

# Experiment #4: Validating Kirchhoff's Laws

## Laboratory Outline

In today's lab we'll carry on developing the fundamental knowledge and skills you'll need to conduct basic experiments. You will learn much about the terminology, tools, and basic laws that govern circuits in an electrical engineering laboratory.

We will continue discussing specific equipment found in the ECE 110 Lab. Keep in mind that while each piece of equipment can come in different shapes and forms based on the manufacturer and the model number, the basic principle of operation remains the same. The next few lab meetings will continue to build your skillset on these specific models in a way in which you can easily utilize other models in later labs. With the skill to use this equipment, you will be ready to analyze the behavior of electronic components and use those components to build interesting circuits such as those required of autonomous vehicles!

In lecture, we will generally assume that bench equipment are ideal devices. Sources will provide whatever voltage and current is demanded of it and measuring devices will not affect the characteristics of the circuit in which it is embedded. In lab you will investigate what happens when the ideal-device assumption fails. For example, motors might demand more current you're your batteries are capable of providing causing non-ideal battery characteristics to appear.

*Please use the Notes margin on the right for both notes to yourself about the experiment as well as for feedback to your TA on the quality or clarity of the lab procedure. Thanks!*

## Learning Objectives

- Interpret a breadboard design and map the circuit into a circuit schematic.
- Interpret a circuit schematic and map the circuit onto a breadboard.
- Use the voltmeter to record voltage differences across circuit elements.
- Dispute common misconceptions of the application of Kirchhoff's voltage law.
- Use voltages to determine currents through resistors via Ohm's law.
- Dispute common misconceptions of the application of Kirchhoff's current law.
- Characterize the operation of a flex sensor.
- Make observations of the voltage-to-resistance relationship of a flex sensor used in a voltage divider.
- Complete the objectives (as time allows) of a semi-required, self-selected **Explore More! Module**.

Name/NetID:

Teammate/NetID:

Section AB/BB:

