

Ohm's Law and Resistance (E3)

Objectives

- Examine the concepts of current, voltage, resistance and resistivity.
- Understand the difference between resistance and resistivity.
- Use Ohm's Law to determine the resistance of resistors in series and in parallel.
- Explore changes of resistance with temperature.

Theory

When discussing electrical devices, one encounters terms such as current, voltage, resistance, ohms, and amps. This experiment attempts to clarify these terms by examining the three basic concepts of current, voltage, and resistance.

A. Current

The current in a wire (or electrical component) is just the flow of charge from one end of a device to the other. Negative charges move in one direction, which is equivalent to positive charges going the other direction. The actual direction of the current is defined as the direction in which the positive charges flow (i.e., the average velocity of charges). In metals, current is carried by negative charges (electrons), so the direction of current is opposite to the average velocity of electrons. The rate of this electrical flow is measured in amperes (A), or amps for short. One amp is equal to the flow of one coulomb of charge per second. The common equation given for current is:

$$I = \frac{\Delta q}{\Delta t}, \text{ where } I \text{ is current and } q \text{ is charge.}$$

B. Voltage

Normally, the charge carriers within a wire move in random directions. However, if a potential difference (voltage) is set up across the ends of a device, the charges will begin to slowly drift. A greater potential difference leads to a greater rate of charge flow (i.e., a greater electrical current).

Did You Know?

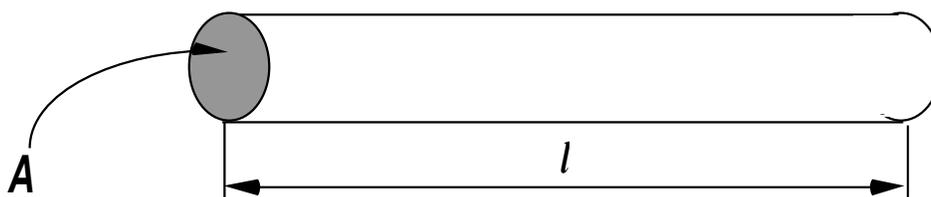
The electric potential between the head and tail of an electric eel can be up to 600V!

C. Resistance

Current depends not only on the voltage supplied by a power source, but also on the resistance of a circuit or component. Anything that opposes the flow of charge (current) is called a resistor and the amount of opposition offered by a resistor is called resistance. The resistance is measured in units called ohms, Ω .

The greater the cross-sectional area of the resistor or wire, the lower the resistance offered. On the other hand, the greater the length of the resistor, the greater the resistance offered. This relationship is shown below.

$$R = \rho \frac{l}{A} \left\{ \begin{array}{l} \rho = \text{resistivity (measured in } \Omega \cdot \text{m)} \\ l = \text{length of a wire (measured in m)} \\ A = \text{cross-sectional area (measured in m}^2\text{)} \end{array} \right\}$$



In the equation above, the resistivity of a material ρ is just a constant of proportionality, which relates length and area directly to the resistance R . This resistivity depends only on the type of the material and has no dependence on geometry.

Remember: **Resistance (R)** describes a particular resistor, whereas **resistivity (ρ)** describes the material used to produce that resistor. The resistance depends on the size and shape of the resistor, whereas the resistivity is an inherent property of the material.

Below are resistivity values at room temperature (i.e., at 20°C) and temperature coefficients of resistance for several materials.

MATERIALS	ρ (in $\Omega \cdot \text{m}$) at 20°C	α (in $1/^\circ\text{C}$)
Copper	1.7×10^{-8}	4.0×10^{-3}
Aluminum	2.7×10^{-8}	3.9×10^{-3}
Iron	1.0×10^{-7}	5.0×10^{-3}
Constantan (55Cu-44Ni-1Mn)	4.9×10^{-7}	1.0×10^{-5}
Tungsten	5.5×10^{-8}	4.5×10^{-3}
Nickel (99.6%)	7.0×10^{-8}	4.7×10^{-3}
Nichrome (35Ni-20Cr-45Fe)	1.0×10^{-6}	4.0×10^{-4}

The change of the resistance (as well as the resistivity) with temperature is described by the following equation:

$$R(T) = R_0 [1 + \alpha(T - T_0)] \quad \left\{ \begin{array}{l} T = \text{temperature measured in } ^\circ\text{C} \\ T_0 = \text{initial temperature measured in } ^\circ\text{C (usually } T_0 = 20 ^\circ\text{C)} \\ R(T) = \text{resistance at temperature } T \\ R_0 = \text{initial resistance at temperature } T_0 \\ \alpha = \text{temperature coefficient of resistance} \end{array} \right\}$$

$$\rho(T) = \rho_0 [1 + \alpha(T - T_0)] \quad \left\{ \begin{array}{l} \rho(T) = \text{resistivity at temperature } T \\ \rho_0 = \text{initial resistivity at temperature } T_0 \end{array} \right\}$$

$$R(T) = R_0 [1 + \alpha(T - T_0)] = R_0 + R_0 \alpha (T - T_0) \quad \text{and} \quad \alpha = \frac{R - R_0}{R_0(T - T_0)} = \frac{\rho - \rho_0}{\rho_0(T - T_0)}$$

The above equation, which says that the changes of resistivity are proportional to the changes of temperature, applies to almost all metals. As the temperature increases, the atoms in the material begin to vibrate more. Because their increased motion makes it more difficult for the current to pass, the resistance increases. For semiconductor materials, the resistivity decreases with temperature. However, in this experiment we will focus our attention on metals.

