EE 307

Project #1

Whac-A-Mole

Performed 10/25/2008 to 11/04/2008

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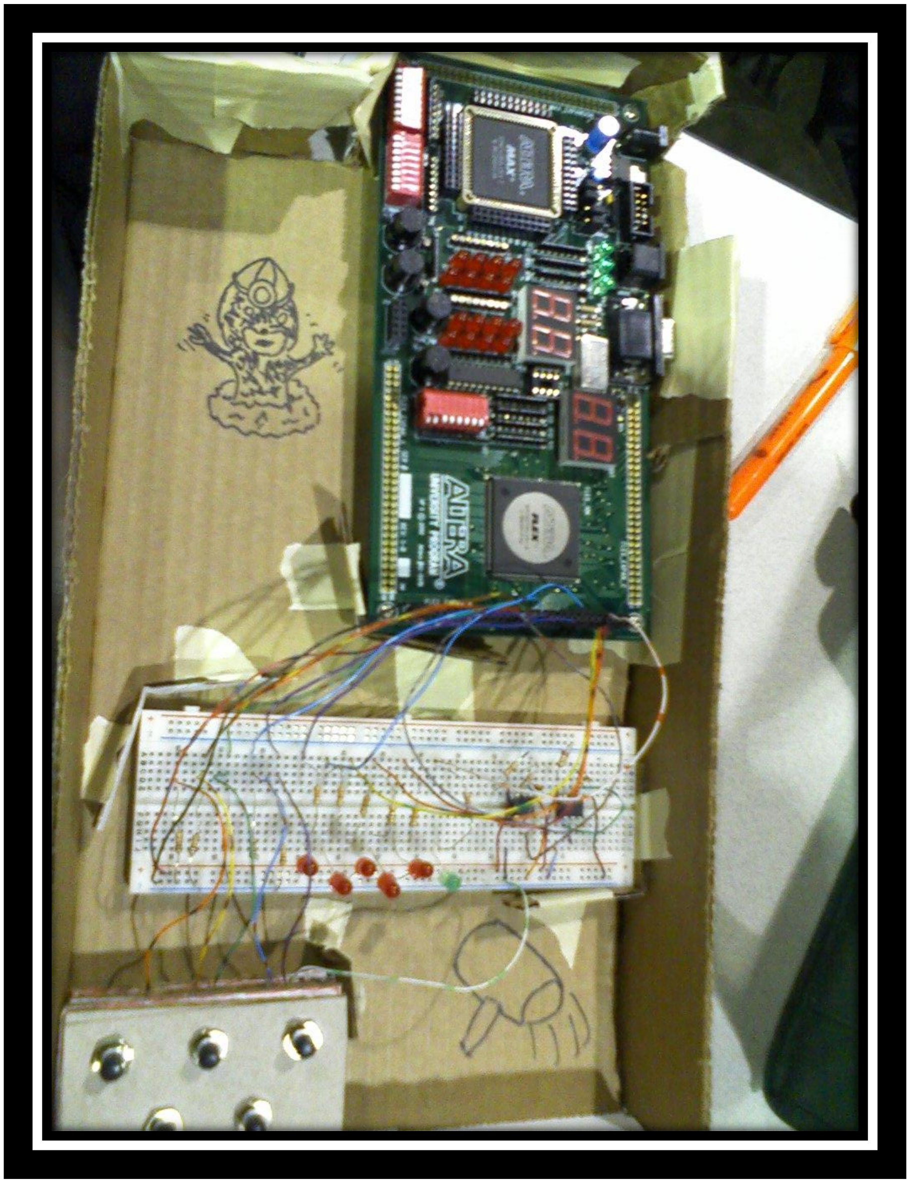

Abstract:

In this project, we made a digital circuit that operates Whac-A-Mole game. Quartus II schematic capture was used to develop our design and downloaded it onto the FPGA board. We will be talking about the background, design, implementation and results of the project in this report.

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Introduction:

The goal of the project was to create the Whac-A-Mole game. We have five LED lights that represent the moles and five push buttons that represent hitting the moles. The player gets points when the corresponding push button is pushed. The quicker the button is pushed after the corresponding LED light is up, the better score the player gets for that mole. This project will call on many of the digital electrical engineering skills we learned in the first labs of ELEC 307.

Background and Theory:

A typical Whac-A-Mole machine consists of a large cabinet with five holes in its top. Each hole contains a single plastic mole and the machinery necessary to move it up and down. Once the game starts, the moles will begin to pop up from their holes randomly and if the player hit an individual mole directly on the head with the mallet, the mole will go back in to the hole, thereby adding to the player's score.[1]

The Whac-A-Mole game is implemented on an FPGA. In order to make the game, we need to make a random number generator so that we could light up a random LED, and each LED lights will be lit for a random time: between 1-8 seconds.

The theory and methods used for the random number generation will be discussed in the next section.