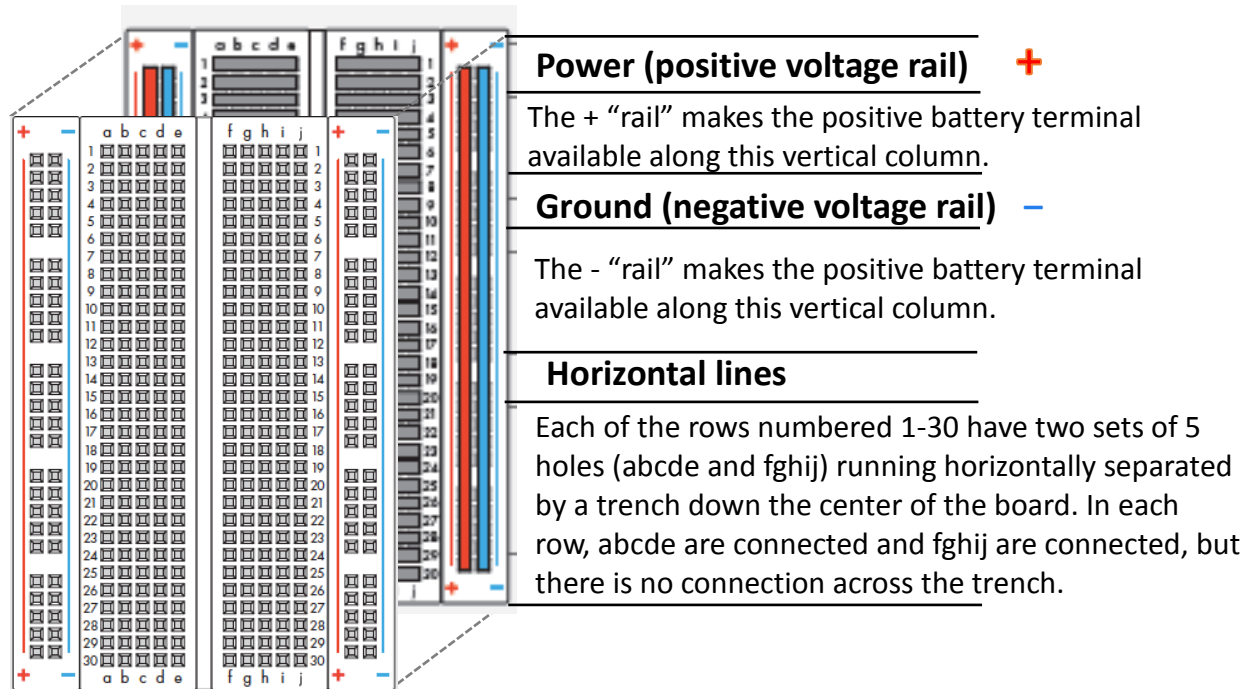
0	1	2	3	4	5	6	7
8	9	A	B	C	D	E	F

(circle one)

You are required to complete a minimum of 8 **Explore More! Modules** during the semester, on a schedule provided to you by your TA. Most may be self-selected from the large set of those available. We encourage you to choose those that may help you personally understand a concept or gain ideas for a final project design. When you find you have extra time (> 5 minutes) after submitting your lab procedure, you must spend the remainder of the period exploring a module.

## Schematics, Breadboards, and Laying Down the Law

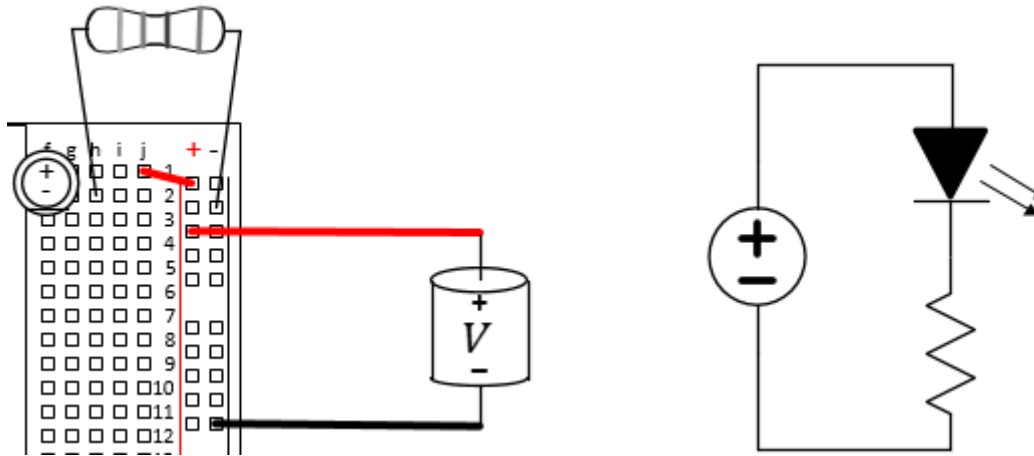
The breadboard is a very convenient tool for electrical circuit prototyping. It allows for *quickly building and reconfiguring* detailed circuits with few wires. Certain holes on the breadboard are internally connected. For example, the holes of each of the four long columns are connected vertically. These four columns are usually reserved for power (delivered by the positive and negative terminals of a voltage supply) and called *power rails*. Also, each row of five holes are connected together, although they are not connected to the other five holes on the other side of the board's center. It is very important to understand how the board is internally connected.



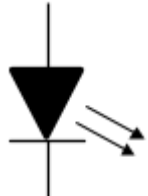



**Figure 1:** The breadboard and its internal connections.

The following figure depicts a physical diagram and the corresponding circuit schematic. While both tell the same story, the physical diagram is more suggestive on the components to be used and a physical location and orientation in which you might place them. The circuit schematic is more abstract and requires that the student be familiar with the circuit symbols used for various circuit lab elements.