D. Ohm's Law

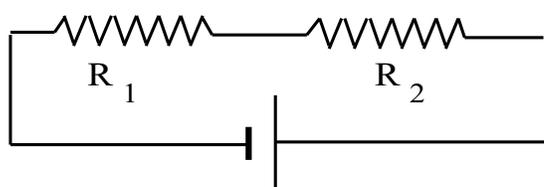
Ohm's law is a simple equation that defines the relationship between current, voltage and resistance.

$$R = \frac{V}{I} \quad \text{or} \quad V = IR \quad \left\{ \begin{array}{l} I = \text{current (measured in amps A)} \\ V = \text{voltage (measured in volts V)} \\ R = \text{resistance (measured in ohms } \Omega) \end{array} \right\}$$

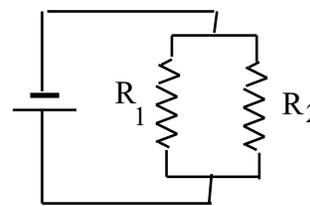
If the voltage difference applied across the ends of a conductor is increased, the current will also increase. However, if the resistance of a conductor is increased, the current will be decreased. The Ohm's law may also be rewritten as: $V = IR$ (i.e., the voltage across any resistor is proportional to the current and the proportionality constant is equal to the resistance).

E. Resistors in Combination

In this experiment, we will look at some very simple circuits containing a power source and some resistors connected either in series or in parallel. For the series resistors shown below, the total resistance may be found by simply adding the individual resistors. For parallel resistors, however, the total resistance is not a simple summation as shown below.



$$R_T = R_1 + R_2$$



$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

F. Non-linear Resistance

Ohm's law applies only to some resistors called “ohmic” or linear resistors. Yet, there is another class of electrical components: “non-ohmic” or non-linear resistors. These components have a resistance that is not constant all the time. Rather, the resistance is dependent on the voltage across it, the temperature of the component, etc. Examples of non-linear resistors are semiconductor diodes, transistors, and incandescent light bulbs.

Diodes and transistors are semiconductor devices. Their nonlinear characteristics are due to their physical structure on the microscopic level. The conductive properties of semiconductors are far beyond the scope of this experiment. However, the incandescent light bulb is not a semiconductor device. Its non-linear resistance is due to the resistance variation as the instantaneous temperature of the light bulb filament changes.

The light bulb used in this lab is a typical incandescent light bulb: a tungsten filament encased inside a glass enclosure filled with a non-reactive gas (or vacuum). When a voltage is applied which is small enough that the heat produced is negligible, the bulb acts as a linear resistor. However, when a high enough voltage is applied and the bulb starts to glow, the resistance changes due to the temperature effects explained in Section C. This change in resistance because of a change in voltage shows that the resistor does not have a constant resistance. This is what we mean by the term: “non-linear resistance”.

G. Electric Power

The electric power is defined as the change of potential energy of travelling electric charges per unit time. The equation to calculate the power P in an electrical circuit is given by the following equation.

$$P = \left| \frac{-\Delta U}{\Delta t} \right| = \left| \frac{Q\Delta V}{\Delta t} \right| = I|\Delta V|$$

If we combine the previous equation with Ohm's Law, then

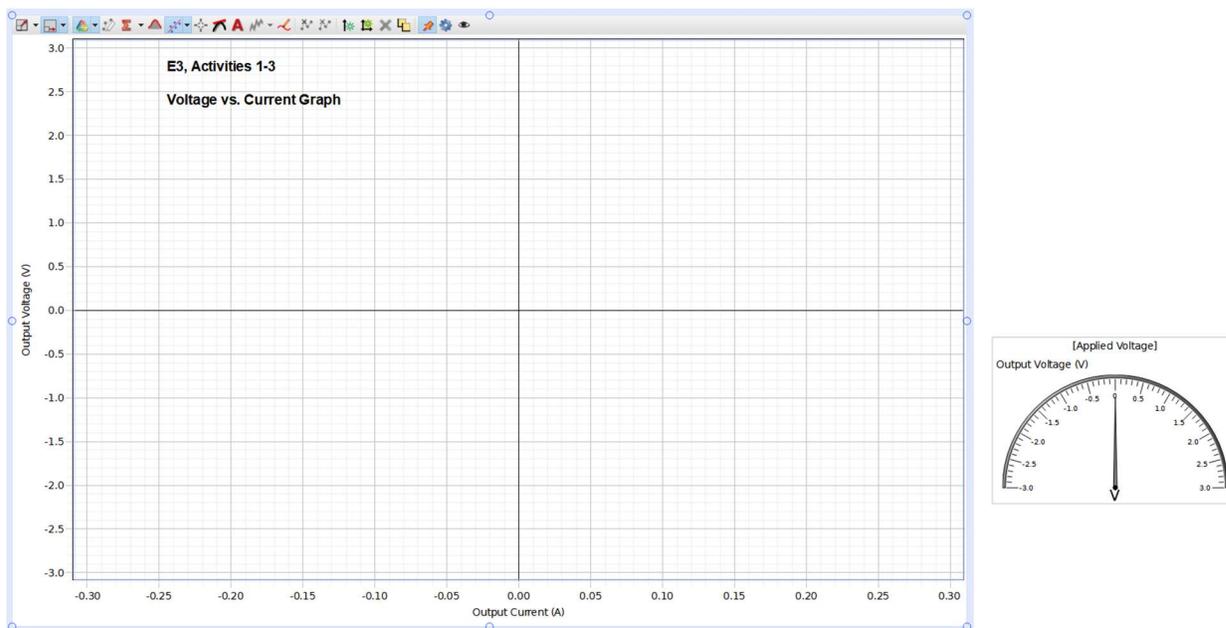
$$P = I|V| = I^2R = V^2/R \quad ; \quad \text{the unit of power is watt: } 1 \text{ W} = 1 \text{ J/s}$$

