Teacher's Guide

Characterizing Electrolytic Materials

Grade Level: High School

Subject area(s): Physics

Time required: 2 (50 minute classes

Learning objectives: Through experimentation understand resistance of materials and importance in electrical conductivity.

Summary: The lab is designed to help students understand that the resistance of an object depends on length, cross-sectional area, and the type of material. Students measure the current through objects to see that different materials resist current in different amounts. Students will find that, for most applications, making the object smaller will produce a better result. They will learn how materials at the nanoscale often have different properties of the macroscale version and why it is important to characterize materials before using them to create devices.

Lesson Background: In order to process and deliver lots of information as with streaming video, Internet gaming, and cell phone applications engineers are making transistors smaller and faster. These transistors are now so small that "[m]ore than 2 million 45 nm (nanometer) transistors could fit on the period at the end of this sentence" or "more than 100 million 22nm tri-gate transistors could fit onto the head of a pin (1.5mm in diameter).[1] These nanoelectronics allow for faster, smaller and more portable systems (think about your smart phone) and they can manage and store large amounts of data/information (think about the increasing storage capacity of USB drives and computers). To do this, engineers test the properties of various materials including conductivity and resistance. Engineers investigate how these materials function *together* so they can find the best solution for a specific application. This lesson emphasizes the engineering practice of *characterizing* a material's properties to use it for a specific application.

At the nanoscale, the properties of materials may and often do exhibit different behavior. For example, gold which we see as yellow at the macroscale will appear to be red or violet at the nanoscale. This is because at the nanoscale, the motion of the gold's electrons is confined. Due to this restricted movement the nanoparticles react differently with light compared to larger-scale gold particles.[2] Thus it becomes important to characterize nano materials to be used in integrated circuits as they may behave differently than their macro version.

Our computers consist of integrated circuits also known as ICs. An IC is a fabricated unit of electronic circuits on a semiconductor material, typically silicon. These have active components such as diodes and transistors and passive components such as resistors and capacitors. The IC is also referred to as a monolithic integrated circuit or what we call a "chip". The chips are very small ranging in size of a few centimeters or millimeters with their components on the micro

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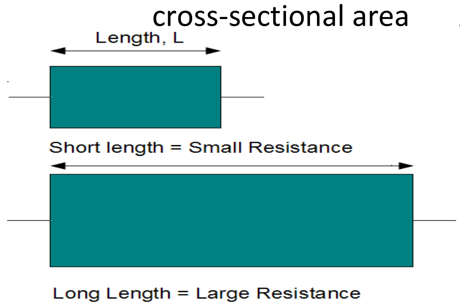
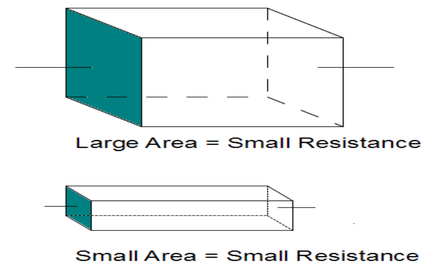
and nanoscales. As the ICs components become reduced in size, it is important to understand how the materials behave at reduced scales.

In this lab, the students will explore what properties of an object affect its resistance. As current passes through an object, the resistance *(R)* depends on the length *(L),* cross-sectional area *(A)* and the type of material. If we divide the length by the cross-sectional area of a material, we can relate its resistance through a number that is unique to *every* material in existence. This number is called the *resistivity*, ρ. It is a measure of how well a material resists the flow of current. This relationship is described by the equation:

$$R \text{ (resistance)} = \frac{\text{resistivity} \times \text{length}}{\text{cross-sectional area}} = \rho \frac{L}{A}$$