Notes:

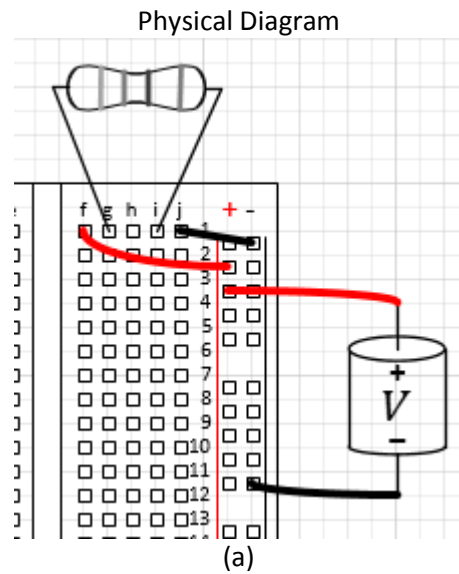


**Figure 1:** A wired breadboard and the corresponding circuit schematic.

Symbol	Representation	Physical
	Light Emitting Diode (LED)	
	Resistor	

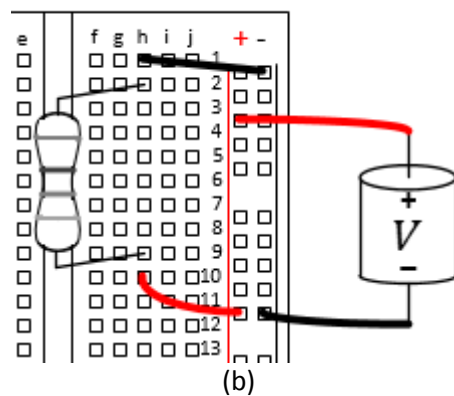
**Table 1:** Common symbols and physical representations of common circuit elements.

**Question 1:** Recall the internal connections of the breadboard to produce a circuit schematic of each physical diagram of the following circuits in the space to the right of each. Then, explain why each is **not** properly connected if the goal is to apply voltage across a resistor.



Circuit Schematic

(c)



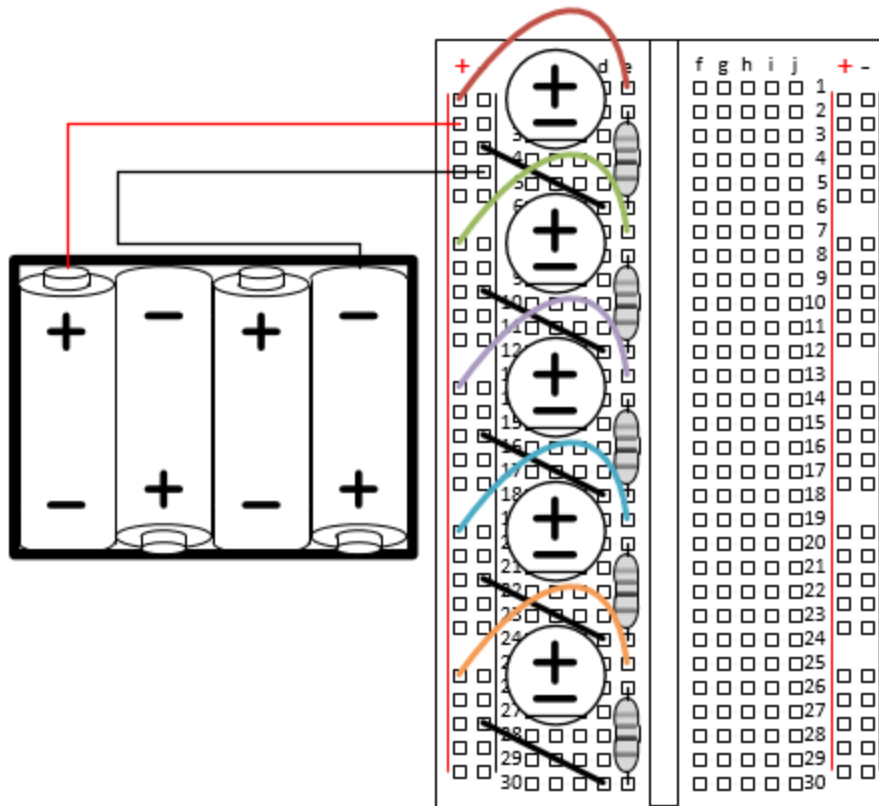
(d)

**Figure 3:** Two examples of *incorrectly* wired circuits.

Being able to derive the circuit schematic from a breadboard is an important skill for electrical engineering. Here are a few tips to help the reverse process.