Procedure.

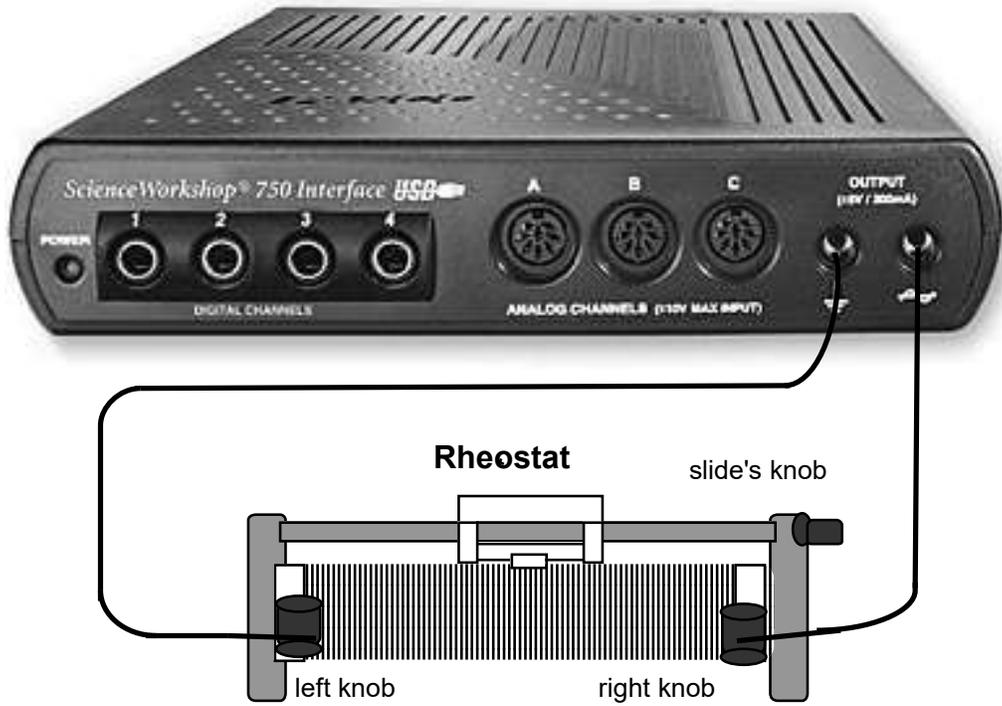
Activity 1: Ohm's Law - Voltage vs. Current Graphs

- 1.1. Download lab files from Brightspace for Physics 221 (or for Physics 252). These files should be in the Lab folder or in the assignments for the current week. Save files on the desktop.
- 1.2. Find the document “E3, Activities 1-3” and double-click to open it. The application “Capstone” by PASCO should open with configuration ready for Activities 1, 2 and 3.

A data acquisition screen will appear as shown below.



- 1.3. *Activity 1* uses a device called a rheostat. This is simply an adjustable resistor formed by a long, coiled piece of high-resistance wire on which rests a sliding contact. By moving the sliding contact, you may increase or decrease the length of wire that lies between the slide and one of the two terminals (left or right) at the ends of the resistive wire. This change in the length, in turn, modifies the resistance and the current. During *Activity 1*, you need to find the **resistance of the whole** rheostat. Therefore, hook current wires to the left and to the right knob of the rheostat leaving the slide unconnected.



Two comments:

1. The position of the slide will not change results for this activity!
2. The red and black wires are identical except for the color of insulation. If someone replaced all red wires with black ones, the result would not change.

Once the rheostat has been properly connected, you may begin your data acquisition by following the directions below.

- 1.4. During the data collection run, the ScienceWorkshop data interface will supply a slowly changing voltage to the rheostat. The voltage changes from +3 V to -3 V and back to +3 V while values of current are measured 5 times per second. These values are both stored in computer's memory and plotted on the graph. The graph shows voltage (on vertical axis) vs. current (on horizontal axis).

