Info Sheet: Voltage Divider

One of the applications of resistors in series that we did not touch on in our first set of labs was the concept of a "voltage divider." When working with a circuit, there are times when you may want to have two (or more) different voltages available to you. Voltage dividers don't work for everything (see caution below), but they are a great tool for using in concert with transistors.

Voltage dividers are very simple circuits, but will be drawn in different ways. For example:

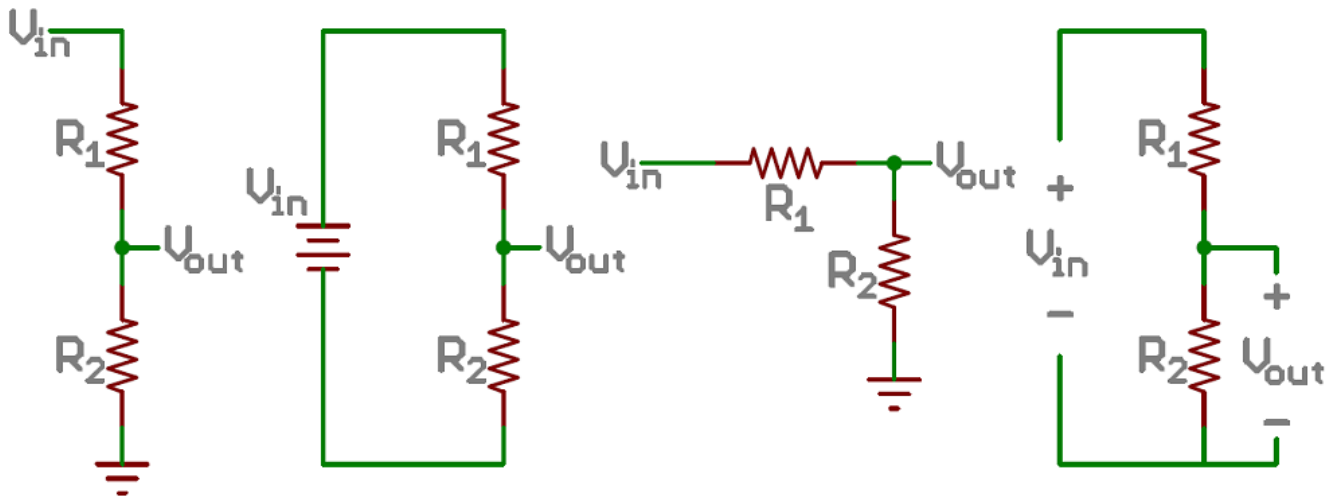


Image Source: sparkfun.com

The idea here is that there is always going to be a significant voltage drop across any resistor. In general, in choosing resistors, you want to choose ones that give you the voltage you're looking for. Through use of Ohm's law and basic circuit logic, you can find that:

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

Note that if R_1=R_2, then the output voltage is half of the input voltage.

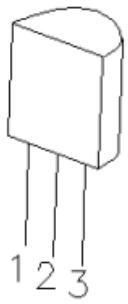
Two Caveats/Cautions:

1. You largely do **not** want to use voltage dividers to power some significant load. Note that, whatever current flows from V_{in} to V_{out} will necessarily flow through R_1. If this is a significant amount of current, you can easily overwhelm/overheat the R_1 resistor. This is also wasteful, since some significant amount of current is being dispelled as heat in the resistor. However, they are very useful for small currents such as the ones we'll use with transistor bases and are great for reading values from variable-resistance sensors (e.g. photoresistors).
2. Voltage dividers are fairly *wasteful* as circuits, since there will always be a current flowing from V_{in} to ground. Choose relatively high resistance resistors (e.g. a couple kΩ) to minimize this.

Lab 9: Transistors[4]

Part A: Testing Transistors

At its heart a bipolar junction transistor (BJT) consists of two "pn junctions" which can each individually act as diodes. These diodes can be tested just like any other diode – in particular, they can be tested with most multimeters. If both diodes test OK, and you measure no conductivity between the collector and emitter, then the transistor is almost always OK as well. This is a quick-and-dirty way to test a transistor and a good way to determine some important info about an unknown bipolar junction transistor.

