

ELE 206/COS 306 Lab 5:

Simon – RTL Design Project

Checkpoint 1 Due Date: November 15th, 2017

Checkpoint 2 Due Date: November 22nd, 2017

Final Submission Due Date: November 29th, 2017

Final Demonstration Required.

Note: This lab should be completed with a partner.

Tutorial Reading: Section 5.2

The lab closely follows the design process outlined in this reading.

Introduction

This lab is a medium-sized project intended to teach you the basics of register-transfer level (RTL) design, datapath construction, and modular testing. This project is significantly more involved than previous labs, so it's best to get started early. Note that there are weekly due dates for portions of the lab, although the only demonstration is for the final product.

Prior to beginning the lab, it is important to closely read section 5.2 of the Verilog tutorial. This section works through an example RTL design problem with example code, and it will serve as a good reference point for you as you work through this lab.

Your task for this lab is to implement a datapath and control circuit for a two-player version of Simon, a popular electronic toy designed to test the memory of its players. You can read more about the game here: [https://en.wikipedia.org/wiki/Simon_\(game\)](https://en.wikipedia.org/wiki/Simon_(game)).

Essentially, the two-player version of Simon works as follows. Alice, who is player one, resets the game. Then, she enters a pattern (in our case, a

4-bit number). The machine plays back that pattern to Bob, who is her opponent. Bob then enters the pattern he saw. If he gets it right, he now gets to add his own pattern to the pattern Alice entered, forming a sequence. The machine will play back the entire sequence (Alice's pattern followed by Bob's pattern) to Alice, who then has to repeat the entire sequence of patterns. If she succeeds, she gets to add another pattern to the sequence. The game goes on until one of the players makes a mistake while repeating the pattern sequence, which keeps getting longer and harder to remember. Once one player makes a mistake, the other player wins.

You will test your circuit thoroughly via simulation. Unlike previous labs, you will now actually get to synthesize your Verilog and program an FPGA so that you can physically play Simon with your lab partner!

To begin the lab, download and unzip *simon.zip* from Blackboard, and follow the instructions in this document. All of the source code for this lab, including testbenches, is stored in the */simon* folder.

A Multiplayer Version of Simon

Inputs and Outputs

Your version of the Simon machine will have the following inputs:

- **pattern** [3:0] – Four switches that can be used to form a pattern.
- **level** – A single switch that controls the difficulty level of the game.
- **rst** – A button for synchronously resetting the game.
- **pclk** – A button for advancing the state of the game. Essentially, this serves as the clock for your system.
- **sysclk** – A 50MHz system clock. This will only be used for *debouncing* pclk, and should not be used except for FPGA synthesis.

Additionally, your machine will have the following outputs:

- **pattern_leds** [3:0] – Four LED's for either showing the current pattern or replaying a pattern sequence.
- **mode_leds** [2:0] – Three LED's that show the current mode/state of the game.

Gameplay

The game begins when the circuit is reset. To reset Simon, the `rst` button must be held down while the `pclk` button is tapped.

When the circuit is reset, two things happen.

First, the current state of the `level` switch is saved for use throughout the current game. If `level` is one, the game is in hard mode, and patterns can be any 4-bit number. If `level` is zero, the game is in easy mode, which means that patterns must have one – and only one – bit set to one. This leaves only four options: `4'b0001`, `4'b0010`, `4'b0100`, or `4'b1000`.

Secondly, the game transitions into input mode (the “initial state” for your machine). Gameplay proceeds by transitioning between four modes – input, playback, repeat, and done. Each of these modes is described in detail below.

- **INPUT** – In this mode, whichever player is currently controlling the game gets to add a new pattern to the game’s sequence. The player first creates a *legal* pattern using the four `pattern` switches, and then presses `pclk` to enter and save the pattern.

As long as the pattern was legal, the game will transition to the playback mode. Otherwise, the game will wait in the input mode and not accept the new pattern. Legality is determined by the `level` switch’s value at the game’s start. Changing the level switch during a game should not affect anything.

Finally, the `pattern_leds` should display whatever the switches are currently set to. If a `pattern` switch is flipped, the corresponding LED should change instantaneously.

- **PLAYBACK** – In this mode, the other player gets to view the sequence of patterns for the current game. Whenever `pclk` is pressed to transition from input to playback, the `pattern_leds` should show the first pattern in the game’s sequence.

For each subsequent press of `pclk`, the `pattern_leds` should update to display the next pattern in the sequence. When the currently-stored sequence has shown its last value, the next clock press will take the game to the repeat mode.

- **REPEAT** – In this mode, the player that just viewed a full playback of the game’s pattern sequence attempts to re-enter that sequence exactly. The player forms the first pattern they remember on the `pattern` switches and then taps `pclk` to register their guess.

If the player's guess was correct and there are still patterns left in the sequence, the game remains in repeat mode and the player continues to make guesses to match the sequence. If a player guesses correctly up to (and including) the final pattern in the current sequence, the game transitions back to input mode for that player to append a new pattern to the sequence.

However, as soon as a player enters an incorrect guess, the game will immediately transition to the done mode.

As in the input mode, the `pattern_leds` should display whatever the `pattern` switches are currently set to.

- **DONE** – In this mode, the game has ended. The stored patterns can be cycled through by pressing `pclk`, just like in the playback mode. This allows the player that lost to view the correct sequence and see what error they made. When the done mode is first entered, the `pattern_leds` should display the *first* pattern in the sequence.

If `pclk` is pressed enough to get to the last element in the sequence, the next push of `pclk` should cycle back around to the first element for another run through the sequence. The only way to escape the done mode is to reset the game.

The current mode is shown to players via the `mode_leds`. A table mapping the current mode to the status of the `mode_leds` is shown below.

Mode	<code>mode_leds</code>
Input	3'b001
Playback	3'b010
Repeat	3'b100
Done	3'b111

Example Game

Here's an example run-through of a game that should hopefully illustrate how Simon works in practice.

1. **Mode: Unknown** – The game is reset by holding down the `rst` button and tapping `pclk`. The `level` switch was set to zero, so this game is on easy mode.
2. **Mode: Input** – Alice enters 4'b0001 on the `pattern` switches, then taps `pclk`.