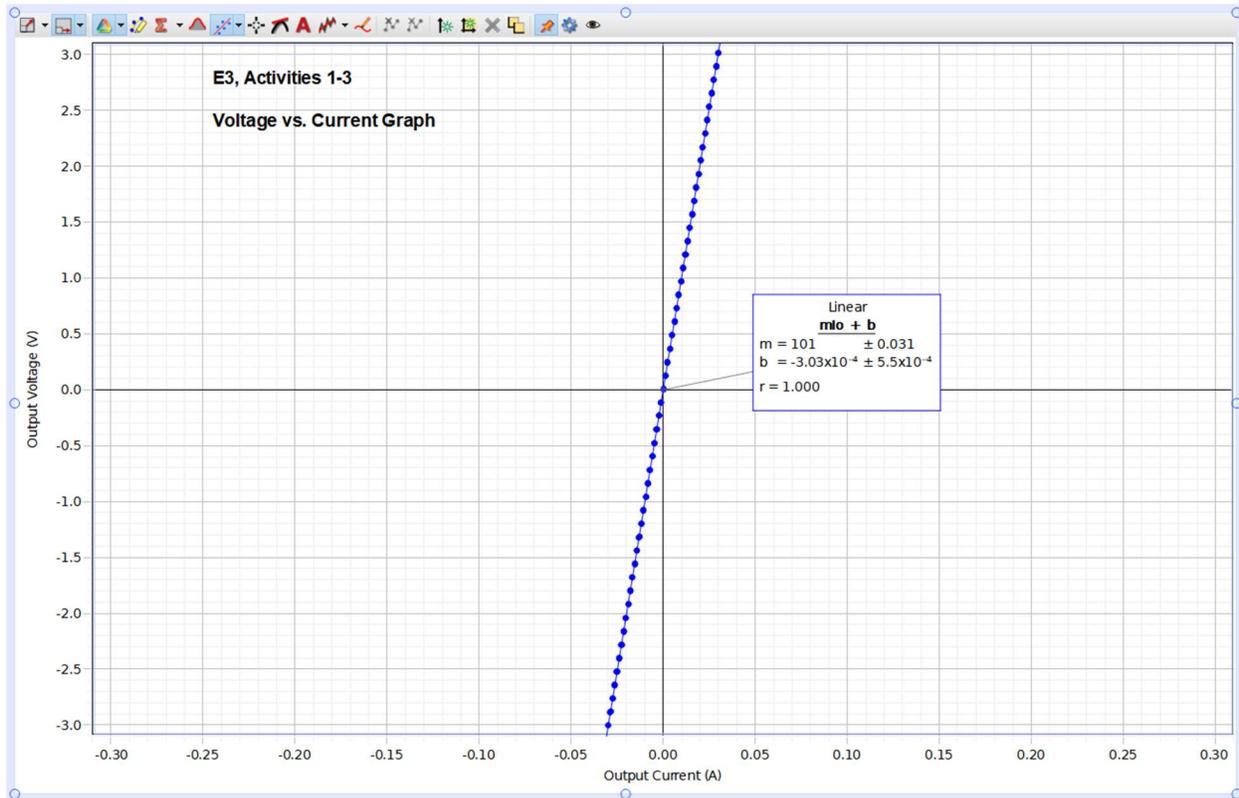


- 1.5. When you are ready to start collecting data, click on the  button located below the graph.
- 1.6. After 20 seconds, the computer will complete measurements and make an analysis of the stored data. The resistance may be calculated ($R = V/I$) for any value of the applied voltage. The resistance should not change with the change of the voltage (this is a linear or ohmic resistor). However, if we use many data points (80 in this case), the value of resistance will be measured with a better accuracy!

As we know from the theory section, voltage should be proportional to the current:

$V = RI$, therefore, the voltage vs. current graph is a straight line and R is the slope of that line. To get the value of resistance, the computer calculates a straight line fit to the experimental data. The equation of that line is given by: $V = \mathbf{m} \cdot \mathbf{I}_0 + \mathbf{b}$. The slope of that straight line is equal to \mathbf{m} , whereas the y-intercept is \mathbf{b} . According to Ohm's Law, \mathbf{b} should be very small ($\mathbf{b} = 0$, zero in theory, but the data interface, like all measuring devices, has limited accuracy and adds some experimental error) and \mathbf{m} is equal to the resistance \mathbf{R} .

- 1.7. If your data fits nicely on a straight line, copy the value of the resistance into the data sheet. The graph should look similar to this (except of the value of the slope). **Print** this graph.



- 1.8. From the value of the resistance R , calculate the resistivity ρ of the rheostat's wire:

$R = \rho \frac{l}{A} \Rightarrow \rho = R \frac{A}{l}$. First, you need to calculate the length l of the wire and the cross-sectional area of the wire A . Note that the wire forms a coil with known radius r . The values of r , number of turns and diameter d of the wire are given on the data sheets.

$$\left\{ A = \pi \left(\frac{d}{2} \right)^2 \right\}$$

- 1.9. Compare your value of ρ with the values given in the table (theory section) and find what metal was used to make the rheostat.
- 1.10. Computer should ask you if you would like to save changes. Do not save any changes.
- 1.11. **Lab Challenge 3.1. (Estimate the number of electrons)**