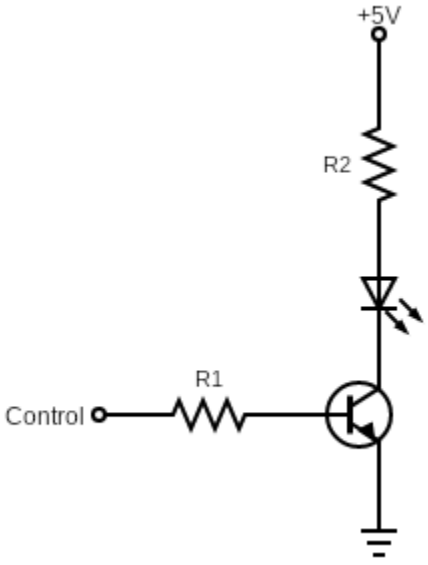


1. Obtain a 2N3904 transistor. Set your multimeter or ohmmeter to its diode test setting. Copy the sketch of the transistor showing the leads as 1, 2, & 3, and a little table like the one shown into your notebook. Measure the conductivity all six ways and record the meter readings in your table. The meter should only indicate significant conductivity in two of the six cases. The common lead to those two cases is the base. Determine which lead is the base. Determine from your data if the transistor is an NPN (base is + lead in both cases) or a PNP (base is - lead in both cases). Also, a slightly lowest meter reading indicates the base-collector junction, and thus which lead is the collector. Confirm with the 2N3904 data sheet.

RED (+)	BLK (−)	Meter Shows Conduction?
1	2	
1	3	
2	3	
2	1	
3	1	
3	2	

Part B: Switches

One of the most fundamental applications of a transistor is using it to control the flow of power to another part of the circuit -- using it as an electric switch. Driving it in either cutoff or saturation mode, the transistor can create the binary on/off effect of a switch. Transistor switches are critical circuit-building blocks; they're used to make logic gates, which go on to create microcontrollers, microprocessors, and other integrated circuits. An example circuit is shown here.



When the voltage at the base is greater than the transistor's threshold voltage (V_{th}), the transistor starts saturating and looks like a short circuit between collector and emitter. When the voltage at the base is less than that threshold voltage, the transistor is in cutoff mode -- no current flows because it looks like an open circuit between C and E.

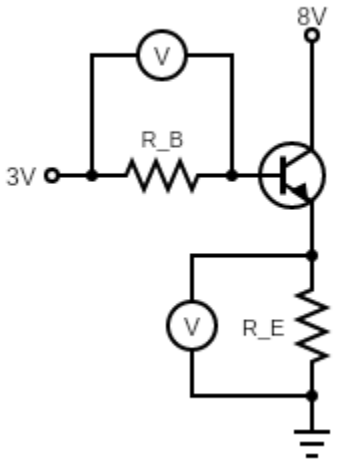
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[4] Parts adapted from: https://learn.sparkfun.com/tutorials/transistors/ and https://my.ece.utah.edu/~ece2100/EE2100labs_S03.htm

2. Build the above circuit with a 2N3904 transistor. For the control voltage, assume that you're using the same 5V as you are using to supply the LED (this won't be true for many of the circuits you build, but we'll do it here for simplicity). You will need to look up the data sheet of the 2N3904 to choose the resistors for R1 (Hint: find the "Base-Emitter saturation voltage" on the data sheet and note the maximum ***base current***). Additionally, look up the specs of the LED to choose R2. Write down the relevant information from the transistor/LED and show any calculations. Verify that switching on and off the "control" voltage causes the light to turn on and off.

Part C: Amplifiers

In addition to its use as a digital switch, another main use for transistors is as a signal amplifier. Recall that $I_C = \beta I_B$. For typically large values of β (e.g. ~100), a small current into the base gives you a large current out of the collector. For this part of the lab, you will create a circuit that allows you to measure this value of the gain for a given transistor. You will make the circuit below (*Note: you will have to utilize a voltage divider to give you the 3V signal; the voltage divider is not shown in this circuit*). **BUT**, don't build the circuit yet; we have some math to do first…



3. V_{CC} is an 8 V supply and V_{BB} is a 3 V supply. Assume that I_B and thus the voltage drop across R_B is negligible so V_B = 3 V. Assume also that V_{BE} = 0.7 V, so V_E ~ 2.3 V. Now, for each of the following emitter current values, calculate values of R_E required to set the emitter current at that value (2.3V/I_E).

a) 0.1 mA b) 3 mA c) 8 mA
d) 30 mA e) 80 mA

Obtain resistors that will (roughly) match the calculated values.

4. Make a table like the one below in your lab notebook. Fill in the R_E column with the resistor values that you have for each of the above cases a) through e).

	R_B	V_{RB}(mV)	I_B(μA)	R_E	V_E(mV)	I_E(mA)	I_C(mA)	β
a	10 kΩ							
b	1 kΩ							
c	1 kΩ							
d	100 Ω							
e	10 Ω							

Make the circuit shown above, using R_B and R_E from the first row in your table. You don't actually need two voltmeters for this circuit; you can simply use your multimeter to probe different parts of the

circuit at different times. You should probably wire your circuit so that you can easily measure the voltage across the two resistors (setting up wires specifically for probing voltage will work well).