3. **Mode: Playback** – Alice hands the game to Bob. The `pattern_leds` display 4'b0001. Bob notes this, and taps `pclk`.
4. **Mode: Repeat** – Bob enters 4'b0001 on the switches and then taps `pclk`. This entry was correct, so now it's Bob's turn.
5. **Mode: Input** – Bob flicks the `level` switch to one, intending to enter a more difficult pattern. He then enters 4'b1010 on the switches and taps `pclk`.
6. **Mode: Input** – Modifying the `level` switch during the game does not change the game's difficulty – the level was locked in at zero when the game was reset. Because Bob's pattern was illegal at level 0, the game remains in input mode. Bob enters 4'b1000 and taps `pclk`, successfully adding a legal pattern.
7. **Mode: Playback** – Bob hands Alice the game. The `pattern_leds` display 4'b0001 – Alice's original pattern. Alice clicks `pclk`.
8. **Mode: Playback** – The `pattern_leds` now display 4'b1000 – Bob's new pattern. Alice taps `pclk`.
9. **Mode: Repeat** – Alice enters 4'b0001 on the switches, then taps `pclk`. This entry was correct, but the sequence isn't complete.
10. **Mode: Repeat** – Alice makes a mistake, entering 4'b0100 on the switches and tapping `pclk`.
11. **Mode: Done** – The game is over, and Bob has won. The LED's display 4'b0001. Alice presses `pclk`.
12. **Mode: Done** – The LED's display 4'b1000. Alice realizes her mistake, but taps `pclk` one more time.
13. **Mode: Done** – The LED's display 4'b0001, wrapping around to the first entry.

Technical Specifications

Here's a list of additional technical specifications that must be met by your design:

- **Number of Patterns to Store** – The game must be able to store a sequence of up to 64 four-bit patterns. Most people lose the game well before this limit is reached.

If the players reach a sequence length of 64 patterns, the ideal behavior would be to begin wrapping around. The first pattern would be deleted and replaced with a new pattern in the next input mode, and the second pattern would become the first in the new sequence. When another pattern is added, the second pattern would be overwritten, and the third pattern would become the new starting point – and so on. The sequence would remain 64 patterns long in perpetuity until someone loses, with the starting point sliding along one pattern at a time.

However, for the purposes of this lab, you do **not** have to handle the wrap-around case. If you do and can demonstrate that to the TAs, you will receive a small amount of extra credit. It shouldn't be much more code to handle this case, but it does require a bit more thinking.

- **Synchronous Resets and Transitions** – Resets are synchronous for Simon. Additionally, your internal FSM and the mode of the game should only transition when `pclk` is pressed.
- **Clock Edges** – Assume that all transitions will be on the rising clock edge, and write your Verilog as such.

Week 1: Datapath and Controller Design

Checkpoint 1 Due Date: November 15th, 2017

The first step in tackling the Simon problem is creating a high-level overview of your design. Following the example set forward in the Verilog tutorial, your high-level design process will follow three main steps:

1. Create a High-Level State Machine (HLSM) that describes the behavior you expect from your game.
2. Create a Datapath. Extract the complex actions, local storage, and other items in your HLSM that cannot be handled by an FSM and create logic to handle them in your datapath.
3. Create a Controller. Re-write your HLSM into a simple FSM that will utilize your datapath (via control signals) to produce the behavior you want.

At the end of the first week of this project, you should have an HLSM, a datapath, and a controller designed. At this phase, the design should be done via technical diagrams. If you draw your components by hand, take legible pictures of them for your checkpoint submission.

The requirements for each of your design's components are listed below.

High-Level State Machine

Your HLSM should look a lot like an FSM, with states, transitions, and transition conditions. However, the HLSM can specify manipulation of local storage, arithmetic operations, and other complex tasks to be performed in each state, and its transition conditions can be complicated. For example, an HLSM might specify that it will remain in a certain state, adding one to a local counter register, and only transition once that counter reaches a certain value.

An HLSM should fully capture the desired behavior of your entire circuit. You may draw it however you like, but please follow these guidelines:

1. Use the rising clock edge for all transitions, and do *not* AND the rising clock edge with every transition condition. All transitions in your machine will be taken synchronously with the clock edge, so just make that implicit.

2. Don't use the system clock at all – it should only be used for debouncing `pclk`, which will be discussed once you get to FPGA synthesis. In other words, assume `pclk` is the clock for your HLSM.
3. Ensure that the values for the outputs of your circuit (`pattern_leds` and `mode_leds`) are clearly indicated for each HLSM state. You can do this in place or in a separate table – whatever is cleanest for your drawing.
4. Don't draw explicit reset transitions from all states to your initial state. Just mark your initial state clearly to save space on your diagram. As usual, leave `rst` out of your transition conditions as well.
5. However, feel free to use `rst` in the action/output logic within your states as needed – just don't use it for transition conditions.

Once you have an HLSM design that you think will work, you can move on to creating a datapath!

A Datapath

To create your datapath, first identify all of the local storage, complex actions, and complex conditions in your HLSM. Analyze what sort of datapath components (i.e. adders, comparators, registers, memories) you might need, and then figure out how to connect those components together to make the datapath work.

The inputs to the datapath should be simple control signals that your control module will drive or external inputs (such as the `pattern` switches). The outputs from your datapath will be Boolean indicator signals (like comparator outputs) that your controller will need for transitions. Additionally, your datapath may directly drive external outputs (such as `pattern_leds`).

One additional note – you will be provided a 64-entry 4-bit memory which you **must** use as a component in your datapath. The memory unit is illustrated in Figure 5.1, and it has the following ports:

- `clk` – The clock for the memory module.
- `rst` – A synchronous reset signal that writes zeros to all entries in the memory on a positive clock edge.
- `r_addr` – The entry to be read.

- **r_data** – The output containing the data stored at **r_addr**. This output is asynchronous – as soon as **r_addr** is updated, **r_data** will reflect that change.
- **w_addr** – The entry to be written.
- **w_data** – The data to be written to **w_addr**.
- **w_en** – The write-enable signal. When this signal is high, data will be written from **w_data** to **w_addr**'s entry on a positive clock edge. Writes are synchronous, and will *only* happen on clock edges.