An interactive simulation of this is at this link: http://phet.colorado.edu/en/simulation/resistance-in-a-wire. (Don't show this link to students until *after* the lab has been completed, so they can figure out the relationships on their own.) *Electric current* is the flow of free electrons in a material. In this lab, students will test and characterize various materials: *metals, insulators, and electrolytes.* Characterization is important in nanotechnology, for researchers must know the properties of materials individually before using them with other materials. *Metals* conduct electricity very well -- they have many free mobile electrons that have very little (or low) resistance to an electric current. Insulators, such as plastics, do not conduct well -- most of their electrons are not free or mobile, so an electric current does not flow well through these materials. *Electrolytes* and *semiconductors* behave somewhere in between metals and insulators. Some common electrolytes are found in food containing water and ions (such as salts). Do not confuse electrolytes with semiconductors -- they conduct electricity differently, yet have similar resistance properties as semiconductors. Unlike conduction through metals, semiconductors, and insulators, *electrolytic conduction* occurs due to the movement of *ions* instead of electrons. To conduct well, an electrolyte needs ions and a conductive path. The materials used in this lab have ions (such as salt) and a conductive path (such as water). For example, if you let some ketchup dry out overnight, it will not conduct well the next day due to the lack of a conductive path. In this lab, the electrolytic materials will be used as a substitute for semiconductor materials due to their similar resistance properties and accessibility compared to semiconductors.

Carefully characterized semiconductor materials are being used to create nanoscale devices such as light-emitting diodes (LEDs). LEDs are simply layered semiconductor materials with carefully engineered properties that emit light when a voltage is put across it. If you wish to learn more about how an LED works, go to http://electronics.howstuffworks.com/led3.htm[3]

Similarly, electrolytes with specific properties can emit light when a voltage is put across them. For example, a pickle, which is an electrolytic material with high sodium content, will glow when a large amount of voltage is put across it. This is shown and explained in this video[4]: https://www.youtube.com/watch?v=0BfQEllRRDE. The video also explains how a specific kind of LED, organic light-emitting diodes, are used to create extremely thin TVs as well as thin computer displays.

LEDs are used everywhere today from stoplights, to television and computer displays, to lasers. There is much ongoing research in making nanoscale LEDs for various applications, and they use materials characterization (the same skills students will develop in this lab) to make LEDs. One application is simply to replace flourescent light bulbs, as LEDs are much more energy efficient than flourescent light bulbs. If they are able to make these LEDs nano-sized, they could put thousands of LEDs in a small space and create the proper brightness needed.

Sources:

1. Intel. "Fun Facts: Exactly How Small (And Powerful) is 45 Nanometers?" and Fun Facts Exactly how small (and cool) is22 Nanometers?
   https://www.intel.com/content/dam/www/public/us/en/documents/corporate-information/history-moores-law-fun-facts-factsheet.pdf
   http://www.intel.com/pressroom/kits/45nm/Intel45nmFunFacts_FINAL.pdf
2. What's so special about the nanoscale? https://www.nano.gov/nanotech-101/special
3. How Stuff Works. "How Light Emitting Diodes Work." (accessed August, 2010) http://electronics.howstuffworks.com/led3.htm
4. How OLED displays work using a glowing pickle, YouTube. https://www.youtube.com/watch?v=0BfQEllRRDE

Pre-requisite Knowledge: Students should know how to create a simple circuit; have knowledge about electric current, resistance, resistivity, voltage; how to use equations to determine results.

Materials per lab group of 3 students

- ammeter or multimeter (harborfreight.com)
- 9V battery (ALK 9V 522) (jameco.com)
- 9V battery clip (A104-R) (jameco.com)
- 6V to 9V light bulb (2182) (jameco.com)
- red LED (LTL-307E) (jameco.com)
- metric ruler
- 5 alligator clip wires (GAL01) (jameco.com)
- 2 alligator clips crimped (GIP006-R) (jameco.com)
- sheet of aluminum foil, approximately 1 ft. ⍰ 1 ft. square (does not need to be exact)
- 4 luer lock syringe, 10 ml without needle (science supply such as Fisher)
- 2 hot dogs, cut in half
- 3 large diameter straws (such as Boba or Bubble tea straws)
- 3 small diameter straws
- 3 paper plates

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- plastic knife
- scissors
- plastic condiments: ketchup, mustard, mayonnaise
- small (4 oz.) plastic cups to hold condiments
- optional buzzer (63S109LA-R) (part #24872 jameco.com)
- paper towels

Safety Information: This lab only uses a low voltage source, a 9V battery, which will make it impossible for students to be hurt due to the low amount of current that would result if put across the high resistance of a human body. Tell the students: **Do not connect the circuit without putting a resistor (hot dog, straw, condiment) in the circuit.**

If any wire heats up, immediately disconnect the circuit. Although we use food with electronics in this lab, remind students that it is best to keep food separate from electronic equipment in order to keep the electronics working. Electronic probes should only touch the aluminum foil, not the food itself.

