

CALIFORNIA STATE UNIVERSITY
LOS ANGELES

Department of Electrical and Computer Engineering

EE-2449 Digital Logic Lab

EXPERIMENT 1
INTRODUCTION TO ELECTRIC CIRCUITS

Required hardware and tools: Breadboard with test circuitry, 15 K Ω (Kilo Ohm) resistor (brown-green-orange), 2.2 K Ω resistor (red-red-red), 330 Ω resistor (orange-orange-brown), 2 green LEDs, 2N4124 NPN Silicon Transistor, AL 21649 pushbutton switch, breadboard wires, and logic probe.

Resistor Color Code Conversion Calculator: To help you determine the value of resistors, you can use this calculator: <http://www.digikey.com/en/resources/conversion-calculators/conversion-calculator-resistor-color-code-4-band>.

Note: While conducting the experiment you should record the circuit diagrams of circuits you are building, record observations from experimenting with the circuits, and record your answers to the questions throughout the experiment in your lab journal (a composition book). If you have not had a chance to purchase the composition book, for the first experiment you can use a piece of paper that you will paste into your lab journal. Every section that requires you to build a circuit and test it has an asterisk (*). For those sections, demonstrate the working circuit to your lab instructor. They will sign off on your experiment. You can often build multiple circuits or variations before getting a sign off and then demonstrate the various versions of the circuit together to your instructor.

1.1 Simply defined, an electric circuit is a closed loop where through which charges (electrons) can continually flow. Electric circuits can be analog or digital. Analog circuits operate on continuous signals whereas digital circuits operate on discrete, usually binary, signals. Binary signals have two discrete values or logic levels – a high value (5V (volts) in this lab) represents logic one and a low value (0V or ground) represents a logic zero. Fundamental components in analog circuits are resistors, capacitors, inductors, diodes, transistors, and operational amplifiers. Fundamental components in digital circuits are transistors, logic gates, and integrated circuits (ICs). ICs are a combination of logic gates that are integrated to implement more complex digital systems like microprocessors and microcontrollers. As you'll discover in this experiment, all digital components are actually analog circuits underneath. Many circuits will have both analog and digital components such as in embedded systems which may have analog inputs such as sensors and analog outputs such as output voltages that control motor speed and a digital microcontroller programmed to control the system.

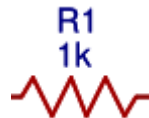
In this experiment, you will be introduced to the basics of voltage, current, and resistance which are the basic building blocks of any electric circuit. You will also discover how transistors work as electrical switches and see how they can be combined to build digital components known as logic gates.

1.2 Electricity is the movement and interaction of electrons which are charged particles. Voltage is a measure of the potential difference in charge between two points in an electric field. Voltage is measured in volts (V) which is a measure of the energy per unit charge. So a battery that is a source of energy (electrons) will have a potential difference in charge between its two terminals. For example a 9V battery would supply 9 Joules of electric potential energy per every 1 Coulomb of charge which moves between its negative and positive terminals. Current is the rate at which electric charge flows past a point in a circuit. Current is measured in amperes (A) which is the rate of flow of an electronic charge. So when a load is connected to the positive and negative terminals of a battery an electric circuit will be formed and current will flow from the negative terminal of the battery to the positive terminal of the battery to the load and back to the negative terminal of the battery. A load in a circuit is an electrical component that consumes electric power such as appliances and lights in your home. All loads have resistance which is a material's ability to reduce current flowing through it. Resistance is measured in Ohms (Ω). **Ohm's Law** defines the relationship between voltage, current, and resistance.

$$V = IR \quad (\text{Eq. 1.1})$$

Here **V** represents the voltage, **I** represents the current, and **R** represents the resistance.

While every electrical component, including wires, have some level of resistance, resistors are electrical components specifically designed to control the amount of current flowing through a circuit. As we'll see, they can also be used to divide voltages in a circuit and pull-up input and output signals. Resistors are passive components that consume power. Resistors have two terminals (end-points) and are represented by a zig-zag line such as:



Here R refers to resistor, 1 refers to a specific resistor in a circuit, and 1K is an abbreviation of $1K\Omega$ (or 1×10^3 Ohms) which is the value of the resistor. Resistors are manufactured to provide various values of resistance. A color code on the resistor is used to determine the value of the resistor¹.