[1] www.wikipedia.org

Design:

Top level

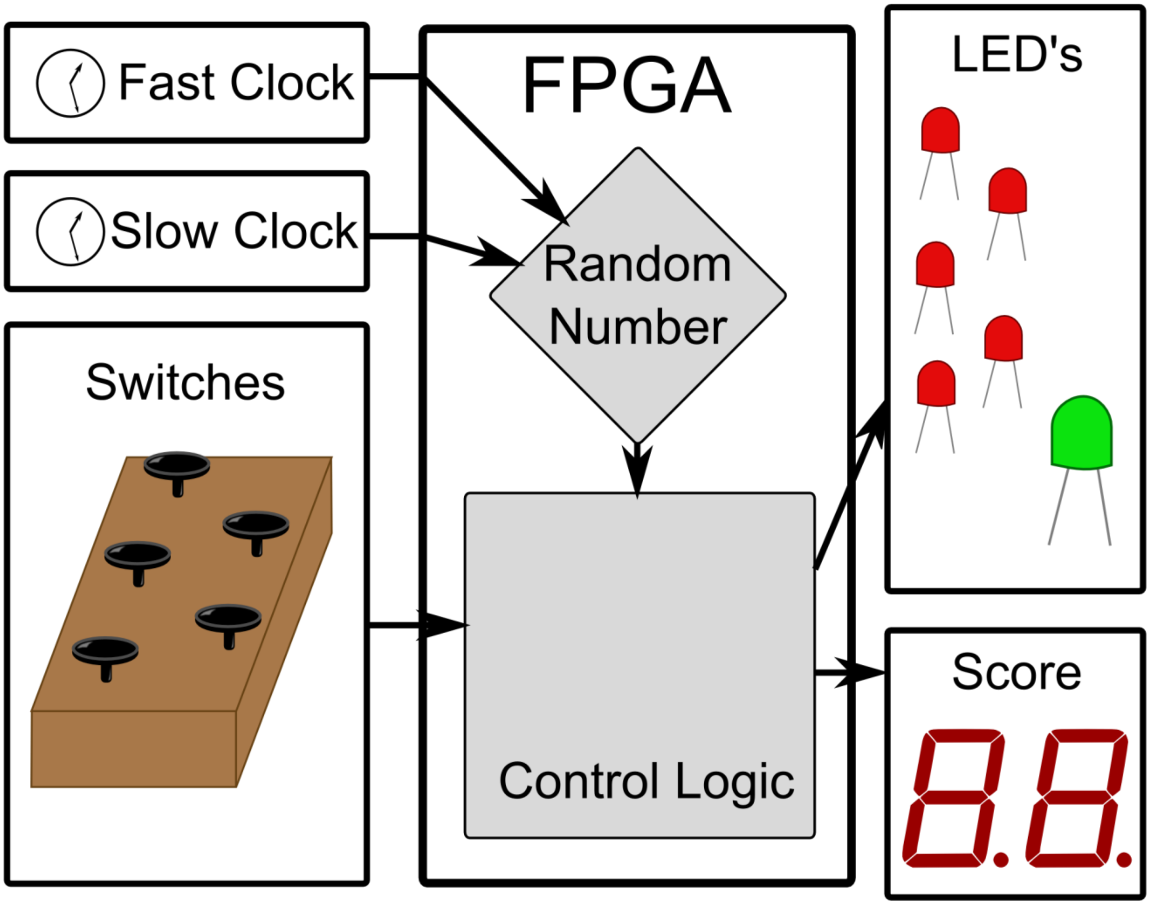

Figure 1

Five LEDs were used to represent five Moles, and five push buttons next to each mole. When one LED lights up, that means the mole is up. The mission of the player is to hit the right pushbutton that represents the lit mole as soon as possible. The player can start the game by hitting the reset button. The score of the game will be shown on the FPGA board. A green light by the side will light up after 15 moles have been up, which means the end of the game. Because there are only five moles and sometime they will be up for a few seconds, it's really easy to hit the right button sometimes. However, there is a maximum score of the game: 37500 = 92 (7C) on the display (in hex), which is next to impossible to get. No points will be taken if the wrong button is hit. You also don't get any points if you hold more the one button at the same time.

As we can see in Figure 1, the LED's, Seven segment Displays, Switches and clocks are outside of the FPGA, and the logic is inside the FPGA.

Random Numbers

Random numbers have an expectation value, for 1 bit (similar to tossing a coin) we want it to be one half of the time and zero the other half of the time. This yields an ideal expectation value of one half, let X be our random variable, one that follows the Bernoulli Trial rules:

$$E(X) = \sum_{i=0}^{n} i \cdot p_i(x)$$

For us, we only have two values, 1 and 0, where p_i is the probability of that number being 'picked':

$\boldsymbol{x}$	0	1
$\boldsymbol{p(X = x)}$	$(1-u)$	u

If u one half, our expected value is one half:

$$E(X) = \sum_{i=0}^{1} i \cdot p_i(x) = 0 \cdot (1-u) + 1 \cdot u = 0 \cdot \frac{1}{2} + 1 \cdot \frac{1}{2} = \frac{1}{2}$$

If we get our random numbers from a clock, we want the clock to have a duty cycle of 50%, this is analogous to saying the expected value of the clock is one half.

