

## **Lab 1: Clocks, Counters, and Buttons** *(Oh my!)*

### **Introduction:**

In this experiment, we will introduce one of the core building blocks of digital circuits: the humble counter. By exploiting the versatility of the counter, a high frequency input clock will be slowed down by several orders of magnitude and then used to drive a bidirectional counter. Additionally, a counter will be used to solve one of the core problems involved with getting manual user input in digital circuits.

### **Part 0 – How does a Counter Work?**

Simulate and inspect the design located at: <http://www.edaplayground.com/x/ieF>  
Read this article: [https://www.doulos.com/knowhow/vhdl\\_designers\\_guide/numeric\\_std/](https://www.doulos.com/knowhow/vhdl_designers_guide/numeric_std/)  
Watch this video on clocks in FPGAs: <https://www.youtube.com/watch?v=htwlb-DuEK8>

Notice that no structure is specified in the counter design. The data is described simply as signals and operations on signals. This is called “behavioral” modeling and is the most common and powerful way of designing digital circuits. An experienced digital designer usually knows how their behavioral code will translate into hardware before they write it (conditionals become multiplexers, signals operated on at clock edges become flops, etc).

In the physical world you could use a chip like: <http://www.ti.com/lit/ds/symlink/sn74f163a.pdf>

The alternative strategy would be to use toggle flip flops designed with discrete master-slave latch pairs and instantiate 4 flops. This is a lot of work and defeats the purpose of using VHDL to design at a higher level of abstraction. That type of “structural” design is used for top level designs and test benches, not individual components usually.

## Part 1 – My Clock is Just Right:

### Background:

The Digilent Zybo board contains a single crystal oscillator that runs at a frequency of 50 MHz. This goes into an Ethernet PHY which generates a 125 MHz clock to feed into the FPGA fabric.

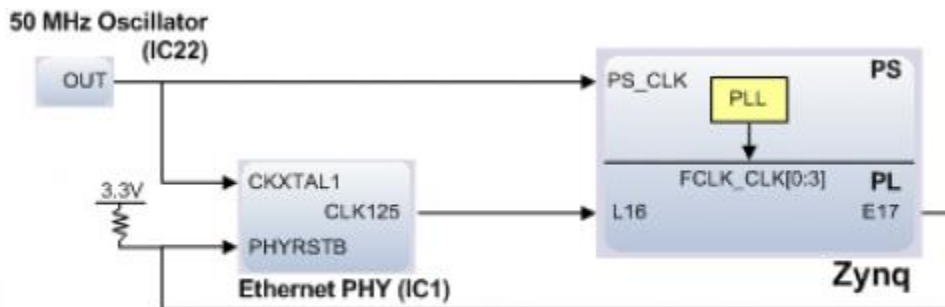


Figure 1: Zybo Clock System Schematic

In this first section, we are going to divide that clock down to a much more human-friendly frequency in order to observe its changes by redirecting the then-divided clock to an LED.

In order to be more human-friendly, we are going to divide the frequency of the clock from 125 MHz down to 2 Hz (a long way indeed!). In order to do so, we are going to utilize a simple counter circuit.

*Question 1: How much do we need to divide our input by to get from 125 MHz to 2 Hz? \_\_\_\_\_*

In order to divide a clock using a counter, we create a simple circuit. It contains a single binary up counter. First, we initialize an n-bit signal to 0. Then, for every rising edge of the input clock, we increment that signal. Once the signal reaches the division ratio, we reset the signal to 0. Concurrently, when the signal is equal to the division ratio we set an output signal to '1'. Using this output signal as a clock enable, we only pass through every "ith" pulse, where "i" is the division ratio. In this way, we can pass along that clock enable to other designs' clock enable pins on their flops to achieve a design that runs at the divided frequency.

*Question 2: How many bits are required to store a counter that can count up to that value? \_\_\_\_*

### Task:

Create a design called “clock\_div” in VHDL that takes as input a 125 MHz clock signal and divides it down to 2 Hz. Utilize a looping testbench to drive 125 million clock cycles on the input of the module and verify that the output produces two full clock cycles. Modify the ZYBO\_Master.xdc file to uncomment the clk and led[0] pins. Create a top-level design called “divider\_top” that uses the output of the divider “AND”-ed with the clk signal to drive an inverting std\_logic signal whose output goes to led[0] and visually confirm the 2 Hz operation speed by loading it onto the Zybo board.