- a) Start from the negative voltage terminal of the power source. We will think of this as our reference voltage, often called "ground".
- b) Insert a symbol for the power source and continue from the positive terminal.
- c) Begin to follow one circuit loop, following a component connected to the positive terminal.
- d) Carefully identify each component connected by the metal in the breadboard or wire as you follow your path. These devices are said to be connected on the same node.
- e) Complete the circuit path by reaching the negative voltage terminal of the power source
- f) Leave the other circuit paths alone until you complete the first path, but remember to go back and complete all the other paths from their divergence points. After each path is complete start another path until all elements are connected.
- g) Be careful to properly label the pins when you encounter a device with multiple leads.

Notes:



**Figure 4:** Physical diagram of a circuit containing a multi-cell battery pack, five resistors and five LEDs.

**Question 2:** Draw a circuit schematic for the physical diagram above. Remember to label all components as necessary. Do not build this circuit.

Students in this course should be comfortable in wiring a circuit on breadboard when given a circuit schematic. A carelessly wired circuit can very easily include mistakes and is very difficult to debug. It is usually a much more efficient use of your time to wire a circuit carefully than rush the wiring process only to waste a lot more time trying to find the mistake on a messy circuit. Below are a list of good practices that can help keep your prototype circuits neat, organized and easy to debug.

- a) Reserve the four columns on the sides to be power rails.
- b) Use red wires to connect to the positive terminal of power source or the positive power rail; use black wires for connection to the negative rail (ground).
- c) Place devices with multiple pins on the board first while reserving sufficient space for all the connections they will require.
- d) Place devices close together when they are to be interconnected. Occasionally, clean up a working circuit to reduce size and extra wires. Cut wires to the proper length to make it fit tight to the breadboard.
- e) Avoid using wire when it is not necessary. Let elements like resistors and diodes span small spaces without the use of extra wires.
- f) Use wires of multiple colors, reserve each color for a unique kind of use.
- g) Complete one positive voltage source terminal's path to ground (visually follow the schematic while completing the path) and then work on other paths that occur from any diverging point.
- h) Verify the final circuit with the schematic side by side.

**Question 3:** Build a circuit following schematic below. Try to obey the suggestions above. When you have completed, ask a TA to verify the circuit. This circuit will be used in later questions so do NOT dismantle the circuit after the TA has verified it.

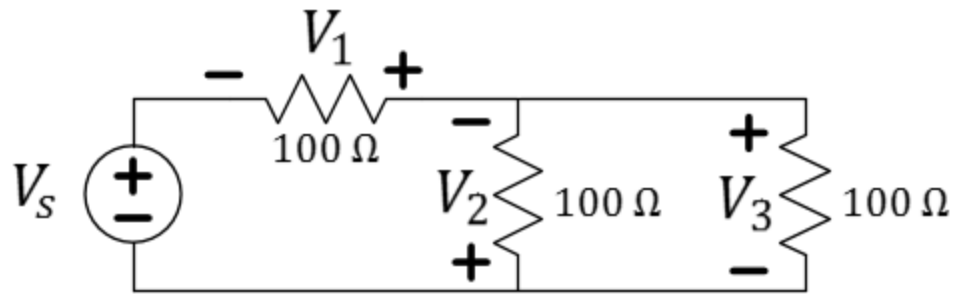


Figure 5: Circuit schematic for investigating KVL.