We are using 555 timers, where it is not possible to get an expected value (duty cycle) of one half. So let us use two clocks, X and Y, with expected values u and v respectively, noting that they are INDEPENDENT upon one another.

$$E(X) = u \qquad\qquad E(Y) = v$$

Let $\otimes$ be the exclusive or operator (XOR), such that:

$\boldsymbol{X}$	$\boldsymbol{Y}$	$\boldsymbol{X \otimes Y}$
0	0	0
0	1	1
1	0	1
1	1	0

Then the expected value of $X \otimes Y$ is:

$$E(X \otimes Y) = u + v - 2uv = \frac{1}{2} - 2\left(u - \frac{1}{2}\right)\left(v - \frac{1}{2}\right)^{2}$$

This says that if u and v are close to one half, then $X \otimes Y$ is even closer to one half.

We connected two 555 timers in Multivibrator mode, see Figure 2.

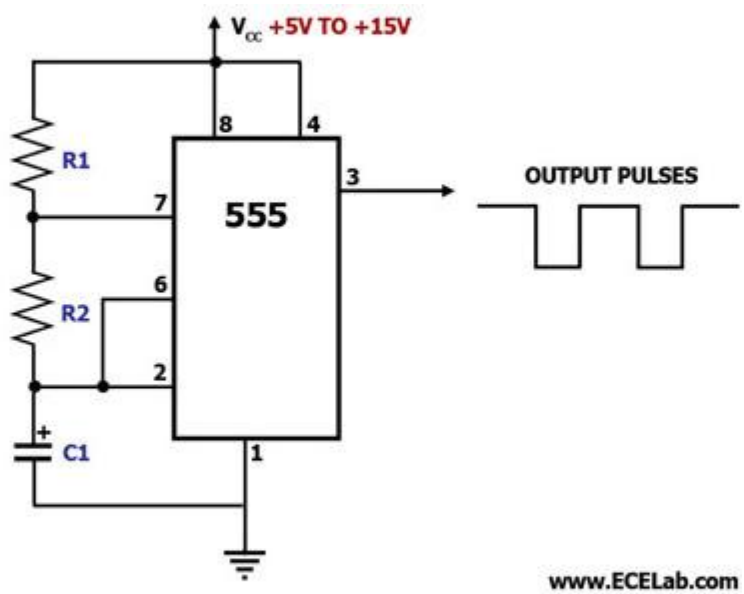

Figure 2

[2] Robert B Davies, "Exclusive OR (XOR) and hardware random number generators" February 28, 2002

With component values and calculations[3]:

	X	Y
R1	220 Ω	220 Ω
R2	6.8 KΩ	1.0 KΩ
C1	2.2 nF	1.0 nF
Frequency	47.5 kHz	650 KHz
Expected Value ($\boldsymbol{u}, \boldsymbol{v}$)	0.5080	0.5495

Therefore if we take our random bit value from $X \otimes Y$, its expected value will be:

$$E(X \otimes Y) = \frac{1}{2} - 2\left(0.5080 - \frac{1}{2}\right)\left(0.5495 - \frac{1}{2}\right) = \mathbf{0.4992}$$

Which is very close to 0.5. This makes sense: our clocks are outputting a '1' slightly more than half of the time, which means there is a greater likelihood of getting $1 \otimes 1 = 0$, but also a less likely change of getting $0 \otimes 0 = 0$.

Now we have a 'random bit' which is 1 close to half of the time. We just need to sample that bit with another timer (we used the one that is on the Altera board: 25.175 MHz, down

[3] http://www.ecelab.com/circuit-astable-555.htm

sampled) to capture this random bit. We shift the previous random bit to another register, and so on Figure 3.

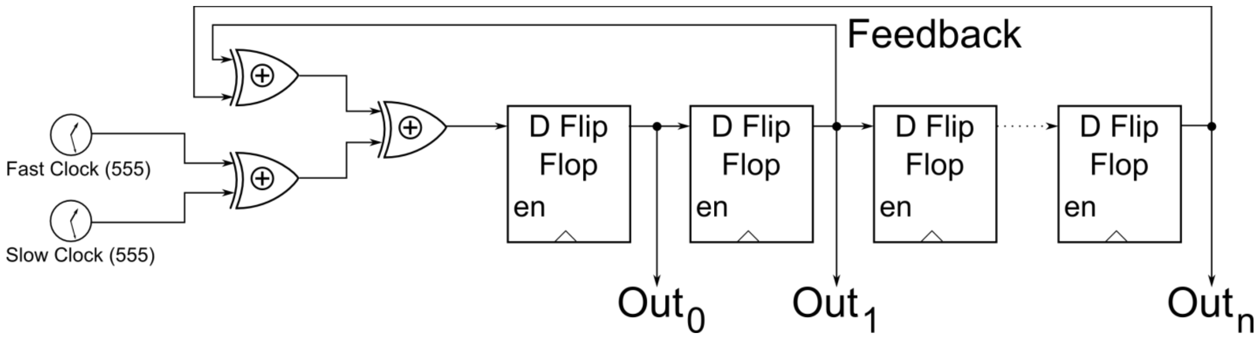

Figure 3

We also use XOR's in the feedback of certain bits to help bring our expected value even closer to 0.5. Figure 3 show this general pattern, which is also used by Linear Feedback Shift Register method of getting a pseudo-random sequence. See Figure 1 in Maxim Integrated Products'[4] "Application Note 1743" to find the optimal 'taps' for the XOR feedbacks, but this feedback is not as important to our model in making a more random number as it is bringing the expected value of each bit closer to 0.5.