Students should wear safety goggles to prevent injuries to the eyes. Students will be using liquids that can go into the eyes. Also, if an LED explodes from connecting it directly to the battery without some resistance (the condiment), a small bit of plastic could fly into their eye.

Vocabulary and Definitions

1. *Current:* The rate at which charged particles flow through a wire or device. Analogy: Similar to water flowing through a pipe.
2. *Voltage:* The amount of electrical potential energy per charge that is either gained or lost from one point in the circuit to another. Electrons gain energy when they move through the battery and lose energy when they move through other devices in the circuit. Analogy: A battery is like an escalator that provides gravitational potential energy, while other devices are like waterfalls that take away gravitational potential energy.
3. *Conductivity:* A property of the material that determines how easily charge is able to flow through the material.
4. *Battery:* An electrical device that provides voltage (energy per charge) to the circuit.
5. *Ammeter:* A measurement device used to measure current.
6. *Characterization:* The identification of the properties of a material. In this lab, we are looking at the conductivity of the material.
7. *Conductivity:* A property of the material that determines how easily charge is able to flow through the material.
8. *Resistance:* A property of an object that represents how well the object resists the flow of current. This depends on the material, length and cross-sectional area. Analogy: Similar to how mass represents how well the material resists movement.
9. *Resistivity:* A property of a material that represents how well the material resists the flow of current. This only depends on the material and is unique to each material.
10. *Resistor:* A component in a circuit that provides resistance.

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11. *Light Emitting Diode (LED):* A device that emits light and allows current to flow in only one direction
12. *Nanoscale*: measured in nanometers; typically referring to materials between 1 and 100 nm but others use up to several hundred nanometers.
13. *Nanometer*: $1x10^{-9}$ or one billionth of a meter.
14. *Nanotechnology*: Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers. It is the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering.

Advance Preparation: Condiments, hot dogs, and straws can be purchased at a grocery store. Put small amounts of condiments in the cups just before the lab. You can purchase large diameter straws from an Asian grocery store (ask for boba tea or bubble tea straws) or from Amazon. Test light bulbs and batteries with a voltmeter. Connect light bulbs in a circuit to make sure they work. Order extra LEDs to have on hand—students who do not pay attention will hook up the LED without a resistor and burn out or explode the LED.

Suggested Teaching Strategies/Tips: This activity works best in groups of 3 students. Tell the students: **Do not connect the circuit without putting a resistor (hot dog, straw, condiment) in the circuit.** An LED will burn out because the current is too high. Have additional LEDs on hand as students will probably burn out a few anyway.

Student Worksheet #1:
Steps 4–5: Demonstrate how to take the measurement of the aluminum foil and explain the equipment safety issues of short circuits. **Very important:** Students must only connect the circuit for an instant (have one probe touching the aluminum foil, then have the second probe touch the other end of the foil for only an instant), as equipment can be damaged if it heats up too much.
Steps 6–9: Show these steps and explain how to measure various electrolytic materials: In order to take accurate measurements, we need a way to control the shape and length of the material being tested. The plastic straw allows us to control the length and area of the material being tested by providing a rigid shape. Because it is plastic, it also acts as an insulator, which prevents current from exiting the material. We also need to make contact with the entire end of the material so that the current will flow through the entire cross-sectional area. We are able to do this by putting a small piece of aluminum foil, which is very conductive, at both ends of the straw. The aluminum foil will also protect the probes by not putting them directly into the material.

Additional lesson enhancements:
1. Buy a chunk of silicon carbide to demonstrate how an LED emits light. Alternatively, see http://www.youtube.com/watch?v=P3PDLsJQcGI (see *Resources* section).
2. You can turn off the lights after most of the class has a working hot dog resistor to allow the students to compare who made the highest/lowest resistor by comparing brightness/dimness of their LEDs.

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3. You can set up 2 circuits with buzzers in them at the front of the class by simply switching the LED with a buzzer. Students can be allowed to come to the front of the class to compare whose buzzer is louder/softer.

