**Score: \_\_\_\_\_**

**Lab01 – Transistors and Switching**

COMP256 – Computing Abstractions

Dickinson College

Spring 2023

Prof. Grant Braught

**Names:** (List both partners. One submission per group.)

**Introduction:**

This lab will introduce you to building electronic circuits using a *breadboard*. You will see how to use a *voltmeter* to measure voltages and logic values in a circuit. You will experiment with switches and observe first-hand that NMOS and PMOS transistors do in fact behave just like switches. Finally, you will build a circuit directly from transistors that performs a computation.

**Breadboards:**

When designing new circuits it is common to use a *Breadboard*. The figure below shows a breadboard with a *Pushbutton*, a Light bulb, a *Coin battery* and a few wires. Wires and components can be connected by inserting them into the little holes in the breadboard. This makes it easy to add, remove and adjust wires and electronic components in a circuit. Your instructor will have demonstrated the use of the TINKERCAD breadboard at the start of lab.



**Extra Breadboard Resources:**

This section is optional and just provides a little more information about breadboards that you can come back to later if you are interested. We’ll be using breadboard’s in TINKERCAD to build and test our circuits. However, physical breadboards are often used for circuit design as well. If you would like to see how a physical breadboard is used you can watch the video *How to Use a Breadboard* from Ben Finio at Science Buddies

* <https://www.youtube.com/watch?v=6WReFkfrUIk> (12:20)

If you would find an example of using a breadboard directly in TINKERCAD helpful, you can watch Remi Wauthy’s video *Introduction to Tinkercad Circuits & Breadboarding - Part 1*.In that video he demonstrates building the resistor/LED circuit from the *How to Use a Breadboard* video above but using TINKERCAD.

* + <https://www.youtube.com/watch?v=LrOM2GABK1g> (15:58)

**Your First Circuit:**

1. Log into our course in TINKERCAD (use the link in Moodle and your Dickinson username as your nickname) and create a new circuit named Lab01-Switch. Give the URL of your Lab01-Switch circuit here:

2. Build and simulate the circuit from the figure on the first page of the lab.

Note: When you build your circuit, it is not necessary that every component and wire be plugged into the same breadboard holes as in the figure. However, you should aim to keep all of your circuits neat and well organized. Rotate and arrange components so that they are oriented and spread out in ways that give you space to work. Add points to route your wires in ways that make them easy to follow. Use different colored wires to make your circuit easy to understand. Think of this kind of like writing well-organized and commented code in a program. It will make it easier for others (i.e. me) to understand your circuit and also easier for you to debug it when it doesn’t work correctly.

There is nothing required here, but your Lab01-Switch circuit must work.

3. Simulate the circuit and then follow the directions in parts a and b below to fill in the cells in the following table.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
|  | **Push Button** | **Light Bulb** | **“Switch”** |  |
|  | Released |  |   |  |
|  | Pressed |  |   |  |
|  |  |  |  |  |

a. Press (i.e. click) and release the push button a few times and observe the behavior. Then fill in the rows in the “Light Bulb” column with “On” or “Off” to indicate whether the light is on or off when the push button is pressed or not.

b. The push button behaves like the switches in our metaphor from class and can be either “Open” or “Closed”.

 

Open Closed

Based on the behavior you observed, fill each row in the “Switch” column with “Open” or “Closed” to indicate if the switch hidden inside the push button is open or closed.

**Transistors are Switches:**

Now recall from class that NMOS (and PMOS) transistors behave like electrically controlled switches. That is, the signal on the Gate will determine if the transistor *behaves like* there is an open switch or a closed switch between the Source and the Drain.

4. Using what you know about NMOS and PMOS transistors fill in the Gate column below with the with a “0” or a “1” to indicate the Gate value that will cause the imaginary switch in the transistor to be open or closed as shown. You should consult the class slides and/or your notes from class to be sure you have these correct.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |
|  |  | **Gate** | **Transistor** |  | **Gate** | **Transistor** |  |
|  | NMOS |  |  |  |  |  |  |
|  | PMOS |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |

Now we will replace the Pushbutton that you used earlier with an NMOS transistor (which *behaves* like a switch) and use a 0 or a 1 to open or close its imaginary “switch.” If all goes well, the circuit will behave just like it did when we opened and closed the switch inside the Pushbutton by clicking it.

5. Duplicate your Lab01-Switch circuit in TINKERCAD and name the copy

Lab01-Transistor-Switch.

