Class #23: Experiment
Introduction to Logic Design

| Analog Discovery | Xilinx Spartan 6 Eval Board |

Figure 1

Purpose: In this experiment we will learn to build and characterize basic logic gates based on transistor switches.

Background: Before doing this experiment, students should be able to
- Review online background materials.
- Build and operate simple circuits on a Protoboard.
- Measure the voltages and determine the currents using a math channel in simple Protoboard circuits using Analog Discovery
- Analyze simple circuits consisting of combinations of resistors, especially voltage dividers.
- Do a transient (time dependent) simulation of circuits using LTspice
- Review the background for the previous experiments.

Learning Outcomes: Students will be able to
- Convert decimal to binary and binary to decimal
- Generate truth tables for simple logic gates and simple combinations of logic gates. Use the truth tables to identify the gate.
- Build, simulate, analyze and BJT logic gates. Identify what 0 and 1 levels actually are in real circuits and begin to identify other differences between real and ideal logic gate circuits.

Resources Required:
- LTspice
- Matlab with activation for RPI students
- Analog Discovery and Parts Kit

Helpful links for this experiment can be found on the course website under Class #23.

Pre-Lab

Required Reading: Before beginning the lab, read over and be generally acquainted with this document and the other **required reading** materials.

Hand-Drawn Circuit Diagrams: Before beginning the lab, hand-drawn circuit diagrams must be prepared for <u>all</u> circuits either to be analyzed using LTspice or physically built and characterized using Analog Discovery.
Due: At the beginning of Class #25

Background Reading & Viewing

Logic Design
- Binary Numbers http://www.electronics-tutorials.ws/binary/bin_1.html
- Logic Gates http://www.electronics-tutorials.ws/logic/logic_1.html (includes information on the topics below also)
- Logic-Lab http://www.neuroproductions.be/logic-lab/
- NAND Logic https://en.wikipedia.org/wiki/NAND_logic
- NOR Logic https://en.wikipedia.org/wiki/NOR_logic
- BJT Based Logic Gates http://vlsi-design-engineers.blogspot.com/2015/07/bjt-based-logic-gates.html
- Boolean Algebra https://en.wikipedia.org/wiki/Boolean_algebra

Part A – Binary Numbers

The power of the digital logic used to construct computers comes from the simplicity of the binary number systems. Binary numbers have only two states (0 & 1) rather than the ten states (0, 1, 2, 3, 4, 5, 6, 7, 8, 9) of decimal numbers. Using binary numbers makes representations very long, but since we will be using a computer to keep track, length does not matter much.

Decimal Number (example): $27 = 2*10^1 + 7*10^0 = 20 + 7$
Binary Number (example): $11011 = 1*2^4 + 1*2^3 + 0*2^2 + 1*2^1 + 1*2^0 = 16 + 8 + 0 + 2 + 1 = 27$

1. Convert the following decimal numbers to binary: 13, 3300
2. Create a table showing all numbers from 0 to 15

Part B – Logic Gates

From Electronics Tutorials, "A **Digital Logic Gate** is an electronic device that makes logical decisions based on the combinations of digital signals present on its inputs. Gates may have more than one input but generally only have one digital output. Individual gates can be connected together to form combinational or sequential circuits, or larger logic gate functions." Logic gates are the building blocks of digital circuits like computer processors. The mathematics used with logic gates is called Boolean Algebra in which the values of the variables are the truth values *true* and *false*, usually denoted 1 and 0 respectively. There is a relatively small number of basic gates, most of which are shown in Figure B-1
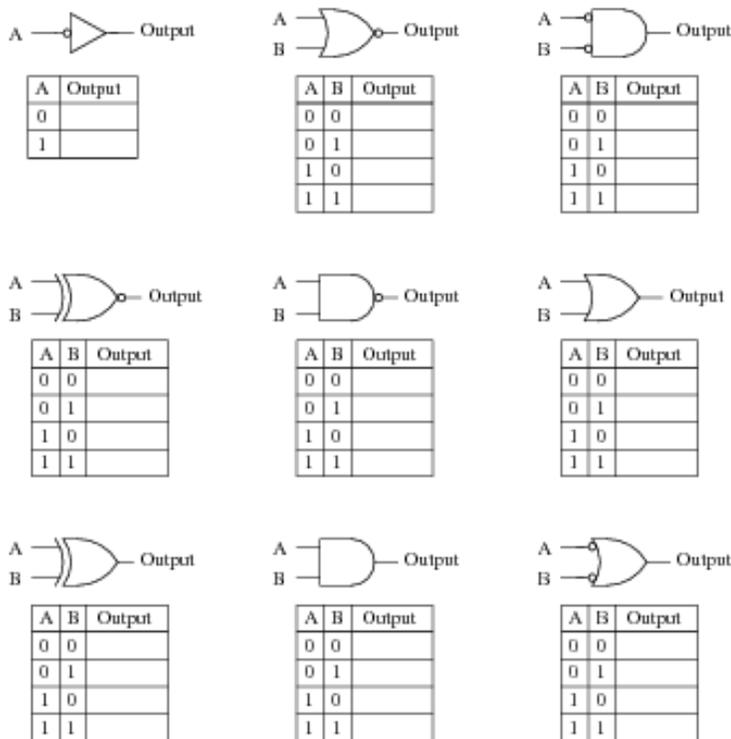
3. Identify each gate in the figure and fill out its truth table.
4. Use Logic-Lab to check your truth tables. Most gates are already set up in one of the examples provided. Use the example and add any additional gates. Set up all of the gates with one input high and one input low (except for the gate with only one input). Capture the screen and include the image in your report. Circle the case shown in the corresponding truth table.