Note that you do *not* have to use the **rst** signal for this memory module if you don't want to. If you choose not to use it, simply wire it to zero in your diagram.

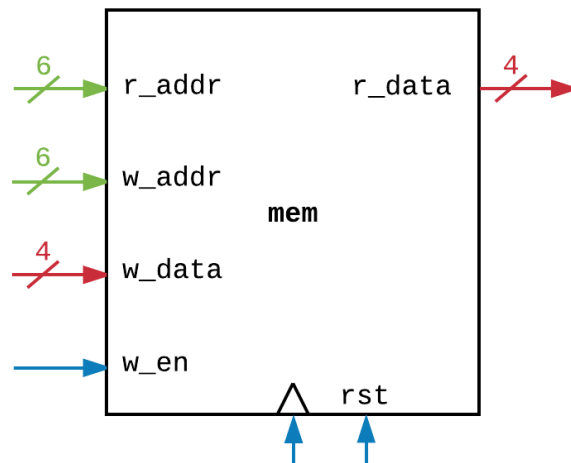


Figure 5.1: Provided 64-entry 4-bit Memory

Draw your datapath as you see fit, but please follow these guidelines:

1. Feel free to use high-level modules like adders, comparators, multi-function registers, and the like. We do **not** want a gate-level description of all of these components – just make assumptions about the control signals available and mark your modules so that it's clear what they do. When in doubt, keep it simple!

2. Clearly label the bit-width of every wire in your design.
3. Clearly indicate the inputs and the outputs of your datapath, and provide names for each. Signal names should be simple but descriptive enough to explain what they do. For example, a control signal that resets a counting register to zero could be labeled with `count_rst`.

Once you have a datapath design that you believe is complete, save a copy of your design and move on to FSM creation!

A Controller

Your final task for preliminary design work is to convert your HLSM into a simple FSM that will serve as the control unit of your circuit. You can do this with a few easy steps:

1. Replace complex actions in your states with simple output logic to manipulate datapath control signals.
2. Replace complex conditions on your transitions and in your output logic with simple Boolean indicators from the datapath's comparator outputs.

Once you perform these steps, your HLSM will be reduced to a simple FSM. Draw that FSM, following the guidelines listed below:

1. For each state, list the controller outputs that are on (active) during that state. If an output does not appear at all in a state's output list, then the output is understood to be set to zero for that state.
2. Feel free to create a Mealy machine, where the outputs in a state can also be affected by the current inputs. For example, you might want different outputs in the same state based on whether `rst` is high or not.
3. Once again, leave `rst` out of all of your transition conditions, and simply mark your initial state clearly.
4. Finally, all transition conditions should be simple Boolean logic statements (ORs, ANDs, and NOTs) based on simple signals. Complex conditions, like numerical comparisons or legality checking for input patterns, should be calculated in the datapath and compressed to simple Boolean indicator signals that can be read by the controller.

Once your FSM design is complete, save yourself a copy of it and move on to submission.

Write-up and Submission

Submit your HLSM, datapath, and controller FSM designs on Blackboard as a single PDF – if you handwrote them, take pictures and save them as a PDF using a document editor of your choice. Name your PDF *netid1_netid2_design.pdf*, with *netid1* and *netid2* replaced with your Princeton NetIDs. To aid *anonymous* review and grading of this write-up, please don't put your name/netid inside the PDF. Only one student should submit on Blackboard – we will use the NetIDs on the writeup to match that submission to both students.

Congratulations! You've finished work for week one. It's a good idea to start the next part early, as it may take longer to complete!

Week 2: Datapath and Controller Implementation

Checkpoint 2 Due Date: November 22nd, 2017

Now that you have a design hammered out for your datapath and controller, you'll implement them in Verilog and test them individually.

Datapath Implementation

Let's begin with the datapath – open up *SimonDatapath.v*, which has been started already for you. You'll notice that the first three inputs for the datapath have been declared for you:

```

1 module SimonDatapath(
2     // External Inputs
3     input      clk,           // Clock
4     input      level,        // Switch for setting level
5     input [3:0] pattern,     // Switches for creating pattern
6     //...
7 );
```

Add control signal inputs, Boolean indicator outputs, and external outputs as needed. Then, get started on creating your internal datapath logic. You have total freedom with regard to how you implement your datapath – just remember to use the provided memory unit, which has already been included in the provided code.

Controller Implementation

Once your datapath is completed, you should implement your controller FSM. This part should be fairly familiar to you – it's essentially the same process that you performed in Lab 4! The code for the controller should be written in *SimonControl.v*. Once again, some code has been supplied for you to help you get started. Feel free to modify it as you wish.

Modular Testing

Once both your datapath and controller have been completed, it's time to test them out. Instead of immediately wiring them together, we're going to test these components individually.

Modular design is a very important way to make comprehensible and reusable circuits, and modular testing makes debugging a large system much easier. Instead of trying to debug the entire Simon game as a monolithic

circuit, we're going to test its primary components individually. This will detect and remove simple bugs that would be much harder to discover and fix once the whole system comes together.

In *SimonDatapath.t.v* and *SimonControl.t.v*, write simple testbenches for each of your modules. You should create several test cases for each module – the tests do not have to cover every possible case, but they should at least simulate some common behaviors that you expect during gameplay.

For example, you'll probably want to test your datapath to ensure that you can write a pattern into memory and read it back out. You'll also want to test your controller, ensuring that it transitions states as you expect based on the Boolean indicators it will eventually receive from the datapath.

We've included a few helpful testing macros in both files for you to use. Feel free to use them or ignore them – they're just there for your convenience.

Once you've completed your testbenches, compile them with the following commands:

```
1 iverilog -g2005 -Wall -Wno-timescale -o SimonControlTest SimonControl.t.v
2 iverilog -g2005 -Wall -Wno-timescale -o SimonDatapathTest SimonDatapath.t.v
```

Fix any compiler errors or warnings, and then execute your tests with the following commands:

```
1 vvp SimonControlTest
2 vvp SimonDatapathTest
```

Ensure that there are no failures. You'll see some warnings that look like this when you compile the datapath tests:

```
1 VCD warning: array word SimonDatapathTest.dpath.mem.mem[0] will conflict with
  an escaped identifier.
```

Just ignore those warnings throughout the rest of the lab – they're caused by dumping out array contents (in this case, your memory) to a VCD file.