TA Signature confirming proper construction:

- ✓ Set the power supply voltage such that  $V_S = 6\text{ V}$ .

**Question 4:** Measure the voltages across all of the devices for the circuit you just built, including the power supply and enter them into the table below and mark them on the schematic provided. **Remember** to connect the positive ( $V - \Omega$ ) terminal of the DMM to the plus sign and the negative (COM) terminal to the negative sign for the element as shown by the polarity in the circuit schematic.

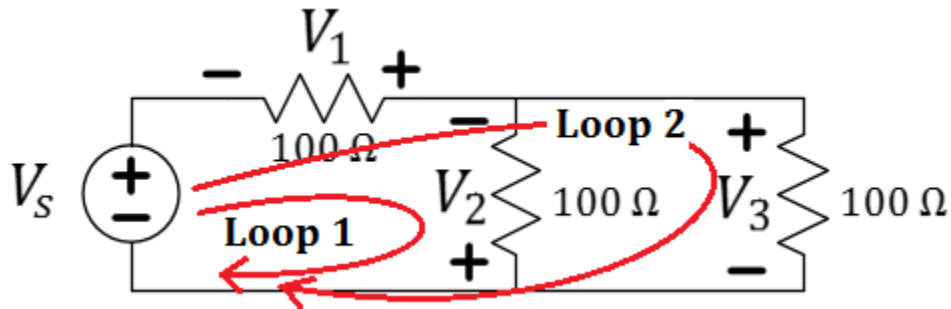
	measured voltage	comments
$V_S$		
$V_1$		
$V_2$		
$V_3$		

Table 2:



**Question 5:** Explain how your answers in this table would change if you were to decrease the supply voltage to 3V.

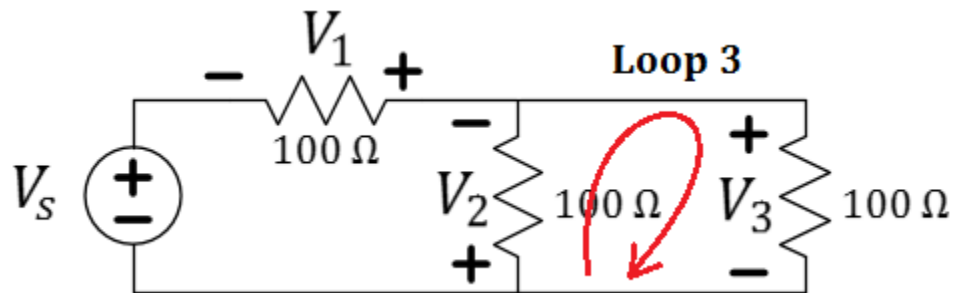
Kirchhoff's Voltage Law (KVL) states that the sum of the voltage drops around a loop will be zero. Let's use our measurements to make sure that this law will be applied correctly.



**Figure 6:** Same circuit with two loops labeled.

**Question 6:** There are two labeled loops in the above circuit. Sum the voltages as you go around loop 1 according to  $V_S + V_1 + V_2$ . What result do you get?

**Question 7:** Sum the voltage around loop 2 according to  $V_S + V_1 + V_3$ . The result is not zero. Explain why this was a misapplication of Kirchhoff's Voltage Law.



**Figure 7:** Same circuit with a third loop labeled.

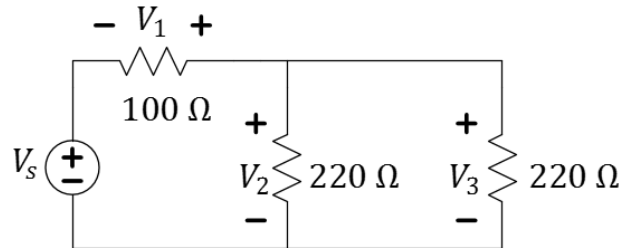
**Question 8:** If you compute  $V_2 + V_3$ , do you get the result you expect? Discuss.