Figure 1.1 shows a simple electric circuit with a power source and a resistor connected together using wires. The power source provides electric energy to the load, which in this case is the resistor. The power source could be a battery or a power supply such as the programmable DC (direct current) adjustable

¹ More information about determining the value of a resistor can be found here:

<http://www.digikey.com/en/resources/conversion-calculators/conversion-calculator-resistor-color-code-4-band>.

regulated power supply that we will be using in this lab. The DC power supply converts AC (alternating current) power from the wall outlet supplied by the power mains. The energy for the AC power main could come from many different sources including wind, solar, fossil fuels (coal, oil, natural gas), hydrogen, hydroelectric (water), and nuclear. The DC power supply is regulated to provide a constant voltage or current. In our lab, we will be using TTL (transistor-transistor-logic) which typically uses a 5V voltage supply. TTL logic will accept input signal voltage levels from 0V to 0.8V as logic low (logic zero) and 2V to 5V as logic high (logic one).

In the circuit in Figure 1.1 current (**I**) will flow through the resistor. To determine how much current will flow, we can use Ohm's Law. For this circuit, determine the value of **I** for three different values of **R** shown in Table 1.1. The first computation has been completed for you. Draw the circuit in your lab journal and compute the value of **I** for the other two resistor values in your lab journal (or on a piece of paper that you'll paste in your lab journal later).

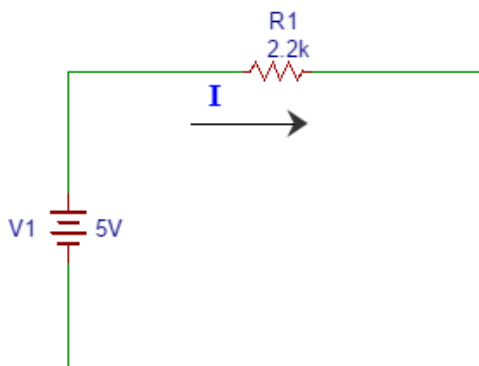


Figure 1.1. Simple electric circuit with a power supply and 2.2K Ω resistor.

Table 1.1. Given a 5V power supply, use Ohm's Law to compute the value of **I** for the various resistor values.

V	R	I = V/R
5V	2.2K Ω	I = 5V/2.2K Ω = 2.27 mA
5V	330 Ω	
5V	15K Ω	

Aside: The source of energy in a battery is a chemical reaction. Batteries are useful because they are portable. Batteries provide a relatively constant voltage level. AA, AAA, C, and D batteries have an average voltage output of approximately 1.2 V (the value depends on the type of battery, e.g., Alkaline, Carbon-Zinc, NiCad, Lithium, etc.). If you want to have a mobile power supply for this course, you can connect 3 or 4 C Alkaline batteries in series (end to end) which will provide between 3.6V (for 3 batteries) and 4.8V (for 4 batteries). You can simply duct tape them together or purchase a battery holder. You can also use AA batteries, but the larger the volume (size) of the battery the greater the energy stored, and thus, it will last longer before you have to replace the batteries.

1.3* (* = lab work) We could build the circuit in Figure 1.1 and confirm your computation by measuring the current using a multimeter (and you will do this type of measurement in your EE 2049 lab). For this course, we just want to gain a basic understanding of electric circuits before delving into digital logic circuits. Rather than measure the current, we want to observe the effect of varying the resistance on another load, namely an LED (light emitting diode). A diode is an electrical component built from semiconductor material that only allows current to flow through in one direction. In an LED, when the

current flows through the diode, light is emitted². LEDs are designed to emit light of a specific wavelength (color) depending on the material that the LED is made from. LEDs are non-ohmic devices (they do not follow Ohm's Law). There will be a voltage drop (called the forward bias voltage) across the LED when it is on. The voltage drop is dependent on what wavelength the LED is designed to emit (e.g., the color of the LED). For the green LED we are using in this experiment, we will assume the voltage drop is 2.1V.

Figure 1.2 shows a circuit diagram with a resistor and LED. Resistors are used to control the amount of current flowing through the LED. If you connect up your circuit without the resistor, the LED will be over-driven, it will light brightly for a while and then burn out.