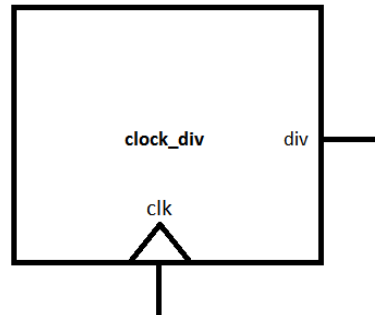


Figure 2: clock\_div block diagram

Signal Name	clk	div	“AND gate”
Direction	input	Output	N/A
Connected To	125 MHz clock, “AND gate”	“AND gate”	Inverting flop to On-board LED

Figure 3: clock\_div I/O information

### Expert Bonus Challenge (No Points):

By taking advantage of built in arithmetic libraries and generics, create a “clock\_div” entity that can be used to divide any input frequency to any possible output frequency achievable through integer division.

#### Hints:

- You will need to calculate the log2 of the division integer in order to find the bit width of your count signal.
- You will probably need to use conversion functions and make your own custom log2 function. See here for reference: <https://www.ics.uci.edu/~jmoorkan/vhdlref/function.html>
- The entity will have two generics (input frequency and division integer).

## Part 2 – Bouncy Buttons:

### Background:

Push buttons are fickle creatures. Due to being mechanical in nature, they are often the bane of existence for digital designers when not dealt with correctly. The problem lies in that mechanical nature. When the button is pushed or released the spring inside causes the contacts to behave like a damped oscillator, which creates spikes in the signal.

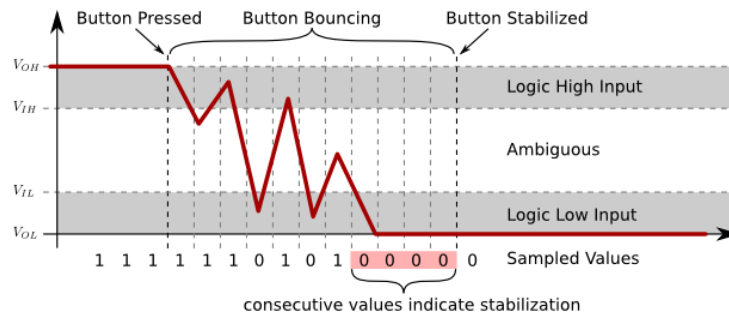


Figure 4: Sample Button Bounce Waveform

In order to avoid this bouncy nature we have two options as engineers: analog or digital debouncing. In the analog world, this would be done by using an RC charge/discharge circuit whose time constant is larger than the amount of bounce time. However, we don't have the luxury of analog circuitry so we are going to use a digital method.

In order to digitally de-bounce the input, we use a simple counter circuit that has an enable and an inverted reset. We sample the button value with respect to a system clock (our 125 MHz clock from the Ethernet PHY) into a 2 bit long shift register [in order to avoid metastable state in between  $V_{IHmin}$  and  $V_{ILmax}$ ] (`std_logic_vector` where each clock bit 0 gets new value and bit 1 gets value at bit 0) and see if the value of the end of the shift register (bit 1 of the vector) is a '1'. If it is, our counter increases by one. Any time our sampled value differs from a '1', we reset our counter. Once the counter hits its maximum value (the number of successive samples we deem enough), the output of the debounce circuit displays a '1' and the counter will no longer increment. At any time the counter has not hit its maximum value, the output of the debounce circuit displays a '0'.

*Note: Due to how the circuit adds based on samples of '1' until a certain number is reached, this circuit is very similar to the aforementioned RC analog version.*

*Question 1: What is the value of the button when it is pressed for the Zybo board? \_\_\_\_\_*

*Question 2 (optional): If it were the other value when pressed, would we have to alter our debounce design? Why or why not?*