5. Disconnect the R_B- base connection to stop the base current. What happens to the emitter and collector currents (as inferred from voltage differences)? Connect your base supply at 3 V and record your voltmeter readings. The voltmeter across R_B shows V_{RB} and the voltmeter across R_E shows V_E (*Note: the voltage drop across R_B is very small, so you will probably need to change the range of your multimeter to the most sensitive setting – "200m" – to measure it*). Now, move on to the second row of the table. Swap out the resistors and measure these voltages again. Repeat until you have measured voltages for each row of your table.

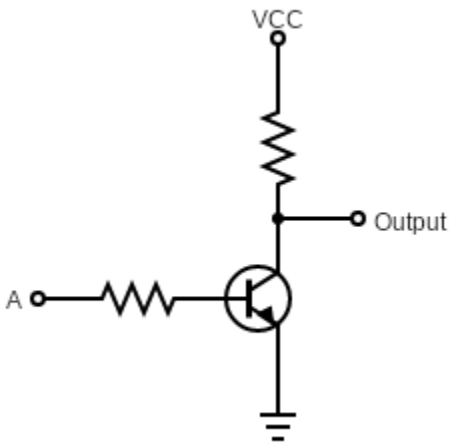
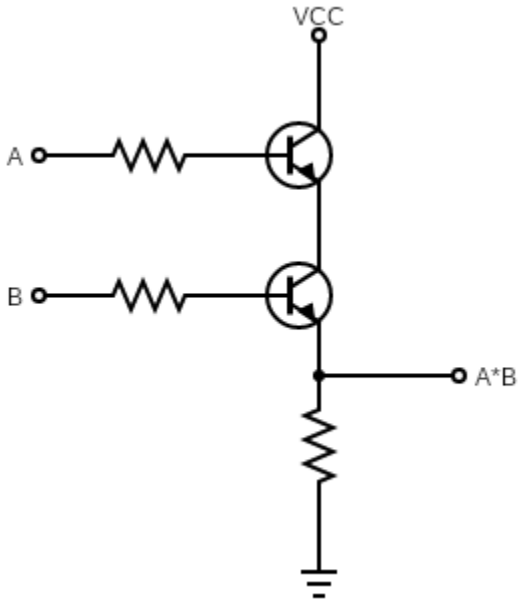
6. Using Ohm's law and basic circuit logic, make the calculations necessary to fill in the currents on your table. (*Note*: $I_C = I_E - I_B$)

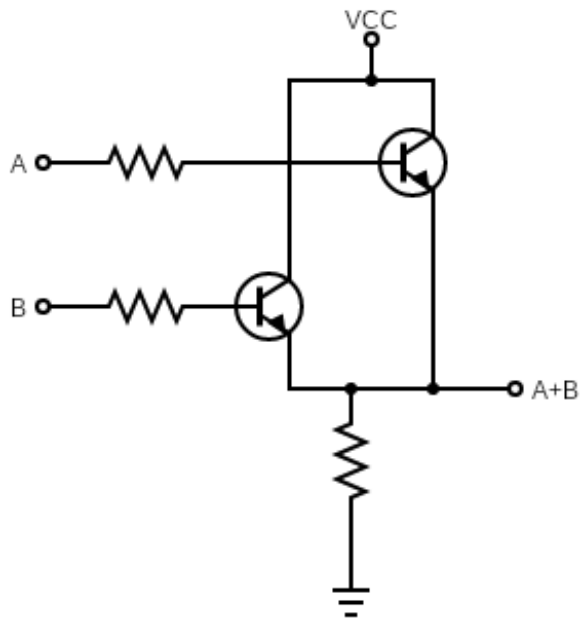
7. Look up a data sheet for your chosen transistor. They should include a graph of the collector current (I_C) vs gain ("h_{FE}" is the same as β). Print out this graph and plot the values you obtained onto this graph. Cut out the graph and paste it in your lab notebook. Don't panic if it's not all that close. One thing you should learn about transistors is that they vary widely from part to part.

8. Very often you will assume that $I_C \cong I_E$ when making transistor calculations. Look back at your table and comment about whether that assumption would have been reasonable in this case.

Part D: Logic Gates

Transistors can be combined to create all our fundamental logic gates: AND, OR, and NOT.