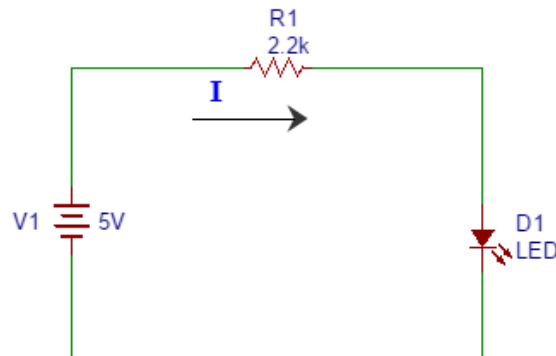


Figure 1.2. Simple electric circuit with resistor and LED.

For the circuit in Figure 1.2, compute the current flowing through the circuit. In this case you have to take into account the voltage drop across the LED. Assuming a 2.1V drop across the LED, the voltage across the resistor is $V_R = 5V - 2.1V = 2.9V$. In Figure 1.1, the voltage across the resistor was equal to the supply voltage (ignoring any voltage drops due to the resistance in the wires). Thus, for the circuit in Figure 1.1 $V_R = 5V$.

Table 1.2. Given a 5V power supply, use Ohm's Law to compute the value of **I** for the various resistor values.

V_R	R	$I = V_R/R$
$5V - 2.1V = 2.9V$	2.2K Ω	$I = 2.9V/2.2K\Omega = 1.32 \text{ mA}$
2.9V	330 Ω	
2.9V	15K Ω	

As you did in part 1.2, draw the circuit in your lab journal and compute the value of **I** for the other two resistor values in your lab journal (or on a piece of paper that you'll paste in your lab journal later).

² If you want to learn more about LEDs, there are many useful resources online. Here is a nice explanation of how they work (<http://www.explainthatstuff.com/diodes.html>). You'll learn more about them in EE 3700.

Question: Assuming that the maximum current through the LED is 20mA and the voltage drop across the LED is 2.1V, compute the smallest value for R that can be used without damaging the LED. Hint: figure out V_R and use Ohm's Law (the current that flows through the resistor is the same current that flows through the LED). *Answer all questions in your lab journal (paper).*

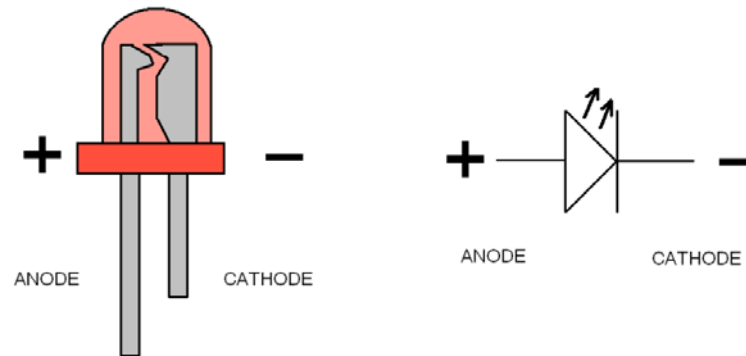


Figure 1.3. LED terminals. The anode (+) terminal has a longer lead and the cathode (-) terminal has a shorter lead.

Build the circuit shown in Figure 1.2 on the breadboard. While the orientation of a resistor in a circuit does not matter (current can flow in either direction through a resistor), current can only flow in one direction in an LED, from the anode (positive terminal) to the cathode (negative terminal). Figure 1.3 shows how to determine which is the anode (longer lead/wire) and which is the cathode (shorter lead). Figure 1.4 shows how to connect the components. Note that on your breadboard the five holes along one row are internally connected. Also note that there are two buses running vertically along each section of the board. The red bus has been wired to connect to the positive terminal of breadboard which you will connect to the positive terminal of the power supply (5V) and the blue bus has been wired to connect to the negative terminal of the breadboard which you will connect to the ground terminal of the power supply (0V). First wire your circuit and then connect the black lead from the negative (ground) terminal of the power supply to the negative terminal plug on your breadboard. Likewise, connect the positive terminal of the power supply to the positive terminal plug on your breadboard. Turn on the power supply and adjust the supply voltage to 5V.