Always remember that the voltmeter polarity must match the labeled polarity of the circuit schematic when entering voltage values to validate Kirchhoff's Voltage Law.

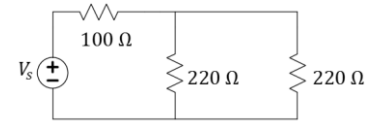
✓ Change two of the  $100\ \Omega$  resistors to  $220\ \Omega$  as shown in Figure 8, then continue.

Notes:

**Question 9:** Recall that we defined the term “node” earlier. Identify all three nodes on the schematic below by encircling them and labeling them as A, B, and C.



**Figure 8:** Circuit schematic for investigating KCL. Notice that we have **changed two resistor values** from before!

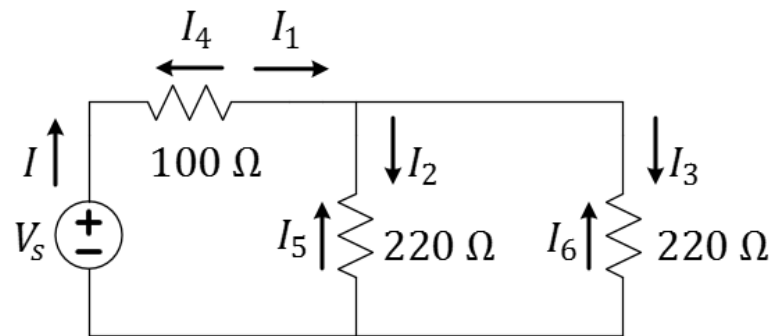


**Question 10:** Use a voltmeter to measure the voltage across each resistor,  $V_1$  through  $V_3$ , with polarities as shown. Enter these values in the table below.

	Measured Voltage
$V_1$	
$V_2$	
$V_3$	

Table 3:

Notes:



**Figure 9:** Circuit schematic for investigating KCL with over-defined current variables.

	Properly-signed Ohm's Law Equation	Calculated current
$I_1$		
$I_2$		
$I_3$		
$I_4$		
$I_5$		
$I_6$		

Table 4:

**Question 11:** Complete the table above by inserting the Ohm's Law equation (with the proper sign  $\pm$ ) such that each current will have both the correct sign and magnitude. Each equation will include one of  $V_1$  through  $V_3$  and either  $100 \Omega$  or  $220 \Omega$ . Discuss your decision making for the signs in the space below.

**Note:** Ohm's Law, properly applied, also maintains that current will flow in the direction of voltage drop in an Ohmic device. When the current arrow points from the + to the - of the defined voltage,  $R = \frac{V}{I}$  will be a positive value and  $I = \frac{V}{R}$  will have the correct sign. When the current arrow (polarity) is in opposition to this rule, merely add a negative sign to Ohm's law to reverse the polarity of the voltage such that  $I = -\frac{V}{R}$ .

Question 12: Kirchhoff's Current Law (KCL) states that the sum of all current flowing into a node will equal zero. If you compute  $I_1 + I_2 + I_3$ , you do not get zero. Does this disprove KCL or is this a misinterpretation of how KCL applies to your measurements? Explain your reasoning.

Question 13: Using the node indicated in the figure on the right, complete a correct version of KCL (with respect to that node) using three of the variables,  $I_1$  through  $I_6$ .

$$\boxed{\phantom{I_1 + I_2 + I_3}} = 0$$

## Resistive Sensors

Resistive sensors are a special type of sensor that changes its resistance according to some input. Consider the flex sensor from SparkFun. Consistent with the name of the device, the resistance of the flex sensor changes based on how much the sensor is flexed.