If you need waveforms for debugging, they will be dumped out as *SimonControlTest.vcd* and *SimonDatapathTest.vcd*. You can open them with these commands (use one at a time):

```
1 gtkwave SimonControlTest.vcd
2 gtkwave SimonDatapathTest.vcd
```

Write-up Question 1:

Briefly explain the test cases you wrote for your testbenches. What behaviors do your test cases verify, and why did you focus on those cases?

Write-up Question 2:

Did you have to modify your design from Week 1? If so, what did you change?

Write-up and Submission

In your write-up for this week, answer the numbered questions from the text in this section briefly but completely. Feel free to create the write-up in whatever program you want to use, but save and submit it as a PDF. Name your PDF *netid1_netid2_midpoint.pdf*, with *netid1* and *netid2* replaced with your Princeton NetIDs. To aid *anonymous* review and grading of this write-up, please don't put your name/netid inside the PDF.

Delete *SimonControlTest*, *SimonDatapathTest*, and any *.vcd* waveform files from the */simon* directory. You can do this via your file browser or with one of the following commands.

On OS X and Linux:

```
1 rm -f *.vcd SimonControlTest SimonDatapathTest
```

On Windows:

```
1 del *.vcd SimonControlTest SimonDatapathTest
```

Then create a *.zip* archive of that directory. Make sure to name it as *netid1_netid2_midpoint.zip*, with *netid1* and *netid2* replaced with your Princeton NetIDs.

On OS X and Linux, simply change directories in your terminal to the the directory that contains the */simon* directory and then execute this command:

```
1 zip -r netid1_netid2_midpoint.zip ./simon
```

On Windows, simply open up File Explorer and locate the */simon* folder. From Command Prompt, you can open your current directory's parent in File Explorer by issuing this command:

```
1 explorer.exe ..
```

Right-click on the */simon* folder and select "Send to", then "Compressed (zipped) folder". This will create a *.zip* file.

Submit the *.zip* file that you created to Blackboard. **Only one student should submit on Blackboard** – we will use the NetIDs on the writeup

and zip folder to match that submission to both students.

For reference, here is a checklist of files that should be in your *.zip*:

- *SimonControl.v*
- *SimonDatapath.v*
- *SimonControl.t.v*
- *SimonDatapath.t.v*

Finally, submit the following to Blackboard:

- *netid1_netid2_midpoint.zip*
- *netid1_netid2_midpoint.pdf*

Congratulations! You've finished work for week two. It's a good idea to start the next part early, as there will be many people in the EE lab in the upcoming week. The next part will have to be completed in the EE lab!

Week 3: Module Combination and Testing

Final Submission Due Date: November 29th, 2017

Now that your individual controller and datapath modules have been written and tested, you will combine them to form the full Simon circuit. Then, you will run the game against a basic testbench written by the TAs and add your own testbench.

Connecting the Datapath and Control Units

This part should be fairly easy – just open up *Simon.v* and add wires for all of the connections between the datapath and control module. Then, connect the two modules by adding those wires to the ports you created in *SimonDatapath.v* and *SimonControl.v*. The module instances are already declared for you – just add to them!

Note that there is a section of commented code that looks like this:

```

1 //=====
2 // Button Debouncer Section
3 //=====
4
5 //-----
6 // IMPORTANT!!!! If simulating, use this line:
7 //-----
8 wire uclk = pclk;
9 //-----
10 // IMPORTANT!!!! If using FPGA, use this line:
11 //-----
12 //wire uclk;
13 //ButtonDebouncer debouncer(
14 //  .sysclk(sysclk),
15 //  .noisy_btn(pclk),
16 //  .clean_btn(uclk)
17 //);
18
19 //=====
20 // End Button Debouncer Section
21 //=====

```

For now, just leave this code as-is. Later, you'll use the button debouncer when you program your FPGA.

Finally, do not modify the Simon module's port list. It is needed for the TA testbench to work correctly.

Running the TA Testbench

There is a basic testbench in *SimonTA.t.v* that actually simulates the basic gameplay sequence described at the beginning of this lab manual. To run it against your code, just run the following command:

```
1 iverilog -g2005 -Wall -Wno-timescale -o SimonTATest SimonTA.t.v
```

Fix any compiler errors or warnings, and then execute the tests with the following command:

```
1 vvp SimonTATest
```

Ensure that there are no failures. If you need waveforms for debugging, they will be dumped out as *SimonTATest.vcd*. You can open them with this command:

```
1 gtkwave SimonTATest.vcd
```

Writing Your Own Testbench

The TA testbench only tests a subset of Simon's functionality. For example, it only performs tests where `level` was set to zero when the game was reset. Your task is to write functional tests that verify Simon's behavior under a wider set of conditions.

Write your code in *Simon.t.v*. Feel free to model your code on the code in *SimonTA.t.v* – we've even included the macros we used there in your testbench for your convenience!

Once your testbench is completed, run your tests with the following command:

```
1 iverilog -g2005 -Wall -Wno-timescale -o SimonTest Simon.t.v
```

Fix any compiler errors or warnings, and then execute the tests with the following command:

```
1 vvp SimonTest
```

Ensure that there are no failures. If you need waveforms for debugging, they will be dumped out as *SimonTest.vcd*. You can open them with this command:

```
1 gtkwave SimonTest.vcd
```

Once you've passed both the TA testbench and your own cases, you're ready to put your code onto an FPGA!

Write-up Question 1:

Explain your functional tests for the overall Simon module. What use cases do they test, and how do they work?

Week 3: Synthesizing for an FPGA

In this section, you will be programming an FPGA with a synthesized version of your Simon code. Unfortunately, the software to synthesize your Verilog and program your FPGA's is only available on the computers in the Undergraduate Lab, so you'll have to go there to work.

FPGA Orientation

The FPGA we'll be using is a Xilinx Artix-7 chip, which is mounted on a Digilent Basys3 board.