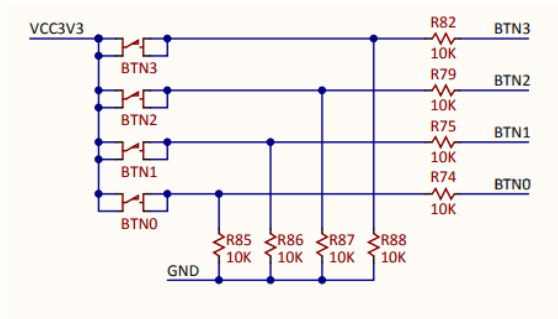


Figure 5: Zybo Pushbutton Circuit Diagram

Question 3: If we want our debounce time to be 20 ms, and our system clock is 125 MHz, how many ticks do we need a steady '1' to be read for it to count as a '1'? \_\_\_\_\_

Question 4: How many bits are required for a counter that can go that high? \_\_\_\_\_

### Task:

Create a design called “debounce” in VHDL that takes as input a single bit signal from a push button and de-bounces it in order to avoid undesirable mechanical behavior. Create a simple testbench with a clock, “button”, and output that shows the de-bouncing behavior of the circuit.

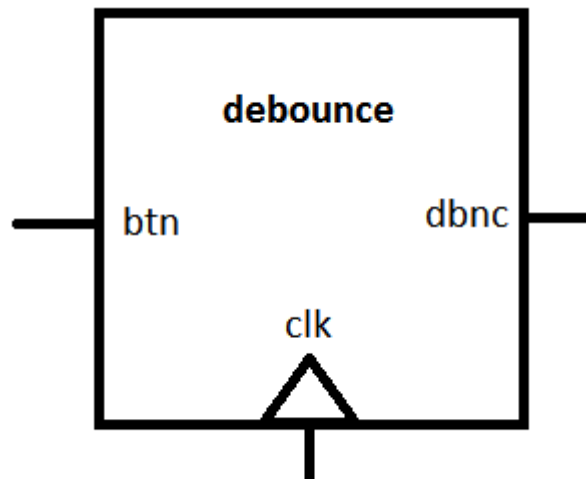


Figure 6: debounce block diagram

Signal Name	clk	btn	dbnc
Direction	input	input	output
Connect To	oscillator	button	Nothing yet

Figure 7: debounce I/O information

### Part 3 – Actually Using a Counter to Count:

#### Background:

A counter needs little introduction, especially since we are now familiar with some of its other uses. In this section, we are going to create a normal bidirectional counter with a couple extra control signals.

#### Task:

Design a 4-bit counter called “fancy\_counter” with the following behavior:

- Unless “en” is ‘1’, nothing will change in the circuit
- Even if “en” is ‘1’, if “clk\_en” is ‘0’ nothing can change the circuit except “rst”
- When “rst” is asserted, no matter what the clock is doing the “cnt” value will become 0.
- It can count either up or down depending on the value of a “direction” register, which is updated at the clock rising edge with the value present at “dir” when “updn” is ‘1’.
- On the clock rising edge, if “ld” is ‘1’, the value present at “val” will be loaded into the “value” register.
- If counting up, it will count until the number in a 4-bit “value” register has been reached, at which point it will roll over to “0000”. If counting down, it will go from “0000” to “value” when it underflows.

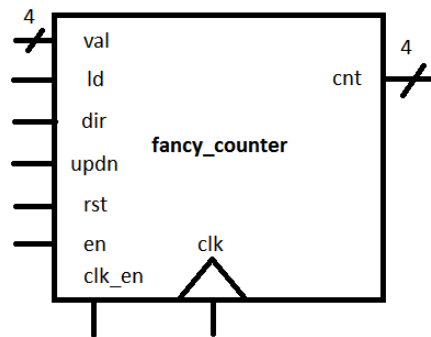


Figure 8: fancy\_counter block diagram

#### Expert Bonus Challenge (No Points):

Create a testbench that demonstrates the direction change, reset, value update, and enable control of “fancy\_counter”

## Part 4 – Bringing it All Together: (this is why we test individual designs)

### Background:

Now that we have all the components assembled and tested, we are going to combine them in a structural top level design to do something useful. Because all of the components have been individually tested, we can say with reasonable confidence that the system will behave as expected.

### Task:

Create a top level design following the diagram shown below called “counter\_top”. Modify the ZYBO\_Master.xdc file to enable the appropriate pins. Load the design onto the Zybo board and demonstrate the correct performance of the final design.