Figure B-1

5. The symbol used for the gate shown in the upper left is not drawn in its most commonly found form. Re-draw the symbol showing how you will usually find it represented.

Part C – BJT Gates

Gates are made with transistors and sometimes other devices. Shown below are two of the most useful gates, made with BJTs and resistors. One is a NAND gate and one is a NOR gate.

6. First, based on what you know about switching the 2N2222 transistor, complete the truth table for each of the circuits and identify which one is the NAND and which one is the NOR gate. Leave room in the table for a second number.
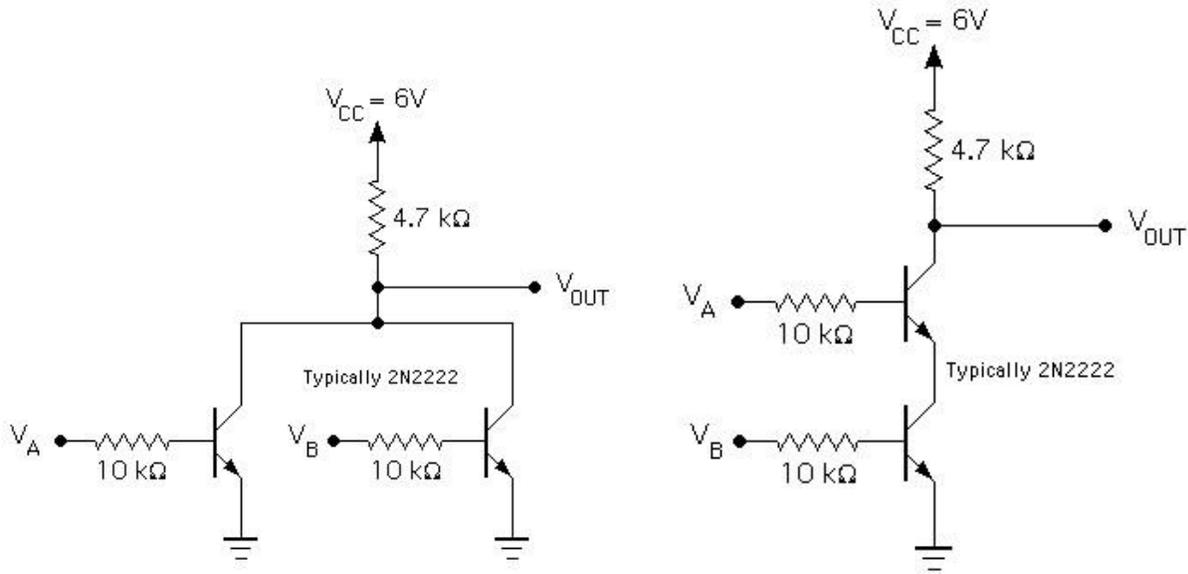