* Go to your “Circuits” page that shows all of your circuits.
* Point at your Lab01-Switch circuit.
* Click the “gear” icon that appears.
* Click “Duplicate”
* When the new circuit appears, click the name in the upper right and rename it.

Give the URL of your Lab01-Transistor-Switch circuit here:

6. Modify your Lab01-Transistor-Switch circuit to look like the circuit below by deleting the Pushbutton and replacing it with a *small signal nMOS transistor* (Note: Be sure not to use an NPN BJT or MOSFET which may look or seem similar but are actually very different transistors and thus will behave differently).



7. If you look closely at the NMOS transistor you will see its three “legs” are labeled D, G, and S for Drain, Gate and Source. Just like our abstraction from class. The gate (G) on the NMOS transistor is not yet connected to anything.

Use a wire to connect the gate to a 0 (i.e. ground or the – rail) and simulate the circuit. Observe what happens. Repeat this with the gate is connected to a 1 (i.e. the + rail). Briefly explain what you have observed and explain how it is consistent with the expected behavior of the imaginary switch inside the NMOS transistor.

8. We know that the PMOS transistor is complementary to the NMOS transistor. Let’s see that in action too. Replace the NMOS transistor in your Lab01-Transistor-Switch circuit with a *small signal PMOS transistor*.

Repeat the experiment from question #7 where you connect the gate of the transistor first to 1 and then to 0. Briefly explain what you have observed and explain how it is consistent with the expected behavior of the imaginary switch inside the PMOS transistor.

**Using a Slidewitch for Inputs:**

Stopping the simulation and rewiring the input (i.e. the gate) from 0 to 1 each time is a little inconvenient. Fortunately, there is another component, called a *Slidewitch* that will help us easily change inputs from 0 to 1 and back again.

9. Add a Slideswitch to your Lab01-Transistor-Switch circuit as shown below. Also, be sure to remove the PMOS transistor and place the NMOS transistor back into the circuit.



Notice that the Slideswitch has three connections (left, right, center). The way the Slide switch works is that when the slider is moved to the left, the left and center are connected. Thus, with the slider to the left the logic value on the left will “flow” to the center. Similarly, when the slider is moved to the right the center and right are connected, and the logic value on the right will “flow” to the center.

a. Examine your circuit and using the explanation of the Slideswitch above and complete the table below by filling in the value (0 or 1) that would appear on the center connection of the Slideswitch.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
|  | **Slideswitch****Position**  | **Logic Value** **at Center** |  |
|  | Left |   |  |
|  | Right |   |  |
|  |  |  |  |

b. Using your answer to part a and what you know about NMOS transistors, complete the table below by filling in the Logic Value column with a “0” or a “1”, the “Switch” position column with “Open” or “Closed” and the Prediction column with “On” or “Off”.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
|  | **Slideswitch****Position**  | **Logic Value** **at NMOS Gate** | **NMOS “Switch” position** | **Prediction****for light** |  |
|  | Left |   |  |  |  |
|  | Right |   |  |  |  |
|  |  |  |  |  |  |

c. Now, simulate your circuit and experiment with the Slideswitch moving it to the left and right. Briefly describe what you observe and explain how it is consistent with your expectations. Note: What you observe should agree with your answer in b. If not, double check part b and double check the wiring of your circuit.

**Our 0’s and 1’s are Abstractions:**

We know that the 0’s and 1’s that we think of the computer operating on are just electrical signals. In this section, we’ll step down one level of abstraction and see how we can look at the actual physical voltages and how we abstract those into 1’s and 0’s.

Recall from class that by convention we define voltages close to ground (- terminal of the battery) as a logical 0 and that we define voltages close to the maximum voltage (+ terminal of the battery) as a logical 1.

10. The maximum voltage in a circuit is determined by the power source that is used and is often call Vss (where the ss stands for source). In our case that is the “Coin Battery” that is in the circuit. The battery will indicate its voltage. That voltage will be the Vss for our circuits. What is our Vss?

As we have noted, logical 0’s and 1’s are represented by voltages that are “near” ground or “near” the maximum voltage (i.e. Vss). The meaning of “near” is usually defined by dividing the range of possible voltages into three ranges. Voltages in the bottom 1/3 of the range (between 0 and (1/3)\*Vss) are defined to be a logical 0. Voltages in the top 1/3 of the range (between (2/3)\*Vss and Vss) are defined to be a logical 1. Voltages in the middle third are neither a 0 nor a 1. Separating the 0 and 1 by this *buffer region* in the middle ensures that if there is some electrical noise in the circuit it will still be possible to distinguish the 0’s from the 1’s.