Inverter/NOT Gate	**AND Gate**
	
Here a high voltage into the base will turn the transistor on, which will effectively connect the collector to the emitter. Since the emitter is connected directly to ground, the collector will be as well (though it will be slightly higher, somewhere around VCE(sat) ~ 0.05-0.2V). If the input is low, on the other hand, the transistor looks like an open circuit, and the output is pulled up to VCC.	If either transistor is turned off, then the output at the second transistor's collector will be pulled low. If both transistors are "on" (bases both high), then the output of the circuit is also high.

OR Gate

In this circuit, if either (or both) A or B are high, that respective transistor will turn on, and pull the output high. If both transistors are off, then the output is pulled low through the resistor.

To Do: Choose *<u>one</u>* of the above circuits and build it, with the output powering an LED. Choose the resistors you need carefully.

- Resistors connected to bases need to ensure that the control voltage/current is at an appropriate level
- Resistors connected through the collector/emitter need to ensure that the "Collector-Emitter Saturation Voltage" is at an appropriate level.

Verify that each logic gate works appropriately and the LED lights up when the logic states are satisfied.

Lab 10: Environmental Sensors[5]

One of the primary uses of a circuit is taking an input signal, processing it in some way, and producing an output signal. Most recently, we've seen this for the high-pass filter and the logic gates that were created in the previous lab. However, these circuits are not directly taking information in from the environment to affect the behavior of the circuit. In this lab, we will begin our investigation of environmental sensors. There are lots of different kinds of sensors that can change their electrical properties in response to environmental stimuli. Broadly, these fall into two categories:

- **Resistive** sensors change their *resistance* in response to external stimuli.
- **Capacitive** sensors change their *capacitance* in response to external stimuli.

1. As a way of exploring environmental sensors, go to: https://www.adafruit.com/category/35 to see the list of sensors of just one vendor. Note that some of these sensors are "bare sensors," in that they are just the sensor, while others are packaged with some kind of digital circuit that can read their output. **Write down in your notebook the names of at least five different kinds of sensors that respond to five different stimuli.** In each case, indicate whether the sensors are *resistive* or *capacitive*, what external stimuli they respond to, and what the limits are (i.e. what physical conditions do they work under?).

Part A: Photoresistors

For this lab, you are going to work with a *photoresistor*[6]. As the name suggests, this is a sensor that changes its resistance due to the amount of light that hits it. **From a circuit perspective, nothing we do here is specific to photoresistors – all resistive sensors follow the basic circuit principles we'll be following here and you could build similar circuits with temperature sensors, vibration sensors, etc.**

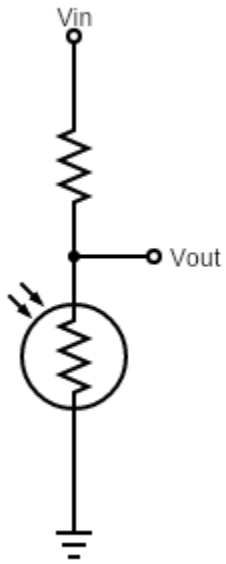
2. Obtain a photoresistor from the back bench. Note (and write down in your lab notebook) the part number of the photoresistor you chose.
3. Using a multimeter, measure and record the resistance of the resistor in four different light conditions:
    - Darkness (i.e. you cover the photoresistor)
    - The ambient light of the room
    - Bright light (e.g. shining your phone flashlight on the photo resistor) at two distances:
        i. Approximately 10cm away from the photoresistor
        ii. Approximately 1 cm away from the photoresistor
4. How does the resistance change in response to light? Does the photoresistor have a *higher* or *lower* resistance as the amount of light goes up? Look up the data sheet for the specific photo resistor you used. Print out the *calibration curve* included in that datasheet and plot your points on the curve. What can you say about the brightness of the room (in units of "Lux") and the brightness of your flashlight (in units of Lux)? In your notebook, create a table that includes the description of the light conditions, the resistance measured on the photoresistor and the implied brightness of the light (in Lux) as read off the calibration curve.

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[5] Excerpts from: https://www.sjsu.edu/people/burford.furman/docs/me106/photoresistorandstampF00.pdf
[6] Also sometimes called a "photodiode" or "photocell" or "CdS cell" or "Light Dependent Resistor" – "LDR"

5. In general, light follows an *inverse square law* relationship. If you are 10x further away from a source, you will measure 10^2 (=100) times less light. Do the two measurements you made using your phone flashlight support this relationship? What other things may be affecting the light measured by the sensor?