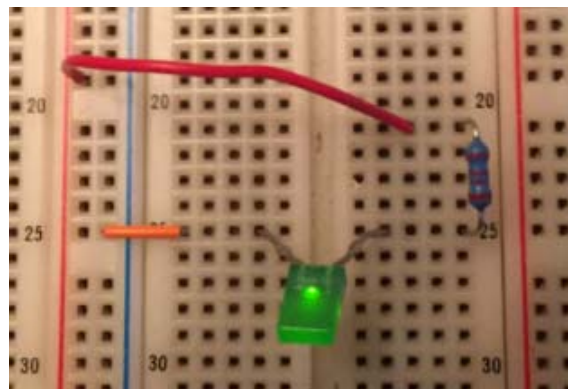


Figure 1.4. Example of how to build the circuit from figure 1.2 on your breadboard.

Vary the values of R and observe the brightness of the LED. Record your observations in your lab journal (paper).

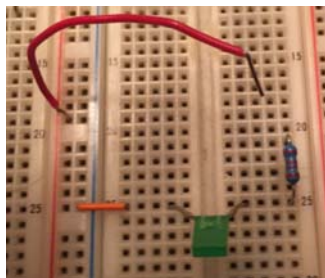
Table 1.3. As you vary the values of R , record your observations of the brightness of the LED.

R	Observations on LED Brightness
2.2K Ω	
330 Ω	
15K Ω	

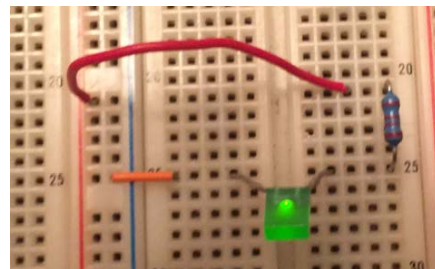
Question: What is the relationship between the amount of current flowing through the LED and the brightness of the LED?

Now vary the voltage being supplied from 0V to 5V and record your observations. At what voltage level does the LED seem to turn off?

1.4* Oftentimes circuits are controlled by a switch. Think about the lights and appliances in your house. In the circuit that you built in section 1.3, you can manually switch on and off the LED by removing one of the wires to create an open circuit (current cannot flow through an open circuit) and then replacing it to close the circuit. Figure 1.5 illustrates how to you can manually switch on and off the LED.



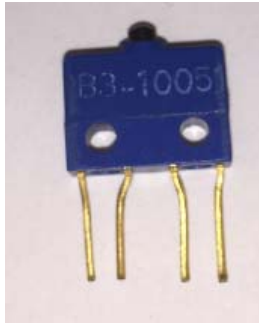
(a) Open circuit



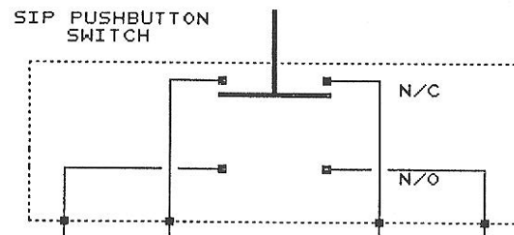
(b) Closed circuit

Figure 1.5. Manually turning off and on the LED by creating an open and closed circuit.

Instead of moving the wire to open and close the circuit we can use a mechanical switch. Consider your lamps at home, you can turn them on and off by plugging them into the wall socket and by unplugging them or you can use a switch to turn the lamp on and off. Obviously, it's more convenient to use a switch. Figure 1.6 show an example of a pushbutton switch. We can use this to control our circuit. We can connect one of the outer leads to the power supply (5V) and the other to the resistor. Since we are using the outer leads, the LED is normally off. But if we push the pushbutton switch and hold it down, the LED will turn on.



(a) Pushbutton switch



(b) Circuit diagram of switch. N/C means normally closed. N/O means normally open.

Figure 1.6. A pushbutton switch. Normally the inner two leads are connected (closed) and the outer two leads are not connected (open). When the button is switched, the switch between the inner two leads will open and switch between the outer two leads will close.