Suggested Instructional Procedure:

Time	**Activity**
Days 1–2	**Characterizing Electrolytic Materials: Guided Inquiry**
5 min	Review the terms and questions in the *Vocabulary* & *Guided Dialog* section. Explain how materials at the nanoscale often have different properties of the macroscale version.
5 min	Distribute *Student Worksheet #1*. Explain that the purpose of the lab is to *characterize* different materials and to learn what affects a material's resistance. Have students make predictions. Demonstrate how to take a measurement.
35 min	Students build the circuit shown on the worksheet. Walk around and help groups when necessary. Students record data and answer worksheet questions.
5 min	Clean up.
Homework	Students create a mini-poster, and finish the questions in the *Draw Conclusions* section.
Day 3	**Engineering a Multilayer Resistor: Independent Inquiry**
5 min	Show silicon carbide video at http://www.youtube.com/watch?v=P3PDLsJQcGI Show OLED pickle video at https://www.youtube.com/watch?v=0BfQEllRRDE (see *Resources* section).
10 min	Ask the questions in the *Guided Dialog* section. Explain the poster assignment in the *Going Further* section now so students can take careful notes during the lab. Explain the challenges on *Student Worksheet #2*.
35 min	Students do the challenges on *Student Worksheet #2*. If they finish early, they can start answering the discussion questions. Just before cleaning up, ask students: If you had access to ideal materials and better technology, how could you make an even more conductive hot dog? *Use materials that conduct very well and make the materials as thin as possible by using a better layering process.*
5 min	Clean up.
Homework	Students finish the homework discussion questions. Also, students create a mini-poster. Each poster must include: a. A labeled diagram of one of the hot dog resistors. b. The data for each individual material in a chart. c. The data for the whole resistor put together. d. A paragraph that explains the strategies and modifications that they used to create the hot dog resistor using physics vocabulary and relationships learned from the activity. (A rubric is in the *Assessment section.*)

Assessment: *Poster Rubric*

Assessment	**Level 1**	**Level 2**	**Level 3**
Diagrams are labeled.	Diagram is drawn, but not labeled.	Diagram is drawn, but some labels are missing.	Diagram is drawn neatly and all parts are labeled.
Data for each individual material and hot dog resistor is complete.	Two or more measurements are missing.	One of the measurements is missing.	Material, current, and length are clearly given in chart form.
Paragraph	Paragraph lacks understanding.	Paragraph shows some understanding of material.	Paragraph shows understanding of material.

Assessment: *Lab Rubric*

Assessment	**Level 1**	**Level 2**	**Level 3**
Diagrams are labeled.	Diagram is drawn, but not labeled.	Diagrams are drawn, but some labels are missing.	Diagrams are drawn neatly and all parts are labeled.
Data for each individual material and hot dog resistor is complete.	Most measurements are missing.	Some measurements are missing.	Material, current, and length are clearly given in chart form.
Discussion Questions	A few or no discussion questions are answered.	Most discussion questions are answered.	Each discussion question is answered.

Additional Resources:

- Collin Cunningham. Make presents: The LED. http://www.youtube.com/watch?v=P3PDLsJQcGI
- Introduction to Circuits and Ohm's Law. Kahn Academy: https://www.khanacademy.org/science/high-school-physics/dc-circuits/electric-current-resistivity-and-ohms-law/v/circuits-part-1
- Integrated Circuit. Wikipedia: https://en.wikipedia.org/wiki/Integrated_circuit
- Integrated Circuits. GalcoTV: https://www.youtube.com/watch?v=71FtcdwR2BU
- Integrated Circuits. PBSTV: https://www.pbs.org/transistor/background1/events/icinv.html
- Nanotechnology 101. National Nanotechnology Initiative: https://www.nano.gov/nanotech-101

Next Generation Science Standards:

- **HS-PS2-6:** Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.* [
- **PS3.A:** Definitions of Energy ♣ "Electrical energy" may mean energy stored in a battery or energy transmitted by electric currents

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- **HS-PS3-5**: Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.