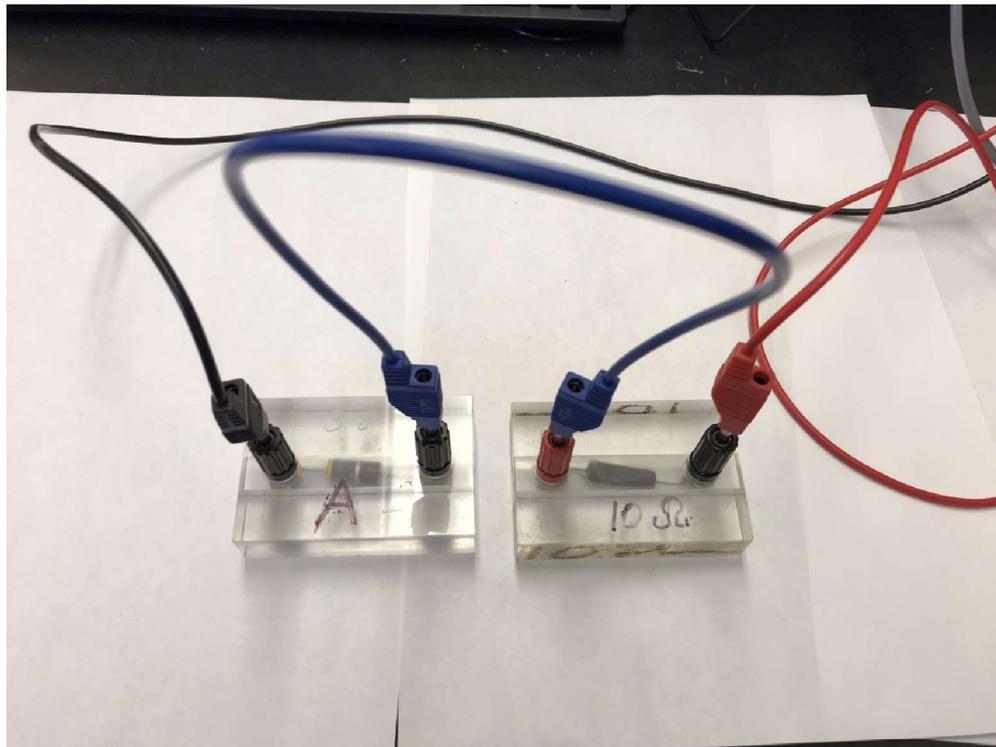
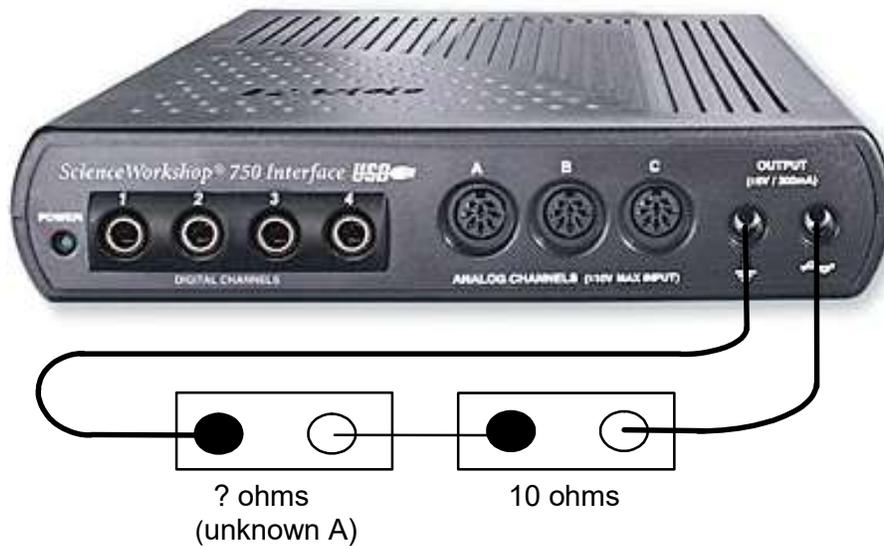
A relatively small current $I = 1.00$ mA is running through a cross section of a copper wire. Calculate the number of electrons running through the wire cross section per second.

Activity 2: Resistors in Series

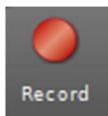
In this activity, you will need to arrange a $10\ \Omega$ and an unknown resistor **in series** using the following materials.

1. One $10\ \Omega$ resistor.
2. One resistor marked unknown A.
3. Three connecting wires.

You should try to set up this circuit yourself. However, if you need a little help, you may refer to the diagram below.