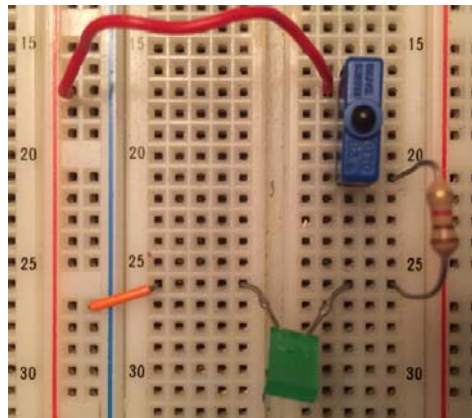
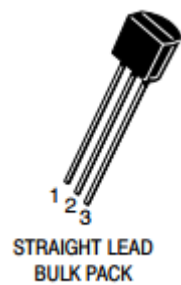


Figure 1.7. Simple resistor-LED circuit with a pushbutton switch to turn on and off the LED.

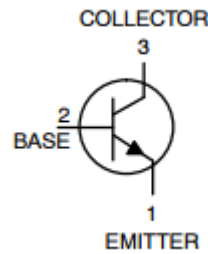
Build the circuit shown in Figure 1.7. Record your observations.

Question: What would happen if you used the inner two leads instead of the outer two leads? How would that change the behavior of the circuit? If you are uncertain, you can try it out!

1.5* There are times when you want to automatically control a circuit rather than manually control it. Consider your air conditioner at home. You could turn it on and off manually, or you can use a thermostat that has a sensor to measure the temperature and a control system to turn the air conditioner on or off in order to maintain a desired temperature. In this case, you need to have a switch that can be controlled electronically. Transistors are electronic switches. Figure 1.8 shows the circuit diagram for an NPN transistor. (Note: In this experiment we want to have a basic understanding of what transistors are and how they work but we will not be able to explore the physics behind semiconductor transistors. You will learn more about transistors in EE 2040 and EE 3700.)



(a) NPN Transistor



(b) Circuit diagram of NPN Transistor.

Figure 1.8. An NPN Transistor is an electronic (semiconductor) switch. The transistor turns on when current flows through the base of the transistor. When the transistor is on, current will flow from the collector to the emitter.

How is an NPN Transistor like a mechanical switch? The transistor is turned on when current flows into the base of the transistor. This is equivalent to pushing the mechanical switch down to close the circuit. When the transistor is on, current will flow from the collector to the emitter. Figure 1.8 shows how to connect the transistor to our simple resistor-LED circuit to control the turning the LED on and off.

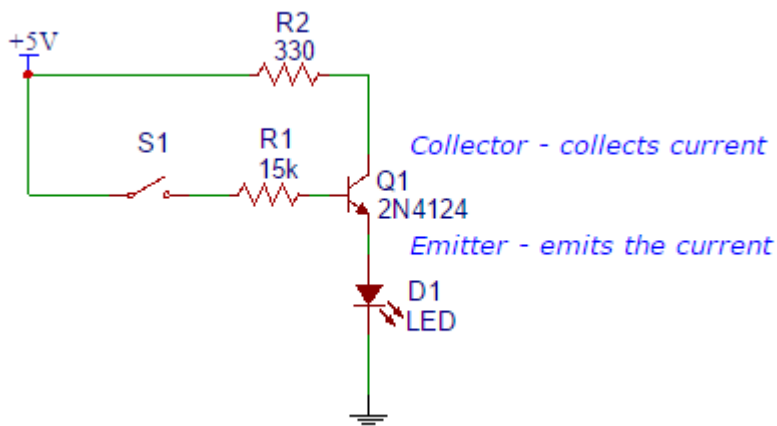
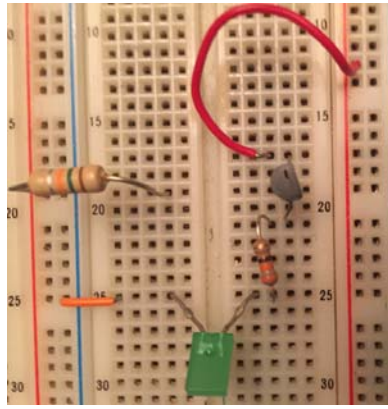
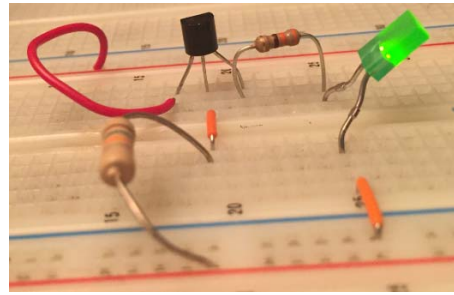


Figure 1.9. Resistor-LED circuit controlled by NPN 2N4124 transistor.

