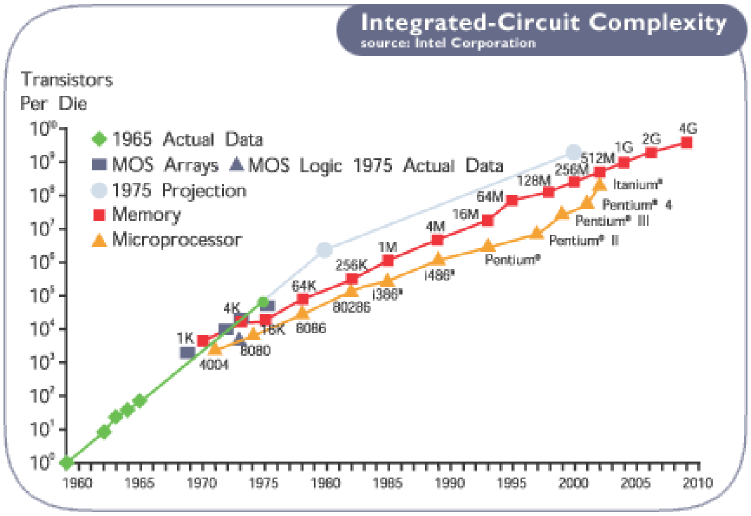
Class #18: Experiment
Transistors & Switches



Purpose: In this experiment we will discuss ways in which transistors can be used as amplifiers and to create binary signals by acting as a switch between two output voltage states. Binary signals can take on only two states: high and low and are the basis of digital electronics.

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

- Determine operating conditions for an NPN transistor when it is providing the functionality of a switch.
- Determine operating conditions for an NPN transistor when it is providing the functionality of an amplifier.
- Determine the Thevenin equivalent source representation of a simple transistor circuit.
- Describe how a transistor can be used as a switch, providing at least one example.

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 #18.

Pre-Lab

Required Reading: Before beginning the lab, at least one team member must 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 #20

Part A – Transistor Experiment

Before beginning this experiment, review the properties of diodes. For a typical diode, how large must the forward voltage be to turn the diode on so it conducts current? Ideally, how much current does a diode conduct when reverse biased? Also, read online materials on transistors, particularly NPN Bipolar Junction Transistors (BJT) because that is the type of transistor to be studied in the experiment (2N2222). Some examples of information on transistors:

a. Sparkfun https://learn.sparkfun.com/tutorials/transistors (This is very well written and quite readable.)
b. Wikipedia: https://en.wikipedia.org/wiki/Bipolar_junction_transistor
c. Electronics Tutorials http://www.electronics-tutorials.ws/transistor/tran_8.html

The circuit you will build and simulate is shown below (Figure A-1). From top to bottom, the three connections to the 2N2222 BJT are Collector, Base and Emitter which are, respectively, N-type P-Type and N-type semiconductors. That is why such transistors are called NPN (see Figure A-2). Thus, transistors have two PN junctions, each of which can act like a diode since semiconductor diodes are made with a PN junction. This is discussed, with an interesting figure, in the Sparkfun link above. The key PN junction characteristic to keep in mind is that current can flow as long as the junction is forward biased by approximately 0.7V. What is especially clever is that current can flow in either direction so, if the base voltage is larger than the emitter voltage by 0.7V and larger than the collector voltage by the same amount, both junctions conduct. How much the base-collector junction conducts depends on the base voltage and the current from the source. This means that the base voltage acts like a control for the current carried from the collector to the base. This current also flows through the resistor R1 (if there is no load resistor R2 or, as is shown, the load resistor is very large. Ohm's Law gives us the voltage across R1, which then determines the output or collector voltage.