It is also important to note that the 555 timers are slightly susceptible to temperature change and when we pick our random numbers is based on the player's reaction time, so we will not get a repeating pattern.

[4] Maxim Integrated Products, "Application Note 1743 - APPLICATION NOTE 1743
Pseudo-Random Number Generation Routine for the
MAX765x Microprocessor," 2008

How the score machine work

When it is time for the mole to 'pop up,' (when we turn on that LED) we also load a 'max score' into a register and start counting down (subtracting one for every millisecond). When the player hits the mole, this score will be added to the cumulative score. (See Figure 4 below) Therefore, the quicker you hit the mole, the better your score will be. We are using UNSIGNED numbers, so when the score that is being counted down hits zero, we stop (so we do not add a larger amount when the player reacts really slow).

We keep track of four hex 'digits' worth of score, but only display the higher two. (So you could get 0x0080 and 0x0090 which would be 0x00 if we kept only two digits, but since we keep all four, is 0x01 (10)).

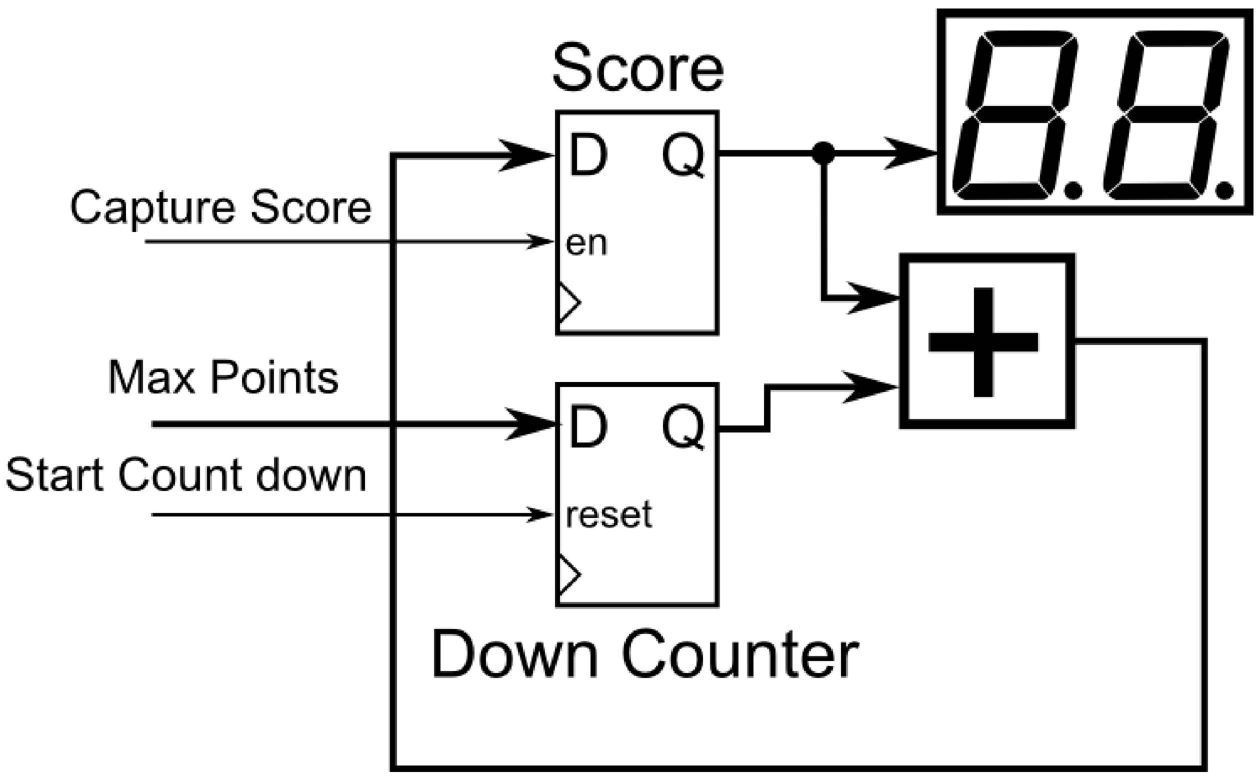

Figure 4

Procedure and Implementation:

We started by making a block diagram and state diagram to plan out our hardware behavior (See Appendix A: Block Diagrams). We were going to use Altera's Max 7000 PLD, but ran into troubles when we could not drive multiple inputs from one output.

Switching to the Altera Flex 10K FPGA gave us greater flexibility to our design, allowing us to implement our design without worry of board size limits. The switches, LED's and 555 timers were the only external architecture and were connected via wire to breadboard and using soldering. We used a pizza box to contain our FPGA, switches, and other components.