In the circuit shown in Figure 1.9, we are still using a mechanical switch to control the current flowing into the base of the transistor. In an actual circuit, the switch would not be needed. Instead, electrical components such as microcontrollers can be used to drive the base current to turn on and off the transistor depending upon input sensor values or other inputs to the circuit. Figure 1.10 shows the circuit. Notice that rather than using a switch, we are using the small orange wire to complete the circuit to provide current to the base of the transistor to turn the transistor on and off which in turn will turn the LED on and off.



(a) Resistor-LED circuit without current flowing to the base of the NPN transistor (orange wire removed).

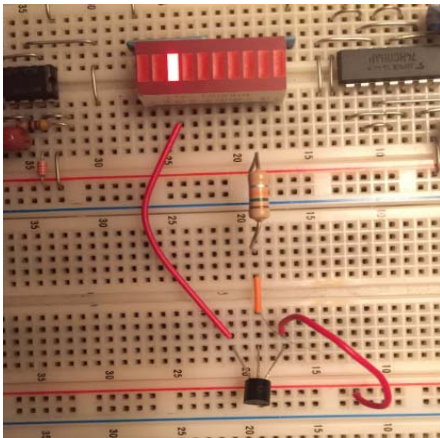


(b) Resistor-LED circuit with current flowing to the base of the NPN transistor (orange wire in place between the 15 KΩ resistor and the base of the transistor. Side view shows the connections to the NPN transistor).

Figure 1.10. Breadboard implementation of the circuit from Figure 1.9. Instead of a switch, an orange wire in the middle of the circuit is used to complete the circuit to allow current to flow into the base of the NPN transistor to turn it on.

Draw the circuit of Figure 1.9 in your lab journal and build the circuit. Record your observations.

1.6 Figure 1.11 shows a different implementation of the circuit of Figure 1.9. In this case, one of the LEDs from the LED bar graph is being used in place of the green LED. Where is the resistor that was connected between the emitter terminal of the NPN transistor and the LED? The first thing to note is that the resistor and LED in Figures 1.9 and 1.10 can exchange places and the circuit will still behave the same (the current limiting resistor needs to be there but can come before or after the LED). On the test circuit on the breadboard you will notice that next to the LED bar graph there are two SIP (single inline package) resistor arrays. The resistor arrays have a common terminal on one end that is connected to ground (0V) in our test circuit. The other end of the resistor is connected to the transistor emitter terminal.

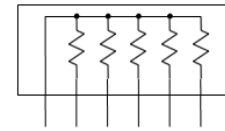


(a) Using the LED bargraph and SIP resistor array in place of the green LED and individual resistor.

Outside view



Inside view



(b) SIP resistor array has one common terminal connected to all resistors. The common terminal has a black dot next to it on the SIP package.

Figure 1.11. Breadboard implementation of the circuit from Figure 1.9. In this circuit a red LED from the test circuit's LED bar graph and SIP resistor array is being used instead of the green LED and stand-alone resistor.

1.7* In the beginning of the lab we mentioned that transistors are the building blocks of digital logic circuits. As mentioned, digital logic uses binary logic signals that are high (logic 1 or a high voltage (e.g., 2V to 5V for TTL) and low (logic 0 or a low voltage (e.g., 0V to 0.8V for TTL)). Why does binary make sense for digital logic circuits? Because they are built using transistors which have two states – on and off. Why do we call them logic circuits? Because with logic, things are true or false. With digital logic built from transistors, we can view the two logic values as True and False. Using what is referred to as “positive logic”, logic 0 would be considered False and logic 1 would be considered True.