Science & Engineering Practices:

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly. (HS-PS1-3)
- Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). (HS-PS2-6)

Crosscutting Concepts:

- Energy and Matter: Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HSPS3-3)
- Structure and Function ♣ Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem. (HS-PS2-6)

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Student Worksheet #1
(with answers in red)

Directions for the Activity
Guided Dialog #1 Before beginning Day 1, review the vocabulary and ask the students the following questions:

1. What is one main requirement to create a working circuit? *The circuit must be closed (no gaps) in order for current to flow.*
2. What provides the energy to the circuit? *The battery.*
3. What is current? *Current is the flow of charged particles through a wire or device.*
4. What are two ways of transferring charge? *Charge is transferred through the movement of electrons and through the movement of ions (at the nanoscale).*
5. Before engineers spend thousands of dollars building electrical devices, what are some of the things that you think they do to give them the best possible chance of being successful? *Engineers carefully test each material individually to test the properties of the material alone. They also learn from previous attempts to make the device. They also compute mathematical equations and check graphs that were made from other, previous models.*

Characterizing Electrolytic Materials: Guided Inquiry

Safety
If any part of the circuit heats, disconnect the battery. Keep electrical equipment, such as probes and wires, out of the food itself. Only allow the probes to touch the aluminum foil.

Introduction: In order to process and deliver lots of information as with streaming video, Internet gaming, and cell phone applications engineers are making transistors smaller and faster. These transistors are now so small that "[m]ore than 2 million 45 nm (nanometer) transistors could fit on the period at the end of this sentence" or "more than 100 million 22nm tri-gate transistors could fit onto the head of a pin (1.5mm in diameter).[1] These nanoelectronics allow for faster, smaller and more portable systems (think about your smart phone) and they can manage and store large amounts of data/information (think about the increasing storage capacity of USB drives and computers). To do this, engineers test the properties of various materials including conductivity and resistance. Engineers investigate how these materials function *together* so they can find the best solution for a specific application. This activity emphasizes the engineering practice of *characterizing* a material's properties to use it for a specific application. In this lab, you will be characterizing various food materials for use in a circuit!

Question 1: Which materials will conduct electricity the best? Which materials will be the worst conductors of electricity?

Make a Prediction: *Example prediction: I think materials such as metals and liquids will conduct the best, while plastics or materials that are dry will not conduct well.*

Materials

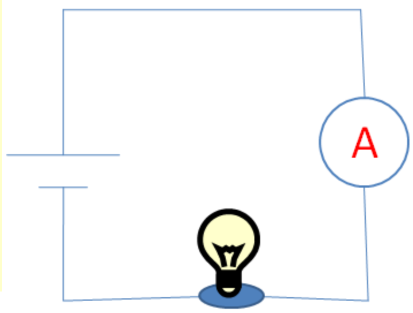
- ammeter or multimeter
- light bulb
- 9V battery
- 9V battery connector
- metric ruler
- 3 alligator clip wires
- 2 alligator clips
- 3 disposable plates
- sheet of aluminum foil
- 3 narrow straws
- 3 wide straws
- 1 cup of each type of condiment: mustard, ketchup, mayonnaise
- hot dog
- scissors
- 4 syringes
- plastic knife

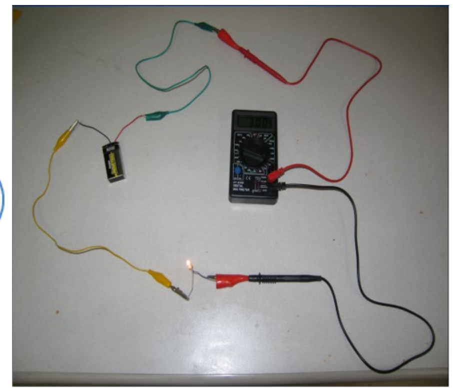
Question 2: Will the amount of the material affect how well it conducts? Why or why not?

Make a Prediction: *Example prediction: I think the amount of the material will affect how well it conducts because it will change the amount of material that the current will have to flow through.*

Procedure:

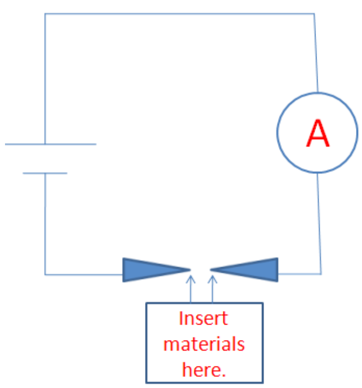
1. Create a circuit as shown:

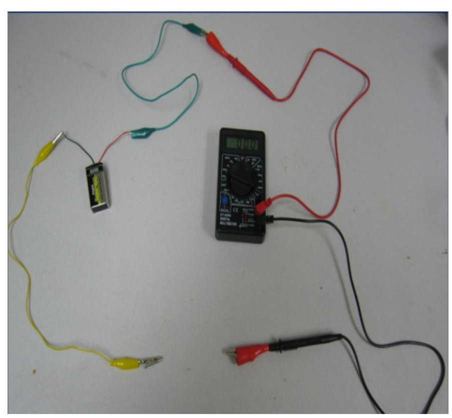




2. Set ammeter to 200 mA. Confirm that the light bulb is on and that the ammeter measures a steady current.

3. Disconnect your light bulb from the circuit. This is where you will insert electrolytic materials (straws with condiments) to test. Your ammeter should now read 0 mA.





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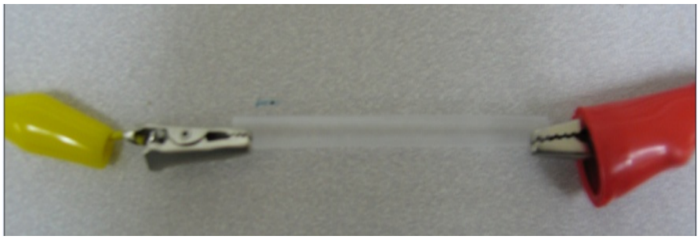
4. Insert a narrow straw into your circuit by clipping the alligator clips to each side of the straw. Then, read the current from the ammeter and record it in the table.



Step 4

Step 5

5. Set the ammeter to 10 A. Cut aluminum foil to be 8 cm long and 2 cm wide. Touch the alligator clips to the foil *for only an instant*. The ammeter may read "1" if the current is too high to measure. Record the current in the table on page 4. **Note: When the current is very high, it is called a *short circuit.* If this occurs, immediately disconnect the circuit.**

Each person will individually do steps 6–13 on one electrolytic material (condiment):

6. Cut your narrow straw 8 cm from one end.

7. Use the syringe to inject your electrolytic material (ketchup, mustard, or mayonnaise—each person in your group will do a different condiment) into the straw to completely fill it with a little bit coming out of each end. *Do not get air bubbles in your straw. It will prevent current from flowing.*

8. Stick a piece of aluminum foil on both ends of the straw so that it touches the condiment. Insert your straw into your circuit by putting a probe at each end of the straw. *Make sure the aluminum doesn't touch each other, or it will create a short circuit.*

9. Set your ammeter to 200 mA. Read the ammeter to measure the current that is flowing through the circuit. Record the material, length, diameter, and the amount of current flowing through the electrolytic material in the table.

10. Cut your narrow straw in half (so it is 4 cm), and repeat steps 7–9.

11. Repeat steps 7–9 again, but this time use an 8 cm piece of the ***wide*** straw.

12. Cut your wide straw in half (so it is 4 cm), and repeat steps 7–9.

13. Share your data with your group.

As a group:

14. Test the current of a hot dog.

   a. Cut a large straw 4 cm from the end.

   b. Cut the ends off the hot dog. Cut the hot dog to be a little longer than your straw.

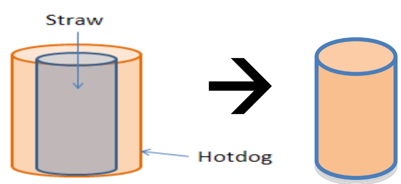
   c. Stick the straw through the middle of the hot dog. Then push it all the way through the hot dog and **push it out the other side.** You should now have a straw with a hot dog in it.

   d. Put a piece of aluminum foil on each side of the straw.

   e. Test the amount of current and record your data in the table.

While pushing: Straw (inside) with hotdog (both inside and outside)

After: Straw (outside with hot dog inside)



Record your Observations:

Which straw	Material	Length (cm)	Diameter (cm)	Radius (cm)	Area (cm^2)	Current (mA)
	straw	8			*0.3*	*0*
	aluminum	8			*N/A*	*500*
Narrow straw	ketchup	8			*0.3*	*3*
	ketchup	4			*0.3*	*6*
Wide straw	ketchup	8			*1.2*	*12*
	ketchup	4			*1.2*	*24*
Narrow straw	mustard	8			*0.3*	*7*
	mustard	4			*0.3*	*14*
Wide straw	mustard	8			*1.2*	*28*
	mustard	4			*1.2*	*56*
Narrow	mayonnaise	8			*0.3*	*.6*

straw	mayonnaise	4			*0.3*	*1.2*
Wide straw	mayonnaise	8			*1.2*	*2.4*
	mayonnaise	4			*1.2*	*4.8*
	hot dog	4			*1.2*	*30*