The data path of our design we implemented in Quartus II's schematic capture tool, the Control logic was a combination of this and VHDL (a state machine and a separate state to control signal decoder). In Figure 5 we can see our inputs (Clock time in milliseconds, reset, random time the mole can be up, which (random) mole will be up and which switch is being pressed). We also have a register to keep track of time: both how much time the mole has left to be up, as well as how much time to wait between moles (1200 ms). The Mole Counter keeps track of how many moles have been up, after 15 we know the game is done.

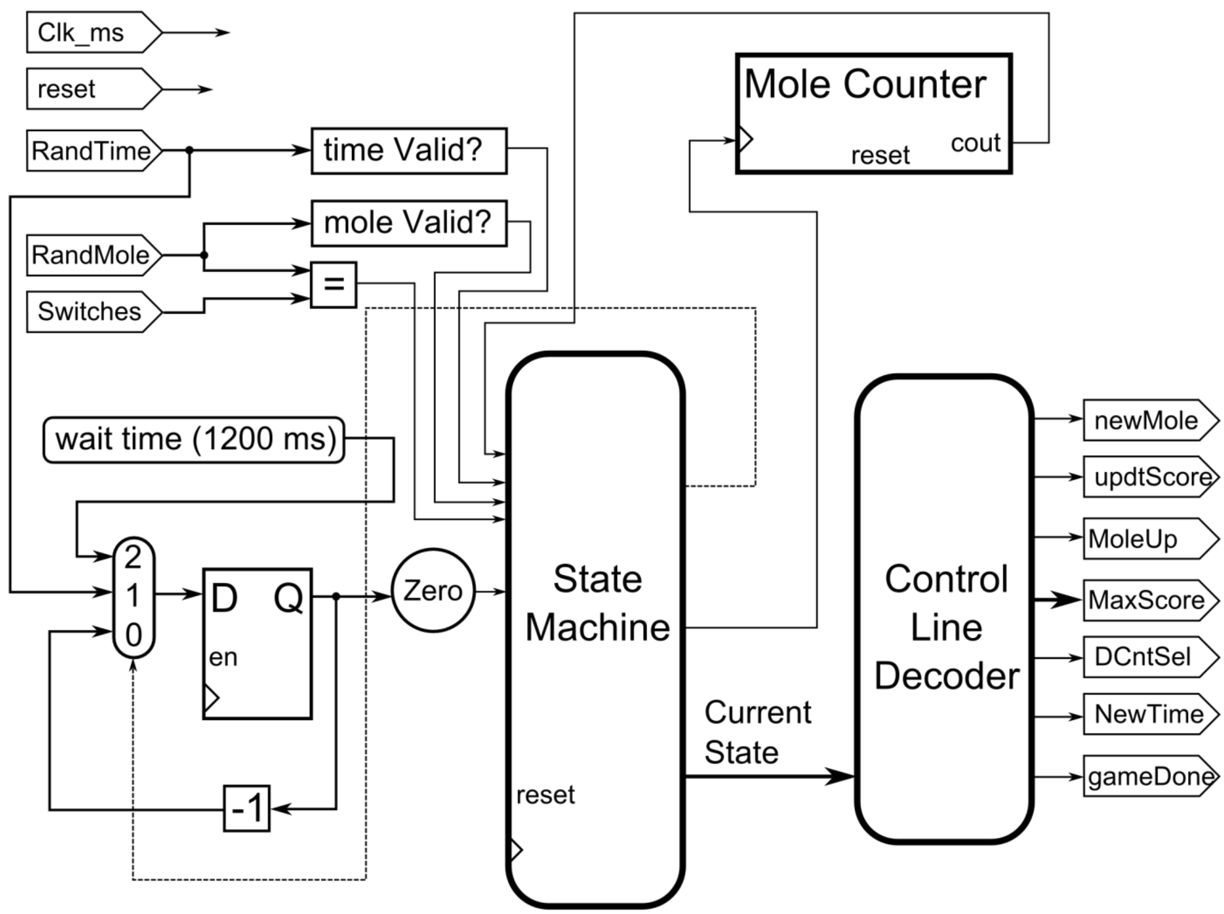
Clk_ms
reset
RandTime
time Valid?
RandMole
mole Valid?
Switches
=
Mole Counter
reset
cout
wait time (1200 ms)
2
1
0
D
Q
en
Zero
-1
State Machine
reset
Current State
Control Line Decoder
newMole
updtScore
MoleUp
MaxScore
DCntSel
NewTime
gameDone

Figure 5

Results and discussion:

Measurements

	Ideal	Actual
• Resister values for the switches:	10 kΩ	–
• Resister values for the LED's:	330 Ω	–
• Vcc from FPGA:	5 V	4.8 V
• 555 Timer X Resistor 1	220 Ω	221. Ω
• 555 Timer X Resister 2	6.8 kΩ	6.78 kΩ
• 555 Timer X Capacitor 1	2.2 nF	2.11 nF
• 555 Timer Y Resistor 1	220 Ω	215. Ω
• 555 Timer Y Resister 2	1 kΩ	0.965 kΩ
• 555 Timer Y Capacitor 1	1.0 nF	0.996 nF

Entertainment

Many people who played our game were eager to get the highest score, though we did not keep track of this. Overall, the moles seemed to stay up too long. There was not much of a challenge to hit the moles before they went back into the ground, only to get a better score.