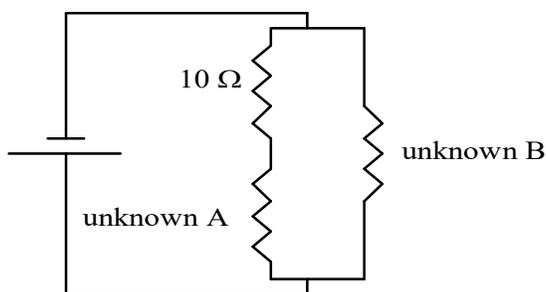




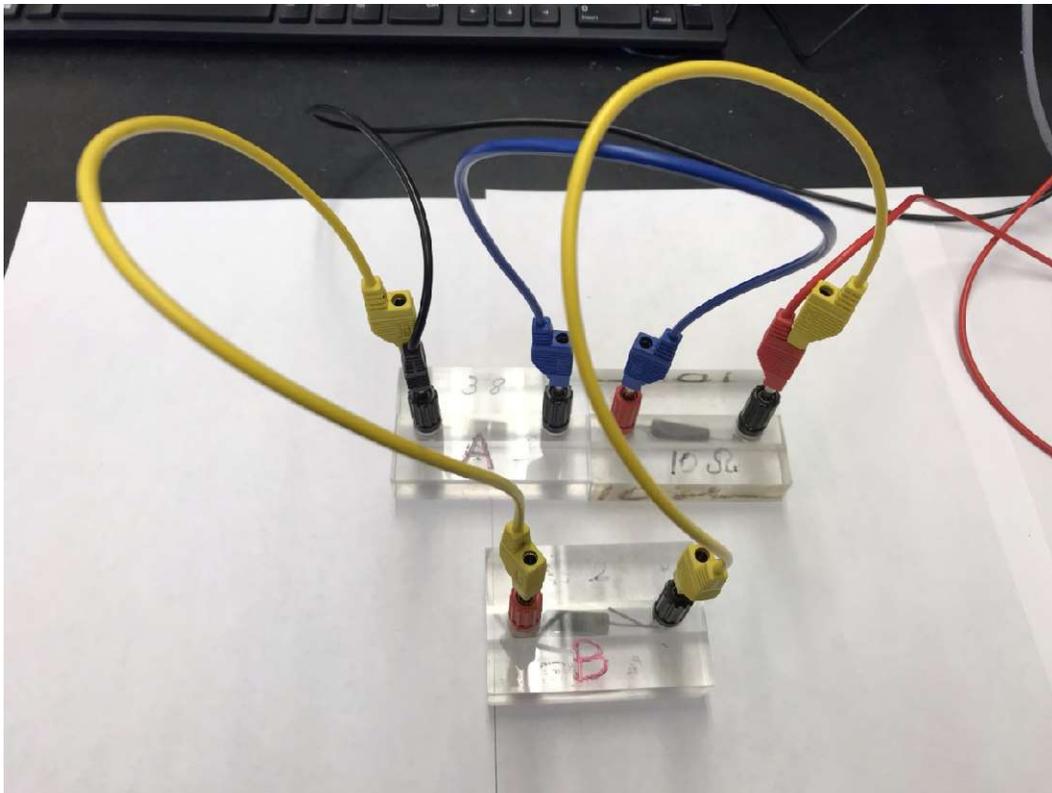
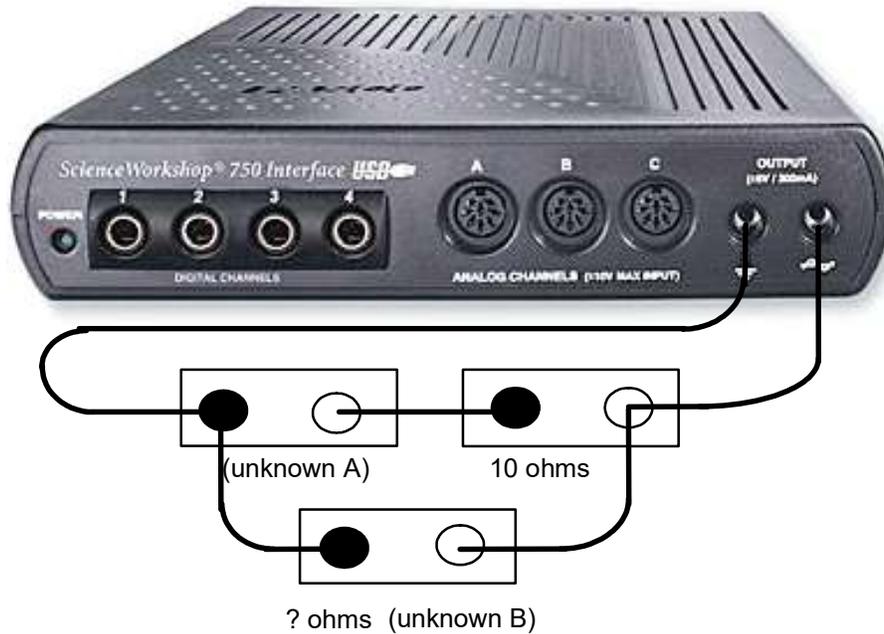
- 2.1. Click once on the  button to begin data acquisition. The computer will then record the current as voltage is slowly varied in the same way as for *Activity 1*.
- 2.2. After 20 seconds, the computer will stop taking data and you will be presented with a final voltage vs. current graph.
 - What is the shape of this graph?
 - On the data sheet, record the slope of this graph.
- 2.3. Do not disconnect wires.

Activity 3: Resistors in Parallel

You will now examine a circuit with resistors in parallel as in the diagram below.



You should try to set up this circuit yourself. However, if you need a little help, you may refer to the diagram below. In fact, it is a combination of resistors in parallel and in series.

