpers JP7 to JP11 should be connected to the GND as shown in the figure. To be able to program the FPGA, we should have already installed the cable drivers as described in a separate document.



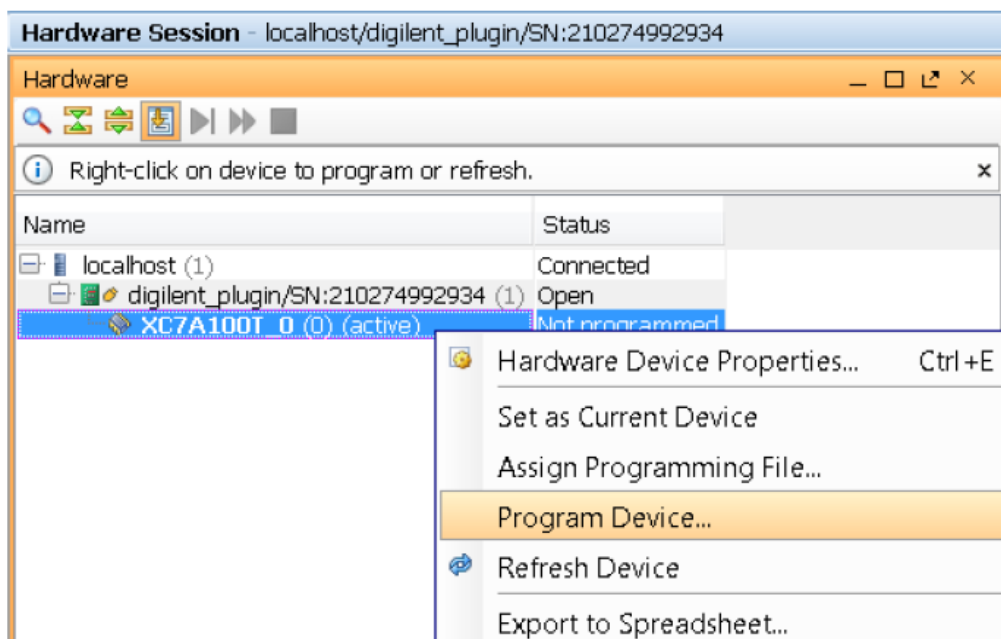
Once all these preparatory steps have been taken, select the *Generate Bitstream* entry under *Program and Debug* in the *Flow Navigator* panel. The bitstream generation process is used to generate the “executable” file that will be downloaded to the FPGA. It runs on

the implemented design and, when completed, a *Bitstream Generation Completed* dialog box with three options will be displayed. The *<Project Name>.bit* file is generated under *impl_1* subdirectory under the *<Project Name>.runs* directory.

Select the *Open Hardware Manager* option and click *OK*. The Hardware session window will open indicating “unconnected” status. Click on the *Open a New Hardware Target* link. You can also click on the *Open Recent Hardware Target* if the board was already targeted before.



Click *Next* to see the Vivado CSE server name. Click *Next* with the localhost port selected. The JTAG cable will be searched and the *Xilinx_tcf* should be detected and identified as a hardware target. It will also show the hardware devices detected in the chain. Click *Next* twice and then *Finish*. The hardware status changes from Unconnected to the server name and the device (i.e. the FPGA) is highlighted. Also notice that the status indicates that it is not programmed. Select the device and verify that the *<Project Name>.bit* bitstream file is selected as the programming file in the General tab. Right click on the device and select *Program Device* to program the target FPGA device.



Click *OK* to program the FPGA with the selected bitstream file. The blue DONE light will light immediately after the FPGA is programmed.

Once the last bit of the bitstream file makes it into the FPGA the design will start running. Hopefully, everything has been done correctly and you can see the red LEDs blinking according to the gray code.

Close the hardware session by selecting *File → Close Hardware Manager*.

Step 5 – Use Buttons to enable Gray Counter

Step 4 required that the Gray counter advances at a 1 Hz frequency without any interaction with the user. Step 5 requires that the counter only advances each time the user presses a button. Each time the user presses the button, the Gray counter will move to the next value, regardless of how long the button is pressed. You should design and implement such a system on the FPGA.

The first step is to construct an edge detection module. This is an FSM-based module that receives as input a multi-cycle pulse signal and generates as output a single-cycle pulse signal. The input pulse signal is generated by the button in the board and can last any number of clock cycles. It corresponds to the user pressing the button. However, such an input pulse that lasts multiple cycles N can trigger as many counter increases as the number of cycles N , which is not what the user requires for the system.

This FSM-based edge detector will produce an output that can be connected to the *clk_en* signal of the gray counter. The input to the edge detector is a button of the Zedboard.

What do you observe? Does your system work?

Debouncing

A problem arises from the mechanical "bounce" inherent in switches: as a metal contact opens and closes it may bounce a couple of times, creating a sequence of on/off transitions in rapid succession. So you need to use debouncing circuitry to filter out these unwanted transitions. You should design *debounce.v* a Verilog implementation of a digital retriggeable one-shot that requires that an input transition be stable for (approximately) $T=0.01\text{sec}$ before reporting a transition on its output. You should use an instance of the module to debounce any switch inputs you use in your designs.

Use a counter to produce an *enable* signal when the input noisy signal has flipped and has remained stable for $T=0.01\text{secs}$. If the input signal changes sooner than T secs, we assume that it was mechanical noise, and we do not pass the noisy signal to the output (clean) signal.

Step 6 (optional) – Speed Buttons

The Gray counter of step 5 advances only when we press the button. Once the button is pressed and the Gray counter counts up once, there is no other change to the value of the Gray counter. Step 6 requires that the value of the Gray counter advances for as long as we press the button. Moreover, the speed of change will increase as we keep the button pressed. It is up to you to determine the initial and final frequency of advancement of the Gray counter.