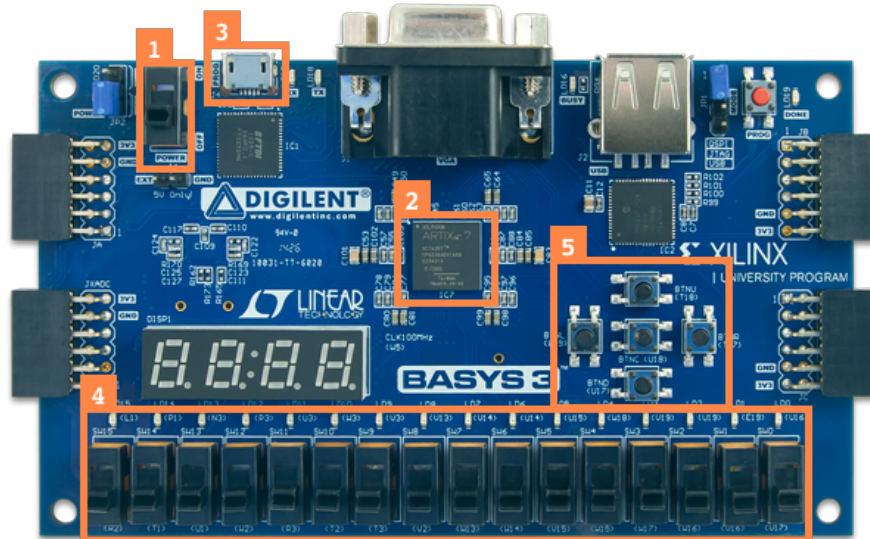


Figure 5.2: Full FPGA Board. 1) Power Switch 2) Xilinx FPGA IC 3) USB Programming Port 4) Switches and LED's 5) Buttons

We'll be using special software to convert your Verilog code into gate specifications to program the Xilinx FPGA. Additionally, we have included a pin specification (XDC) file that will link the inputs and outputs of your Simon module to physical switches and buttons on the Basys3 board.

Figure 5.3 shows a closeup of the button array. The buttons that we're going to connect to `pclk` and `rst` are labeled.

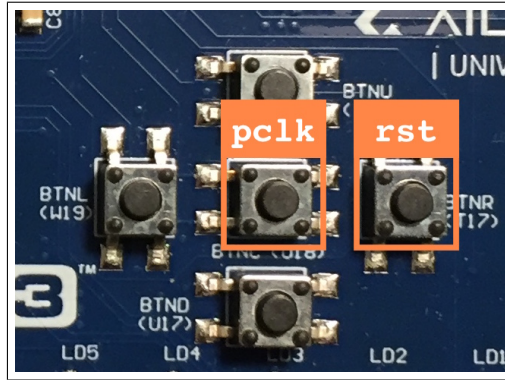


Figure 5.3: FPGA Buttons

Figure 5.4 shows a closeup of the switch and LED array that we'll be using for `pattern`, `pattern_leds`, `level`, and `mode_leds`.

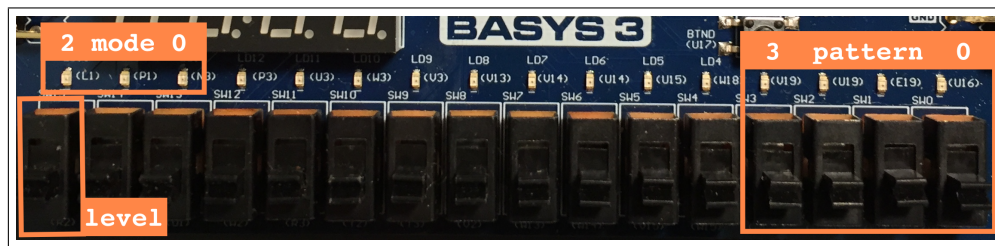


Figure 5.4: FPGA Switches and LED's

Button Debouncing

Unfortunately, mechanical buttons are not perfect. In fact, they will frequently exhibit the behavior shown in Figure 5.5, where the button's signal will oscillate rapidly for a brief time as the button transitions. This behavior is caused by the button's contacts actually physically bouncing off of one another, and it's difficult to get rid of mechanically.

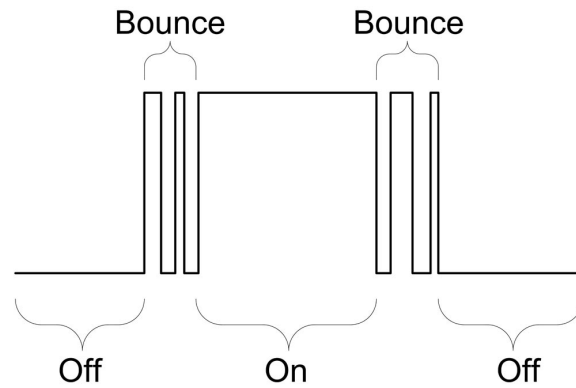


Figure 5.5: Illustration of Button Bounce Phenomenon

In order to deal with this, we resort to a special circuit called a *button debouncer*. This circuit will produce a noiseless button signal by only transitioning whenever the external switch has been stable for a certain time period. This method is illustrated below in Figure 5.6.

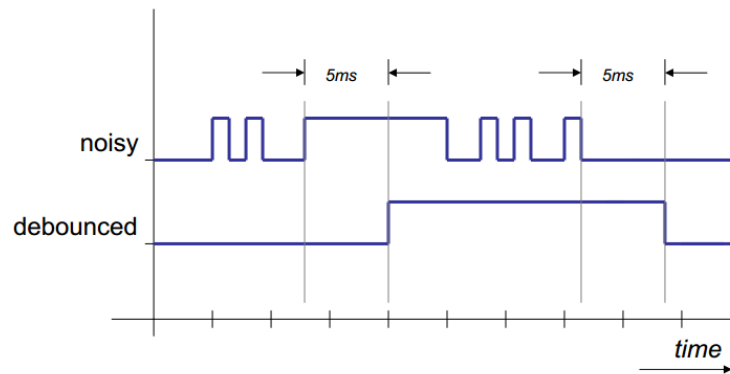


Figure 5.6: Button Debouncing with Stability Time Requirement

We've written a circuit that does this. It's already been included in your *Simon.v* – all you need to do is remove the comments surrounding it:

```

1 //=====
2 // Button Debouncer Section
3 //=====
4
5 //-----

```

```
6 // IMPORTANT!!!! If simulating, use this line:
7 //-----
8 //wire uclk = pclk;
9 //-----
10 // IMPORTANT!!!! If using FPGA, use this line:
11 //-----
12 wire uclk;
13 ButtonDebouncer debouncer(
14     .sysclk(sysclk),
15     .noisy_btn(pclk),
16     .clean_btn(uclk)
17 );
18
19 //=====
20 // End Button Debouncer Section
21 //=====
```

Programming Your FPGA

Next, you will synthesize your code and program your Xilinx FPGA! In order to do this, log onto one of the lab computers and open up the Xilinx Vivado Design Suite (search for “Vivado” in the Windows start menu and the program is called “Vivado 2016.2 or 2016.3”). Please verify you are using a lab computer that has a Basys3 board attached to it.