Results vs. Expectations

Our results met our expectations. Our game worked just as we wanted it too. The only thing that got in our way is that we needed to use another FPGA to implement our design.

For the random numbers, we were going to use memory filled with computer calculated (ahead of time) random numbers. This was more accurate; less biased than the hardware methods. But our original PLD did not support memory, and when we switched to the FPGA we kept with the two timer method of random number generation.

Random Number Observation

In the dozens of games we played with our board, we have seen everything from getting a different mole each time to getting the same one 5 times in a row. Other random number generators repeat after some time (the LFSR based ones) and never have the chance of getting the same number so many times in a row, but ours has does not have these draw backs. The slight bias towards numbers that have more zeros in them (mole 0x0 = 000b, and 001b, 010b, 100b) was not noticeable, which supports our 0.4992% expected value (on average, out of 10,000 bits, there would be 8 more zeros than ones).

Figure 9 in Appendix B: Simulations shows how the random numbers might occur in a given simulation.

If we had more time

If we had more time we would have implemented:

- Keeping track of high score
- Multiple moles up at once (cannot do with decoder/encoder)
- Making the moles come up quicker as the game goes on

Standards and Social Impact:

Whac-A-Mole is a game that entertains people. Though it will not change the way we live, the game does test the player's reaction time.

The typical game has the moles in the holes that could be up and down, but our Whac-A-Mole game has LEDs and pushbutton to represent the moles and mallet. However, the missions of both of them are to test people's reaction time. The faster reactions, the better score you get.

Conclusion:

Two 555 timers, a couple XOR gates and a few flip flops can yield exceptional random number generation, with almost no bias and no pattern repetition. This can be use for just one bit or many bits, representing everything from time to picking which event will take place (which mole will pop up and how long it will stay up).

Our Wack-A-Mole game helped developed FPGA programming skills and taught as the value of learning everything we can about the equipment we will use. We were lucky and had another FPGA available when the first one did not meet our needs. The game was fun and used many of the techniques and tools we used in the previous ELEC 307 labs.

Appendix A: Block Diagrams

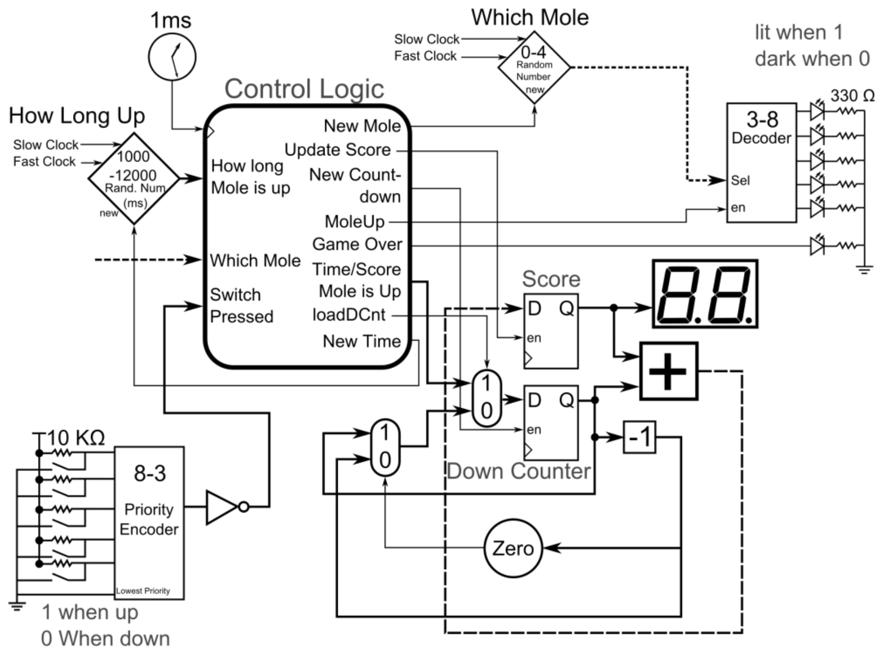

Figure 6

Here we see the data path. The switches, Slow and Fast Clocks and LED's are external to the FPGA board. The Seven Segment Displays and 1 ms clock are on the Altera board.

The Switches are active low, so we invert them and feed those signals before sending them to the control unit. Random number generators (fed by the fast and slow clocks) generate which mole is up and how long the mole should be up. This is monitored by the control unit to make sure that the numbers are in the bounds we set.

The score is updated when the correct mole is hit. There is a down counter that counts down for every microsecond you do NOT hit the mole after it pops up. If the counter reaches zero, it does not go into negative numbers (we are using unsigned representations for our machine).

There is logic to translate hexadecimal signals to seven segment display outputs. The decoder takes what mole is up and translates this to which LED should be lit. Only one can be up at the same time.