Part B: Photoresistors in a Voltage Divider



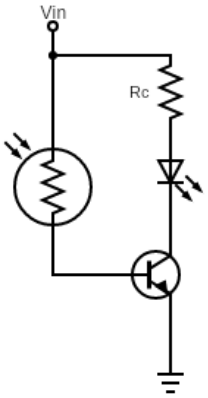
While variable resistance sensors are useful, in many electronic circuits, there is no easy way to measure resistance. It is much easier to measure *voltage*. In this way, **voltage dividers** are very useful tools. Recall that the relative resistance of the two resistors in a voltage divider determines the voltage measured at Vout. In that way, a changing *resistance* for a resistor in a voltage divider translates to a changing *voltage* at the output for the voltage divider. In the circuit to the left, the circled resistor with the lines pointing into it is the photoresistor, while the resistor above it is simply a traditional resistor.

6. Using the relationship between the top resistor and the bottom resistor from the "Voltage Divider" handout and the information you determined about your photoresistor in the first part of this lab, determine whether increasing light leads to a *higher* or *lower* voltage at "Vout". Explain your reasoning.

7. Create the circuit at left. Choose the top resistor such that the Vout value varies significantly depending on the light hitting the photoresistor. This will depend on the calibration curve for your resistor and the variable light conditions in the room. Try to pick your resistor such that a "medium" light condition gives you approximately half the voltage going into Vout.

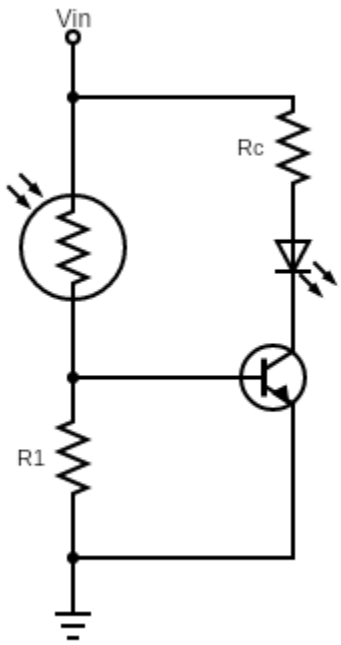
8. For the same four light conditions given in Step 3, record the voltage measured at Vout. Write them down in a table in your lab notebook.

Part C: Photodiodes, LEDs, and Transistors



As we've previously learned, you typically need a resistor in an LED circuit. While you could just repurpose a photoresistor to control the LED in a circuit, the LED largely doesn't respond well to in-between voltages. A transistor can be added to the light-controlled-switch circuit to improve its sensitivity and to eliminate the 'half-on-half-off' state of the LED. A rudimentary circuit to do so is shown to the right in the figure (you don't have to build this one). Here the photoresistor controls the transistor's base current, which is then amplified by the transistor. The collector current of the transistor, in turn, controls the LED. Unfortunately, this circuit may not function properly, because when the photoresistor is in the dark state, (and the LED is supposed to be turned off), the base current may be large enough that the LED may stay lit!

9. Prove this, by calculating the collector current for the circuit when Vin=10 V, R_{PR}=100 kΩ, Rc=220 Ω and β=100.



Consider the improved circuit here, which employs a voltage divider. This is the circuit that you will build and experiment with next. With a properly selected resistor R1, the voltage at the base of the transistor in the dark state is less than the Base-Emitter saturation voltage of 0.65 V, and therefore the transistor is in the cut-off state. As the photoresistor's resistance decreases (as the result of an increase in light intensity), the base voltage increases. Once the base voltage reaches ~0.65 V, the base current starts to flow, and any further decrease in the photoresistor's resistance causes an increase of base current. This base current increment will be amplified by the current gain of the transistor.

10. Choose the supply voltage. The supply voltage is often a predetermined value rather than a design choice. For example, if a battery is to be used, the voltage should be either 3, 6, or 9 V. In the following calculation and in later circuit construction, use any voltage of your choice between 6 V to 15 V.

11. Select R1. To do this, first determine a value of the photo resistor's resistance at which you would like the LED to be turned on (call it R_{on}). The resistance value can be that for when the photoresistor is covered or uncovered, it's up to you. (Just make it clear in your notebook). Knowing what you know about Voltage dividers, choose the value for R1 such that the voltage provided to the base of the transistor is sufficient to switch it on (i.e. V~0.65V). *Suggestion: Use a variable resistor (also called a "potentiometer" or "pot") for R1 so that the turn-on value can be adjusted - there's a box of them on the back bench.*

12. Select Rc, the current limiting resistor. With this resistor, the collector current is limited to $I_{max}=(Vin - V_{LED} - 0.3)/Rc$, where V_{LED} is the voltage drop across the LED, and 0.3 V is a typical saturation voltage between the collector and emitter (check your data sheet for the transistor you're using). Select R_C so that the LED current is limited so as to not fry the LED. Construct and test the circuit.