Notes:

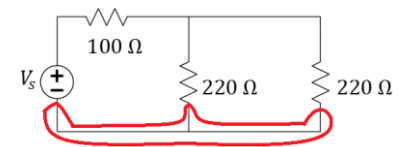
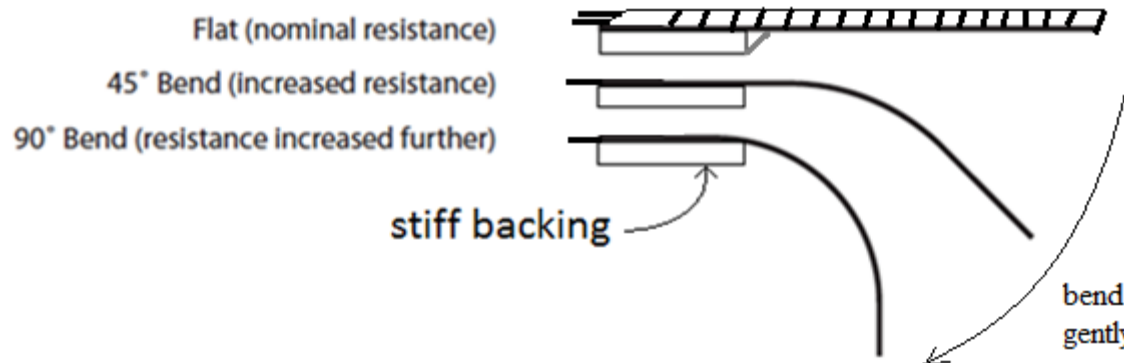
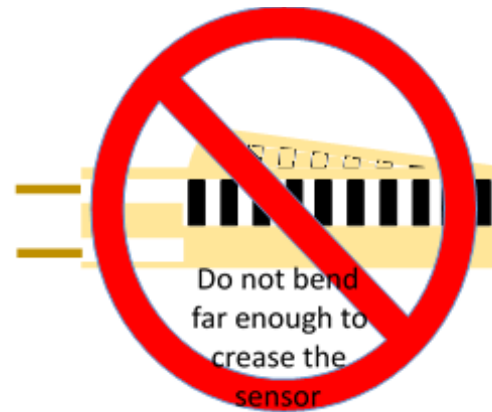


Figure: One essential Node.

Your TA will help you connect your leads to a circuit.



**Figure 9:** Proper bending of the flex sensor. Notice that a stiff edge should be provided around which the sensor can gradually bend. Do not bend sharply or too close to the “terminals”.

Let’s represent the resistance across the two terminals of the flex sensor as  $R_{flex}$ . See Figure 9 for the correct way to bend the sensor. We will mount the flex sensor to a stiff edge and bend the sensor gently (as seen in the figure above). The lines should be on the outside of the bend and the text of the sensor on the inside of the bend. Never make a sharp bend with it or you will destroy it! Also, do not bend the sensor too close to the terminal.

Notes:

**Warning:** Do not make a “sharp” bend, or you will damage your sensor. Allow the sensor to bend in an arc with a large radius. The visible “printed lines” must face the outside of the arc formed.

Notes:

**Question 14:** Measure the resistance for flex angles of 0, 45, and 90 degrees (approximately), for all the flex sensors you and your partner have. Use a permanent marker to number your flex sensors.

degrees	$R_{flex}$ #1	$R_{flex}$ #2	$R_{flex}$ #3	$R_{flex}$ #4	comments
0					
45					
90					

Table 4:

**Question 15:** Plot your results with the approximate angle on the x-axis and the resistance  $R_{flex}$  on the y-axis. Print this plot and attach it to your report.

✓ Choose the flex sensor with the most change for the next part.

**Question 16:** Use your breadboard to wire the circuit as shown in the schematic below with  $R_{bias}$  set to the value  $R_{flex}(at 0^\circ)$ . Fill in the table with your measurements.

**Note:** the flex sensor should change by more than 50% of its nominal value when bent to 90 degrees. For example, if an unbent flex sensor has a resistance of  $10\text{ k}\Omega$ , then it should read at least  $15\text{ k}\Omega$  when bent. If you do not have two flex sensors that meet this criteria, please see your TA.