You should be presented with a main menu that offers the option to create a new project:

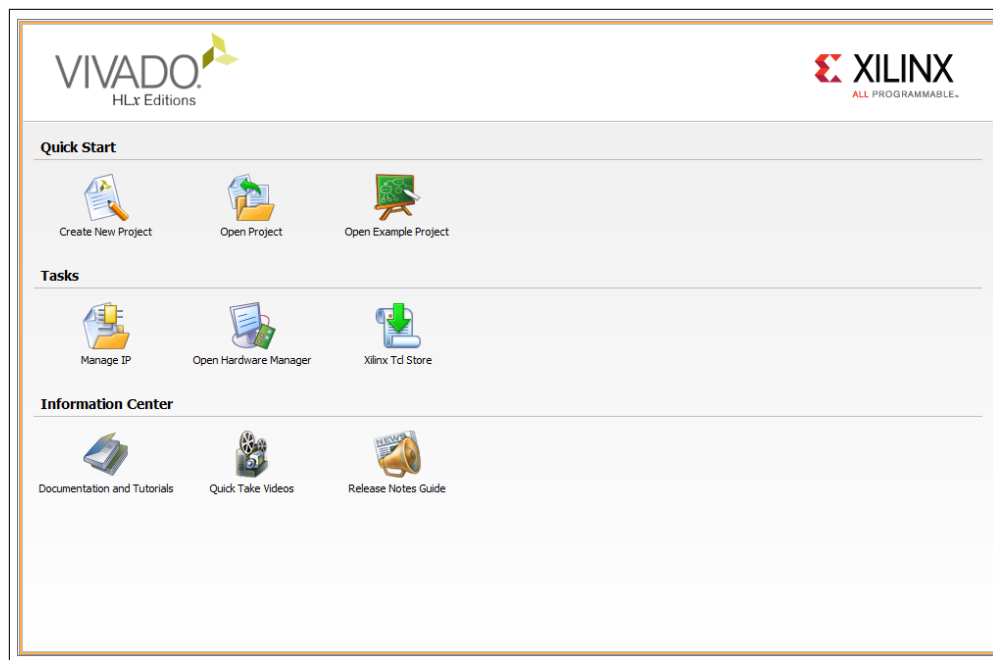
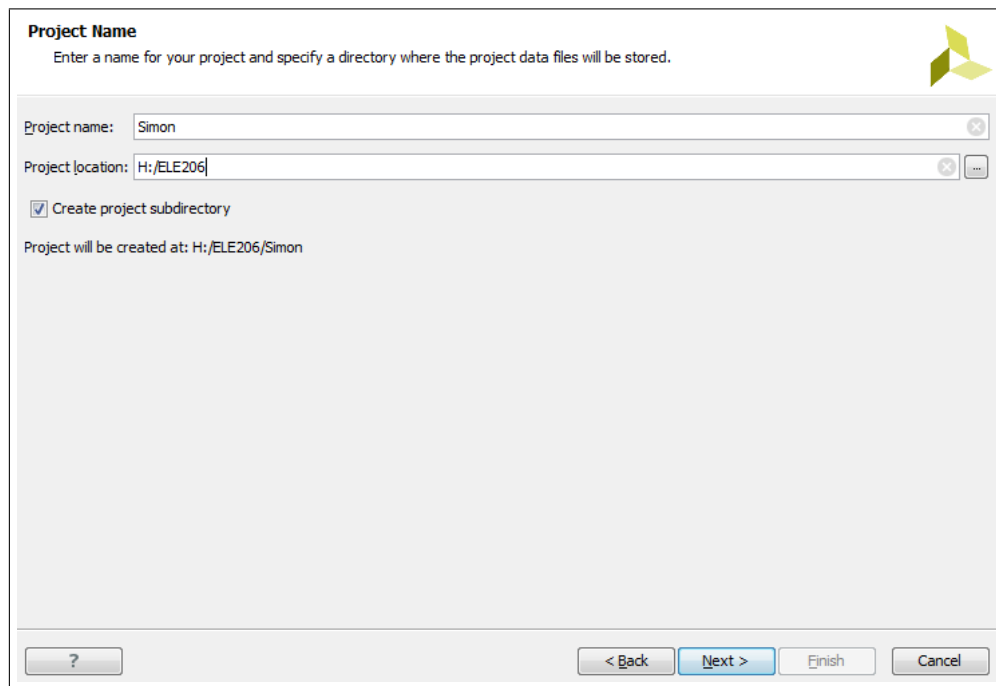


Figure 5.7: Xilinx Vivado Main Menu

Simply click the “Create New Project” button to start your Simon project. A New Project Wizard will appear. Click “Next” to begin creating the project. A menu will appear that looks like this:



The screenshot shows a dialog box titled "Project Name" with a subtitle "Enter a name for your project and specify a directory where the project data files will be stored." The dialog box contains two text input fields: "Project name:" with the value "Simon" and "Project location:" with the value "H:/ELE206". Below these fields is a checkbox labeled "Create project subdirectory" which is checked. Underneath the checkbox, it says "Project will be created at: H:/ELE206/Simon". At the bottom of the dialog box, there are four buttons: a question mark icon, "< Back", "Next >", and "Cancel". The "Next >" button is highlighted with a blue border.

Figure 5.8: New Project Menu

Name your project “Simon” and pick a location to save your project. We recommend using your H:/ drive since computer availability is not guaranteed. Then, click “Next”.

The next menu will ask you to specify the “Project Type”. Select “RTL Project” and select the “Do not specify sources at this time” option. Then, click “Next”.