Analyze the Results:

1. Calculate the **radius** and **area** for each length of electrolytic material, and complete the table above. Use these equations:

Equation for calculating *radius*

$$r = \frac{d}{2}$$

where *r*: radius and *d*: diameter

Equation for calculating *area*

$$area = \pi r^2$$

where *r*: radius

2. Complete the chart below. Calculate the **resistance** and **resistivity** of the materials listed in the chart below using **<u>one</u>** of your measurements. Use the 4 cm length measurements on the wide diameter straw for each of these calculations. *Note: The **current** must first be converted from* **mA** *to* **A** *by dividing the amount in mA by 1000 to use these equations.*

Equation for calculating *resistance*		Equation for calculating *resistivity*		
$resistance = R = \frac{V}{I} = \frac{voltage}{current}$		$resistivity = \rho = \frac{AR}{L} = \frac{cross\text{-}sectional\ area \times resistance}{length}$		
Material	**Voltage (V)**	**Current (A)**	**Resistance (Ω)**	**Resistivity (Ω*cm)**
ketchup	9	*0.024*	*375*	*112.5*
mustard	*9*	*0.056*	*160.7*	*4.8*
mayonnaise	*9*	*0.0048*	*1875*	*562.5*
hot dog	*9*	*0.03*	*300*	*90*

3. Organize your results from the most conductive material to the least conductive material. Include the straw and the aluminum foil.

1. *aluminum foil*	2. *mustard*	3. *ketchup*
4. *hot dog*	5. *mayonnaise*	6. *plastic straw*

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Draw Conclusions:

1. a) Which material conducted the best?
   Aluminum foil conducted the best.
   b) Which material conducted the worst?
   Plastic straws conducted the worst.
   c) Why do you think some materials conduct better than others?
   The condiments/hot dog varied in conductivity, but were between aluminum and plastic. Different materials have different atomic structures. Metals conduct well due to having lots of free electrons while plastic has very few. The condiments with the highest ion/water concentration have good electrolytic conduction, such as the mustard.

2. a) Was there a relationship between length and how well it conducted? If so, how were they related?
   Yes, as the length increased, it was less conductive than when it was shorter.
   b) What do you think causes this?
   As the length increases, the ions/electrons have to travel through more material, which will make it harder to conduct due to the electrons experiencing more collisions.
3. a) Was there a relationship between the cross-sectional area of the straw and how well it conducted? If so, how are they related?
   Yes, as the area increased, conductivity improved.
   b) What do you think causes this to occur?
   As the area increases, the ions/electrons have more paths that they can take to get across the material, which makes it easier for it to conduct. Analogy: if you increase the amount of lanes on a highway, cars have more paths to take, which will increase the flow of traffic.
4. a) Depending on the properties of a material, it will have a specific resistivity. What do you think resistivity is?
   Resistivity is a measurement of how well the material will oppose current flow. This is similar to how mass is a measurement of how well the object will oppose a change in velocity.
   b) What measurement during the lab would resistivity affect the most?
   Resistivity would affect the current the most.
   c) What relationship would exist between this measurement and resistance?
   As the resistance increases, the current decreases.
5. a) What was the purpose of using a plastic straw and aluminum foil in order to take our measurements?
   The plastic straw allowed us to control the length and area of the material being tested by providing a rigid shape. Because it was plastic, it also acted as an insulator, which prevented current from taking other paths. The aluminum foil allowed us to make contact with the entire cross-sectional area of the material.