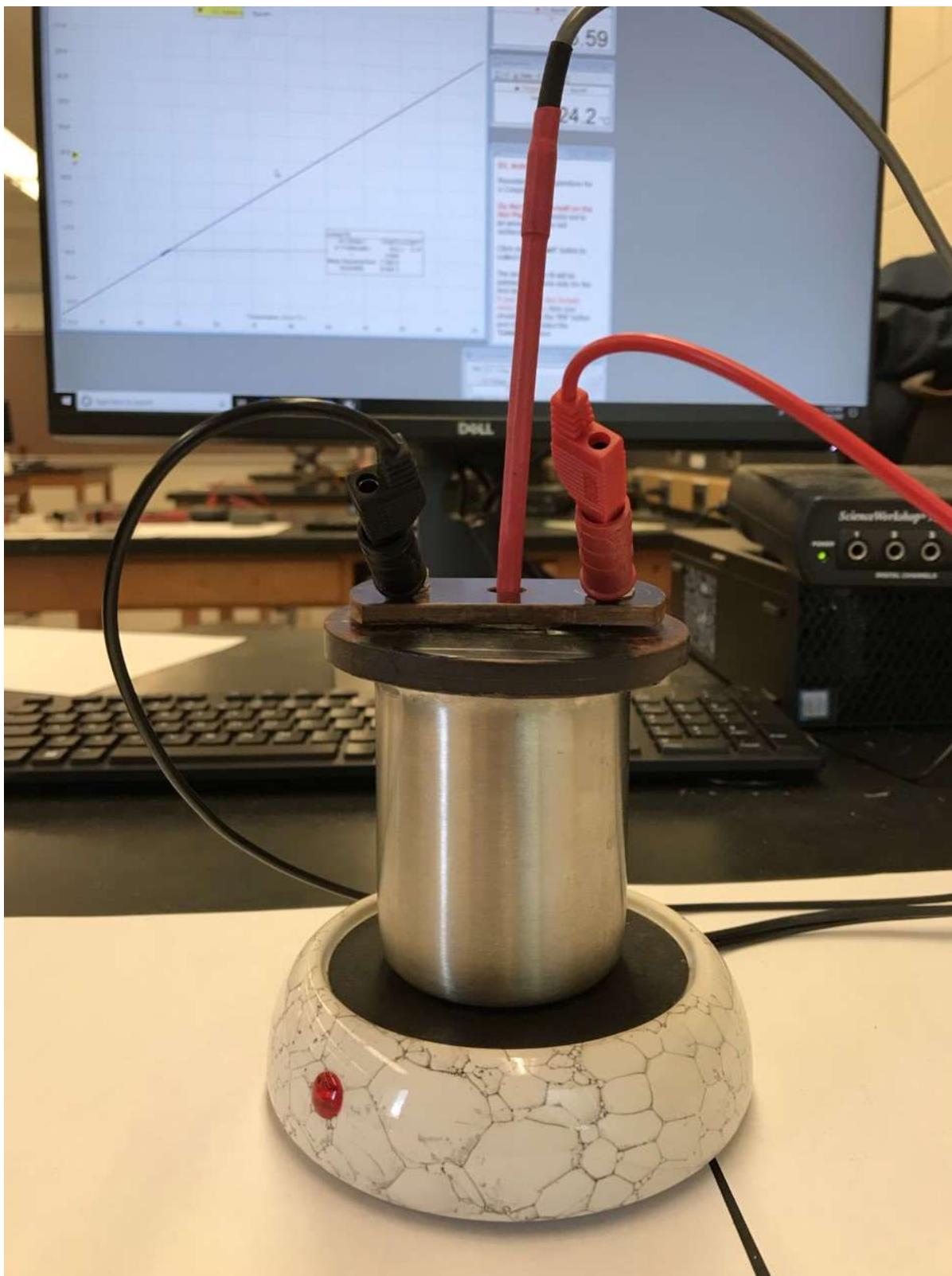


Record the voltage vs. current graph for the combination of these three resistors. The computer will collect data points just as it did in *Activity 2*. On the data sheet, record the slope of this graph, i.e., the total resistance for this combination of resistors. You may now disassemble your circuit. Exit Capstone application.

Activity 4: Resistance vs. Temperature for Metals

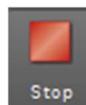
In this activity, you will examine the relationship between temperature and resistance for a **Copper wire**. Before you can begin taking measurements, the data interface OUTPUT” must be connected to the terminals on the top of the heating jar as shown below.





Once the terminals on the lid have been wired to the data interface, you may begin the rest of the activity.

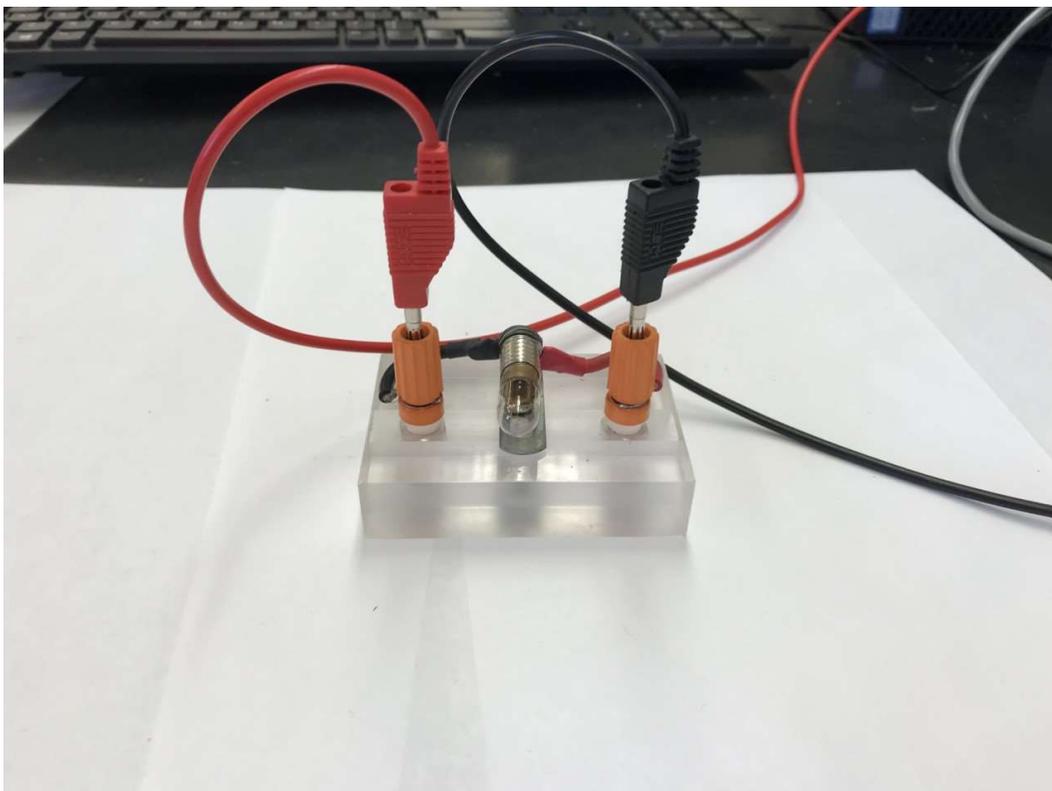
Find the document “E3, Activity 4” and double-click to open it.