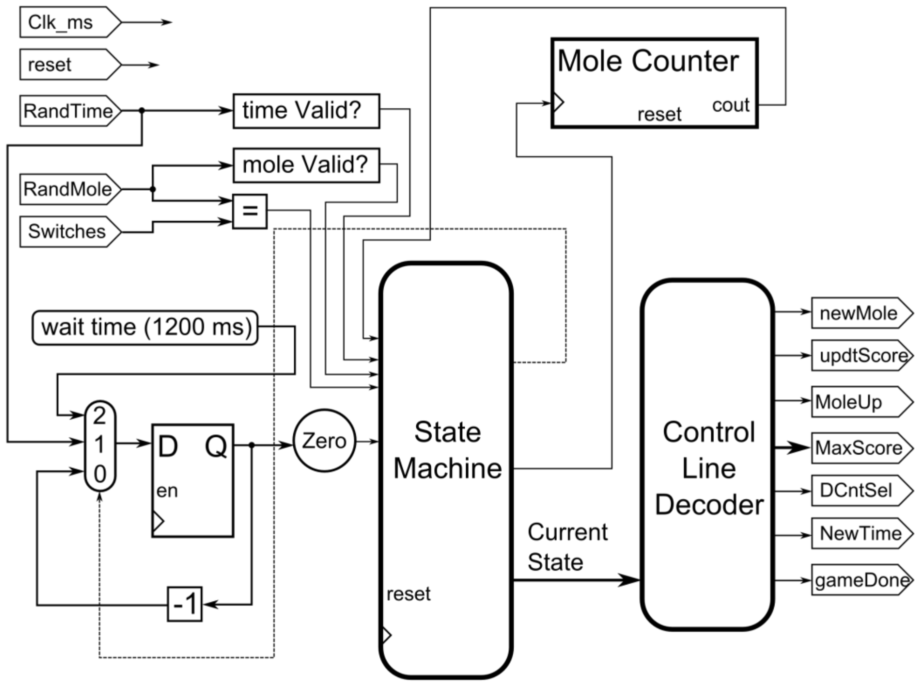

Figure 7

Here we use simple gate logic to determine if the time and moles are valid, as well if the switch pressed is equal to the mole that is up. These signals, as well as if we have had 15 moles and if our time is out (for the current mole) are fed into the state machine.

The state machine (see figure UPDATE ME on the next page) uses Moore State Machine VHDL logic and these input signals to control which state we are in. The decoder takes the state and outputs the correct control signals to the data path.

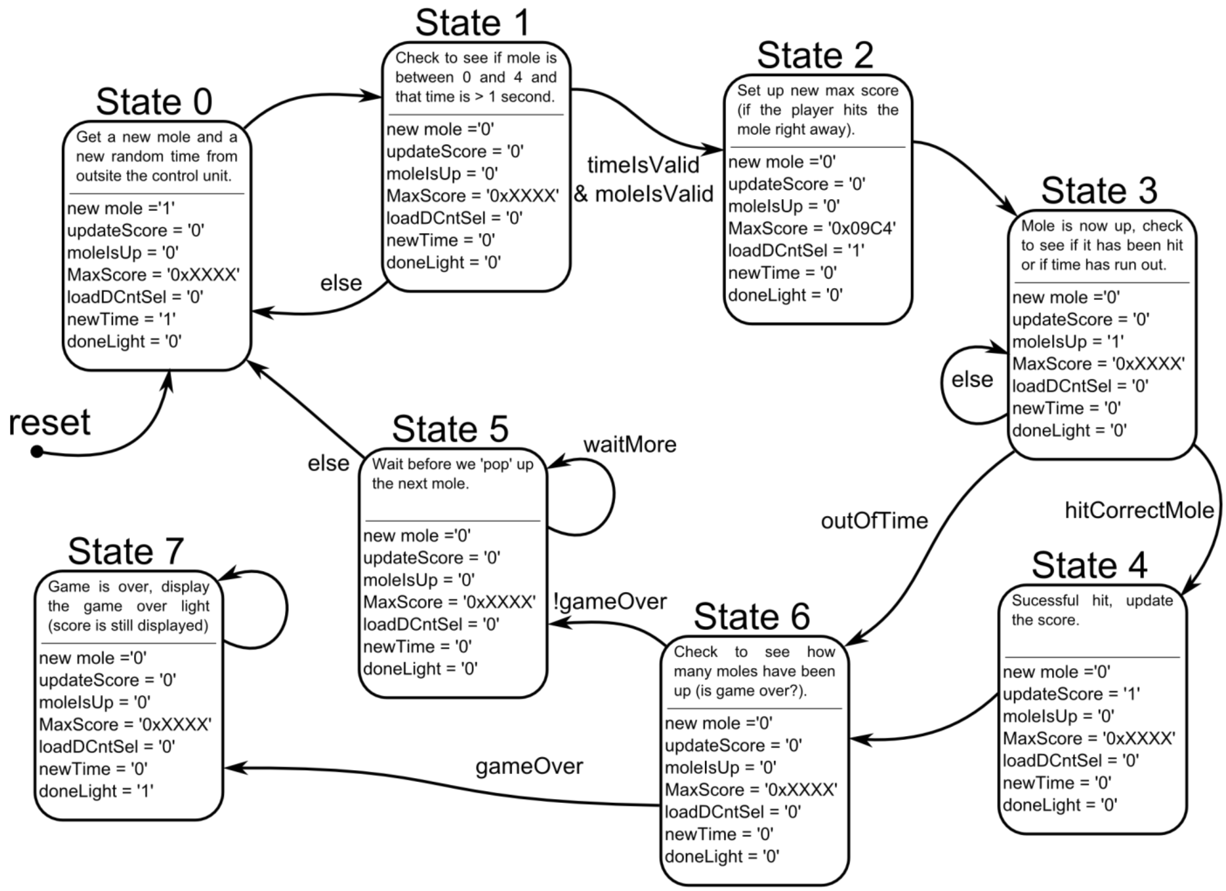

Figure 8

This is the state machine that directs the control signals on the data path. It is here for reference only.