A simple logic function is the NOT function. How does it behave? If the input to the function is True then the output is False (NOT True). Likewise, if the input to the function is False then the output is True (NOT False). We can describe the behavior of a logic circuit using a “truth table”. Figure 1.12 shows the truth table for a NOT function. The inputs to the logic function are shown on the left of the table and the corresponding output is shown on the right of the table.

Input	Output
False	True
True	False

(a) Truth table of a NOT function.

Input	Output
0	1
1	0

(b) Truth table of a NOT function using positive logic (0 = False, 1 = True).

Figure 1.12. Truth table of a NOT function is used to describe the behavior of the function.

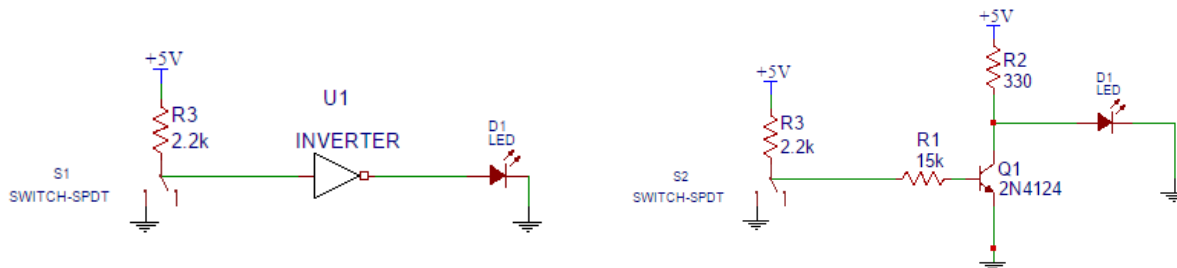
A NOT function (also known as an INVERTER) can be built using transistors. We refer to basic digital logic circuits as “gates”. Other basic logic functions include AND, OR, XOR, NAND, NOR, and XNOR. You will learn more about these in Experiment 3. Figure 1.13 shows the symbol of a NOT gate (also called an INVERTER gate) and the circuit to build a NOT gate using an NPN transistor and resistors.

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Figure 1.13. An INVERTER gate (NOT gate) can be built using an NPN transistor and resistors as shown on the right.

Based on your understanding of how the NPN transistor works, we can understand how the circuit in Figure 1.13 will behave as an INVERTER. When a logic 1 (high voltage) is applied to the circuit, there will be a base current and the transistor will be on (current will flow from the collector to the emitter) and the output signal (on the wire connected to the collector of the NPN) will essentially be connected to ground (0V or logic 0). When a logic 0 (low voltage) is applied to the circuit, there will not be any base current, and thus, no current will flow from the collector to the emitter. In this case, there will be no path to ground and so the output signal will be pulled high by the “pull up resistor” connected to the power supply (5V). The pull up resistor will ensure that when the transistor is on, that there is not a short between power and ground and that the path that the current will flow will be mostly to ground (the path of least resistance).

Build the INVERTER circuit shown in Figure 1.13 on your breadboard. Test the behavior of the INVERTER by connecting the input of the INVERTER to a switch from the test circuit on the breadboard and by connecting the output of the INVERTER to an LED. The complete circuit is shown in Figure 1.14.



(a) Circuit to test an INVERTER gate.
Connect to test circuit switch and test circuit LED from LED bar graph.

(b) Complete circuit showing the test circuit and the circuit for the INVERTER gate.

Figure 1.14. Truth table of a NOT function is used to describe the behavior of the function.

Write the truth table of the NOT function (INVERTER function), draw the circuit in your lab journal, build the circuit and test it. Verify that it behaves as described by the truth table.

1.8* Now that you understand more about how electric circuits work. Referring to the test circuit schematic in the Introduction section of the Lab Manual, use your logic probe to verify that the test circuit inputs all work properly (pushbutton switch outputs, SPDT switch outputs, and clock outputs). For the clock output you won't be able to observe the behavior of the clock using the logic probe but if you have a

probe with a buzzer, you should be able to hear the difference in clock frequency when you switch from the low frequency clock to the high frequency clock. For the test circuit outputs (LED bar graph) you can test each one by connecting a wire from the push button switch to each LED on the bar graph.