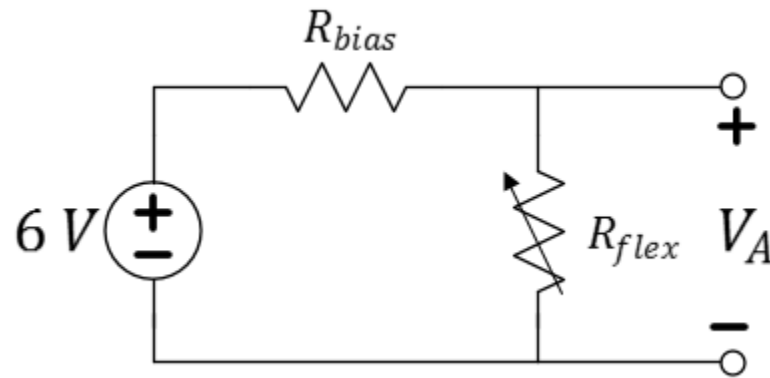


Figure 10: A voltage divider circuit typical for resistive sensors.

$V_A$ at $0^\circ$	$V_A$ at $45^\circ$	$V_A$ at $90^\circ$	comments

Table 5:

This circuit is often called a **voltage divider**. While the flex sensor transfers mechanical change to a varying resistance, the voltage divider translates the resistance to a voltage. The voltage may be used by other electronic components which can respond to the flexing sensor or be measured by other electronic devices such as a microprocessor (like the popular Arduino). A voltage divider is simple and is a very common method of integrating resistive sensors into a circuit. Careful selection of the resistance values  $R_{flex}$  and  $R_{bias}$  will allow the designer to gain a broad range of voltages (inherently immune to noisy measurement errors) while reducing energy wasted.



## Conclusion

**Question 17:** Complete this conclusion by discussing your findings in this lab. Be sure to specifically address the equipment, schematics, Ohm's Law, KVL and KCL and how these things are valuable to us.

## What You Learned

In this lab, you have both improved your understanding of the DC equipment as you used to confirm Kirchhoff's circuit laws. You should be able to read circuit schematics and record measurements that are consistent with the indicated polarity of the labeled voltages and currents. You should be able to confirm that voltage measurements conform to KVL and that current measurements conform to KCL and use inconsistencies to identify erroneous measurements. You should be able to identify a voltage divider and build a circuit voltage divider that utilizes a flex sensor that outputs a voltage as the sensor bends.

## Explore More!

At the end of each regular lab procedure, as time permits, you will be provided with materials to continue to improve your mastery of the materials. The suggested modules for this lab will be provided by the TA. You are to work on these as long as time permits. The modules will be submitted to your TA when finished. Completion of eight modules will count in your final grade.

Recommended module for today: ***Explore More! Arduino as a Power Supply.***

## Lab Report Rubric

The following rubric will be provided at the end of each lab procedure. As a final step in preparing your lab report, you will use this rubric to analyze your own performance.

Section	Criterion	Comments:
<i>Experimental Setup and/or Design Description</i>	Circuit Schematics are drawn neatly, accurately, and properly labeled. Decisions regarding experimental setup and design are clearly explained.	
<i>Measurements</i>	Tables include units and proper precision. Any <i>new device</i> introduced should be characterized using measurements!	
<i>Computations</i>	Computations performed on raw data are <i>explicitly</i> described and follow rules for significant figures.	
<i>Analysis</i>	Graphs have title, labels, units, scale, legend; Lines for curve-fitting appear in the graph when needed and parameters like the intercepts and the slope are labeled.	
<i>Modeling</i>	A mathematical model for the curve-fit graph allows for more abstract references to the device's behavior. The expected behavior is explained in the context of the graph.	
<i>Conclusion</i>	Conclusions are drawn from your experimental results to support the reason(s) for completing the experiment. Closes the loop on the Introduction.	
<i>General Formatting</i>	Answers to questions clearly labeled. The overall appearance of the report is professional.	
<i>Self-assessment</i>	This table has been thoughtfully completed.	