Day 2: Guided Dialog: *Before* beginning the lab, ask students:

1. If the conductivity of a material is very low, what does that tell us about the resistance of the material? *The resistance of the material is very high. There is an inverse relationship.*

2. How does length affect the resistance of the material? *The longer the length, the bigger the resistance. There is a linear relationship.*
3. How does area affect the resistance of the material? *The bigger the area, the smaller the resistance. There is an inverse relationship.*

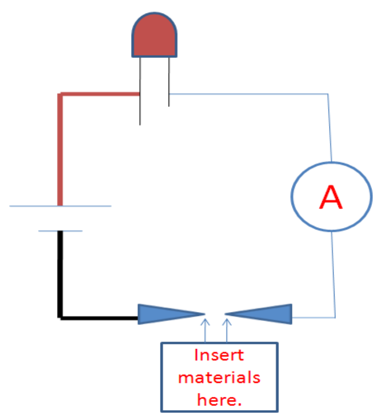
Student Worksheet #2
(with answers in red)

Engineering a Multilayer Resistor: Design Challenge

Safety
If any part of the circuit heats, disconnect the battery. Keep electrical equipment, such as probes and wires, out of the food itself. Only allow the probes to touch the aluminum foil.

Materials
- ammeter or multimeter
- LED
- 9V battery
- 9V battery connector
- metric ruler
- 5 alligator clip wires
- 2 alligator clips
- 3 paper plates
- sheet of aluminum foil
- straws
- 1 cup of each type of condiment: mustard, ketchup, mayonnaise
- hot dog
- scissors
- syringe
- plastic knife

Before you begin: Create the circuit below. Leave one part disconnected where various materials will insert into the circuit. The long leg of the LED points to the positive battery terminal. ***Do not close the circuit without your resistor.*** *This will burn out the LED.*



Design Challenge Rules:
- You must use at least **2 cm** of a **hot dog** and **at least 1 condiment in the straw.** *Put the hot dog in the straw last.*
- **All** materials must fit in a straw.
- Draw and label your resistor.
- Record the current.
- Modify your first design and improve it.

Challenge #1
Create a hot dog resistor that allows the **most current** to create the **brightest** LED! **Hint:** Use your chart from the last lab. Remember how **length** and **area** affect resistance to create the **most** conductive hot dog resistor!

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Challenge #2
Create a hot dog resistor that allows the **least current** to create the **dimmest** LED!
Challenge #3
Combine your Challenge #1 resistor and your Challenge #2 resistor by putting them back-to-back. What is the current? Is the current higher or lower than the current when each resistor is tested individually? Explain. *The current is lower than the current when tested individually because now the current has to flow through two resistors.*

Record Your Observations:

Hotdog Resistor Diagram (Remember to label)	Current (mA)
Challenge #1	
Modified and Improved Challenge #1	

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Hotdog Resistor Diagram (Remember to label)	Current (mA)
Challenge #2	
Modified and Improved Challenge #2	

Name:________________________________Date:_______________Class:________________

Engineering A Multilayer Resistor: Homework

1. How did stacking various materials on top of each other affect how well it conducted? Did the resistance of the resistor go up or down as you stacked more ingredients on it?

As we added more materials to the hot dog resistor, it was less conductive. The resistance went up.

2. What strategy did you use to make the LED the brightest? Why?

We tried to make a resistor with the lowest resistance. We tried to make the resistor's length as short as possible because the shorter the length, the lower the resistance is in the resistor. Also, we picked the straw with the biggest area because the bigger the area, the lower the resistance is in the resistor. We also tried to use materials that we found to have the least resistance from our tests.

3. What strategy did you use to make the LED the dimmest? Why?

We made a resistor with the highest resistance. We tried to make the resistor's length as long as possible because the longer the length, the higher the resistance is in the resistor. Also, we

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picked the straw with the biggest area because the bigger the area, the lower the resistance is in the resistor. We also tried to use materials that we found to have the least resistance from our tests.

4. What complications did you come across? How did you fix them?

A few times we ended up getting no current to flow across our resistor. We figured out that we needed to have a good seal between our materials because otherwise the circuit would be open. As we make our resistor thinner and thinner, it became harder to make a good seal.

5. When would a scientist or engineer want to use a material that has:

a) a lot of resistance? *When electricians work on circuits, they want gloves that have a high resistance so that they are not electrocuted. If you want to make a light dimmer, you would want higher resistance.*

b) a little resistance? *If you want to make a light brighter, you would want lower resistance. When transferring electricity from a power plant, you would want your wires to have very little resistance in order to not waste as much energy.*

6. Why is it important for engineers to characterize electrolytic materials on the nanoscale?

Nanoscale materials may behave differently at the this level in comparison to the macroscale version.

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