Appendix B: Simulations

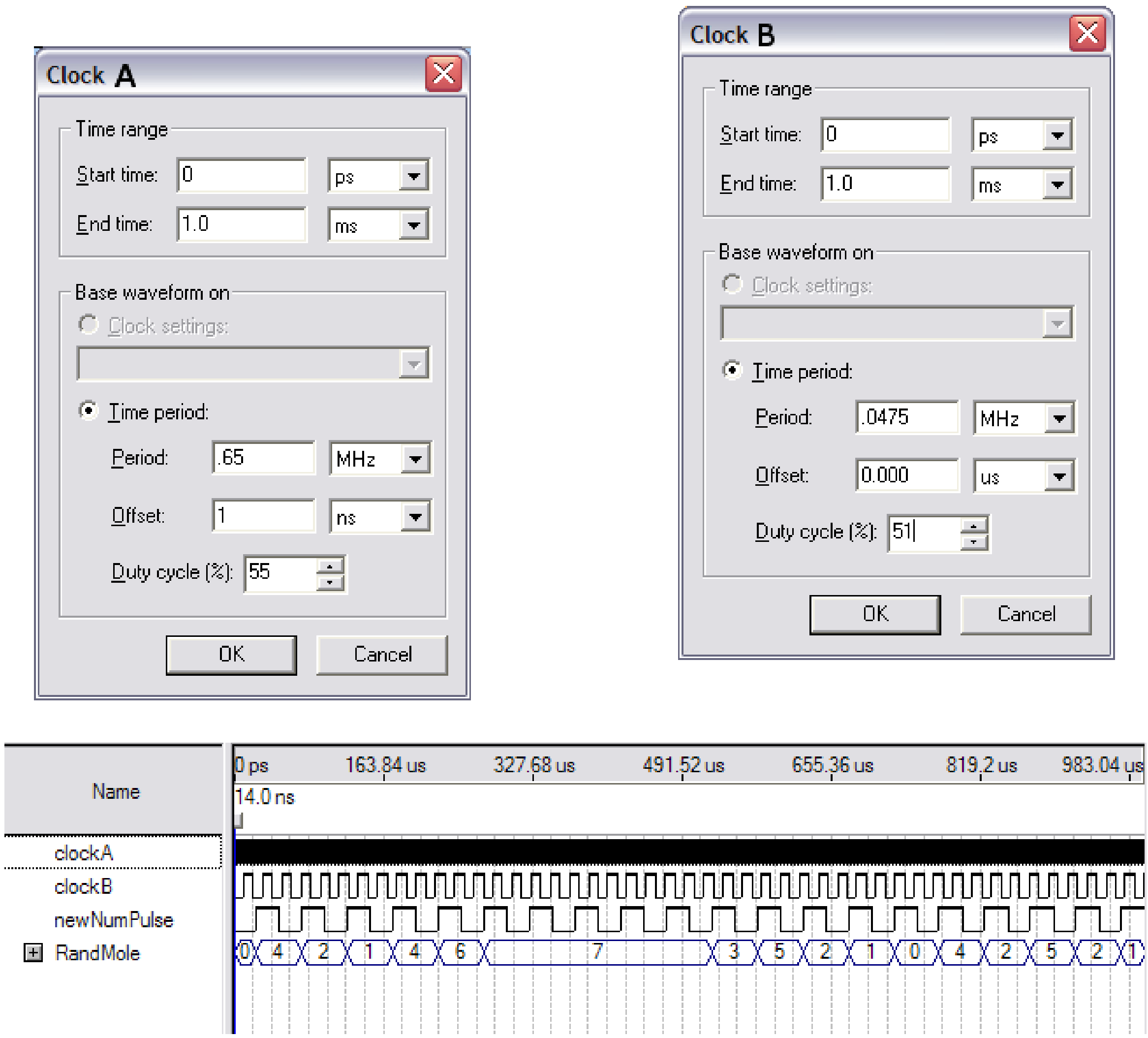

Figure 9

Here we can see different random numbers that occur with the clock frequencies and duty cycles that match the ones used with our 555 timers.

Appendix C: References

Whac-a-Mole background

http://en.wikipedia.org/wiki/Whac-a-mole

Less Biased random numbers

Robert B Davies, "Exclusive OR (XOR) and hardware random number generators" February 28, 2002

555 timer multivibrator setup

http://www.ecelab.com/circuit-astable-555.htm

Optimal Feedback in Linear Feedback Shift Register

Maxim Integrated Products, "Application Note 1743 - APPLICATION NOTE 1743 Pseudo-Random Number Generation Routine for the MAX765x Microprocessor," 2008