11. The voltages (1/3)\*Vss and (2/3)\*Vss are called the *cutoff voltages* for 0 and 1 respectively. Complete the table below to indicate our cutoff voltages for 0 (Vc0) and 1 (Vc1) given the Vss for our circuits.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
|  | **Cutoff Voltage** | **Value (V)** | **Logic Value** |  |
|  | Vc0 |  |  |  |
|  | Vc1 |  |  |  |
|  |  |  |  |  |

**Measuring Electrical Voltages:**

Now that we know how to interpret voltages as 0’s and 1’s in our circuit, we will measure some of these voltages directly.

A *voltmeter* is a device that we can use to directly measure electric voltages. We can then interpret those voltages as logical 0’s and 1’s using the cutoff voltages you computed above. In TINKERCAD a voltmeter looks as shown below.



Technically this is a *multimeter*, which is a multifunction meter with one of its functions being that of a voltmeter. When the V on its right side is shaded in, the multimeter is operating as a voltmeter. For our purposes I will just refer to the multimeter as a voltmeter because we will not be using any of its other functions in this class.

To use a voltmeter to measure voltages, you will always connect the black (negative) lead to ground (or the “–“ terminal of the power source) and then connect the red (positive) lead to the point where you want to measure the voltage.

12. Just quick fact check of an important point to be sure you are reading…

To use the multimeter to measure voltages connect the…

a. black lead to …

 b. red lead to …

13. Add a voltmeter to your Lab01-Transistor-Switch circuit. Use the voltmeter to measure the voltages at the locations indicated in the table below. Then use the cutoff voltages that you computed to fill in the Logic Value column indicating if the voltage represents a 0 or a 1.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
|  | **Location** | **Voltage (V)** | **Logic Value** |  |
|  | + Rail |   |   |  |
|  | - Rail |   |   |  |
|  | NMOS Gate with Slideswitch left |   |   |  |
|  | NMOS Gate with Slideswitch right |   |   |  |
|  |  |  |  |  |

Now that we know how to measure voltages and interpret them as logical 1’s and 0’s we’ll be using the voltmeter to measure logic values in our circuits.

**A CMOS Circuit:**

In class we saw the CMOS circuit shown below.



14. Create a new circuit in TINKERCAD named Lab01-CMOS-Circuit. Use an NMOS and PMOS transistor to Implement the above circuit with the following considerations:

* Pay close attention to the NMOS and PMOS transistors in TINKERCAD. Their “legs” are labeled with S, G, D. Be sure they are connected as shown in the circuit above. For example:
	+ The source of the PMOS should be connected to a 1 (i.e. the + rail)
	+ The Drain of the PMOS should be connected to the Drain of the NMOS.
	+ Etc…
* Use a Slideswitch to provide a 0 or a 1 as the input to the Gates.
* Use a voltmeter to measure the voltage at the output.
* Do not include a lightbulb in the circuit.
* Be sure to keep the components and wires of your circuit neatly organized.
	+ Bend the wires by clicking on them and dragging to make them easier to follow.
	+ Use wire colors to make your circuit easier to understand.
		- Use red for 1 or Vcc
		- Black for 0 or ground
		- Other colors for connections that can be 0 or 1.

Give the URL of your Lab01-CMOS-Circuit circuit here:

15. Use your circuit to complete the following table.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
|  | **Switch Position** | **Logic Valueat Input** | **Voltage atOutput** | **Logic Valueat Output** |  |
|  | Left |   |   |   |  |
|  | Right |   |   |   |  |
|  |  |  |  |  |  |

16. Optional: Create a new circuit in TINKERCAD named Lab01-2Input-CMOS-Circuit. Then implement the circuit below that we saw at the end of the Hardware Abstractions class #2. Your circuit should use:

* Two NMOS transistors
* Two PMOS transistors
* Two Sliderswitches for the inputs A and B.
* The labeling tool in TINKERCAD to indicate which of your switches is a A and which is B.



a. Give the URL of your Lab01-2Input-CMOS-Circuit circuit here:

 b. Use a Voltmeter and experiment with your circuit to complete the table below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
|  | **Logic Value for A** | **Logic Valuefor B** | **Voltage atOutput** | **Logic Valueat Output** |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |

Optional: To help me improve and scope these activities for future semesters please consider providing the following feedback.

a. Approximately how much time did you spend on this Lab (include both the 2-hour lab period and any time you spent after lab in your total)?

b. Please comment on any particular challenges you faced in completing this Lab.