Default Part
Choose a default Xilinx part or board for your project. This can be changed later.

Select: **Parts** Boards

Filter

Product category: All Speed grade: -1
Family: Artix-7 Temp grade: All Remaining
Package: cpg236

Reset All Filters

Search:

Part	I/O Pin Count	Block RAMs	DSPs	FlipFlops	GTPE2 Transceivers	Gb Transceivers	Available IOBs	LUT Elements
xc7a15tcp236-1	236	25	45	20800	2	2	106	10400
xc7a35tcp236-1	236	50	90	41600	2	2	106	20800
xc7a50tcp236-1	236	75	120	65200	2	2	106	32600

Figure 5.9: New Project Part Menu

The next menu will allow you to associate the Basys board's FPGA with your project. Use the following information to locate your board in the list:

- **Family** – Artix-7
- **Package** – cpg236
- **Speed Grade** – -1

Once you have selected the appropriate board, click “Next”. Verify that the new “New Project Summary” contains the following details and then click “Finish”:

- **Default Part:** xc7a35tcp236-1
- **Product:** Artix-7

Now, you'll see the "Project Manager" screen. Pull your source code in */simon* over to the lab computer via flash drive, your H:/ drive, or a Dropbox-like service. In the left-hand "Flow Navigator" menu, shown in Figure 5.10, click the "Add Sources" button. **Please ensure you've uncommented the debounced clock code in *Simon.v* before adding files.**

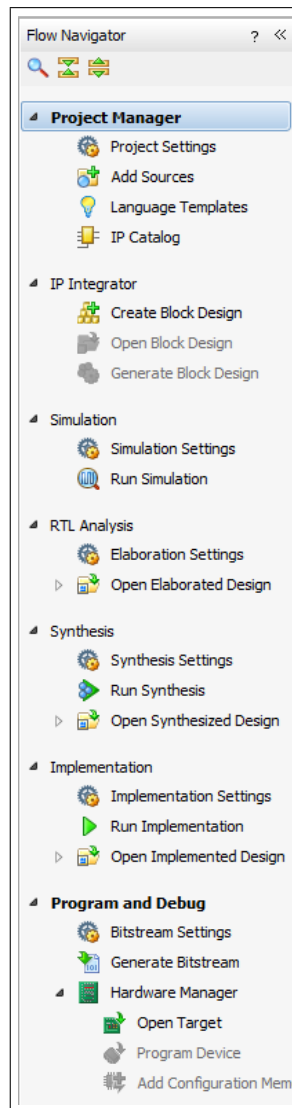


Figure 5.10: Flow Navigator

Select “Add or create design sources”. Then, click “Next”. You will be presented with a blank file list. Here, select the “Scan and add RTL include files into project” and ‘Copy sources into project” options, as shown in Figure 5.11 and add following file to the project:

- *Simon.v*

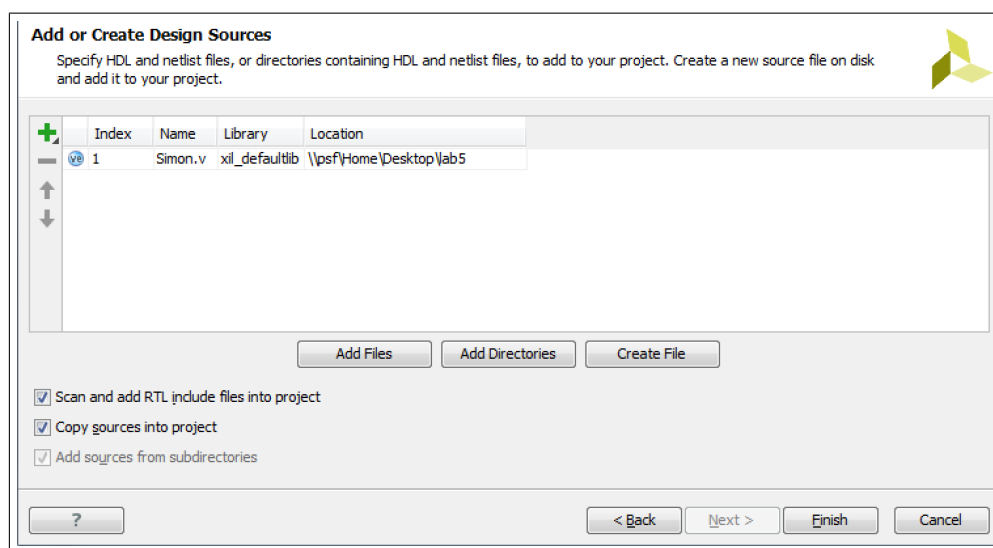


Figure 5.11: Add Sources Menu

Since we have ‘include directives linking the files of our project, Vivado should scan and add all of these files automatically. This should work without error as long as the directives have been unchanged and the files are all located in the same directory. Click “Finish” once you’ve added the file.

Now, we will add the constraints file by, once again, selecting the “Add Sources” button, but this time choosing “Add or create constraints”. Now, you will add the provided *Simon.xdc* file. Do not forget to select the “Copy constraints file into project” option!

After these steps, the sources hierarchy should look similar to Figure 5.12. If you find that a file is missing, you may need to add it manually. Alternatively, you can add all of the files manually, but when synthesizing, you may be presented with a warning – “overwriting previous definition of module..” – you can safely ignore this.

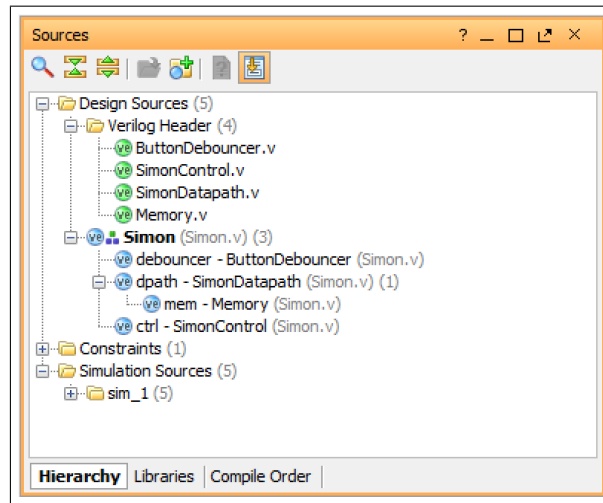


Figure 5.12: Sources Hierarchy

Finally, we're going to synthesize your code into a bitfile that will be used to program the FPGA. The *Simon.xdc* file specifies how to connect ports in your Simon module to physical LEDs and switches on the FPGA.