- 4.1. Fill the metal container approximately $\frac{2}{3}$ full of water and place the lid on top. **Wait ~3 min.** to make the coil temperature even with the temperature of water.
- 4.2. Place the thermometer in the small hole in the center of the lid and push it all the way to the bottom of the hole. The thermometer is attached to Channel A of the signal interface. Place the container with the thermometer and copper wire on the top of the hotplate. Make sure that cables do not touch the hotplate!
- 4.3. Record the initial temperature (without heating) on your data sheet. Press the “Record” button. The computer will now plot the resistance and temperature points on the graph in front of you.
- 4.4. Now plug in the hotplate and turn it on (the on/off switch is located on the power cable). From this point on do not touch the hotplate or let the wires touch the hotplate. Be patient. This part of the experiment takes approximately 20-25 minutes to complete. It takes ~3-5 minutes before you will see any significant temperature change.
- 4.5. When the temperature reaches **45 °C** you should stop the data acquisition. Click on .
- 4.6. As soon as you stop collecting data **turn the hot plate off.** It will need time to cool down.
- 4.7. Examine your resistance vs. temperature (R vs. T) graph.
 - What is the shape of this R vs. T graph?
 - Is this the expected shape of the R vs. T graph?
 - On the data sheet, record the slope as well as the y-intercept.
- 4.8. From Print/Printing preferences, select landscape orientation and **print a copy of your graph.**
- 4.9. On your data sheet **calculate the temperature coefficient of resistance α .**
- 4.10. **Remove the container** with water and the copper coil from the hot plate. **Dump the water.**
- 4.11. Close the activity without saving any changes and quit the program. Do not unplug the thermometer from Channel A. Check again that the coffee warmer (our hotplate) **is turned off.**

Activity 5: Temperature of the Bulb's Filament

In this activity, you will estimate the operating temperature of the tungsten filament inside a typical 6.0 V incandescent light bulb.

- 5.1. Select “E3, Activity 5a” and open it.
- 5.2. Next, connect the light bulb to the data interface as in the diagram shown below:



- 5.3. Use *Activity 5a* to measure the resistance R_0 of the “cold” bulb (the filament is at the room temperature $T_0 = 20\text{ }^\circ\text{C}$). For that purpose, we will use a very small current. The value of the current used in *Activity 5a* is too small to “light” the bulb or even to increase the temperature of the filament noticeably.
- 5.4. Measure the resistance R_0 of the filament at the room temperature T_0 .
- 5.5. Leave the bulb connected to the computer interface and open “E3, Activity 5b”. In this activity, the current through the bulb’s filament will be much larger than that for Activity 5a. The applied current will start at zero and then gradually increase to the max. The maximum voltage applied is equal to 5.0 V.



- 5.6. Click on the  button. The computer will record and store the voltage vs. current curve for this bulb.

NOTE: **The resistance changes with the applied current!** The hot bulb is an example of **non-linear resistor**. Most of the semiconductor devices like diodes and transistors are also non-linear resistors. In this case the increase of current in the bulb increases the temperature of the filament. The warmer filament gets larger resistance resulting in a non-linear response to the current.

- 5.7. The resistance “meter” at the top of the screen recorded the last data point (the point when the bulb was at its brightest). That is the resistance of the hot bulb filament. Write this resistance on your data sheets.
- 5.8. Now, print this graph (click anywhere inside the graph window top make it active and select **Print** from the **File** menu).
- 5.9. Using the thermal resistance equation, $R(T) = R_0[1 + \alpha(T - T_0)]$, the measured resistance R_0 of the bulb at the room temperature T_0 , the resistance of the **hot** filament $R(T)$ and knowing that the filament is made of tungsten (for Tungsten: $\alpha = 0.0045/^\circ\text{C}$) calculate what is the temperature T of the hot, bright filament.

Make sure to complete the following tasks:

You must submit the answers to the prelaboratory questions online. (3.5 points)

1. Graphs from *Activities 1, 4 and 5*. (1.5 points)

(Title and write your name and those of your partners on each graph.)

2. Your completed Data Sheets. (5 points)

3. Return the completed lab report to your lab TA.