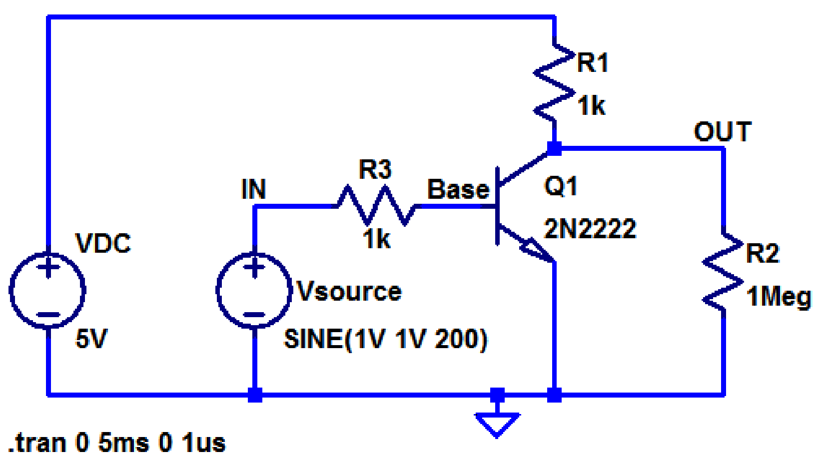


Figure A-1

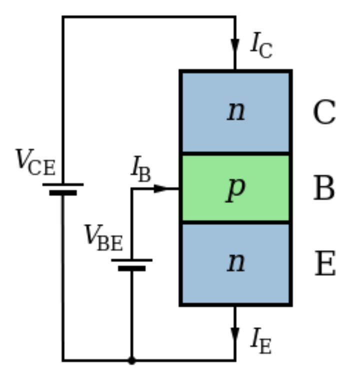


Figure A-2

To see how this works, set up the circuit in Figure A-1 on your Protoboard. The 5V voltage supply is the red wire on your Analog Discovery. Connect the Analog Discovery ground to the bottom end of the circuit, as shown. Measure the output voltage with Channel 2 and the Base voltage with Channel 1 of the oscilloscope. Use a triangular wave source with amplitude and offset equal to 1V. We use an offset here to assure that the base voltage is always positive because we know we need a positive voltage to forward bias both junctions. The 1kΩ resistors are chosen because they are easy to find and should give reasonable results. Do not connect the resistor R2 at this point. Initial tests should be for no load. Do not forget to turn the 5V supply on. If you have set up the circuit correctly, you should see the output voltage cycle back and forth between 0V and a higher voltage.

1. Plot the base and collector voltages using your oscilloscope. Also add a math channel displaying the base voltages minus the collector voltage. Save your plot to your report and fully annotate it. Be sure you label the regions in time where both PN junctions are forward-biased at a level large enough to allow current to flow. Also label the highest collector voltage an where it is zero.

2. When operating correctly, the current through the resistor R1 will flow through the transistor from the collector to the emitter. From the information in the circuit and your plot, determine the current when the collector voltage is high and when it is zero.
3. Also determine the voltage from the collector to the emitter when the transistor is conducting current. Is your answer consistent with the forward voltages across the two junctions.
4. Finally, when the input voltage is at its highest value, is the collector voltage also at its highest value or at zero? When the input voltage is at zero (its lowest value), is the collector voltage at its highest or lowest value?

As you will see, you have just built a type of digital logic gate called a NOT gate, which should give you a clue on the answer to question 4.

Part B – Simulation of Transistor Experiment

Next, you are to repeat the same steps using LTspice to simulate the circuit. You do not have to compare the results in Excel or Matlab. Just produce the same plot and discuss all similarities and differences (if any). Note that LTspice can directly give you answers to questions like #2 above.

5. through 8. Same questions as 1. through 4.

Our primary interest in transistors is as switches. However, they can also produce current gain. That is, one of the parameters you can find in a spec sheet is the ratio of collector current to base current in the forward active operating regime where the device amplifies. This is a region where the base-emitter PN junction is forward biased, but the base-collector junction is not. Some current still flows when the B-C junction is not forward biased. The amount of current is directly controlled by the base current. For the LTspice model of the 2N2222 transistor, this amplification is about 200.

6. To check this, plot the collector current and 200 times the base current and find the time period where the to curves are close to one another.

If you have time, return to the experiment and measure the base and collector currents as functions of time. This will require at least three measurements and you only have two channels. Thus, you will have to measure the input and base voltages and then move the channel from the input to the collector and do it again. When you have to do more than two measurements, it is essential to always have a common measurement so you can compare results with some accuracy.

7. Use Analog Discovery to repeat questions 6 by doing it twice as described above, including a math channel for the currents. Note that the current gain will not necessarily be 200. You will have to determine what the gain is from your measurements.

Part C – Output Impedance (Thevenin Source Representation)

The circuit in Figure A-1 can drive a variety of loads. When using it as a source, we can replace the complete circuit by a single voltage source and resistor in series in what is called its Thevenin equivalent. This concept is discussed in Wikipedia (https://en.wikipedia.org/wiki/Th%C3%A9venin's_theorem) where it is discussed that most circuits with two output connections (signal and ground) can be replaced by a simple equivalent, as shown in Figure C-1.

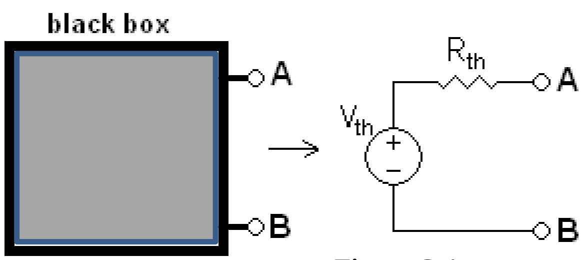


Figure C-1

8. To test out this idea, connect a series of load resistors R2 to the circuit and fill out the table below. Once you have the table filled in completely, use the information in the table to determine both V_{th} and R_{th}. Do this only for the high output voltage because the low voltage is zero and the results will be trivial. You were asked a similar question on Quiz 1.

Trial	Rload	V(OUT)
1	1MΩ	
2	100kΩ	
3	10kΩ	
4	1kΩ	
5	100Ω	
6	10Ω	

Part D – Task List

- Build transistor circuit using 2N2222 NPN BJT, make and label the required measurements and calculations and fully annotate the plot as described.
- Repeat the same four tasks using LTspice to simulate the circuit. TA/Instructor ____________________
- Find the operating conditions for which the collector current is approximately 200 times the base current.
- Repeat the previous question for the experiment and determine the gain of the 2N2222 transistor
- Find the Thevenin equivalent source (voltage and resistance) for the test circuit in Figure A-1. TA/Instructor ___________________

Part E – Reflection

Take a moment to reflect on what you have learned in this experiment. Then describe how a transistor can be used as a switch and why it is useful in that role. Provide and briefly discuss at least one example of how a transistor switch can be used in a practical application or in the construction of an electronic device. Finally, describe how the activities in this experiment helped you to understand more completely or accurately something you learned earlier in this course.