Figure C-1

V_A	V_B	V_{OUT}		V_A	V_B	V_{OUT}
0	0			0	0	
0	1			0	1	
1	0			1	0	
1	1			1	1	

7. For the circuits in Figure C-1, also write the actual voltage levels that will be measured at the output for each state. Also, do the same for the inputs. For the high (1) and low (0) inputs, choose typical values that will cause the transistors to switch the way they should. Any reasonable value will be accepted.
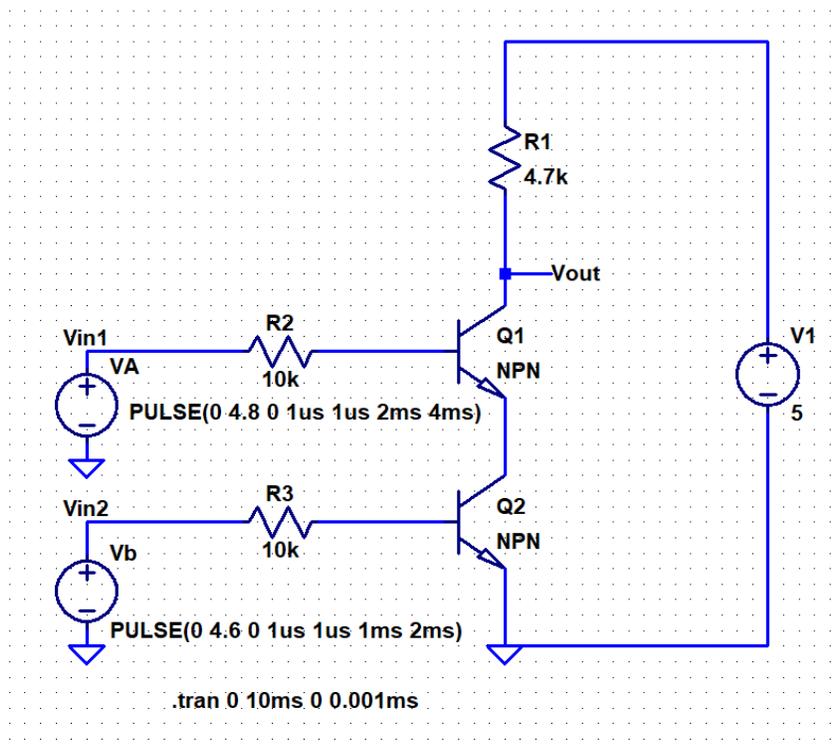
Figure C-2

Next, simulate the same two circuits using LTspice. The circuit for the NAND gate is shown in Figure C-2. You will have to create your own circuit for the other gate. To realize all possible inputs as a function of time, note that two square waves are used for V_A and V_B. Also, the pulse levels for the two inputs are slightly different to make the input and output voltage plots easier to identify. Finite delays and rise and fall times for the pulses are also included to make the simulation more realistic and to avoid some confusing responses from this overly simple circuit.

V_A	V_B	V_{OUT}		V_A	V_B	V_{OUT}
0	0			0	0	
0	1			0	1	
1	0			1	0	
1	1			1	1	

8. Fill out the same table using the simulated results for both circuits. Save and annotate your LTspice circuit diagrams and voltage plots in your report.

Finally, build the two circuits on your Protoboard and do the same measurements as you simulated. For V1, you should use the 5V power supply (red wire) from the Discovery Board. Your transistors should be the **2N3904** from your parts kit. Since you can only make two measurements at one time, you will have to create two plots for each circuit. Rather than use pulse signals for both inputs, set VA to a constant high voltage (5V) and VB to a square wave pulse signal oscillating from 0 to 5V. Obtain oscilloscope plots of VB and Vout, making a note that VA is always high. Repeat with VA always low (0V) (Yes! You get to use both function generators this time!)

9. Fill out the same table using experimental results for both circuits. Save and annotate your hand drawn circuit diagrams and voltage measurement plots in your report.

V_A	V_B	V_{OUT} (NAND)		V_A	V_B	V_{OUT} (NOR)
0	0			0	0	
0	1			0	1	
1	0			1	0	
1	1			1	1	

Part D – NAND and NOR Logic

From the reading suggested above, it is seen that one can build all gates from NAND or NOR gates.
10. Using your LTspice NAND circuit and the information from the reference, build an AND gate out of NAND gates in LTspice and run the same simulation as before. Save and annotate your circuit diagram and voltage plots in your report.

Part E – Task List
- Binary number conversions
- Identify gates and complete truth tables. Verify answers using Logic-Lab.
- What is the common symbol for a NOT gate?
- Generate the truth table, including actual voltages, for the BJT NAND and NOR gates.
- Using LTspice, generate the truth table, including actual voltages, for the BJT NAND and NOR gates.
- Using Analog Discovery and your built circuit, generate the truth table, including actual voltages, for the BJT NAND and NOR gates.
- In LTspice, simulate an AND gate made with NAND gates. Demonstrate that it works as it should.

Part E – Reflection
Take a moment to reflect on what you have learned in this experiment. Then discuss what you have learned in this experiment. In particular, compare and contrast the ideal operation of logic gates switching between 0 and 1 with what is observed in both simulations and experiments. Discuss anything that still confuses you and/or anything else you would like to know about this topic and any other experiments or simulations you think might be worth doing. A general recommendation for what to address in your reflections – you will usually do analysis, simulation and experiments that will rarely completely agree. Discuss how the three approaches are consistent and are not consistent. Include the reflections in your report and email a copy to your instructor.