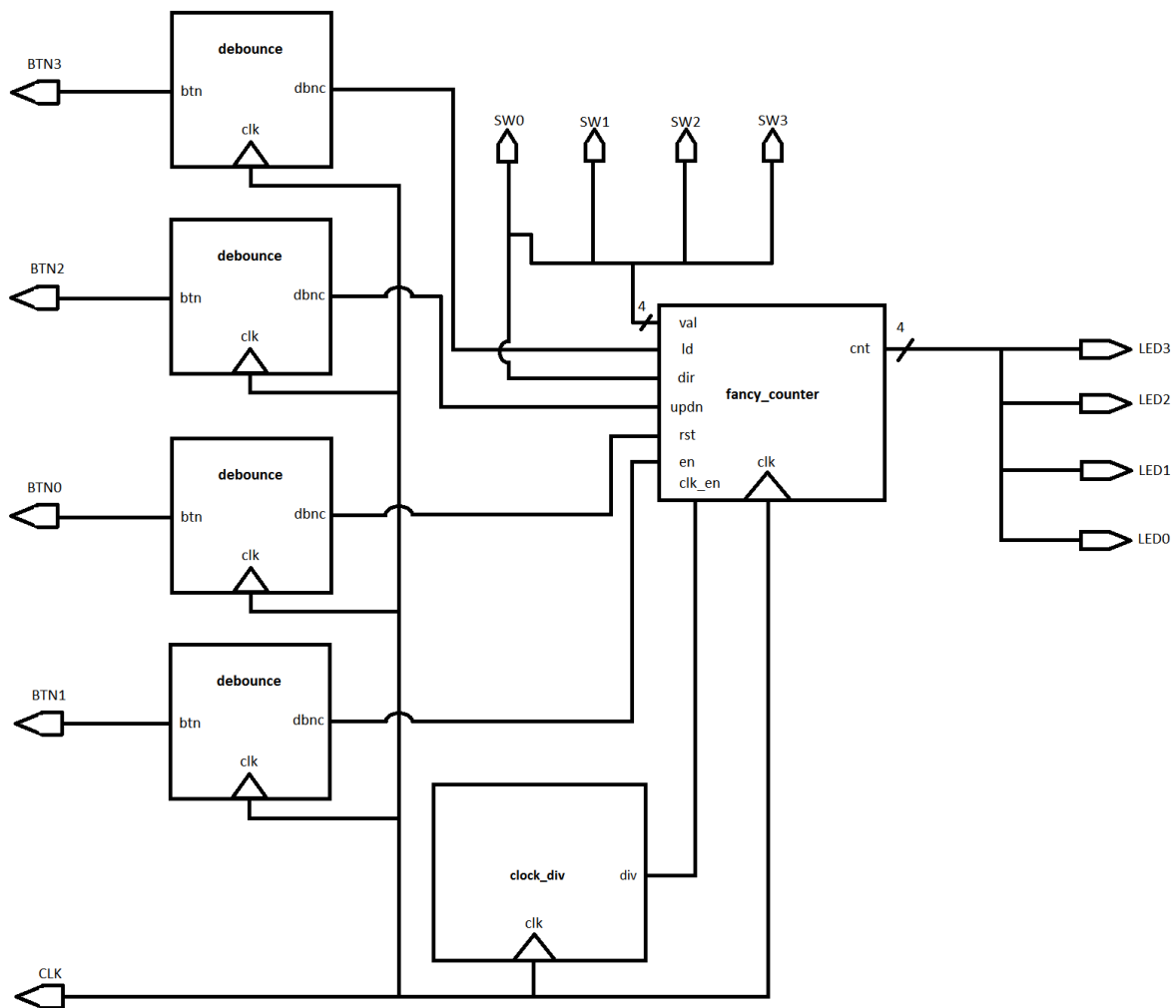


Figure 9: counter\_top block diagram

**Report:**

See the associated lab report format guideline in Resources

**Sources:**

[https://www.wayneandlayne.com/files/metronome/images/button\\_bounce.png](https://www.wayneandlayne.com/files/metronome/images/button_bounce.png)

<https://reference.digilentinc.com/reference/programmable-logic/zybo/reference-manual>

[https://reference.digilentinc.com/\\_media/zybo/zybo\\_sch.pdf](https://reference.digilentinc.com/_media/zybo/zybo_sch.pdf)

Microsoft Paint and painstaking effort