To generate your bitfile, complete the following steps. Each step should pass without errors:

1. **Synthesis:** Select "Run Synthesis" in the "Flow Navigator", shown in Figure 5.10. If there are errors, resolve them and try again. If Synthesis is successful, a window will appear. From here, you will choose to "Run Implementation".
2. **Implementation:** You can also select "Run Implementation" from the "Flow Navigator". A window will appear if implementation is successful. From here, you will choose to "Generate Bitstream".
3. **Generate Bitstream:** You can also select "Generate Bitstream" from the "Flow Navigator". Once again, a window will appear if the bitstream was successfully generated.

Write-up Question 2:

Did you have any trouble synthesizing your code? If so, what was the problem?

Next, you will program the FPGA with the generated bitfile. Make sure to power on the Basys board at the lab computer before proceeding. You should see at least a few LEDs light up on the board.

1. Under “Hardware Manager” in the “Program and Debug” section of the “Flow Navigator”, select “Open Target” then “Auto-Connect”. Now the Hardware Manager should open with a “xc7a35t” device listed, as seen in Figure 5.13.
2. Click “Program Device” in the “Flow Navigator”. You can also right-click device and click “Program Device”. The *Simon.bit* file should automatically populate the bitstream file field. If not, manually locate the bitstream file. Then, select “Program”. You can ignore any warnings about the missing debug core.
3. Programming should take only a few seconds. The Done LED on the Basys board will turn on when complete.
4. Play a game of Simon with your lab partner, and celebrate your success! Do not unplug the FPGA from its power supply, as you’ll need to re-program it if it loses power.
5. **Please power off Basys3 board when leaving the lab!**

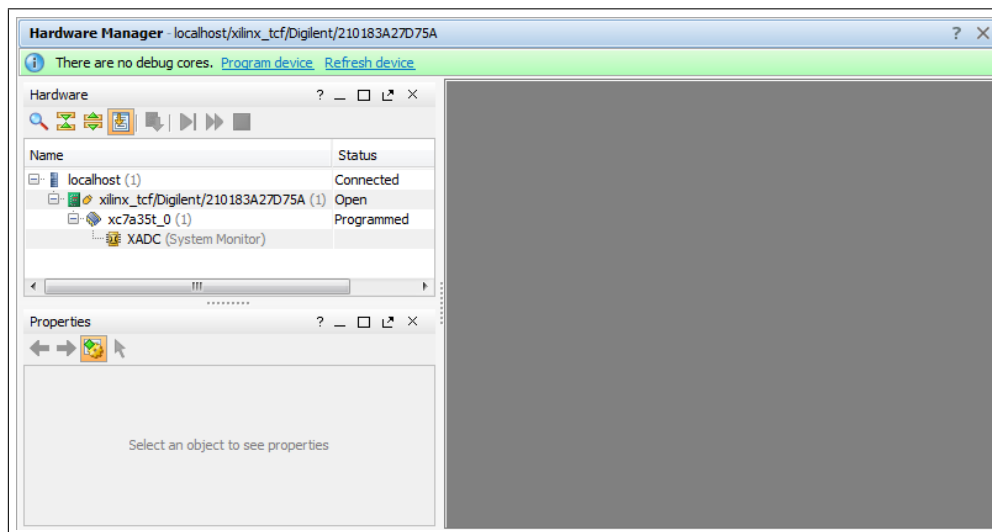


Figure 5.13: Hardware Manager Window

Write-up Question 3:

Please leave a bit of feedback regarding this lab. How much time did it take, how difficult was it, did you get stuck anywhere? There are no wrong answers here – we'll be using the feedback to adjust this lab for the future.

Demo, Final Write-Up, and Submission

Demonstration

For your demonstration, play a game of Simon with a TA. Show them that your level switch works correctly and that all modes perform as expected. If you completed the extra credit (wrap-around), mention that during your demo and explain how you implemented it to your TA. Both students are expected to be present at the demo; otherwise, each partner can demo at different times, but will only receive credit at that time.

Write-Up

For your write-up, answer the numbered questions from the text briefly but completely. Feel free to create the write-up in whatever program you want to use, but save and submit it as a PDF. Name your PDF *netid1_netid2_simon_writeup.pdf*, with *netid1* and *netid2* replaced with your Princeton NetIDs.

Submission

Delete *SimonTATest*, *SimonTest*, *SimonDatapathTest*, *SimonControlTest*, and any *.vcd* waveform files from the */simon* directory. You can do this via your file browser or with one of the following commands.

On OS X and Linux:

```
1 rm -f *.vcd SimonTATest SimonTest SimonDatapathTest SimonControlTest
```

On Windows:

```
1 del *.vcd SimonTATest SimonTest SimonDatapathTest SimonControlTest
```

Then create a *.zip* archive of that directory. On OS X and Linux, simply change directories in your terminal to the directory that contains the */simon* directory and then execute this command:

```
1 zip -r netid1_netid2_simon.zip ./simon
```

On Windows, simply open up File Explorer and locate the */simon* folder. From Command Prompt, you can open your current directory's parent in File Explorer by issuing this command:

```
1 explorer.exe ..
```

Right-click on the */simon* folder and select “Send to”, then “Compressed (zipped) folder”. This will create a *.zip* file – rename it as *netid1_netid2_simon.zip*,

with *netid1* and *netid2* replaced with your Princeton NetIDs.

Submit the *.zip* file that you created to Blackboard. **Only one student should submit on Blackboard** – we will use the NetIDs on the writeup and zip folder to match that submission to both students.

For reference, here is a checklist of files that should be in your *.zip*:

- *Simon.v*
- *Simon.t.v*
- *SimonControl.v*
- *SimonControl.t.v*
- *SimonDatapath.v*
- *SimonDatapath.t.v*

Finally, submit the following to Blackboard:

- *netid1_netid2_simon.zip*
- *netid1_netid2_simon_writeup.pdf*